The Future Resilience of the UK Trunk Road Network

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Abstract

This thesis investigates the future resilience of the UK Trunk Road network, with the primary aim of determining the future impact of precipitation on the traffic flux. In order to make future Trunk Road adaptation strategies to address future climatic changes it is important to understand the resilience of the Trunk Road network to changing weather conditions and so this thesis significantly addresses this issue by investigating the impact of future weather conditions within the 2050s on traffic flux. The result and proposed methodology of this thesis could be used alongside further impact assessments where other factors such as changes in accident rate may be included to produce clearer impact projections. This thesis demonstrates that without taking into consideration changes in the drivers' behaviours which may result in changes in accident rate, future weather conditions are expected to improve traffic fluxes on the Trunk Road network during the summer and winter periods compared to the baseline weather condition (i.e. an observed or simulated weather data from 1961-1990). While most of the thesis is based on the conventional development system for the UK (the CDSU), it also investigates the impact of future weather conditions on traffic flux under other socio-economic scenarios. The investigation revealed that a more consumeristic scenario would generally experience higher rises in traffic capacity compared to the CDSU while a more community-oriented scenario would experience less rises in traffic capacity. In a paper by KPMG (2015) it was indicated that by 2030 connected and autonomous vehicles would be trending on the UK roads hence an investigation into the potential impact of autonomous vehicles on future traffic flux was carried out in this thesis. The investigation showed that the presence of autonomous vehicles would generally result in rises in the traffic flux and these rises will increase with increasing percentage composition of autonomous vehicles in the traffic stream. The sensitivity of the traffic stream to weather conditions also dropped with increases in the number of autonomous vehicles in the stream. The Northern and Southern parts of the UK have distinct weather conditions, with the Northern areas being generally wetter and cooler compared to the south. This resulted in both areas experiencing different weather conditions impact on traffic flux as shown in the result of investigating the effect of geographical location on future traffic performance. It was observed that during summer periods southern England appeared to observe higher rises in traffic flux compared to Northern Scotland while during the winter period Northern Scotland showed higher rises in traffic flux compared to Southern England.

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Firstly, I would like to express my sincere gratitude to my supervisors Prof. Chris Baker and Dr. Andrew Quinn for their continuous support of my PhD study and related research, for their patience, motivation, and immense knowledge. Their guidance helped me in all the time of research and writing of this thesis. I could not have imagined having better supervisors for my PhD study.

Besides my supervisors, I would like to thank the rest of my thesis committee: Prof. Miles Tight, and Dr. David Jaroszweski, for their insightful comments and encouragement, but also for the tough questions which incented me to widen my research from various perspectives.

Last but not the least, I would like to thank my family: my parents and to my brothers and sister for supporting me spiritually throughout writing this thesis and my life in general.

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List of abbreviations

aA: The observed vehicle’s acceleration when its target point is overshot
aB: The observed vehicle’s acceleration when its lead vehicle is pulling away
aC: The observed vehicle’s acceleration when its speed is constant, or it is approaching its lead vehicle.
accel: The observed vehicle’s current acceleration
CDF: Cumulative distribution function
CDSU: The conventional development system for the UK
CSV: Comma-separated values
DLC: Discretionary lane change
DVU: Driver Vehicle Unit
FHWA: The Federal Highway Administration
GHG: Greenhouse gas
HGV: Heavy goods vehicle
IPCC: Intergovernmental Panel on Climate Change
IWIS: The Integrated Weather Impact Simulation Tool
MATLAB: Matrix laboratory
max_accel: The observed vehicle’s maximum acceleration
max_velo: The observed vehicle’s maximum speed
mean_velo_cur: The mean speed of the current lane
mean_velo_left: The mean speed on the left lane
mean_velo_right: The mean speed on the right lane
MLC: Mandatory lane changes
OV: Observed Vehicle
PDF: Probability distribution function
refL: The observed vehicle’s lead vehicle on the left lane
refR: The observed vehicle’s lead vehicle on the right lane
ROI: The region of interest
UKCIP: United Kingdom Climate Impacts Programme
UKCP09: The UK Climate Projections 2009
velo: The observed vehicle’s current speed
velo_refC: The speed of the observed vehicle’s lead vehicle on the current lane
velo_refL: The speed of the observed vehicle’s lead vehicle on the left lane
velo_refR: The speed of the observed vehicle’s lead vehicle on the right lane
WG: Weather generator

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The traffic flux (flow rate) [8.48]

Chapter 1 – Introduction

1.1. Introduction

Global warming currently has a huge influence in today's environmental factors and this would potentially be the case for the next few decades. It's been known for a while now that global warming is currently on the rise due to anthropogenic activities associated with the emission of Greenhouse gases (GHG) hence various mitigation and adaptation strategies are being put forward to curb its impact.

Global warming would generally have negative impacts on road transportation affecting the behaviours of drivers through adverse weather conditions. For example weather conditions such as snowfall that result in reduced visibility and slippery road surfaces would have an impact on the acceleration, headway between vehicles, response time and speed of the vehicle resulting in higher journey times and reduced traffic capacity (Asamer, 2011; Chung et al., 2006; Amison-Agbolosu, 2004) and lower temperatures can result in higher traffic demand as more vehicles tend to be used during this condition resulting in increased traffic congestion. Slippery conditions and general increased hazardous conditions on the other hand can result in drivers seeking alternative transportation means (such as mass transit) to get to their destinations to avoid accidents (Maze et al., 2006; Asamer, 2011). Traffic safety decreases under adverse weather conditions for example high temperatures have been found to increase fatigue (Zohar, 1980) and affect the irritability (such as aggression) of drivers (Anderson, 1989; Boyanowski et al., 1981). Weiner & Hutchinson (1945) suggested an increase in drivers' reaction time while Stern & Zehavi (1990) suggested a reduction due to loss of concentration leading to crashes.

To make future Trunk Road adaptation strategies to address future climatic changes it is important to understand the resilience of the Trunk Road network to changing weather conditions. This thesis seeks to address the future impact of weather conditions on traffic flux in the 2050s by investigating the impact on traffic flow based on the conventional development system of the UK (the CDSU), how changes in the development system may impact the flow, the impact of technological advancements on the flow as well as the impact of geographical location on the flow.

Using axes is a simplified way of having an insight into the relationship between the two dimensions of change as various possible scenarios could be explored by adjusting the proportion of contribution of each axis. The horizontal axis captures two different socio-economic values which are consumerism where private consumption is primary and community where everyone works together for a common goal. The vertical axis captures two different government natures. One end of the spectrum captures an interdependent government that is inclined towards local unions and the global society while the opposite end captures an autonomous government where decision making depends entirely on its own laws. An Interdependent government would be likely to show more sensitivity towards global issues that have global impacts such as global warming while an autonomous government would be less likely to show much sensitivity towards such issues. Although the UK is currently part of the EU and some of its decisions are influenced by EU laws BREXIT may not necessarily mean the government's lower sensitivity towards global issues. Being a technologically advanced country would also have an impact on issues such as sustainable growth because a technologically advanced country would have better awareness about global issues as opposed to a less technologically advanced country where sustainable growth may not necessarily be much of a concern.

The CDSU favours more of consumerism than community meaning more private consumption than public consumption. Generally, this means individuals would seek to utilise privately owned properties rather than public properties meaning more privately-owned vehicles are expected to be on the road. It was indicated on DFT (2016) that as of 2014 the ratio of cars to HGVs on the UK road was 16:1. For a more consumeristic oriented scenario it was assumed that the ratio of cars to HGVs would be more in favour of the cars while for a community-oriented scenario it was assumed that the ratio would be less than the CDSU. The values in the ratio may vary but for this thesis a value of 24:1 and 8:1 were used for the consumeristic and community-oriented scenarios respectively.

The result and proposed methodology of this thesis could be used alongside further impact assessments where other factors such as changes in accident rate, demographic and economic growth may be included to produce clearer impact projections.

Highways England, which was formerly referred to as the Highways Agency is the UK government owned entity in charge of operating and improving the 4,300 miles of motorway and major A-roads forming the strategic road network which is one of the country's most important infrastructure assets. A resilient and effective strategic road network is an important aspect of a strong growing economy. Climate change poses a major threat to the operation of the UK strategic road network which is why Highways England is currently engaged in minimising the causes and managing the risks involved with it. Among other activities, doing so involves carrying out research projects related to resilience, adaptability and sustainability of the network. This thesis provides valuable knowledge in these core areas to both Highways England and their partner stakeholders which include owners of other UK infrastructure systems, freight organisations, local authorities, technology and innovation partners, sustainability and environmental bodies and motorway service operators.

1.2. Aim and Objectives

1.2.1. Aim

The aim of this thesis is to investigate how future weather conditions would affect traffic capacity on the UK Trunk Road network. This work has been made possible by the availability of UK Climate Projections tool which was produced in 2009 (UKCP09). It utilises existing weather data and random number sampling to develop lengthy time series of statistically credible daily and hourly weather data using the 5km daily observed or simulated baseline weather condition of 1961-1990.

1.2.2. Objectives

The Objectives of this thesis are:

- To investigate the impact of projected future weather conditions on the UK road network under the Current Development system of the UK.

  How would changes in the weather conditions affect the traffic flux?

- To investigate the impact of changes in the Current Development System of the UK on the future traffic flux

  Would changes in the current government nature and socio-economic values have an impact on the future traffic flux under future climate?

- To investigate the impact of technological advancements in the UK on future traffic flux

  Would the introduction of autonomous vehicles on the UK road network have a significant impact on the future traffic flux?

- To investigate how the traffic fluxes for different geographical locations of the UK may be affected by future weather conditions

  How would the future traffic flux of various geographical locations in the UK respond to changes in the weather condition?

1.2.3. Structure

This paper structure is as follows:

Chapter 2 starts off by discussing the impact of weather conditions on road networks, reviewing studies on various countries from various researchers and relating them to the UK road network. It considers the major factors of extreme weather and their impact on road networks. It then went on to discuss traffic flow modelling and various modelling tools that were considered during the research as well as the fundamentals of traffic flow. The factors affecting the future of road transport were then discussed, they were split into Independent factors where the factors of change and their relationship to the Conventional Development system of the UK was addressed and dependent factors where economic and demographic growth as well as technological advancements and their potential impacts were discussed.

Chapter 3 then discusses the traffic flow algorithm used which was a microscopic traffic flow model based on Paramics car following algorithm, the UK Highway Code, an innovated collision detection algorithm, an innovated lane changing algorithm and Rakha et al. (1999)'s vehicle dynamics model for estimating maximum truck acceleration levels. This discussion also includes the traffic analysis as well as validation based on the fundamental traffic flow diagram.

Chapter 4 examines the UKCP09 weather generator, its output weather data, the various emissions scenarios, how the tool was effectively used to generate hourly weather data, the limitation of the tool as well as suggestions to compliment the limitation. The weather data was consistent with the general projection of future dryer summer months and wetter winter months.

Chapter 5 then discussed the Integrated Weather Impact simulator (IWIS) which was used to integrate the generated weather data and the traffic flow output data. It discusses the variables of the weather data that were utilised as inputs, the user inputs, how the traffic data was utilised and how the input data were synchronised to produce various simulation output data in the form of distribution functions.

Chapter 6 looks at the effect of weather on traffic performance by examining the results of the simulations carried out using the IWIS. It discusses the impact of the projected future weather conditions on traffic flux under the CDSU, the potential impact on traffic flux if the CDSU was altered, the impact of technological advancement on traffic flux and how the traffic fluxes of different geographical locations of the UK may be affected.

Chapter 7 finally summarises the results of the research and concludes the thesis

Chapter 2 – The Literature Review

2.1. Weather and Road Transportation

2.1.1. The Impact of weather conditions on road networks

2.1.1.1. Precipitation and road traffic

Traffic flow and speed are affected by precipitation leading to increase in journey times which would most likely be exacerbated in the future should there be rises in precipitation levels. A study by Keay and Simmonds (2005) on Melbourne roads, Australia showed that rainfall especially during winter and spring had the greatest impact on traffic volumes. A similar study by Akin et al. (2011) on urban motorways in Istanbul showed a similar result. These studies along with studies by Hooper et al. (2012) and El Faouzi et al. (2010) also pointed out that inclement weather especially rainfall led to significant speed reductions and increased traffic congestion while snow led to a significant reduction in the demand for the road hence a reduction in traffic volume. Khattak and Knapp (2000) examined Iowa motorway data and discovered that traffic volumes on the motorway reduced by 30% during snowy conditions compared to normal dry conditions and rainy conditions. This was also discovered by ElDessouki et al (2004) during an examination on accident risk on Connecticut motorways. While most studies were concentrated on motorways, Keay and Simmonds (2005) study was focused on an urban area in Melbourne while Hooper et al. (2012) study although it did include several sections which passed through urban areas, it was more focused on a motorway between London and Glasgow in the UK. It was discovered in both urban studies that increased rainfall led to reduction in speeds and increased traffic congestion, this result is like the studies carried out on motorways, but the speed reductions are less significant on the motorways as pointed out in a literature review by Pisano and Goodwin (2004) regarding weather effects on urban arterials.

Studies from all over the world (Ibrahim and Hall, 1994; Maze et al., 2006) including the UK (Hooper, 2013; Smith K., 1982) have shown that inclement weather conditions have negative effects on traffic flow. Their effects were split into two main categories by Jaroszweski et al (2014) which are those effects that occur because of behavioural changes to driver due to the stress induced by weather and those that are influenced by physical failure of the infrastructure or by the set off of natural disasters such as low temperature induced potholes. The behavioural changes may include reduced speed, acceleration, start-up times and wider gaps between moving vehicles in a traffic stream (Amison-Agbolosu and Sadek, 2004). These behaviours are due to factors that occur during inclement weather conditions such as reduced traction and visibility.

Several studies (Ibrahim and Hall, 1994, Agarwal et al., 2005, Kyte et al., 2001) have been carried out to determine the degree of speed reductions under several inclement weather conditions at various intensities. The study by Ibrahim and Hall (1994) which was focused on a motorway showed that there was a speed reduction of approximately 2km/hr when it rained slightly and 3km/hr when it snowed slightly while when it rained heavily there was a speed reduction of up to 10km/hr while heavy snow resulted in speed reduction up to 50km/hr. A summary of Ibrahim et al's findings is shown in the table 2.1. The Federal Highway Administration (FHWA, 1977) in the US offered a weather classification scheme to the study of the impact of precipitation on motorway systems. The classification ranged between dry roads with a percentage speed reduction of 0% and snow packed road with a percentage speed reduction of 42%. Maze et al. (2006) discovered that when visibility was less than 0.25 miles, a 12% reduction in speed was maintained in the Minneapolis / St. Paul area for over a four-year study period. A summary of the FHWA data is shown in the table 2.2. Kyte et al. (2001) explicitly defined a critical visibility distance of 0.3 km (0.18 mile), below which speed was reduced by 0.77 km/hr (0.48 mph) for every 0.01 km (0.0062 mile) reduction in visibility.

Agarwal et al (2005) carried out a research on quantifying the impact of rain, snow and pavement surface conditions on traffic flow. They estimated the relationship between highway capacity and traffic speed on congested freeways in the Minneapolis/St. Paul (the Twin Cities) metropolitan area where they utilised freeway traffic in-pavement system detectors data collected from a four-year period, weather data from three Automated Surface Observing Systems (ASOS) and five RWIS sensors. Results from this research indicated that severe precipitation (mainly rain and snow) and visibility impairment resulted in the most significant speed and capacity reductions (Agarwal et al., 2005). The findings are summarised in the table 2.3.

Agbolosu-Amison and Sadek (2004) referred to a report by Bernardin Lochmueller and Associates, Inc. (1995), the report was the result of an assessment on the speed variations and saturation flows during inclement weather conditions on a network containing 24 signals. Measurements of several traffic parameters (such as startup lost times, speed and saturation flow) were taken during average summer conditions and average winter conditions. Their report showed that the signalling time used for summer conditions were not satisfactory for winter conditions (inclement weather conditions). They suggested that travel time during inclement weather conditions could be reduced by up to 13% and average delay by up to 23% if purposely designed signalling times were used during inclement weather conditions (Agbolosu-Amison and Sadek, 2004).

Weather Events		Speed Reduction
Rain	Light rain	1.2 mi/h (free-flow speeds) 10% at a flow rate of 2,400 veh/h
	Heavy rain	3 to 4 mi/h (free-flow speeds) 16% at a flow rate of 2,400 veh/h
Snow	Light snow	0.6 mi/h (free-flow speeds)
	Heavy snow	38%

Table 2.1: Speed reduction in inclement weather (Ibrahim and Hall, 1994)

Pavement Condition	Speed Reduction (%)
Dry	0
Wet	0
Wet and snowing	13
Wet and slushy	22
Slushy in wheel paths	30
Snowy and sticking	35
Snowing and packed	42

Table 2.2: Speed reduction in inclement weather (FHWA, 1977)

Weather Variable	Intensity (inch/hour)	Percentage reduction in capacity compared to Clear	Percentage reduction in speed compared to Clear
Rain	0	0	0
	0-0.0.01	2%	2%
	0.01-0.25	7%	4%
	>0.25	14%	6%
Snow	0		
	<=0.05	4%	4%
	0.06-0.1	9%	8%
	0.11-0.5	11%	9%
	>0.5	22%	13%

Table 2.3: Average impact of precipitation on speed and capacity (Agarwal et al., 2005)

2.1.1.2. Precipitation and acceleration

In a paper by Asamer et al. (2011) it was pointed out that precipitated conditions (such as rainfall and snow) result in slippery road surfaces which tends to reduce the friction between road surfaces and tires hence drivers tend to decelerate or accelerate more slowly compared to dry conditions specially to avoid skidding. It was also indicated that that lower acceleration rates are expected of moving vehicles compared to vehicles accelerating from the stop line. It is agreed that there is a relationship between maximum acceleration and weather conditions (FHWA, 2004) although no paper has explicitly identified these relationships. Hoogendoorn et al. (2011) identified a relationship between the speed of the lead vehicle, the action point (i.e. response point of the following vehicle) of the following vehicle and the acceleration of the following vehicle. He concluded that following vehicles are less sensitive to speed changes of their lead vehicle under foggy conditions because of low visibility affecting their perception of their lead vehicle.

Although explicit relationships between weather conditions and driver's maximum acceleration have not been identified by any author the relationship between start-up loss time and weather conditions have been analysed. FHWA (2009) indicated that the start-up loss time increases significantly with the severity of the road conditions with the highest start-up loss times occurring when slush accumulates on the pavement surface. Increase in start-up loss time has been known to occur during reduced visibility, and reduced pavement friction. Lieu and Lin (2004) identified a 20% increase in start-up loss time during wet and slushy weather conditions while Maki (1999) identified a start-up loss time increase of 2-3sec under inclement weather conditions after an experiment.

An extensive review on the impact of weather on road transport was discussed in appendix 1.

2.2. Traffic flow modelling

Traffic flow models are tools often used in the study of real-world traffic systems. Given certain demand levels they may be used to determine when queues will build up, the length of the queues, the propagation of the queues in terms of time and space and the duration of the congestion. Depending on the level of detailing traffic flow models may be classified into macroscopic, mesoscopic and microscopic models. With macroscopic method, entities, their activities and their interactions are described at a low level of detail (Mathew, 2014). An aggregated measure is used to represent traffic stream in terms of characteristics such as speed, flow and density. They are more suitable for short-term forecasting in the context of network-wide coordinated traffic management. They are applicable in the development of dynamic traffic management and control systems, designed to optimise the traffic system and can be used to estimate and predict average traffic flow operations (Hoogendoorn and Knoop, 2019).

With microscopic models' entities, their activities and their interactions are described at a higher level of detail (Mathew, 2014) while mesoscopic falls in between macroscopic and mesoscopic models and views vehicles in groups. Unlike the macroscopic method, the microscopic method attempts to analyse traffic flow by modelling the interaction between drivers (driver-driver interaction) and the interaction between drivers and roads (driver-road features (such as traffic light) interaction). They are suitable for Intelligent Transportation Systems (ITS) applications, such as dynamic traffic management and route guidance which are now seen as important tools for traffic management. These applications involve the broadcasting of information from a traffic management centre to DVUs and deployment of management and control schemes. The only realistic modelling approach for the impact of information and control strategies on the traffic flow is by considering the response of the individual drivers to the information. An example is the modelling of drivers' response signs and lane change behaviour to evaluate different response strategies that require the use of lane use signs. Microscopic simulation models are often used in such applications as they represent the behaviour of individual drivers in detail. The detailed level of behaviour modelling in microscopic simulation models is particularly critical when disaggregate relations between vehicles are more important than aggregate traffic flow characteristics. An example is the study of safety impacts, for which headway distributions, frequency of emergency braking and the number and locations of lane changes may provide better indication of the impact on safety of different geometric design plans than aggregate measures such as average speed, flow and density (Toledo et al, 2015).

Microscopic traffic flow models are generally split into two main components:

- The car following model
- The lane changing model

2.2.1. Car following models

Car following models are used to represent how a following vehicle follows a lead vehicle in an uninterrupted traffic stream. The reaction of drivers to changes in the position of the lead vehicle have been formulated by various models such as Paramics, General Motors, Forbes, Pipes, and Optimal velocity model (Matthew, 2019). Car following models are generally classified into three main groups:

Car following models are generally grouped into classes depending on the logic they are based on. Some of these classes include:

- *Gazis-Herman-Rothery models (GHR)*: Models under this classification assume that the acceleration of the following vehicle is proportional to its speed, the speed difference between itself and its corresponding lead vehicle and the space headway between them. An example is the Optimal Velocity model. MITSIM traffic flow model software package uses a car following model in this class.
- *Safety-distance models*: These models assume that the following vehicle always keeps a safe distance from their lead vehicle. Examples include the Pipe's model and General motors' model. AIMSUN traffic flow model software package uses a car following model in this class.
- *Psycho-physical car-following models*: These models use thresholds for various parameters such as the minimum speed difference between follower and leader perceived by the follower. Examples include the Fritzsche model and Forbes' model. VISSIM and Paramics traffic flow model software packages use a car following model in this class.

A general limitation of the GHR and the Safety-distance models is that they both require the following driver to always have an absolute knowledge of its lead vehicle speed and position at any given time rather than a more realistic approach found in the psycho-physical car following models which involves the perception of these parameters by the following vehicle using thresholds rather than absolute values. Paramics (discussed later) which is based on the Fritzsche car following model was chosen for this reason.

2.2.1.1. Pipe's model

Pipe's model assumes that the minimum safety distance increases with speed and that a driver should allow at least a car length between their vehicle and their lead vehicle for every ten miles per hour of speed at which they are travelling. The limitation of this model is that the minimum headway proposed by this model are significantly less than the corresponding field measurements at low speed (Matthew, 2019).

2.2.1.2. Forbes' model

Forbes' model considers the reaction time that the following vehicle need to perceive it needs to decelerate hence the time gap between the follower's front bumper and the leader's rear bumper should always be equal to or more than the reaction time of the following driver. This mean that the minimum time headway should be equal to the reaction time and the total time the lead vehicle needs to cover a distance equal to its length. Like Pipe's model the limitation to this model is that at low and high speeds there is a wide difference in the minimum distance headway (Matthew, 2019).

2.2.1.3. Optimal Velocity model

Optimal Velocity model assumes that each driver in the traffic stream attempts to achieve an optimal velocity relative to the distance of their corresponding lead vehicle and the speed difference between itself and its lead vehicle. It assumes that the desired speed depends on the distance headway (Matthew, 2019).

2.2.1.4. General motors' model

This model is based on follow the leader concept which is based on the assumptions that the higher the speed of the following vehicle, the higher the spacing between the lead and following vehicles and a following driver must maintain a safe distance to avoid collision with its lead vehicle (Matthew, 2019).

2.2.1.5. The Fritzsche's model

The car following model featured in Paramics (discussed later) is based on the psycho-physical model developed by Fritzsche and the differences between both models are not publicly known (Olstam and Tapani, 2004). The Fritzsche model takes human perception into account in its definitions. For example, the following driver would only perceive speed differences if they are above a certain threshold. The speed thresholds are classified into thresholds for negative and positive speed differences and drivers are assumed to observe smaller negative speed differences than positive. In addition to the speed difference thresholds, four thresholds for the follower's space headway to its leader are also used (Olstam and Tapani, 2004).

2.2.1.6. Paramics

Paramics car following model is a psycho-physical car following model which utilises thresholds for various parameters such as separation between the leader and the follower as perceived by the follower.

In paramics drivers are given memories which hold their speed at some point in the past as well as their position, since their speed is based around the speed of the lead driver-vehicle unit (DVU) they can decide what their current speed would be based on their memory of previous speed and position. Each driver is also given a *headway* which they try to attain by varying their speed. More aggressive drivers accept smaller headways while drivers with more awareness accept longer headways.

Paramics car following model has three modes based on the following car's perception of the speed of the lead vehicle. They are Braking, cruising and acceleration modes. Figure 2.1 shows a diagrammatic overview of the relationship between the lead and following vehicle in a traffic stream.

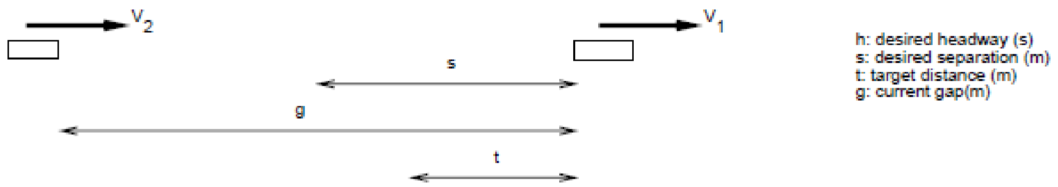


Figure 2.1: Diagrammatic overview of the relationship between the lead and following vehicle (Duncan, 1998)

The following vehicle varies the separation between it and the lead vehicle until its target point is achieved as shown in figure 2.1. Various parameters were calculated as:

$$s = h\Delta V \qquad [2.1]$$

$$\Delta V = V_1 - V_2 \qquad [2.2]$$

$$t = \frac{s^2}{g} \qquad [2.3]$$

$$c = k_1 \frac{g - 2.0}{g} \qquad [2.4]$$

Where *s* is the separation between both vehicles, *DV* is the difference between the speed of the lead vehicle at some point in time and the current speed of the following vehicle, *t* is the target point to be achieved by the following vehicle, *g* is the gap between both vehicles, *c* is a bunching acceleration used to bring vehicles faster together and k_1 is a constant given as $1.0s^{-2}$ (Duncan, 1998).

2.2.1.6.1. Cruise mode

The following vehicle possesses three types of acceleration when in this mode. They are (Duncan, 1998):

Target point overshot: This acceleration is triggered when the headway is lower than the desired value and an attempt is made to achieve the desired speed as soon as possible hence the DVU starts decelerating.

$$a_A = k_2 \Delta V \qquad [2.5]$$

Lead DVU pulling away: This acceleration is triggered when the lead DVU's speed is sufficiently higher than the following DVU's speed that their separation starts increasing.

$$a_B = k_2 \Delta V + k_1 \frac{g - t}{t} \qquad [2.6]$$

Constant speed or coming together: This acceleration is triggered when the lead DVU is travelling at a constant separation or both DVUs were coming together

$$a_C = c - \frac{(\Delta V)^2}{g - t} \qquad [2.7]$$

k_1 and k_2 are constants given as $1.0s^{-2}$ and $1.0s^{-1}$ respectively (Duncan, 1998).

2.2.1.6.2. Braking and maximum acceleration modes

Brake: The following DVU brakes when it perceives the lead DVUs deceleration is greater than a certain threshold. This mode was not explicitly defined on the paramics technical report hence a method related to the given information was used when modelling.

$$a_D = k_3 \qquad [2.8]$$

Where k_3 is a constant given as $1.0ms^{-2}$

Maximum acceleration: Maximum acceleration is triggered by the following DVU when it perceives the lead DVU to be accelerating at a high rate and its position is greater than the following DVU's safe stopping distance.

$$a_E = a_{MAX} \qquad [2.9]$$

The maximum acceleration the driver is willing to utilise

The maximum acceleration of DVUs under various weather conditions was modelled using Rakha et al. (1999)'s vehicle dynamics model for estimating maximum vehicle acceleration levels based on vehicle's tractive effort and aerodynamic, rolling and grade resistance forces. Although Rakha et al. (1999) designed their model for trucks; Snare (2002) study showed that the model could also be effectively applied to lighter vehicles. The model and its implementation were extensively explained in chapter 3.

2.2.2. Lane Changing model

Lane change is referred to as the movement of a vehicle from a given lane to another lane. It is very important on traffic flow hence lane changing models are important components in microscopic traffic simulators which are very important in traffic-related applications at the operational level. Lane changing modelling is a lot more complex and challenging compared to car following modelling because car following models require only the speed and location of the lead vehicle while lane changing models considers the decision to change lane which considers several objectives that sometimes conflict. Gap acceptance models are used to model the execution of lane changes and a lane change is only executed if the available gap is more than the smallest acceptable gap. Gaps are referred to in terms or time or free space. Lane changing model is discussed extensively in section 3.2.4.

2.2.3. Fundamentals of traffic flow

Road traffic is characterised by the traffic flux (flow rate), the density and the mean speed. Immers and Logghe (2002) described the fundamental road traffic flow characteristics using figure 2.2.

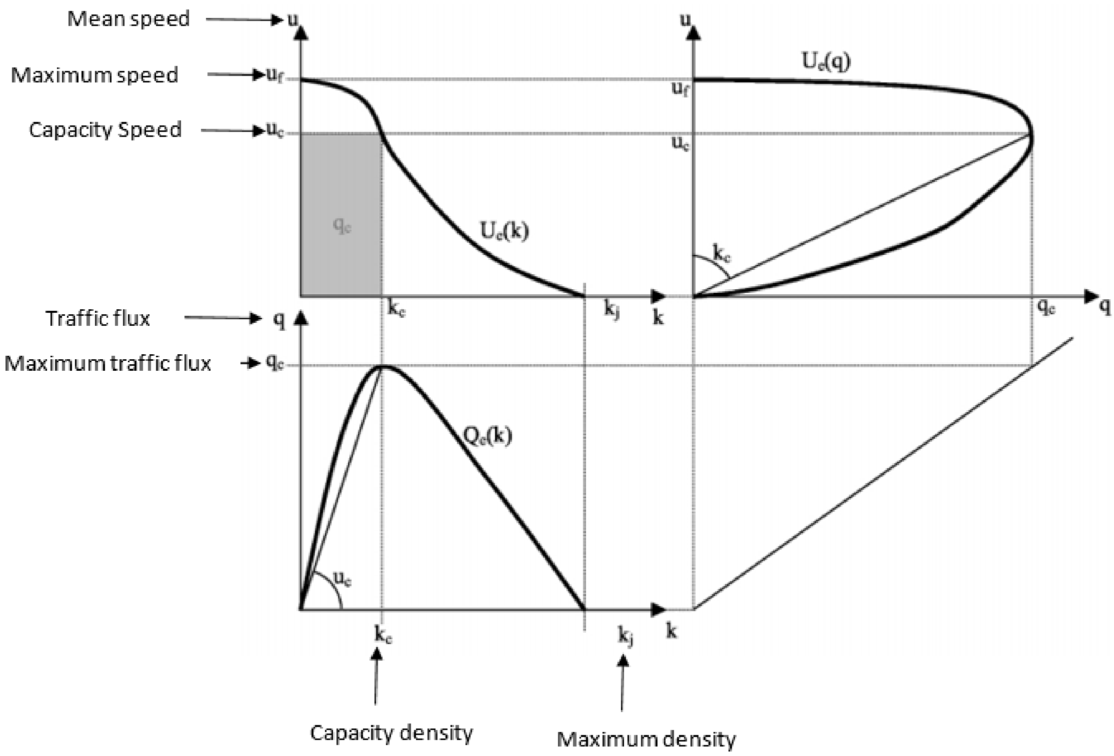


Figure 2.2: The three related road traffic flow fundamental diagrams (Immers and Logghe, 2002)

Figure 2.2 relates the mean speed (u) along a given link to its density (k). The traffic flux (q) along the link is the product of the mean speed and the density. It was plotted on the k-q figure as an angle while an area was used to represent it on the k-u figure. Immers and Logghe (2002) pointed out that a stationary and homogeneous traffic state can always be located along the curves of the fundamental diagrams. The states of a given traffic which are usually of major concern are:

2.2.3.1. Free flowing traffic

At this state DVUs travel freely at a maximum speed of u_f and are not impeded by other traffic. The maximum speed (free speed) depends on the speed limit of the link, speed restrictions during operation at any given time and weather conditions. The density of the link and its traffic flux would be close to zero during free speed (Immers and Logghe, 2002).

2.2.3.2. Saturated traffic

When a link is in this state its traffic flux and mean speed would be close to zero as a result of the DVUs queuing and as a result of the maximum density k_j (jam density) of the link reached (Immers and Logghe, 2002).

2.2.3.3. Capacity traffic

The capacity of a link is defined as its maximum traffic flux q_c. The maximum traffic flux (q_c) has a corresponding capacity speed (u_c) which is located below the maximum speed (u_f) and a capacity density (k_c) (Immers and Logghe, 2002).

2.3. Factors affecting the future of road transportation

To project the shape of future (2030+) road transportation in the UK it is important to consider various factors that are likely to affect the outcome of the transportation system. These factors could be grouped into:

- Fundamental/Independent Factors
  - The Nature of Governance
  - The Social and Political Values
- Dependent Factors
  - Economic growth
  - Demographic growth
  - Technological advancement

2.3.1. Fundamental/Independent Factors

Change is a general factor that would affect the future of transportation. "*It is axiomatic nowadays to say that change is a constant*" (Victor and Franckeiss, 2002). It is often viewed in terms of dimensions as this provides a robust, integrated and pragmatic approach in understanding the dynamics of the change process.

Although the dimensions of change may vary depending on the application Jaroszweski (2010) explained in his thesis that the fundamental and independent determinants of future change in a society are its 'social and political values' and 'nature of governance' (the

Interest of the organisation). It was explained in a paper on ‘Socio-economic scenarios for climate change impact assessment’ by UKCIP (2000) that economic, demographic and technological change are the main outcomes of the relationship between the fundamental and independent determinants.

Using axes is a simplified way of having an insight into the relationship of two dimensions as various possible scenarios could be explored by adjusting the proportion of contribution of each axis. Figure 2.3 shows four socio-economic scenarios, and a conventional development system for the UK. The horizontal axis captures two different socio-economic values. One end of the spectrum captures consumerism where private consumption and personal freedom are primary values with individual rights and the present favoured over the community goals and the future. The opposite end of the axis captures community where everyone works together for a common goal, the future is favoured over the present and resources are allocated based on personal needs. Under consumerism private vehicle ownership would be a trend resulting in the possibility of higher traffic congestion while under community public transport would be more relied on resulting in lower traffic congestion.

The vertical axis captures two different government natures. One end of the spectrum captures an interdependent government that is inclined towards local unions (the UK is currently part of the EU and some of its decisions are influenced by EU laws) and the global society while the opposite end captures an autonomous government where decision making depends entirely on its own laws. An Interdependent government would be likely to show more sensitivity towards global issues that have global impacts such as global warming while an autonomous government would be less likely to show much sensitivity towards such issues.

Figure 2.3: The UKCIP socio-economic scenarios (Jaroszweski, 2010)

2.3.1.1. Global warming

Due to the nature of the UK government global warming is currently an issue being actively addressed nationwide. Legislations by the EU as well as the UK local legislations have led to various campaigns currently being carried out across the UK to curb Global warming and its impacts (such as Recycle now (Recyclenow, 2016) and Clean British energy (FOE, 2016) campaigns).

Global warming currently has a huge influence in today's environmental factors and this would potentially be the case for the next few decades. It's been known for a while now that global warming is currently on the rise due to anthropogenic activities associated with the emission of Greenhouse gases (GHG) hence various mitigation and adaptation strategies are being put forward to curb its impact. According to IPCC (2014) CO_2 was the highest Greenhouse gas emitted between 1970 and 2010 this is quite evident due to the world's dependence on fossil fuel within the period. Figure 2.4 shows the Total Annual Anthropogenic GHG Emissions by Groups of Gases 1970 – 2010. From the figure GHG emission was on the rise within this period. IPCC (2014) indicated that globally, the main factors influencing the rise in CO_2 emissions from fossil fuel combustion are economic and population growth.

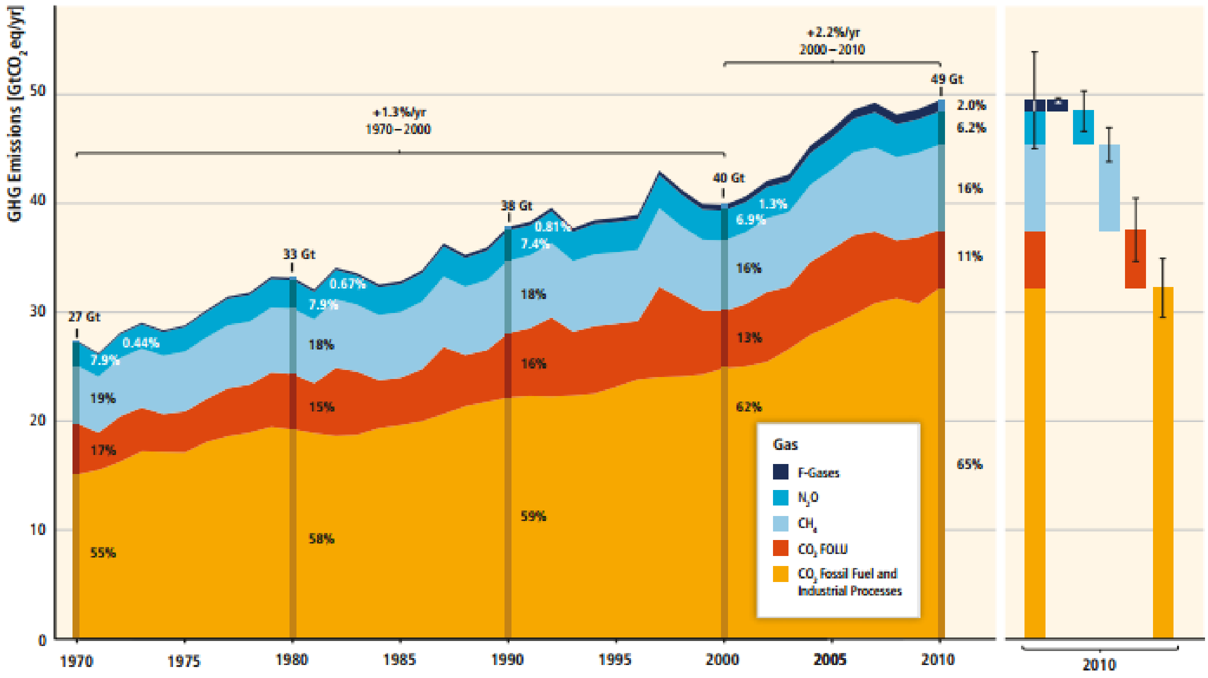


Figure 2.4: Total Annual Anthropogenic GHG Emissions by Groups of Gases 1970 – 2010 (IPCC, 2014)

Figure 2.5 below shows Greenhouse gas emissions by economic sectors for the period of 1970-2010. From the chat transport is a big player in greenhouse gas emission making up 14% of the total direct emissions and 0.3% of indirect emissions. *Emissions that occur from sources owned or controlled by the reporting entity are known as direct GHG emissions while emissions that occur because of activities of the reporting entity but occur at sources owned or controlled by a different entity are referred to as indirect emissions* (Jones, 2010).

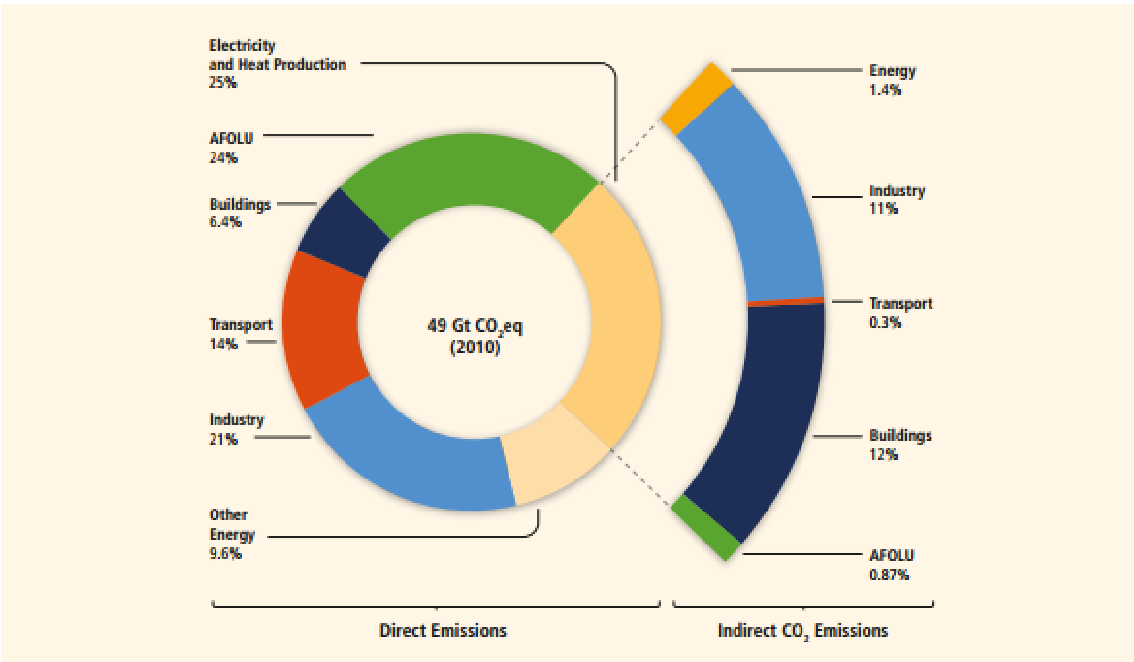


Figure 2.5: Greenhouse Gas Emissions by Economic Sectors IPCC (2014)

A report by the Department of Energy and climate change (DECC, 2015) on Greenhouse gas emissions shows that progress is being made in controlling greenhouse gas emission in the UK. The report showed that there was a decline in CO_2 gas emission between the periods of 1990-2013 and an overall decrease in GHG emission within the same period as shown in Figure 2.6. The report indicated that in 2013, CO_2 made up 82% of the total GHG gas emissions in the UK as shown in figure 2.7 and transport sector made up for a huge percentage as shown in figure 2.8.

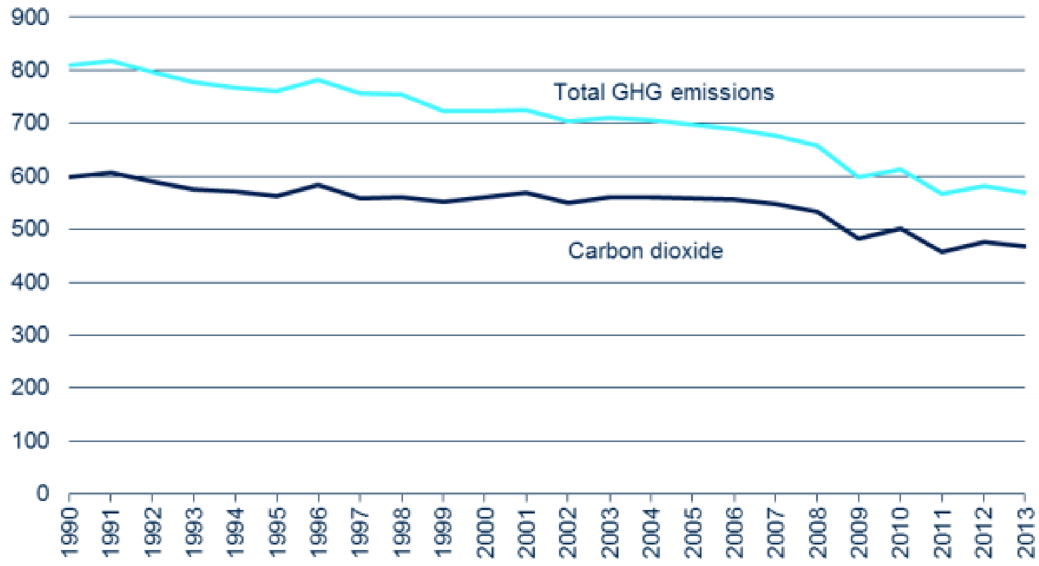


Figure 2.6: Emissions of greenhouse gases, UK and Crown Dependencies 1990-2013 (MtCO₂e) (DECC, 2015)

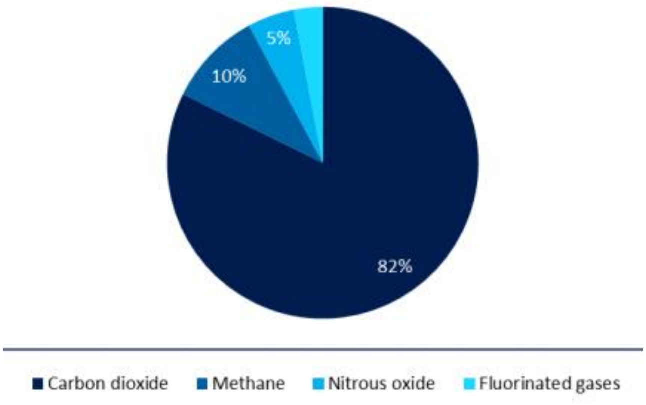


Figure 2.7: Greenhouse gas emissions by gas, UK and Crown Dependencies 2013 (%) (DECC, 2015)

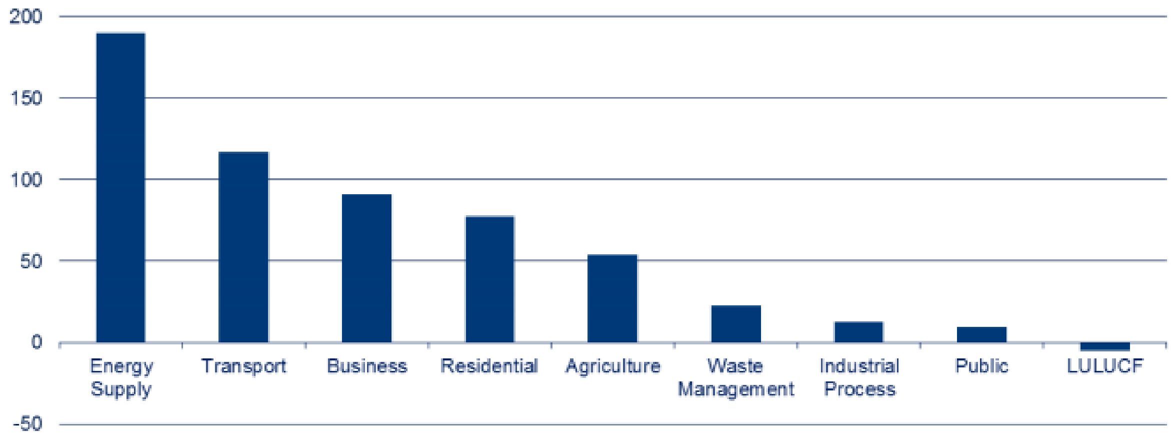


Figure 2.8: Greenhouse gas emissions by source sector (excluding LULUCF), UK and Crown Dependencies 2013 (MtCO2e) (DECC, 2015)

A review by Stern (2006) estimated that if no action is taken to reduce the impact of global warming, by 2035 the carbon dioxide concentration would be doubled in the atmosphere compared to pre-industrial levels. Regardless of the impact of anthropogenic activities on temperature rise, there may be a surge in temperature up to more than 2^{O}C above preindustrial levels. This would most likely still occur regardless of if large scale greenhouse gas mitigation activities were to commence now (IPCC, 2007). Global warming is currently impacting every sector of our socio-economic life from reductions in the social inclusion of individuals to reductions in the productivity of industries, impacting through adverse weather conditions. Mitigation strategies such as CO_2 emission legislation, recycling program and afforestation are currently being utilised by the UK to curb global warming however regardless of if these strategies are being adhered to and practiced thoroughly worldwide the weather impact of global warming would still be exacerbated before improvement commences (IPPC, 2007). Technological advancements such as improved road infrastructures, vehicle autonomy and advancements in other transportation modes are resulting in better road transport adaptation to global warming impacts in the UK (HM government, 2011).

Global warming effects would generally have negative impacts on road transportation affecting the behaviours of drivers through adverse weather conditions. For example weather conditions such as snowfall that result in reduced visibility and slippery road surfaces would have an impact on the acceleration, headway between vehicles, response time and speed of the vehicle resulting in higher journey times and reduced traffic capacity (Asamer, 2011; Chung et al., 2006; Agbolosu-Amison, 2004) and lower temperatures can result in higher traffic demand as more vehicles tend to be used during this condition resulting in increased traffic congestion. Slippery conditions and general increased hazardous conditions on the other hand can result in drivers seeking alternative transportation means (such as mass transit) to get to their destinations to avoid accidents (Maze et al., 2006; Asamer, 2011). Traffic safety decreases under adverse weather conditions for example high temperatures have been found to increase fatigue (Zohar, 1980) and affect the irritability (such as aggression) of drivers (Anderson, 1989; Boyanowski et al., 1981). Weiner & Hutchinson (1945) suggested an increase in drivers' reaction time while Stern & Zehavi (1990) suggested a reduction due to loss of concentration leading to crashes. However according to Elvik's (2006) law of accident causation which states that "*the rate at which a hazard occurs is proportional to its relative accident rate, with drivers getting more familiar with conditions that they are frequently exposed to"* drivers will potentially adapt to driving under adverse weather conditions as the frequency of their exposure to such conditions increases hence when extrapolating future accident rates and traffic parameters in general during inclement weather conditions it is important to consider the possibilities of drivers adapting to future weather conditions. Fridstrøm et al. (1995) study showed that accident rate reduced by approximately 1.2% for each additional snow day in Denmark. This is in line with the risk compensation by drivers discussed earlier which suggested that as drivers become more exposed to precipitation on road networks they become more aware and cautious of the risk involved. Maze and Hans (2006) concluded that accident risk is 3.5 times more at the start of a winter season than at its end. Mobility is negatively affected during inclement weather conditions as people feel less inclined towards travelling resulting in reduced social inclusion (Hooper et al., 2012 and El Faouzi et al., 2010). Some vehicle manufacturers and OEMs feeling under pressure to meet certain legislations that have been put in place to reduce CO_2 emission (e.g. EU CO_2 emission legislation (DFT, 2016).

The Climate Change Act 2008 (Climate Change Act 2008, 2008) was set up by the UK parliament to ensure that the net UK carbon account for all six Kyoto greenhouse gases for the year 2050 would be a minimum of 80% lower than the 1990 baseline to prevent hazardous climate change.

Highways England which is a government owned entity, is devoted to understanding, assessing and taking appropriate management actions to mitigate the risks faced by strategic road networks due to changing climate. They do this by following a climate change strategy and adaptation framework which provides a consistent approach to assessing and understanding the risks faced by the strategic road network. In their paper (Highways England, 2016) Highways England identified various trends that England will experience up to 2080 under a high emissions scenario from the UKCP09 and this is summarised in the figure 2.9 below.

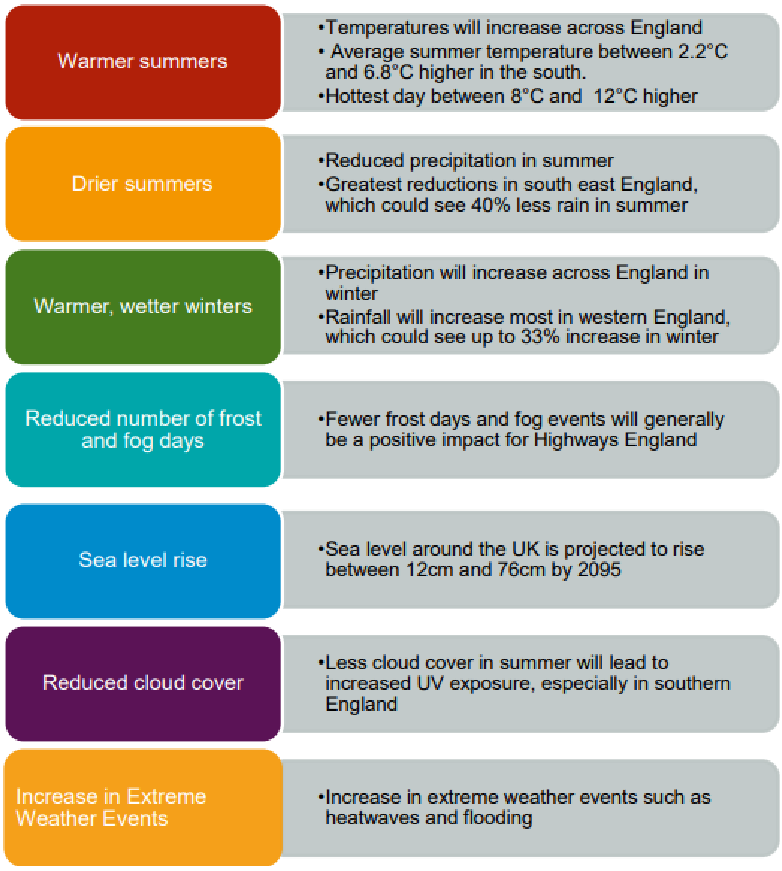


Figure 2.9: Headline Projected Climate Change Impacts from UKCP09 (Highways England, 2016)

From figure 2.9 as mentioned earlier in section 2.1, summer periods are expected to become warmer and drier, while the winter periods are expected to become warmer and wetter. Generally, fewer number of frost and fog days are expected due to warmer conditions. This is viewed as a positive impact for the strategic road network because frost and fog both result in poor driving conditions due the issues they pose such as reduced vehicle traction and poor visibility. Increase in the average temperatures may result in better driving conditions but increase in the maximum temperature may pose risks to the strategic network in the forms of increased irritability of drivers which could result in aggressive driving and damages to the infrastructure (such as rutting and shoving) as pointed out in section 2.1. Other factors that are expected to pose risks to the strategic road network include sea level rise around the UK which resulting in higher frequency of extreme storms and posing a risk of damages to the infrastructure and interruptions to traffic flow, reduced cloud cover resulting in higher temperatures which would pose a risk to both the drivers' behaviours and the infrastructure, and increase in extreme weather events such as heatwaves and flooding which are linked to the points made earlier.

Highways England (2016) also highlighted climate change hazards with potential to impact their services and the network users. They categorised the hazards into primary climate changes and secondary climate change impacts and this is shown in table 2.4.

Climate change hazards – Significance to Highways England		
Primary climatic changes	Secondary climatic change impacts	Importance for users
Increase in average temperature	Longer growing season Reduction in fog days in winter Reduction of icy days in winter	Low
Increase in maximum temperature	Extreme summer temperatures	High
Increase in winter rainfall	Flooding Increase in snowfall	High
Reduction in summer rainfall	Reduction in soil moisture	Low
More extreme rainfall events	Flooding	High
Increased wind speed for worst gales	Wind speed more frequently exceeding operational limits	High
Sea level rise	Higher Frequency of extreme storm surges	Low

Table 2.4: Climate change hazards (Highways England, 2016)

From table 2.4 a general increase in the average temperatures would not pose a real threat to the road network but rises in the maximum temperature is where the real threat lies. Temperature rise will also have various negative impacts that are of great concern such as increases in winter rainfall resulting in flooding, more extreme rainfall events and increased wind speed for worst gales. Highways England (2016) also used Climate change hazards to identify their vulnerabilities, which were listed in their paper. They also discussed adaptation plans which incorporate their preferred adaptation options.

Except for rises in the wind speed for worst gales, this thesis is focused on the climate change hazards that pose the most threat to the UK Trunk road network.

2.3.2. Dependent Factors

2.3.2.1. Demographic and Economic growth

Transport has an important role to play in supporting a sustainable economic growth and its investment is even more important in times of economic challenges to secure sustainable growth and international competitiveness (DFT, 2013). Transportation development and economic growth could be seen as two interdependent factors since the growth of one factor positively influences the growth of the other.

Badger (2013) discussed the impact of congestion and gridlock on economic growth. She indicated that congestion may be a positive sign that an urban area is active and vibrant, but it could also mean that access is impeded, freight deliveries are delayed and people within the region are generally not happy. Furthermore, she mentioned that higher levels of congestions are usually an indication of faster economic growth but beyond a certain threshold it starts becoming a burden on growth. She emphasised that congestion appears to reduce job growth rate when it is above 35 to 37 hours of delay per commuter per year and that a similar threshold also exists when the entire road network gets excessively saturated throughout the day.

Demographic growth of the UK would have a significant impact in the UK future road transport network and this impact would depend on the demographic composition. A composition that supports economic growth would potentially have a positive influence in the state of the transport network since a higher economic growth would potentially result in higher transportation development. Demographic and Economic growth as dependent factors were discussed extensively in appendix 1.

2.3.2.2. Technological Advancement

Various research and developments (R&D) are aiding the advancement of road transport such as R&D on road infrastructures (e.g. drainage projects such as the SUDS project (Environment Agency, 2012) and intelligent transport project such as SPaT (California PATH Program, 2011), vehicle autonomy (e.g. SARTRE (SARTRE, 2012) and HAVEit (HAVEit, 2012) projects) and other transportation modes (such as advancements in the railway industry e.g. the Shanghai Maglev project (Transrapid International-USA, 2007) and High Speed 2 rail (HS2) (DFT, 2015)).

2.3.2.2.1. Road infrastructure and vehicles

The UK road network is a fundamental aspect of the economy (HM Treasury, 2013)**.** It is the most heavily used mode of transport in England making up for 90% of passenger journeys and 67% of freight and passengers covering over 440 billion vehicle miles by road (DFT, 2013). As at 2005 the UK transport network was valued at £62 billion making it the single most valuable asset of the UK government (Hooper, 2013).

Investment

In a report by HM Treasury (2013) on 'Investing in Britain's future' it was indicated that as at 2011 due to Demographic and economic growth road traffic and congestion increased in the UK although investment over the preceding decades had declined. The UK government has planned to treble its investment in major new road enhancements from their current levels by 2020-2021 with focus on the Strategic Road Network (SRN) which is made up of approximately 4,300 miles of motorways and major 'trunk' A-roads in England alone (HM Treasury, 2013**;** Butcher, 2015). A full review on the investment on the UK road network can be seen in appendix 1.

Technological advancement

In a paper by KPMG (2015) on 'Connected and Autonomous Vehicles – The UK Economic Opportunity' projections on semi-autonomous and autonomous vehicles UK market penetration indicated that these classes of vehicles would be trending by 2030 (further discussed in a later section). Proper investment in these technologies could result in a very significant elimination of GHG emission from car travel. The UK government has already shown its support by investing £400 million to assist the uptake of new vehicles and aims to provide over £500 million additional capital investment by the end of the decade (DFT, 2013). A full review on the technological advancement can be seen in appendix 1.

2.3.2.2.2. Autonomous Vehicles

The trend in transport research has expanded from economic and safe transportation network to include other factors such as carbon emission and sustainability. Black (2000) mentioned that there has been an argument about the sustainability of the current motor vehicle highway transportation system. The argument pointed out that the current system is not sustainable because it uses a finite fuel system (fossil fuel), pollution problems because of the fuels system and global warming issues. The issues discussed were:

- Fuel system: The fuel system is finite (fossil fuel), results in pollution and global warming issues
- Safety: The system results in a significant amount of injuries and fatalities
- Congestion: The system is very prone to congestion

Various suggestions to tackle these issues have been put forward such as the use of alternative renewable fuel systems that do not pollute the environment, increasing the safety of vehicles using intelligent transportation systems and reducing the demand for privately owned motor vehicles through various policies (Black, 2000). *Autonomous vehicles* are currently being developed and they have the potential to address these issues to certain degrees.

> *"We are also preparing for new technology and setting up the UK as a global leader in ultra-low emission vehicles*" (DFT, 2013).

History of Autonomous Cars

The idea of autonomous vehicles dates to Futurama which was an exhibit that was hosted at the 1939 New York World's Fair. The exhibit was created by General Motors with the aim of envisioning what the world would look like in 20years time which included the vision of a possible automated highway system that would guide self-driving cars. During the exhibition Norman Bel Geddes introduced the first self-driving car which was an electric vehicle guided by radio-controlled electromagnetic fields generated with magnetized metal spikes embedded in the roadway. This concept was then made a reality in 1958 by General Motors. The developed vehicle was guided using sensors referred to as pick-up coils which could detect the current flowing through a wire embedded in the road. The vehicle was then controlled by manipulating the flow of current in the wire (Gringer, 2017; Snyder, 2010).

This idea was later improved on by the Japanese and in 1977 a vehicle featuring image processing capabilities was introduced. The main limitation of this vehicle was that it was only capable of speeds up to 20mph. A decade later the Germans introduced the VaMoRs which was an improvement from the Japanese version and was capable of speeds up to

56mph. Technological advancements have played an important role in the advancement of autonomous vehicle R&D (Gringer, 2017).

Autonomous Cars today

Modern autonomous vehicle technology R&D first commenced in the UK by Oxford researchers who later revealed their prototype in March 2011 which was based on a Bowler Wildcat 4X4 built by BAE. Google subsequently started testing their autonomous vehicles a year later in California (Wilton, 2015; Google, 2016). Today various researches are being carried out by private industries and government institutions (Mercedes-Benz, 2016; Mobile Robotics Group, 2016). The UK has shown great interest in autonomous vehicle technology with various R&D related to this field currently being carried out. Oxford University in collaboration with Nissan are currently developing an autonomous vehicle based on a Nissan Leaf (Mobile Robotics Group, 2016). The UK government and various private industries have shown interest in autonomous vehicle technology R&D by donating £40 million towards the testing programme currently being carried out in Bristol, Milton Keynes and Coventry (Catapult, 2014). Legislations have also reviewed to promote testing of prototypes on the UK roads (DFT et al, 2015). A review of the existing legislation by the Department for transport showed that the current legal and regulatory framework in the UK is not a barrier to the testing of automated vehicles on public roads. "*Real-world testing of automated technologies is possible in the UK today, providing a test driver is present and takes responsibility for the safe operation of the vehicle; and that the vehicle can be used compatibly with road traffic law*" (DFT, 2015). Real-world tests in the UK are not limited to test tracks or designated geographical locations, certificates or permits do not need to be obtained and no surety bond is required provided full insurance is arranged (DFT, 2015).

2.3.2.2.2.1. Autonomous Vehicles Potentials

Autonomous vehicles have the potential to change the dynamics of the UK roads. Its impact could change the basics of motoring improving various factors such as improved road safety and social inclusion, reduced emission and ease congestion which could result in significant economic, environmental and social benefits. While completely autonomous (driverless) vehicles are still under development and are projected to be available commercially within the next decade, various technologies to be featured in these vehicles are already being featured in current production vehicles. For example, some vehicles are capable of automated cruise control and lane keeping on the motorway, major A-roads and congested traffic by utilising automated acceleration, braking and steering (KPMG, 2015; DFT, 2015). Other technologies currently available include advanced emergency braking system and self-parking systems.

Socially, even with the advancement in vehicle technologies an average driver in the UK still spends an average of 235 hours driving because 100% concentration is still required but with completely autonomous vehicles this value would be significantly reduced as drivers will have the option of either driving or leave full control of the vehicle to the control system thereby being able to attend to other things (DFT, 2015). Driverless vehicles are expected to improve mobility since people who are unable to drive (such as those without a driver's license, some older people and disabled people declared unfit to drive) may be driven around by driverless vehicles.

In terms of safety, over 90% of road accidents have been attributed to human error. Figure 2.10 shows various causes of road accidents due to human error. Humans are prone to poor judgment while driving and various situations such as being in a hurry or being distracted tends to exacerbate this issue. Driverless vehicles will be less prone to errors as they are fitted with sensors constantly monitoring the dynamics of their environment. Since automated vehicles are less prone to collision insurance premiums will be significantly lower. Insurance companies will find it easier when determining whether a product's manufacturer or the consumer is to blame after an accident (III, 2015). DFT (2015) report on 'The pathway to driverless cars' indicated that insurance companies are currently encouraging new vehicles to be fitted with automatic emergency braking system which would result in lower collision rate hence lower premiums. Generally, driverless vehicles are expected to significantly reduce collisions, injuries and fatalities since they will be required to adhere to all traffic laws.

Figure 2.10: Humans are highly prone to errors (DFT, 2015)

Driverless vehicles will be able to communicate with their environment and other vehicles to optimise traffic and provide more consistent journey times using "connected vehicles" technology. This technology will allow vehicles to communicate with each other as well as roadside infrastructure (e.g. traffic light) to identify optimum route and reduce fuel consumption hence emissions. Automated vehicles may also be designed to run on alternative renewable fuel system instead of fossil fuel there by reducing pollution and emission significantly. DFT (2015) projected that autonomous vehicles are expected to be featured more readily in urban areas as there is a higher potential for vehicle sharing and they are more likely to be electric powered to save on operating cost and to meet the EU

CO_2 legislation. Kavathekar (2012) mentioned that moving vehicles could be supplied with energy on demand through a wireless energy transfer known as inductive coupling in a scenario where overhead wires are eliminated, and infrastructures upgraded by electrifying highways.

KPMG (2015) provided an economic impact assessment of the projected contribution of intelligent vehicles to the UK. According to the assessment the overall economic and social benefit of connected and autonomous vehicles could be in the region of £51 billion per year by 2030. It also concluded that these vehicles could create 320,000 jobs in the UK by 2030 with 25,000 being in automotive manufacturing. It also stated that autonomous vehicles could improve safety and projected that 2,500 lives could be saved while over 25,000 serious accidents could be prevented in the UK.

2.3.2.2.2.2. Automation Levels

ATA and MCFT (2015) showed SAE international levels of vehicle automation in their report. The classification ranged between 6 levels with the lowest level (L0) possessing no autonomy whatsoever while the highest level (L5) possesses full autonomy. It was identified that connected L3, L4 and L5 vehicles shown in figure 2.11 would result in significant economic benefits. Figure 2.12 below shows a projected technology timeline for autonomous vehicles.

SAE level	Name	Narrative Definition	Execution of Steering and Acceleration/ Deceleration	*Monitoring* of Driving Environment	Fallback Performance of *Dynamic Driving Task*	System Capability *(Driving Modes)*
Human driver **monitors the driving environment**						
0	No Automation	the full-time performance by the *human driver* of all aspects of the *dynamic driving task*, even when enhanced by warning or intervention systems	Human driver	Human driver	Human driver	n/a
1	Driver Assistance	the *driving mode*-specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	Human driver and system	Human driver	Human driver	Some driving modes
2	Partial Automation	the *driving mode*-specific execution by one or more driver assistance systems of both steering and acceleration/ deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	**System**	Human driver	Human driver	Some driving modes
Automated driving system **("system") monitors the driving environment**						
3	Conditional Automation	the *driving mode*-specific performance by an *automated driving system* of all aspects of the dynamic driving task with the expectation that the *human driver* will respond appropriately to a *request to intervene*	System	**System**	Human driver	Some driving modes
4	High Automation	the *driving mode*-specific performance by an automated driving system of all aspects of the *dynamic driving task*, even if a *human driver* does not respond appropriately to a *request to intervene*	System	System	**System**	Some driving modes
5	Full Automation	the full-time performance by an *automated driving system* of all aspects of the *dynamic driving task* under all roadway and environmental conditions that can be managed by a *human driver*	System	System	System	**All driving modes**

Figure 2.11: SAE international Levels of vehicle automation (ATA and MCFT, 2015)

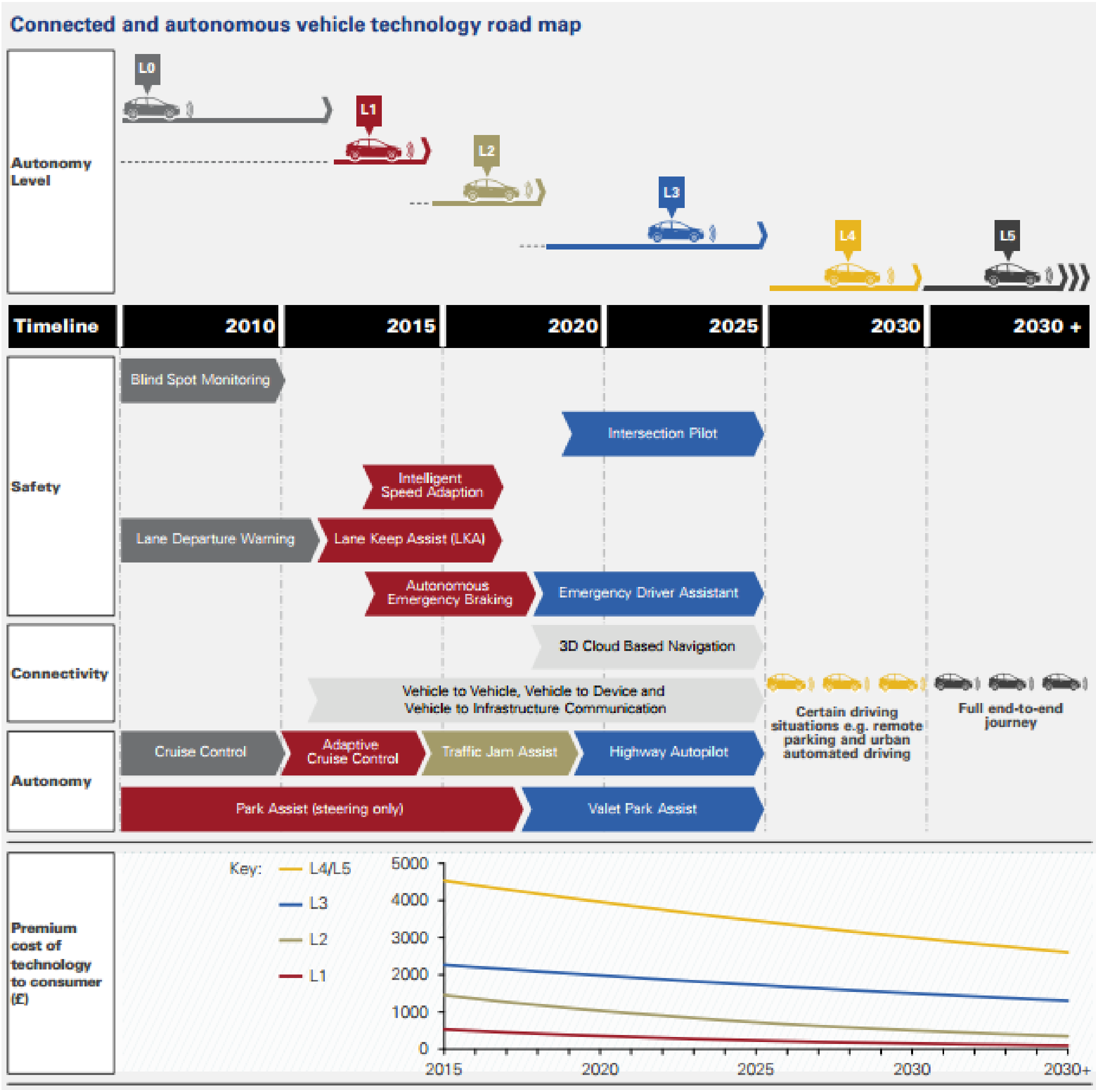


Figure 2.12: Projected time line for autonomous vehicles (KPMG, 2015)

Figure 2.11 shows SAE International levels of vehicle automation while figure 2.12 shows the projected timeline of vehicle automation technologies. Vehicles levels of automation ranges between 6 levels as shown in figure 2.11. The lowest level of automation (L0) always requires full performance of the driver even when the vehicles are fitted with warning or intervention systems while the highest level of automation requires no input whatsoever from the driver in any situation.

From figure 2.12 higher levels of autonomy are expected to kick off by 2017 while full autonomy is expected after 2030. There are still major issues to be resolved before full autonomy can be achieved such as refinement of prediction and decision-making algorithms and cyber security (ATA and MCFT, 2015). Before full autonomy would be achieved various technologies are expected to be developed such as intersection pilot and highway autonomy which are expected to be featured in L3 vehicles while some have already been invented such as lane departure warning, autonomous emergency braking and traffic jam assist found in L0, L1 and L2 vehicles respectively. Some technologies are expected to be developed to pave way for other technologies to be developed. For example, Traffic Jam assist (L2 technology) which gives the vehicle control under heavy traffic conditions at speeds of up to 40mph is a combination of adaptive cruise control and lane departure monitoring system which are both L1 technologies (KPMG, 2015).

2.3.2.2.2.3. Various Vehicle Technology R&Ds

2.3.2.2.2.3.1. Connectivity

Vehicle are becoming connected via mobile data network and various communication protocols which establish communication within vehicles (V2V), vehicles and other devices or machines (V2D) and vehicles and infrastructure (V2I) connectivity technology is expected to be completed 2025 (KPMG, 2015). An illustration of connected vehicles and their environment is illustrated in figure 2.13.

Today, car developers are taking advantage of communication technologies such as Ethernet, Bluetooth and wireless LAN technologies to improve the experiences of drivers and passengers. In-demand vehicle features such as maintenance and repair logistics, infotainment, safety cameras and sensors are often connected via Ethernet. Due to the advancements of Wi-Fi technology some vehicles now give users the option to project their smartphone or tablet home screen to the in-car screen for better experience. This experience will be improved with the introduction of 5G WIFI (Schmidt, 2012).

Future connectivity technology should aid in journey time reduction, improved social inclusion and safer traffic when combined with adaptive cruise control and autonomous emergency braking. In a paper by Electronic Product Design & Test (2016) it was mentioned that connectivity within a car has been enabled for the past two decades and this decade will enable cars to be capable of connecting to their environment. Vehicles connectivity technology was projected to be completed by 2025.

"*There is no doubt that the Connected Car will shape the future of the automotive industry as the focus is now to develop the car's ability to digitally connect with the outside world and enhance the in-car experience. The connected car is a significant step towards autonomous vehicles, the next potential revolution*" (Electronic Product Design & Test, 2016).

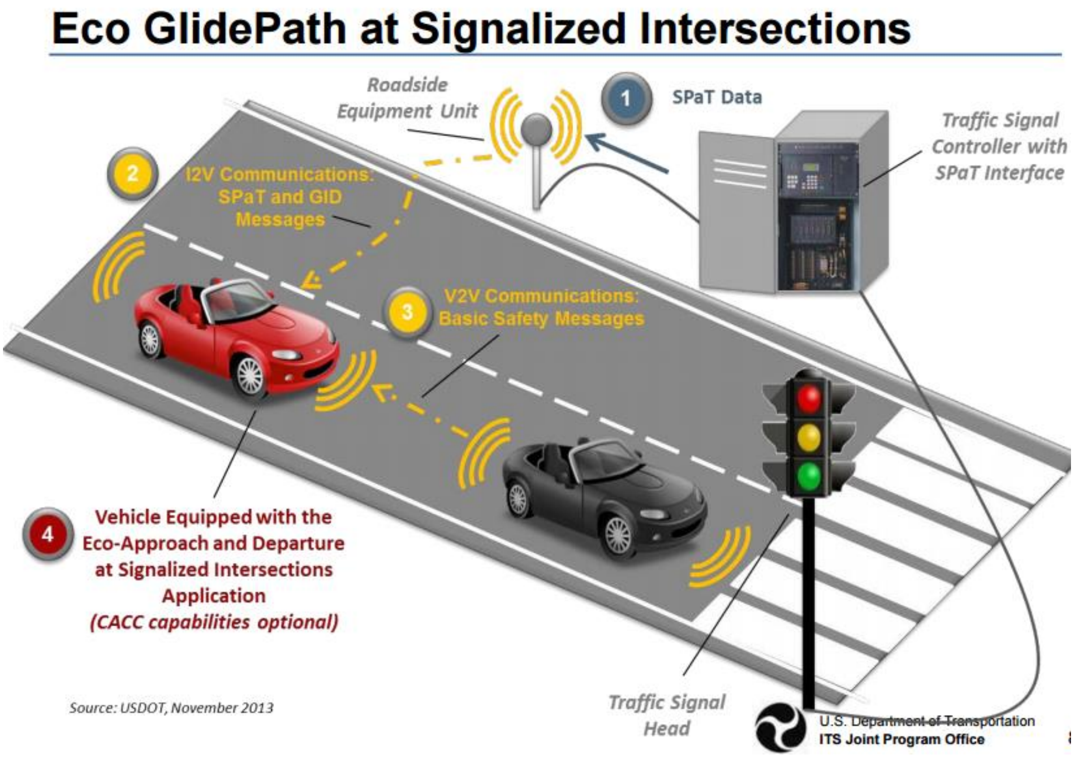


Figure 2.13: Connected vehicles and their environment (Dopart, 2015)

From Figure 2.13 a V2V connection exists between both vehicles allowing safety messages to be communicated between them and V2I connection between a vehicle and a road side equipment unit allowing traffic information to be communicated between the traffic signal controller and the vehicle

2.3.2.2.2.3.2. Vehicle platooning

Vehicle platooning is an important innovation in the automotive industry which involves the formation of platoons by two or more in-lane vehicles possessing at least level 2 automation maintaining close headway which is facilitated using radar and vehicle-vehicle (V2V) communications that control their longitudinal (inter-vehicular spacing control) and lateral (steering)

Kavathekar (2012) defined vehicle platooning in an automated highway scenario as a string of vehicles equipped with wireless communication capabilities following one another in a platoon while communicating with one another (V2V) in other to maintain their formation as a platoon. He described such vehicles as cognitive devices which suggest these devices are capable of learning and adapting to their environment. He suggested vehicles driving in platoons run on dedicated lanes on the highway as this would reduce the possibility of drivers attempting to cut other vehicles moving in platoons hence reducing chances of collisions and disruption of the platoons by human drivers. Some of the potential benefits of this technology include improved mileage, efficiency and journey time. According to the vehicle’s autonomy classification L3-L5 vehicles will be able to carry out Highway patrol autonomously. This technology is currently being researched in the various countries including the UK.

Hee et al. (2015) identified two main types of vehicle platooning which are adaptive cruise control (ACC) and cooperative adaptive cruise control (CACC). While ACC operates based on the perception of the immediate lead vehicle via sensors CACC involves the communication of vehicles in a platoon via V2V providing advanced information to the ACC controller allowing vehicles to follow each other with higher accuracy, faster response, shorter gaps, advanced traffic flow stability and potentially improved safety. Illustrations of both controllers are shown in the figure 2.14a & b.

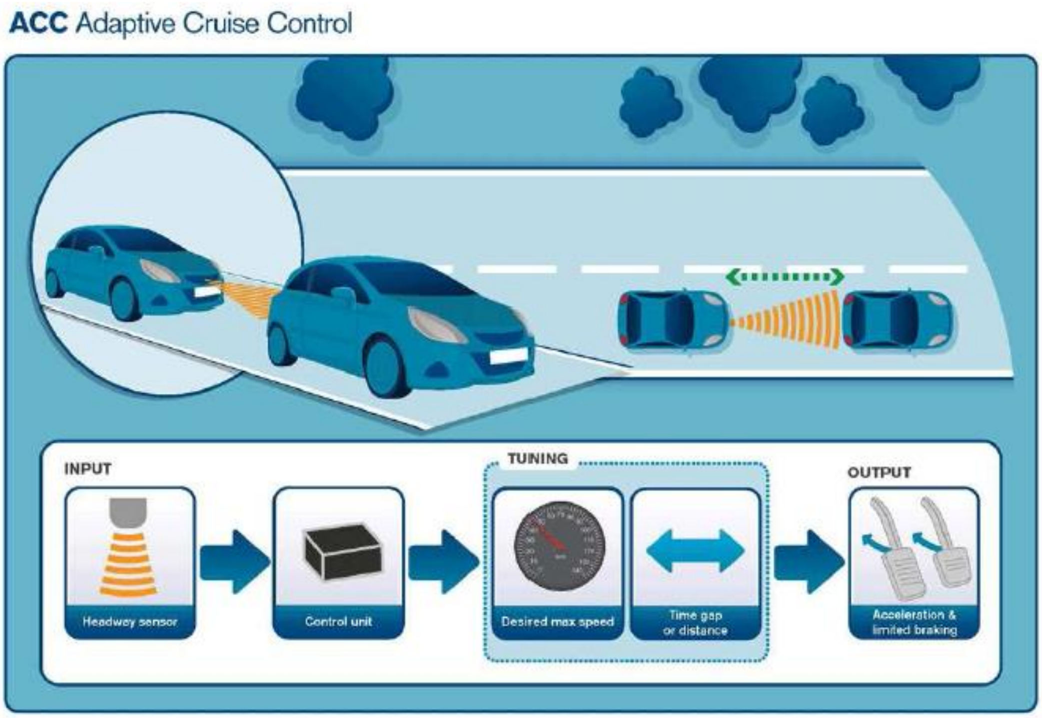


Figure 2.14a

Figure 2.14: a). Adaptive Cruise Control illustration b). Cooperative Adaptive Cruise Control illustration (Hee et al., 2015)

From Figure 2.14a the following vehicle perceives the lead vehicle through its headway sensor the information received is then relayed to its control unit (ACC controller) which then computes suitable parameters for the various actuators required for the vehicle to continue following its lead vehicle safely. In Figure 2.14b a Dedicated Short-Range Communications module (DSRC is a two-way short to medium range wireless communication that permits very high data transmission which is important in communications-based active safety applications (USDOT, 2014)) relays information received from its environment (V2V and V2I communications) to the CACC controller providing information and also sends information it receives from the CACC controller to its environment. The CACC controller is linked to a CAN bus (a type of short-range communication module) enabling it to exchange information with the ACC sensor, the ACC controller and the Engine Control Module (ECM).

Figure 2.15 shows projected highway capacity as well as inter-vehicle distance based on three different vehicle levels of autonomy.

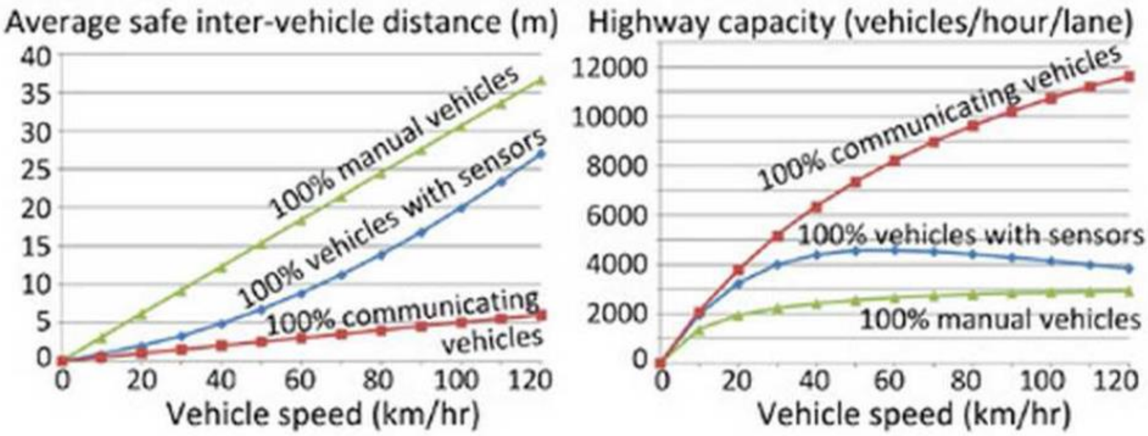


Figure 2.15: Various traffic parameters based on different vehicle autonomy levels (Hee et al., 2015)

From Figure 2.15 as the level of automation increased from manual to 100% communication the inter-vehicle distance reduced significantly. In fact, the average inter-vehicle distance between 100% communicating vehicles at 120km/hr is approximately the same as 100% manual vehicles moving at 20km/hr. Capacity is also affected in a similar way with 100% communicating vehicles resulting in significantly higher capacity compared to 100% manual vehicles.

Europe's SARTRE (SAfe Road TRains for the Environment) project (Dávila and Nombela, 2013) was set up to investigate the possibility of implementing road trains on highways with platooned traffic operating in a mixed environment with other road users. The expectation of the project was that each platoon would be led by a vehicle controlled by an experienced driver who would be in full control of every function of the vehicle and is thoroughly familiar with the route. Other drivers could then decide to join the train allowing advanced control features to take control the vehicle. The lead vehicle communicates information about its driving parameters (such as its acceleration, position and velocity) to its followers. A following vehicle communicates with the leader of the platoon as well as their immediate lead vehicle. Their control algorithm then adjusts their driving parameters (such as position, velocity and acceleration required to maintain a safe headway) based on the information received from the leader of the platoon as well as their immediate lead vehicle.

Depending on the gap between vehicles which could be as low as 0.2 meters, vehicles could benefit from slipstreaming which results in better fuel economy and combining this effect with reduced speed variations also experienced when in a platoon could mean vehicles experiencing 20% average reduction in fuel consumption on highways (high speed) driving. This benefit would vary depending on the number of vehicles in the platoon, the inter-vehicle spacing and the aerodynamic geometry of the vehicles (more on the aerodynamic performance of platoons can be found in Zabat et al., 1995). Figure 2.16 shows the average decrease in fuel consumption for platooning vehicles in highway operation for all vehicle geometries. The variability bar at the top of the figure for a given spacing represents the degree of variation due to the vehicle's geometry. The figure shows that there is a possibility of up to 27% fuel consumption reduction from isolated vehicle consumption for spacing between 0.1 and 0.2 vehicle lengths in large platoons on the highway (high speed). Other benefits mentioned include improved safety and traffic flow due to reduced speed variation. The variability bars suggest that the savings in likely to fall within 22%-32% regardless of the geometry at this spacing. Cars following HGVs are likely to experience greater benefits compared to HGVs following Cars.

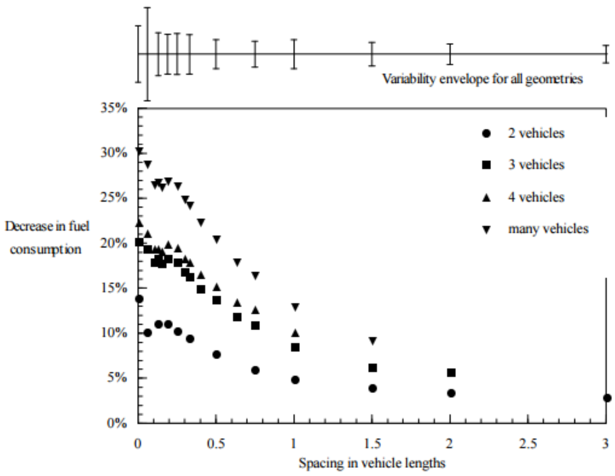


*Figure 2.16**:** All geometries-average decrease in fuel consumption for platooning vehicles in highway operation (Zabat et al., 1995)*

In urban areas (low speed) the fuel savings is significantly lower because of reduced drag during low speed and higher speed variations resulting in between 5-10% saving (Zabat et al., 1995). Figure 2.17 represents the potential savings in urban areas**.**

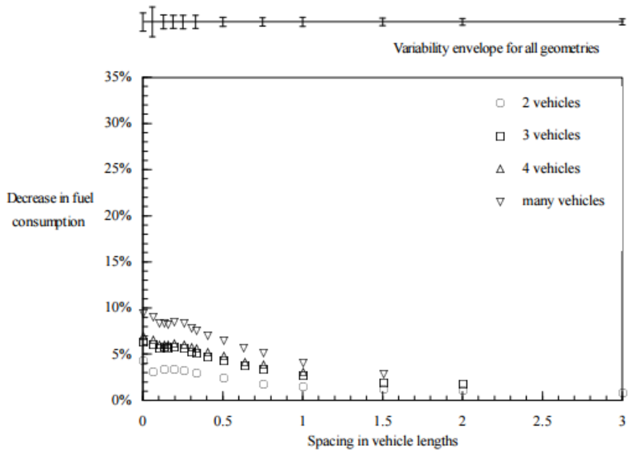


Figure 2.17: All geometries-average decrease in fuel consumption for platooning vehicles in urban operation (Zabat et al., 1995)

Although Zabat et al (1995) suggested that vehicles could benefit from low fuel consumption from as low as 0.1m spacing but their test was done in a wind tunnel and in a real-world application a smaller spacing would be a lot more challenging for control systems, so a trade-off is therefore important. Dávila and Nombela (2013) suggested that 1 meter spacing could be the initial aim which is approximately 0.2 vehicle lengths. They also said speed factor of the road train is also important for environmental benefit. Figure 2.18 shows the fuel consumption contributions due to drag resistance ($(\text{litres/km})_{DR}$) and roll resistance ($(\text{litres/km})_{RR}$) as a percentages of the total fuel consumption (litres/km) for a range of velocities based on approximated performance stats of a Chevrolet Lumina APV. At velocities below 65Km/hr (40mph) the dominant force which the engine must overcome is the roll resistance while at above 80km/hr drag resistance is the main contributor, accounting for approximately 80% of the consumption at 130km/hr (80mph).

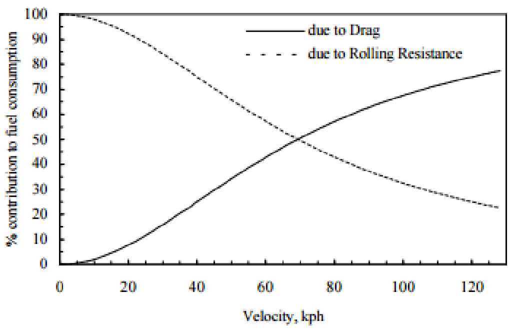


Figure 2.18: Fuel consumption due to drag and to roll resistance as a percentage of total fuel consumption (Zabat et al., 1995)

The Inter-vehicle space (headway) setting controller

The inter-vehicle space setting controller of a following vehicle in a platoon takes various factors into consideration when setting the safety gap. ATA and MCFT (2015) mentioned some of these factors:

- Engine horsepower
- Estimated mass of each vehicle
- Estimated braking ability of each vehicle (measured in real time). Factors affecting braking performance include:
  - Estimated mass of each vehicle
  - Weather conditions
  - Brake condition
  - Road conditions
- Ability to cool engine with adequate air flow
- Driver acceptance
- Traffic conditions
- Road configuration (including tight curvature and/or dense entry/exit sections)

Higher temperatures have negative impacts on vehicles' engines or battery packs performance hence as temperature increases because of global warming, vehicles will require better cooling systems or air flow to improve or maintain their performance (Prudhvi et al., 2013; Dober, 2018). One of the main advantages of platooning is the reduction of air drag which improves the vehicles' efficiency. The disadvantage of this effect is the engine or battery pack of the following vehicle may not receive enough air intake required to cool hence this impact must be taken into consideration when setting the safety gap (Baniasadi et al., 2014).

Figure 2.19 represents various platoon scenarios. Vehicles can join and exit platoons both laterally and longitudinally depending on the availability of a gap and safety.

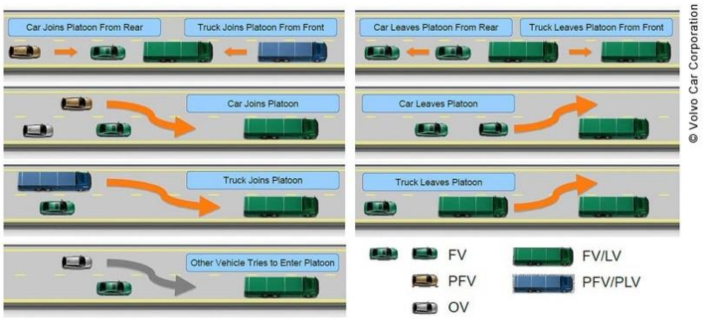
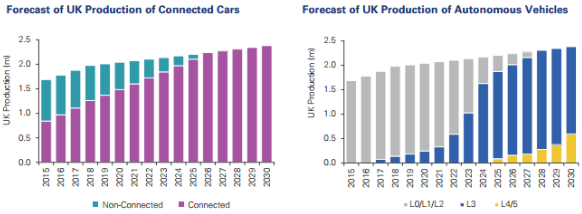


Figure 2.19: SARTRE vehicle-manoeuvring use cases

NOTE: FV = following vehicle, LV = lead vehicle, PFV/PLV = potential following vehicle/potential lead vehicle, OV = other vehicle (not part of the platoon) (Hee et al., 2015)

2.3.2.2.2.4. Autonomous and Connected vehicles and the UK market

The projection of UK production of connected cars and autonomous vehicles is shown in figure 2.20.



Year	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Connected Car Penetration	50%	55%	59%	64%	68%	73%	77%	82%	86%	91%	95%	100%	100%	100%	100%	100%
L3 Production Penetration	0%	0%	4%	7%	8%	12%	16%	25%	48%	75%	81%	83%	87%	88%	84%	75%
L4/5 Production Penetration	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	4%	7%	8%	12%	16%	25%

Figure 2.20: The projection of UK production of connected cars and autonomous vehicles (KPMG (2015)

From figure 2.20 KPMG (2015) report projected connected vehicles to be on the rise this period (2016) and by 2026 every vehicle on the UK road is expected to be connected. An illustration of a typical connected car found today is shown in figure 2.21 while figure 2.22 shows an illustration of a future connected car. While the production of L3 vehicles is expected to commence from 2017 and reach its peak at 2028, production of L4/L5 vehicles is expected to commence at 2025 and by 2030 25% of vehicles on the UK road are expected to be L4/L5 vehicles.

Figure 2.21: Illustration of a typical connected car found today (AT&T, 2016)

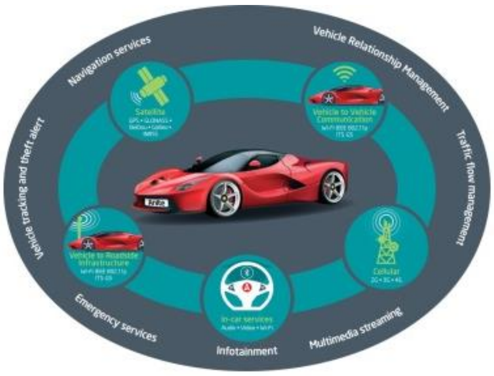


Figure 2.22: illustration of a typical connected car of the future (Electronic Product Design & Test, 2016)

2.3.2.2.3. Other modes of transportation

2.3.2.2.3.1. Modal Shift

There is currently high pressure on the UK road network and it is the most heavily used mode of transport in England making up for 90% of passenger journeys and 67% of freight with passengers covering over 440 billion vehicle miles by road (DFT, 2013). It estimated that even in the worst economic case and low population growth, strategic roads will experience a 24% rise in traffic by 2040 and the central case traffic will increase by 46% compared to the current situation. Enhancing the network to accommodate rising traffic volumes is an important step towards tackling the issue but it is also important to divert some traffic pressure away from the network.

Advancements in other mode of transport would potentially result in less demand for road transportation resulting in lower traffic congestion. For example, Tight's (2009) paper on 'visions for walking and cycling focussed urban transport system' discussed the potential benefits of a shift from the current transport structure in the UK to a more conservative form of transportation where walking and cycling are primary. He concluded that there would be great benefits from such a shift such as reduced local noise and air pollution, reduced CO_2 emission, improved safety, better fitness levels of the population and improved social inclusion. Figure 2.23 shows illustrations of urban locations as they may look if walking and cycling had higher priorities. From the figure larger areas would be required for pedestrians and cyclists. A paper by Tomorrow's Rail (Network rail, 2012**)** on **'**Scenarios 2025 imagining the future' discussed various scenarios of societies that are more inclined towards railway transportation. If such visions were to be implemented there would be a reduction in the demand for road transport resulting in less traffic congestion as well as other benefits such as lower CO_2 emission.

Road transport would remain central to most journeys due to the nature of the journeys. The National Policy Statement for Networks (DFT, 2014) indicated policies to facilitate sustainable transport modes are being implemented which includes public transport, significant improvements to rail capacity and quality, cycling and walking. They went on to mention that it would not be feasible for these modes of transport to replace private cars for all journeys especially in rural areas and for some longer and multi-leg journeys.

In a report by MTRU (2015) on the 'Potential reductions in congestion on the strategic road network from alternatives to HGV use' a statement from The National Policy Statement on National Networks by DFT (2014) was quoted:

"*In general, the nature of some journeys on the Strategic Road Network means that there will tend to be less scope for the use of alternative transport modes. If rail use was to increase by 50% (in terms of passenger kilometres) this would only be equivalent to a reduction of 5% in all road use. If freight carried by rail was to increase by 50% (in terms of* *tonne kilometres) this would only be equivalent to a reduction of around 7% in goods carried by road.*"

However, MTRU (2015) went on to indicate that the statistics in this statement are only valid when average figures for all road freight are used and sections are not considered independently. They concluded that freight transfer from road to alternative modes (rail and water) would result in a significant reduction in environmental and congestion costs. There would potentially be a drop in HGV traffic by 21% and overall vehicle traffic by 5-6% with the most congested places experiencing a drop of 15-25% (more information at MTRU, 2015).

Figure 2.23: Urban locations as they may look if walking and cycling had higher priorities (Tight, 2009)

2.3.2.2.3.2. Technological Advancement

The UK government has shown commitment to sustainable transport and has made plans to invest more on the railway network by 2021 with £16 billion of the investment to be spent on High Speed 2 (HS2). HS2 is expected to increase the capacity of the UK railways improving connectivity and journey times. It would connect eight of Britain's ten largest cities and is estimated to serve one fifth of the UK's population encouraging more passengers to use trains and more freight operators to use rails rather than road resulting in fewer cars and HGV on the road hence lower congestion and carbon emission (DFT, 2015). Figure 2.24 shows an illustration of a High speed 2 train (Railway Gazette, 2013).

*Figure 2.24**:** High speed 2 (Railway Gazette, 2013)*

As the R&D of automated cars keeps growing and gaining more popularity other related avenues are being considered. Catapult Transport Systems based in the UK developed a new innovative form of transport known as the LUTZ pathfinder pod (shown in figure 2.25) which is a small, two-seater driverless vehicle that was set to roll along pedestrianised areas travelling at up to 24km/h (TSC, 2015). It was equipped with Oxford-developed autonomy software and was capable of learning information it required to travel from its origin to its destination through interaction with pedestrians, cyclists and other obstacles. It was successfully tested in public for the first time in the UK in October 2016.

*Figure 2.25**:** LUTZ pathfinder pod (TSC, 2015)*

The GATEway project which was carried out by Transportation Research Laboratory, TRL featured a fleet of autonomous pods rendering a shuttle service around the Greenwich Peninsula to understand public reaction towards autonomous vehicles (TRL, 2019). The project which had a unique aspect in that it primarily focused on people has helped in promoting the UK's position in the advancement of autonomous vehicles. It provided valuable and sociological insight into mobility solutions and their possible contributions in future cities through its exploration of how people feel about utilising and sharing space with autonomous vehicles. Figure 2.26 shows GATEway pods.

Figure 2.26: GATEway Pods (TRL, 2019)

2.4. Summary and Conclusion

This chapter started off by reviewing the impact of weather on road transport. Precipitation being the main weather factor has been known to affect road transport through several ways in which weather affects road transportation which include behavioural changes to drivers such as speed reduction because of visibility impairment and physical failure of infrastructures such as temperature induced potholes. The general impact of precipitation which include driver capabilities (such as visibility), pavement friction, crash risk, roadway infrastructure, productivity and traffic flow have been split into three main categories:

- Traffic Congestion and Speed reduction
- Traffic Safety
- Roadway Infrastructure

This thesis focuses on the impact of precipitation on traffic congestion and speed. It utilises a microscopic traffic flow model hence instead of deterministic relationships between the traffic parameters (i.e. flow, speed and density) as found in macroscopic models, Driver Vehicle Units (DVUs) behaviours and interactions during simulations were used to determine these relationships. The behaviours of the DVUs such as their acceleration, headway etc. were influenced by the weather conditions. The behaviours of the drivers under various weather conditions were calibrated using various data from this review such as the data found in tables 2.1-2.3.

The chapter then reviewed traffic flow modelling discussing the various classifications which were macroscopic, mesoscopic and microscopic traffic flow models. With macroscopic method, entities, their activities and their interactions are described at a low level of detail and they are more suitable for short-term forecasting in the context of network-wide coordinated traffic management. While with microscopic models' entities, their activities and their interactions are described at a higher level of detail and they are more suitable for

Intelligent Transportation Systems (ITS) applications, such as dynamic traffic management and route guidance which are now seen as important tools for traffic management (Toledo et al, 2015). Microscopic model was chosen for this research because detail interactions between drivers and drivers and their environment are required when investigating intrinsic factors of a traffic stream that can only be investigated by considering the behaviours of drivers such as the average acceleration and start-up loss times. The components of microscopic traffic flow models were then discussed and Paramics car following algorithm which is based on the Fritzche's model was chosen for this research because it operates based on perception rather than impulse as observed in the GHR models and safety distance models. With the latter models, the following drivers always have the exact knowledge of their lead vehicle's speed and position rather than an estimate which is more realistic.

The fundamentals of traffic flow were then reviewed where it was revealed that road traffic is characterised by the traffic flux (flow rate), the density and the mean speed. The road traffic flow fundamental diagrams showed the states of a given traffic which are usually of major concern and the states were identified as free flowing traffic where vehicles travel freely without being impeded by other traffic, saturated traffic where vehicles queue and move at very low speeds because of the maximum density reached and capacity traffic which is the maximum flow rate on the link. The road traffic flow fundamental diagrams were later used to validate the traffic flow algorithm in chapter 3.

The factors affecting the future of road transport were then investigated. They were grouped into independent and dependent factors. The independent factors constitute the nature of governance and the social and political values of a given society while the dependent factors constitute the economic and demographic growths as well as the technological advancement of the society. The interactions between the independent factors is viewed in terms of the dimensions of change as this provides a robust, integrated and pragmatic approach in understanding the dynamics of change process. The interactions between the dimensions were later used in chapter 6 to define various socio-economic scenarios. Technological advancement is the only dependent factor that was considered in this thesis and various technological advancements in the UK have been projected to arrive by 2050. This includes the introduction of smart highways and connected and autonomous vehicles. Autonomous vehicles have the potential to change the dynamics of the UK roads. Besides potential improvements in road safety, emission and social inclusion, through platooning autonomous vehicles have the potential to improve traffic congestion. The impact of autonomous vehicles on the road traffic congestion was investigated in chapter 6.

In the next chapter the design and implementation of the traffic flow model used for this thesis will be discussed. The traffic flow model was used to simulate the interaction of drivers and drivers and their environment in traffic streams. The output of the simulations was integrated with the weather data obtained from the weather generator (discussed in chapter 4) using the integrated weather impact simulator (IWIS, discussed in chapter 5), this was used to determine the impact of the weather data on various traffic streams. The IWIS is a model that was designed due to the simulation speed limitation of the traffic flow model which will be discussed in chapter 3 and 5.

Chapter 3 – Methodology: The Traffic Flow Algorithm

3.1. Introduction

In the previous chapter a literature review was carried out on various topics related to the research which helped in the discovery of various statistical knowledge that exists related to the research topic. This chapter will discuss the design and implementation of the traffic flow model used for this thesis.

Developing a traffic flow model is often an important step when analysing a real-world traffic system. To determine the resilience of a road network to future climatic conditions it is important to have in place a traffic flow model of the network which could be subjected to various future weather conditions (which may be generated using weather projection tools such as the UKCP09 weather generator) to determine their effects on the traffic parameters.

The choice of the type of traffic flow model to be used for the analysis would depend on how much detail is required off the model. Microscopic traffic flow models offer a deep insight into the interactions between drivers and driver and their environment resulting in more realistic traffic flow parameters when compared to both macroscopic and mesoscopic models.

Various traffic flow modelling platforms were considered for the research but were eventually decided against mainly because they generally do not have any parameters that explicitly relate to weather, and its effects and they were not open-source tools which made modifying their source code to include weather data and weather conditions impacts impossible. This resulted in a plan which involved the development of traffic flow models based on a car following model. Various car following models such as Paramics, AIMSUN and MITSIM were considered but due to time constraint and the resources available only Paramics car following model was eventually utilised.

Paramics car following model which is a variant of the Fritzsche model is a Psycho-physical car following model which uses thresholds for various parameters such as the minimum speed difference between a leader and a follower perceived by the follower (Olstam and Tapani, 2004). Paramics technical report (Duncan, 1998) was the main source of information for Paramics car following model. While being very informative, it appeared certain information required to design a model based entirely on the information provided were omitted hence some assumptions had to be made throughout the design of this model. Although to a certain degree the driver-driver interaction logic was obtained directly from Paramics technical report certain logic which aided smoother traffic flow is innovative. For example, although the information provided on the Paramics technical report is enough to design a traffic stream, at certain isolated times collisions and overlapping occurred during simulation most likely because of certain omitted information (which were not included on the technical report) not being accounted for during the design. To tackle this issue additional logics were required to detect when such collisions were likely to occur, and measures were taken to avoid them. The main logic involves the following driver constantly comparing their speed against the leader's speed to determining if a collision would occur should the leader suddenly start braking. This logic therefore acted as a fail proof, but it did not consistently affect the smooth operation of Paramics car following model as the model barely failed during operation. The interactions between the drivers and their environment (link) were designed from scratch. These interactions mainly involve the behaviour of drivers when entering or exiting a link (signalised intersection or the presence of a roundabout where congestion was induced at the end of the link) and lane changing in the case of multiple lanes traffic flow.

The maximum acceleration of vehicles under various weather conditions was modelled using Rakha et al. (1999)'s vehicle dynamics model for estimating maximum vehicle acceleration levels based on vehicle's tractive effort and aerodynamic, rolling and grade resistance forces. Although Rakha et al. (1999) designed their model for trucks, Snare (2002) study showed that the model could also be effectively applied to lighter vehicles.

The traffic flow model designed was based on three different models and the UK Highway code. The models were:

- Paramics car following model,
- an innovated lane changing model and
- Rakha et al. (1999)'s model for estimating maximum vehicle acceleration

It featured multiple lanes split into patches and DVUs were simulated based on their patch number and lane number. It had multiple modes of operation from single lane to up to four lanes, homogeneous or heterogeneous vehicle types, congested or free flowing mode. The research focused on two hypothetical trunk roads both 1km long containing 3 lanes and were based in an area between Winwick and Croft, Greater Manchester. One of the roads contained a signal-controlled link end while the other contained a roundabout controlled link end in order to explore the most common junction types used in the UK (VisitBritain, 2012; Gov.UK, 2015). Both single lane and three lane roads were utilised in this research, the single lane roads were featured during the testing while the 3 lane roads were featured during the testing and the actual simulation runs.

Validating the simulation output involved comparing the outputs to the fundamentals of traffic flow for consistency. To simplify the validation process only the simulation output of a mixed traffic under normal condition was focused on and examinations were done on both signal controlled and roundabout controlled traffic for both a single and 3 lane links.

Research was carried out by Agarwal et al (2005) to quantify the impact of rain, snow and pavement surface conditions on traffic flow. They estimated relationship between highway capacity and traffic speed on congested freeways in the Minneapolis/St. Paul (the Twin Cities) metropolitan area where they utilised freeway traffic in-pavement system detectors data collected from a four-year period, weather data from three Automated Surface Observing Systems (ASOS) and five RWIS sensors. Results from this research indicated that severe precipitation (mainly rain and snow) and visibility impairment resulted in the most significant speed and capacity reductions (Agarwal et al, 2005). The findings of Agarwal et al (2005) research were used to validate the impact of weather conditions on the output of the simulations produced during this research.

Road traffic is characterised by the traffic flux (flow rate), the density and the mean speed. Immers and Logghe (2002) described the fundamental road traffic flow characteristics shown in the literature review.

3.2. Designing the Traffic Flow Model

The traffic flow model was designed and simulated using a *patch-wise* method. This method involved splitting the link into equal patches with each patch being 8 meters long meaning in a 1000m link there was a total of 125 patches. Each patch contained registers where DVUs contained in the patch must be registered to. The average passenger vehicle is 4.7m long (World Heritage Encyclopedia, 2016) while the average city bus is 14m long (Ryczkowski, 2016) meaning a single patch could fit one and a fraction of another car or a fraction of an average city bus. The patch-wise model ensured patches were simulated sequentially hence DVUs contained in Patch 1 were always simulated before the DVUs in Patch 2 etc.

When considering multiple lanes, each lane in a way was considered as a separate link, meaning each lane was split into patches (P1 to Pn) and DVUs were free to switch lanes provided *the lane changing rules* were met and for each patch each lane was simulated.

Figure 3.1 shows a four lanes link segment containing two patches (patches 2 and 3) with their border-lines signified by the red lines. This section was explained in detail in appendix 2.

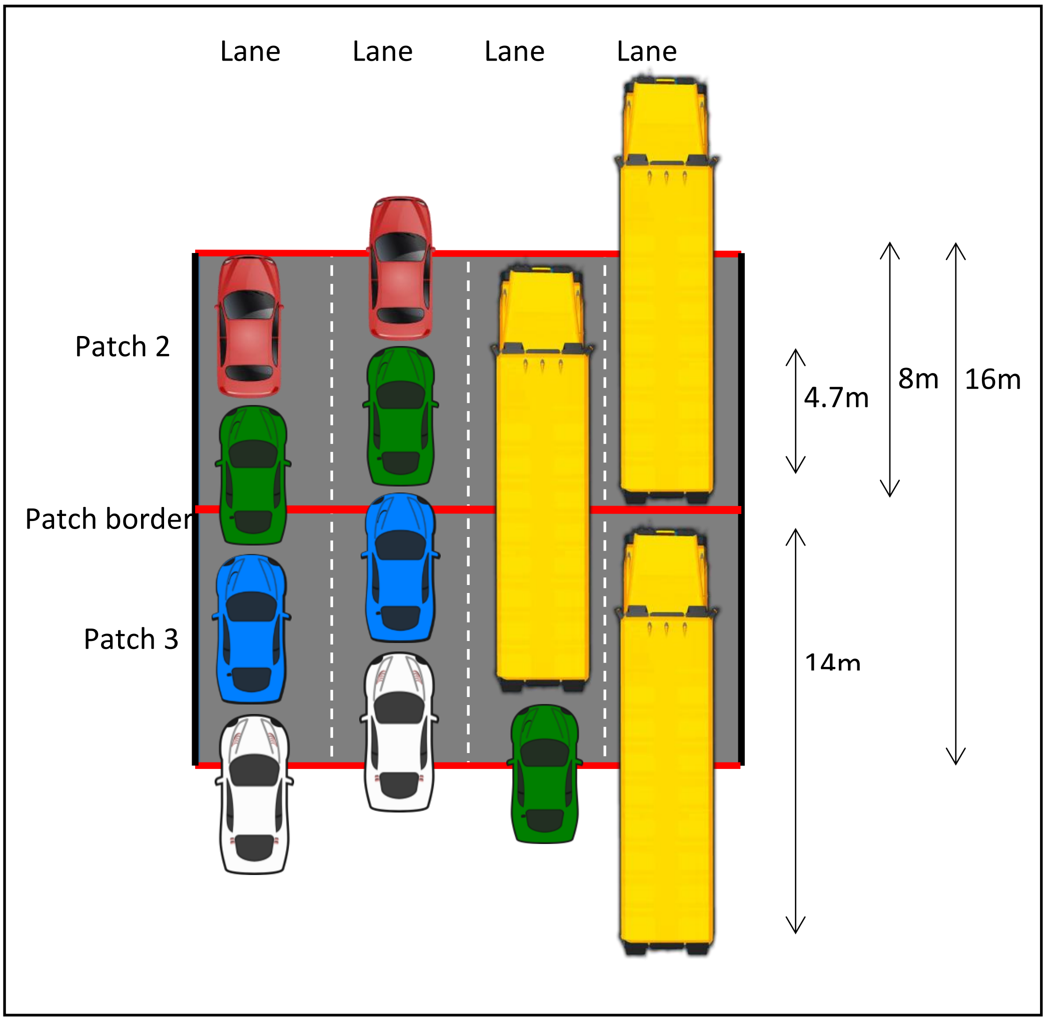


Figure 3.1: The Patch-wise model

Key Functions

The multiple lane model had 7 main user options which were:

- Traffic mode
- Signal mode
- Stop sign status
- Vehicle composition
- Vehicle Type
- Weather condition
- Number of lanes

3.2.1. Traffic control modes

This option had three different modes which were:

- roundabout controlled traffic,
- free flowing traffic

- signal controlled traffic modes

3.2.1.1. Free flowing and roundabout traffic-controlled modes

When free flowing traffic was activated, lead DVUs exited the link without any special speed requirement (except the speed limit of the link) while when roundabout controlled traffic was activated lead DVUs were required to either come to a complete stop at the end of the link if the stop sign status was on there by simulating the worst case scenario of a traffic jam or in cases were the stop sign status was off drivers were required to reduce their speed to a special speed requirement (5m/s) there by simulating a general traffic jam. This section was explained in detail in appendix 2 while the code is shown in appendix 6.

3.2.1.2. Signal controlled traffic mode

When the signal-controlled traffic mode was activated, the signal state periodically alternated between two states. These were the red and green states, whenever there was a state change a timer commenced. The code for the signal counter is shown in appendix 6.

Basically, the signal automatically controlled the stop sign explained under the previous heading. Whenever the signal was red the stop sign was switched on and lead DVUs of each lane were required to stop behind the stop line while whenever the signal was green the stop sign was switched off and DVUs were required to drive pass the stop sign. The code used to automatically control the stop sign is shown in appendix 6. This section was explained in detail in appendix 2.

3.2.2. The Traffic Stream Vehicle Composition

The traffic composition could be set to either uniform length where all vehicles have the same length and attributes such as mass, frontal area, power etc. or heterogeneous length where vehicles may differ in length and other attributes. When the uniform vehicles option was selected the user was then required to choose between HGV and car lengths. This is shown in the code in appendix 6. Cars had a length of 4.7m while HGVs had a length of 14m (Larsson, 2009 and World Heritage Encyclopaedia, 2016). When heterogeneous vehicles option was selected the user was then required to select the desired combination ratio. For the conventional development system of the UK (explained in a later section) the ratio of cars to HGVs entered was 16:1. This is shown in appendix 6. This section was explained in detail in appendix 2.

3.2.3. The Weather Conditions

Although temperature has been known to affect the aggression of drivers as mentioned in chapter 1, but for simplicity it was mainly used to differentiate between rainfall and snowfall. The classification of weather conditions based on their precipitation intensities and temperature was shown in chapter 4. Basically, the weather conditions were classified into 5 categories which were:

- Dry/Normal

- Light Rain
- Light Snow
- Heavy Rain
- Heavy Snow

These conditions affected the behaviour of the driver which was mainly the top speed it was willing to achieve as well as the parameters of the vehicle which were the maximum acceleration and deceleration of the vehicle. The relationship between the weather conditions the vehicles maximum acceleration and deceleration would be later explained under the maximum acceleration and deceleration section. The relationship between weather and the top speed of drivers was derived from Agarwal et al (2005) where estimated drops in speed for various weather conditions were indicated. To be aligned with the UK motorway and trunk road driving rules where 70mph has been indicated as the speed limit, only the speed differences between the dry condition and the various weather conditions found in Agarwal et al (2005) were used. The speed differences between Agarwal et al (2005) dry condition and the other conditions were then used to obtain the maximum speed for the other weather conditions for this thesis. This was done by subtracting the corresponding difference of a given weather condition from 70mph to obtain the maximum speed under the weather condition for this thesis. The derived maximum speed for the various weather conditions is shown in the Table 3.1. The implementation in code is shown in appendix 6. This section was explained in detail in appendix 2.

Weather condition	Speed (mph)
Dry/Normal	70
Light Rain	63.79
Light Snow	63.79
Heavy Rain	57.57
Heavy Snow	38.93

Table 3.1: The Maximum Speeds for various weather conditions

3.2.4. The Lane Changing model

Lane changing refers to the movement of a DVU from its current lane to an adjacent lane. It is an integral aspect of multiple lane microscopic traffic simulation and it involves complex decision making by the model drivers which often rely on several objectives that sometimes conflict (Mathew, 2014). Ramanujam (2007) indicated that lane changes are often expressed in terms of *gap acceptance* and *target lane* where a driver intending to switch lanes chooses a target lane then determines if there is an acceptable gap in the selected target lane. An acceptable gap which may be time gap or free space gap must be greater than or equal to the critical gap (minimum acceptable gap required for a lane change execution) for the lane change to be executed.

Lane change durations for various models often range between 4-6 seconds which seems practical except DVUs may take longer than realistic timing when attempting to change lane in various situations such as where a driver becomes desperate after failing to switch lanes following multiple attempts, situations where the driving conditions of the current lane becomes favourable while attempting to switch lanes (depending on the reason for switching lane i.e. mandatory or discrete discussed later), or being able to simultaneously observe multiple lanes for preferred driving conditions (left, current and right lanes) which is often the case in the real world. This thesis introduces a new timing method which is an extension of the conventional lane change timing method (expressed in seconds) used in previous works. In this method time expressed in seconds was replaced with interest levels where the interest level of a driver may increment or reduce by one level or remain unchanged during each time-step. The levels ranged from 0 to 50, the maximum level 50 was adopted from the average lane change duration utilised by other works. This model was designed based on the UK Highway Code (DFT, 2016) and drivers looking to switch lanes for better driving conditions take this into account when deciding.

3.2.4.1. Mandatory and discretionary lane change

Mandatory lane changes (MLC) are compulsory lane changes such as changes a driver must make to complete his journey or drivers attempting to adhere to the UK highway codes.

Discretionary lane changes (DLC) are executed when a driver intends to seek better driving conditions from an adjacent lane, avoid merging traffic, avoid following bigger vehicles etc. (Mathew**,** 2014).

Traffic-flow models often combine the MLC and DLC and during selection clashes the MLC always precede over the DLC. This work has not observed drivers making left or right turns on the Trunk Road. This section was explained in detail in appendix 2.

3.2.4.2. The Point Based Lane Changing Process

It has been split into three stages:

Decision to change lane: This stage involved the driver observing the driving conditions on its current lane. When it is close enough to the lead DVU on its current lane it decides if the mean speed of the lane is favourable and if the DVU ahead is moving at a favourable speed, if these conditions are not met it decides *to change lane*. To meet the UK Highway code specification, if these conditions are met it then compares the mean speed with that of the inner lane, if the mean speed of the inner lane is less than the mean speed of the current lane but the difference falls within a certain threshold then a *decision to change lane* is also made.

Mathew (2014) discussed various equations by Gipps (1986) which may be used to determine *a driver's desire to change lane, feasibility of changing lane and gap acceptance*. While the method seems rather complex, this thesis introduced a simplified method for carrying out the above lane changing processing. Thorough tests of the model proposed in this thesis revealed that the model performed the required tasks without errors.

In this work, to determine a driver's desire to change lane the driver was designed to observe its driving condition until 20 *interest levels* had been gained. An interest to change lane gained a point at each time step when the driving conditions were not favourable and lost a point when it was favourable. After 20 interest driving levels had been gained the driver became unsatisfied and a *decision to change lane* was then made.

The driver was then unable to change his mind from switching to a different lane until 10 *interest levels against* switching lanes had been made. This was done to prevent drivers from changing their decisions rapidly. A point was gained *against switching lanes* if the driving condition of the current lane suddenly became favourable during a time-step while all points were completely lost if the conditions became unfavourable during a time-step to reduce the delay when attempting to switch lanes. This entire stage was only featured when the driver intended to switch to an outer lane as he was required to switch to an inner lane if the driving conditions were favourable regardless of if its current driving conditions were favourable.

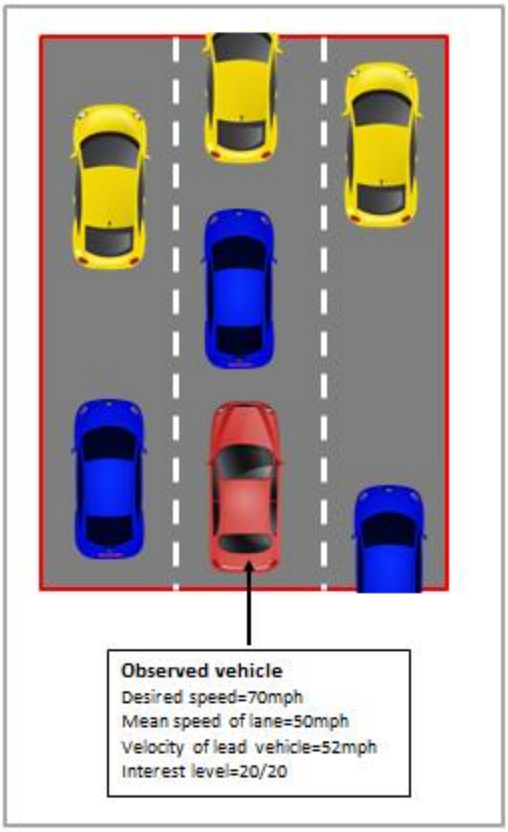


Figure 3.2: Decision to change lane illustration

Figure 3.2 above illustrates a driver who has decided to change lanes perception of his environment. The driver interest in changing lane is on level 20 meaning he has been observing his current lane for a while (not necessarily 20 time steps as the interest level may gain or lose a point at each clock cycle depending on the driving condition of the current lane), has decided it is not favourable and has made a decision to change lane. His *mind change level* remained at level 0 because the driving condition has either not improved in the current time step or improved and gained a point in a previous time step but became unfavourable in a different time step where all points were immediately lost.

The code in appendix 6 was used by each driver when observing the condition of its current lane. This section was explained in detail in appendix 2.

Driving condition on adjacent lanes (feasibility of changing lane): After a decision to change lane had been made the next step was to determine the driver's feasibility of changing lane. The driver commenced observing the driving conditions of the adjacent lanes as well as its current lane (points against switching lanes as explained above). He observed both the outer and inner lane simultaneously, both lanes had interest levels which ranged from 0-40, a point was gained in favour of the inner lane if the driving conditions were favourable and lost if they were not favourable in a given time-step regardless of if a *decision to change lane* had been made by the driver or not. The outer lane started gaining or losing points after a *decision to change lane* had been made. To prevent the DVU from deciding to switch to the inner lane (possibly slower lane since favourable conditions for the inner lane were designed to be lower than the current lane) a counter was used to determine when the right lane driving conditions were not favourable for 20 consecutive time-steps. A decision to switch to the left lane was only possible if the interest to switch to the right lane was zero or the interest in the right lane lost points for 20 consecutive time steps. The driver stopped observing the right lane (i.e. interest level of the right lane returned to 0) if his *mind change level* was at maximum (i.e. if he felt his current lane driving conditions were better than the right lane or favourable).

The driver also observed the speed of the lead DVU on the adjacent lane with interest points being gained or lost depending on the speed of the lead DVU with respect to its current speed.

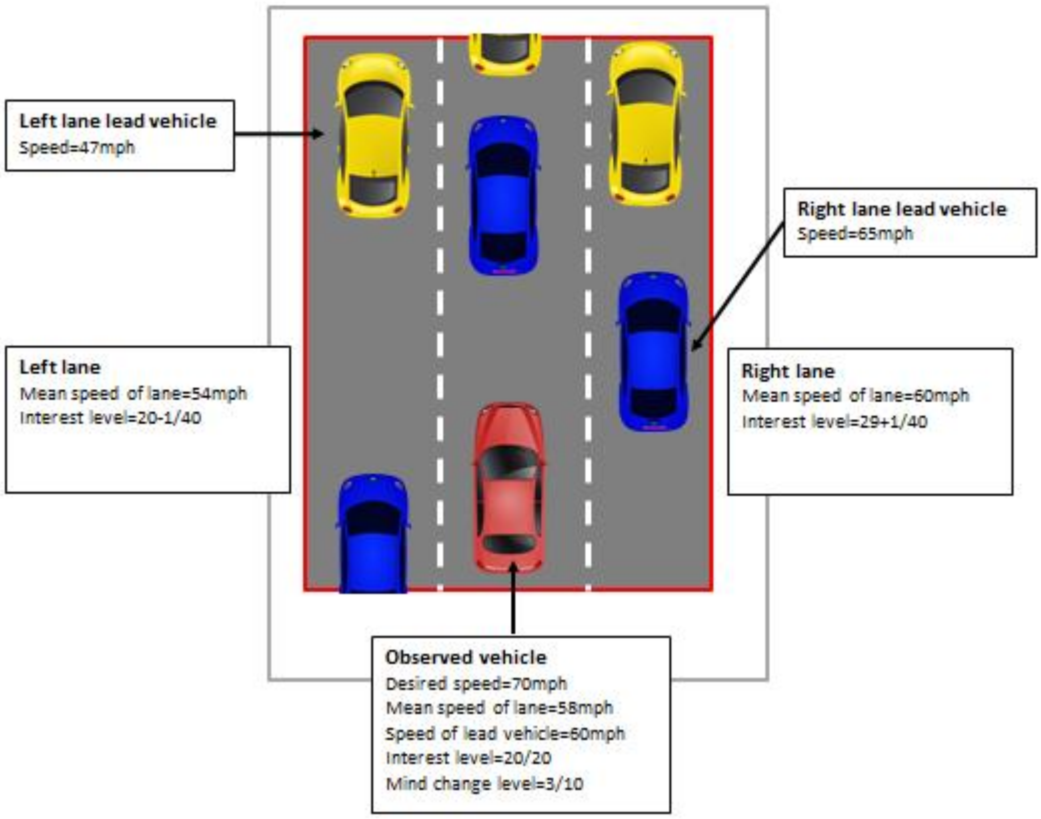


Figure 3.3: Illustration of the driver's perception of the neighbouring lanes

Figure 3.3 above illustrates an observed driver's perception of his neighbouring lanes at a given time step after he had made up his mind to change lane. The mean speed of the right lane was 60mph and the lead DVU (i.e. the DVU on the neighbouring lane in front of the observed DVU) speed was 65mph which was a more favourable condition than the current lane which had a mean speed of 58mph and lead DVU speed of 60mph hence the interest level for the right lane gained a point on this time step. On the left lane the mean speed was 54mph which was less than the current lane's mean speed, but the difference was within an acceptable threshold but the lead DVU's speed was 47mph which was below the threshold and deemed unfavourable hence the interest level for the left lane lost a point during that time step.

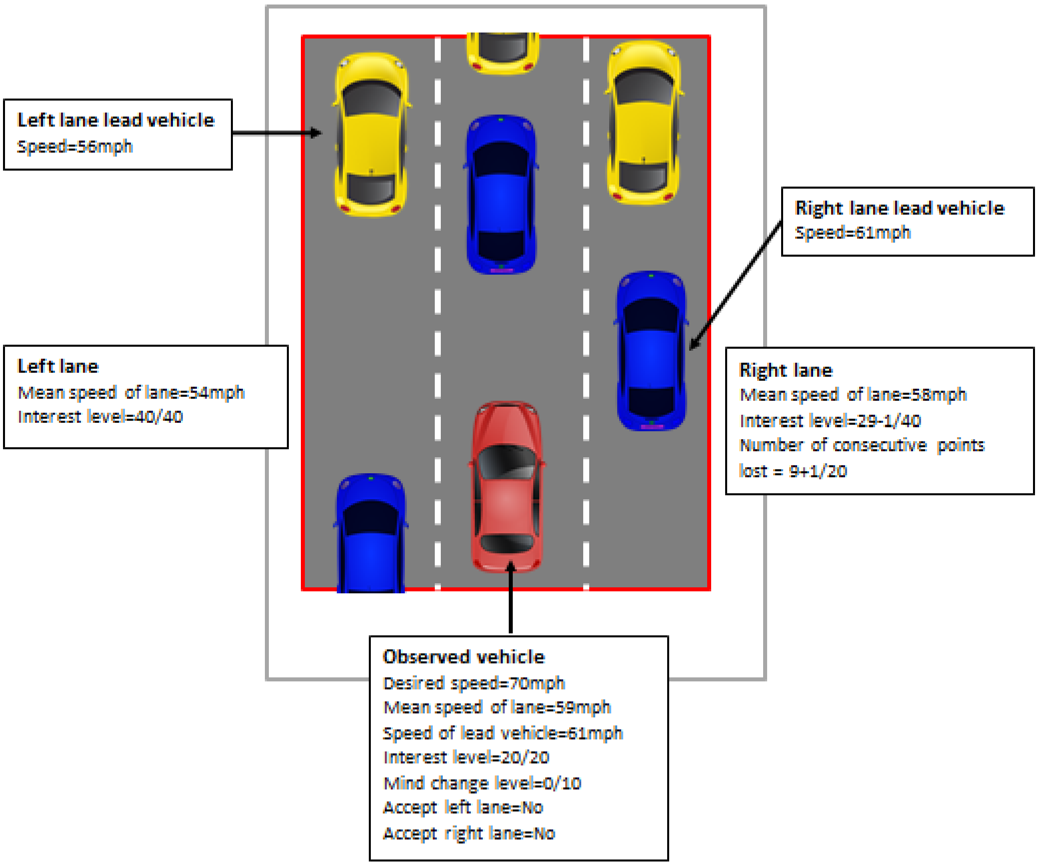


Figure 3.4: Decision when selecting a lane

Figure 3.4 above although the interest level on the left lane was at maximum, the interest level on the right lane was neither at the minimum value nor had it lost points for 20 consecutive levels hence the driver decided to continue his observation until either these conditions were met before switching to the left lane or until the driving conditions on its current lane or the right lane became favourable. The code is shown in appendix 6.

The driver continued observing the inner lane regardless of its satisfaction with its current lane. As mentioned earlier the driver was always willing to accept a lower speed on the inner lane provided the speed was within an acceptable threshold from its desired speed or its current lane mean speed, it was also happy if there was no lead DVU on the inner lane. The driver completely lost interest in the outer lane when it had no lead DVU on its current lane while its interest in its current lane gained a point, it gained or lost an interest point in its outer lane and current lane depending on the condition of the outer lane.

An interest point was gained for the outer lane only when the driving condition of that lane met certain threshold values which were set to always be better than its current lane conditions. This section was explained in detail in appendix 2. The driving conditions were defined in a later section.

Gap acceptance and execution: After a desired lane had been selected the driver then determined if switching lanes would potentially result in a collision between their vehicle and their lead or following DVU. This was done by determining if there was enough gap between the lead DVU and the following DVU on the adjacent lane as well as if a collision would occur if the lead DVU suddenly started braking and if a collision would occur with the following DVU if the driver of the observed car suddenly started braking. If the conditions were positive lane change was then executed else the DVU waited until the conditions were satisfied while observing the driving conditions of all three lanes and making changes to its decision when required. This is illustrated in figure 3.5.

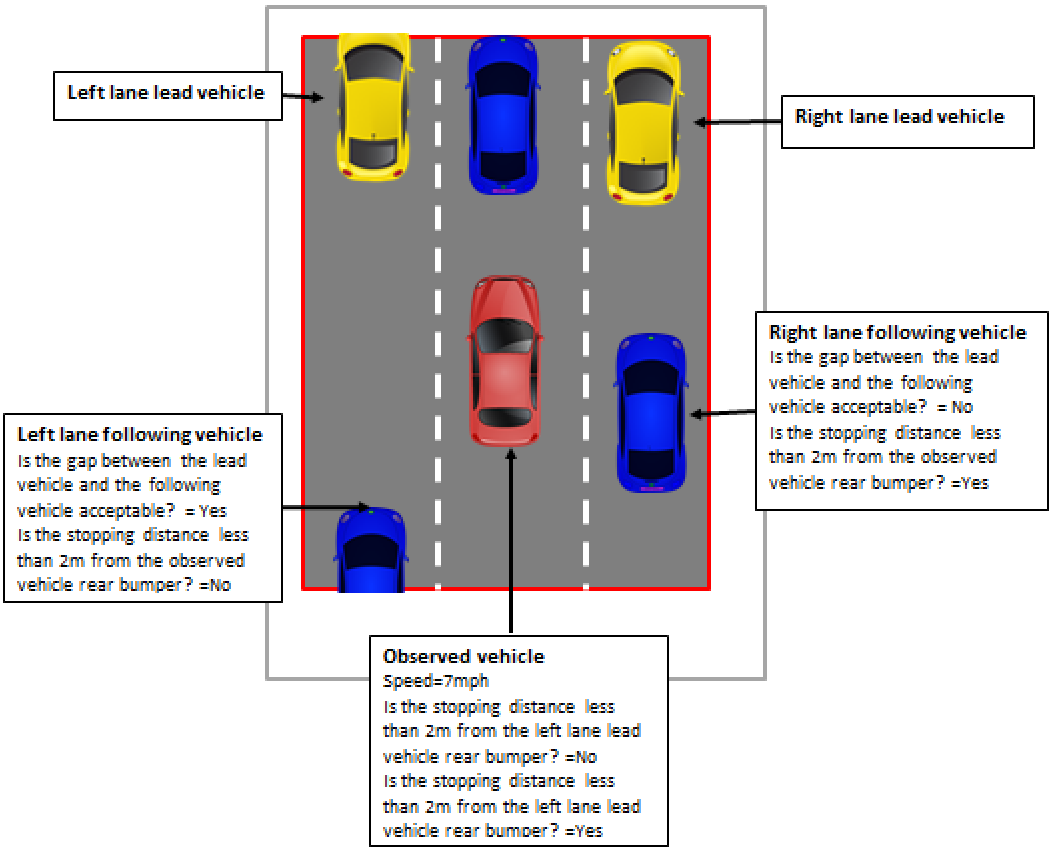


Figure 3.5: Decision on gap

Figure 3.5 above the gap between the lead and following DVUs on the right lane is not acceptable, although switching lanes would not result in a collision with the lead DVU it would potentially result in a collision with the following DVU as the stopping distance of the following DVU would be less than 2 meters from the observed DVU's rear bumper hence if even if the right lane driving condition was favourable lane change would not be executed until a suitable gap is observed. On the left lane the gap between the lead and following DVUs on the right lane is acceptable, switching lanes would not result in a collision with neither the lead DVU nor the following DVU as the stopping distance of the observed DVU would be less than 2 meters from the lead DVU's rear bumper and the stopping distance of the following DVU would be less than 2 meters from the observed DVU's rear bumper hence if the left lane driving conditions were favourable, lane change would be executed. The code shown in appendix 6 was used by the driver of the observed DVU when deciding on whether to change its lane or remain in its current lane during the current time step. This section was explained in detail in appendix 2.

3.2.4.3. The UK Highway Code

The UK Highway code prohibits drivers from using the right-hand lane when the road is clear, and it restricts heavier vehicles such as buses from using the right-hand lane. It also prohibits drivers from overtaking using the left lane except during congestion where traffic in the left-hand lane may be moving faster than traffic in the right-hand lane. Vehicles are also prohibited from weaving in and out of lanes to overtake (DFT, 2018).

3.2.4.4. Lane changing model test result

Test of the lane changing algorithm showed drivers exhibiting a realistic decision-making attribute as drivers were able to simultaneously evaluate the driving conditions of all three lanes during the decision-making process. Test results showed that drivers spent an average of 4.9 seconds between deciding to change lanes and executing the lane change under low traffic density with drivers generally completing this process within 4 seconds (40 time-steps) without any disruptions to the decision-making process.

3.2.5. Driving conditions definitions

The Current lane Good driving conditions

This condition was true when the speed of the observed DVU was less than its maximum speed and its acceleration was greater than or equals its acceleration whenever the lead DVU was pulling away or its current acceleration was its maximum acceleration. It was also true whenever the observed DVU was travelling at its maximum speed. This is shown in the logic equation below:

velo<max_velo & (accel>=aB OR accel=max_accel) OR velo=max_velo [3.1]

The Current lane Bad driving conditions

This condition was true when the speed of the observed DVU was less than its maximum speed and its acceleration was less than or equals its acceleration when the lead DVU overshoots its target separation or less than its acceleration when the lead DVU was pulling away or less than or equals its acceleration when it was cruising with its lead DVU or getting closer to it or when the speed of the lead DVU on its current lane was less than the mean speed of the current lane.

velo<max_velo & (accel<=aA OR accel<aB OR accel<=aC OR velo_refC<mean_velo_cur) [3.2]

The Left lane Good driving conditions

This condition was true when the mean speed of the left lane was greater than the maximum speed of the observed DVU minus 10m/s or the mean speed of the left lane was greater than or equals the mean speed of the current lane minus 2m/s or no lead DVU on the left lane. It was also true when no lead DVU on the left lane and the observed DVU's speed was less than the mean speed of the left lane minus 2m/s.

mean_velo_left>max_velo-10 OR mean_velo_left>=mean_velo_cur-2 OR refL=0 OR (refL=0 & velo<mean_velo_left-2) [3.3]

refL=0 means no lead DVU on the left lane

The left lane Bad driving conditions

This condition was true when the mean speed of the left lane was less than the maximum speed of the observed DVU minus 10m/s and the mean speed of the left lane was less than or equals the mean speed of the current lane minus 2m/s. It was also true when the speed of the lead DVU on the left lane was less than the mean speed of the left lane.

(mean_velo_left<max_velo-10 & mean_velo_left<=mean_velo_cur-2) OR velo_refL<mean_velo_left [3.4]

The Right lane Good driving conditions

This condition was true when the mean speed of the right lane was greater than the mean speed of the current lane plus 2m/s, it was also true when there was no lead DVU on the right lane, it was also true when the speed of the lead DVU on the current lane was less than the mean speed of the right lane minus 2m/s.

mean_velo_right>mean_velo_cur+2 OR refR=0 OR velo_refC<mean_velo_right-2 [3.5]

refR=0 means no lead DVU on the right lane

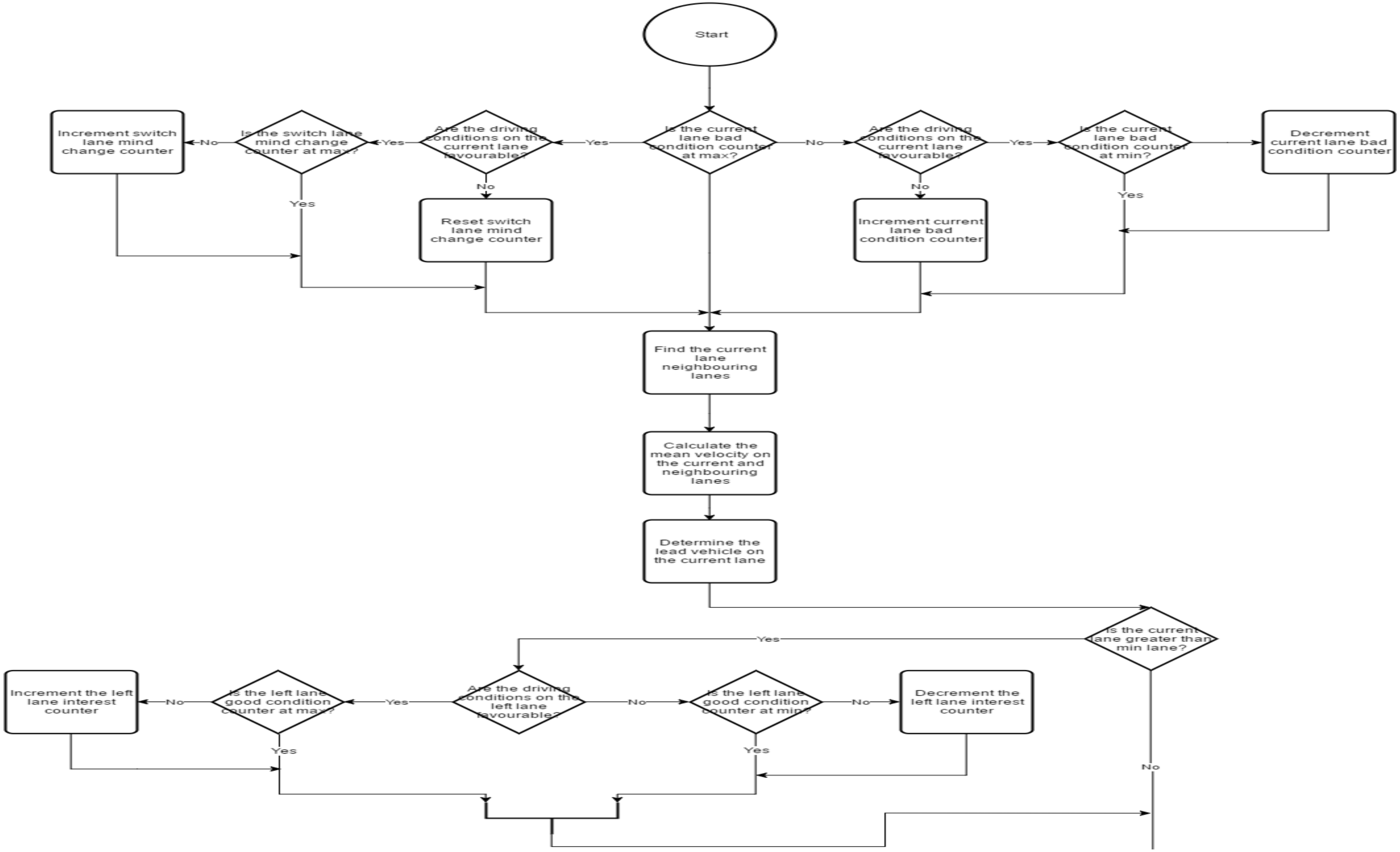
The Right lane Bad driving conditions

This condition was true when there was no lead DVU on the current lane, it was also true when there was a lead DVU on the current lane and the mean speed of the right lane was less than the mean speed of the left lane plus 2m/s or the speed of the lead DVU on the right lane was less than the mean speed of the current lane plus 2m/s.

refC=0 OR refC>0 & (mean_velo_right<mean_velo_left+2 OR velo_refR<mean_velo_cur+2 [3.6]

The Lane changing model flow chart

The flow chart for the lane changing model is shown in figure 3.6


Start
Is the current lane bad condition counter at max?
Yes
No
Are the driving conditions on the current lane favourable?
Yes
No
Is the switch lane mind change counter at max?
No
Yes
Increment switch lane mind change counter
Reset switch lane mind change counter
Are the driving conditions on the current lane favourable?
Yes
No
Is the current lane bad condition counter at min?
Yes
Decrement current lane bad condition counter
Increment current lane bad condition counter
Find the current lane neighbouring lanes
Calculate the mean velocity on the current and neighbouring lanes
Determine the lead vehicle on the current lane
Is the current lane greater than min lane?
Yes
No
Are the driving conditions on the left lane favourable?
Yes
No
Is the left lane good condition counter at max?
No
Yes
Increment the left lane interest counter
Is the left lane good condition counter at min?
No
Yes
Decrement the left lane interest counter

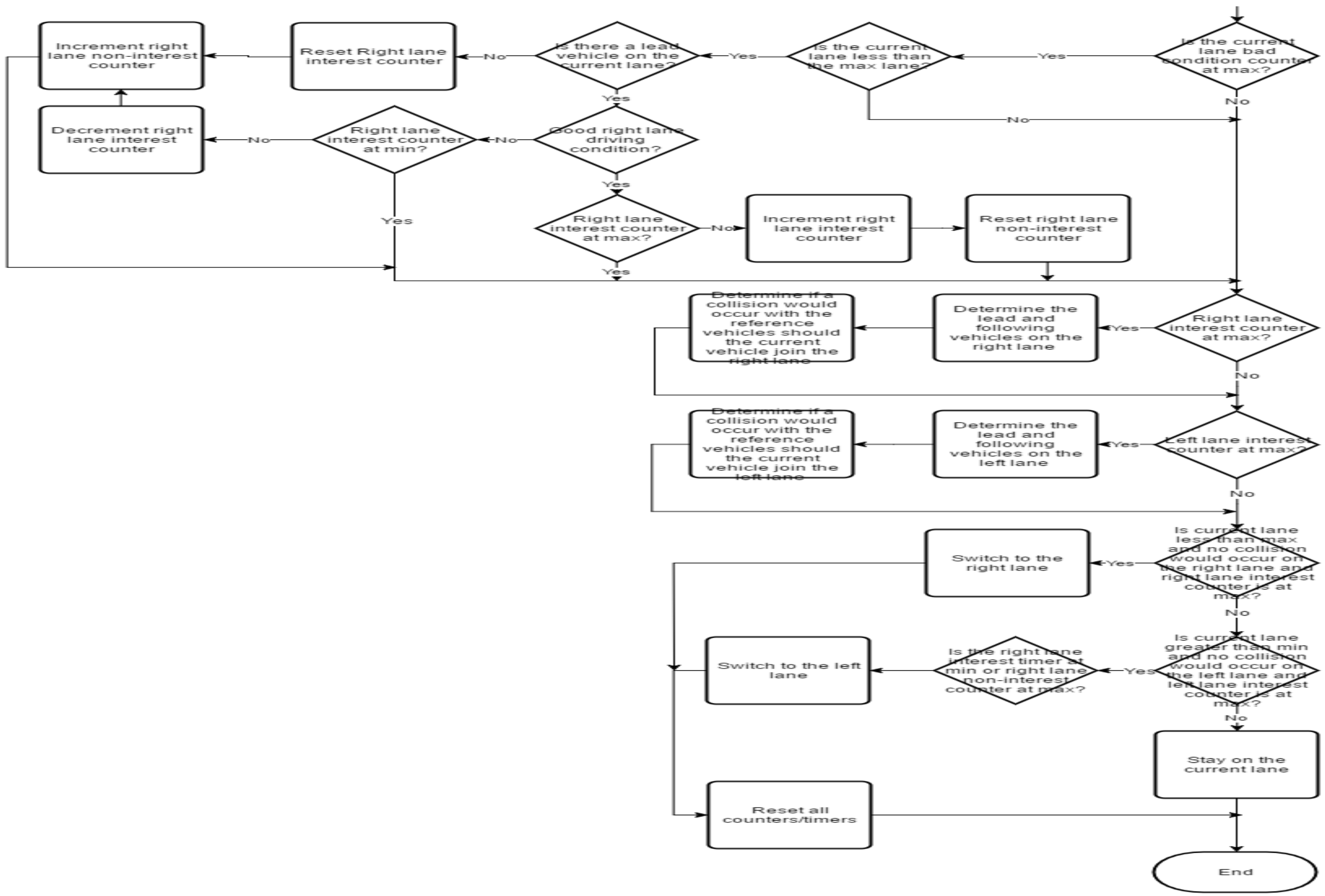


Figure 3.6: Flow chart for the lane changing model

Figure 3.6 above shows the flow chat of the lane changing algorithm, the full code can be seen in appendix 6.

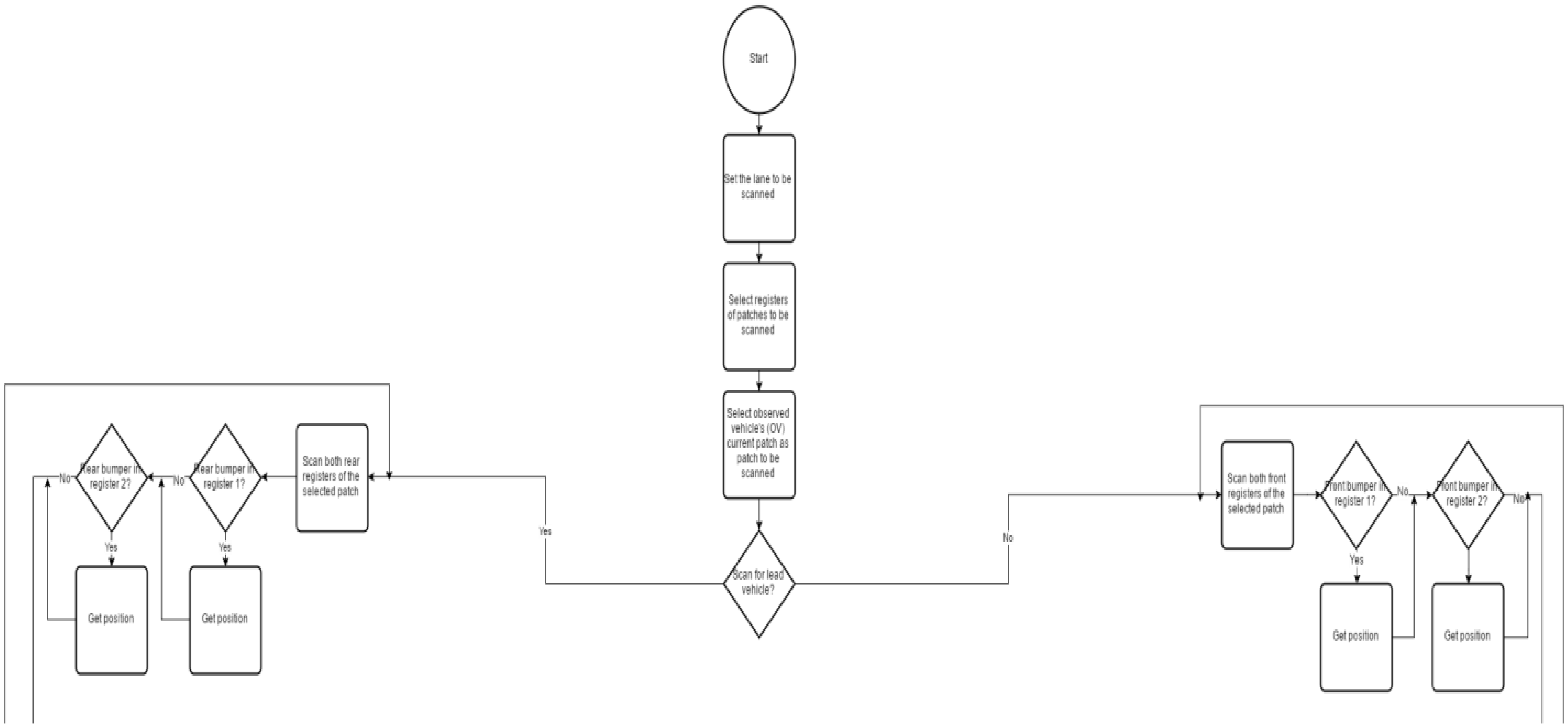
3.2.6. Other key functions

3.2.6.1. Reference Driver-Vehicle Unit (DVU) detection

This function was used to detect the lead and following vehicles of an observed vehicle. On the current lane of a vehicle being observed, it was used to detect its lead vehicle on its current lane while during a lane changing operation it was used to detect its corresponding lead and following vehicles on its neighbouring lanes.

The function operated by initially scanning through the registers of the patch containing the observed vehicle for possible front or rear bumper registration numbers of other vehicles. When a vehicle's bumper was detected it then compared the position of the bumper to the bumper of the vehicle being observed. When a lead vehicle was being scanned for, it compared the detected rear bumper positions to the position of the front bumper of the vehicle being observed. The vehicle with the rear bumper closest to the front bumper of the vehicle being observed became its lead vehicle. In a situation where a rear bumper was not detected within the scanned registers, the scan was then expanded to other patches ahead starting from the patch immediately in front.

When a vehicle registration number was detected in a patch register it meant the patch register contained a bumper of the detected vehicle. This section was explained in detail in appendix 2 while the code is shown in appendices 6.18-6.20. An overview of the algorithm is shown in figure 3.7.


Start
Set the lane to be scanned
Select registers of patches to be scanned
Select observed vehicle's (OV) current patch as patch to be scanned
Scan for lead vehicle?
Yes
No
Scan both rear registers of the selected patch
Rear bumper in register 1?
Rear bumper in register 2?
Get position
Get position
Scan both front registers of the selected patch
Front bumper in register 1?
Front bumper in register 2?
Get position
Get position

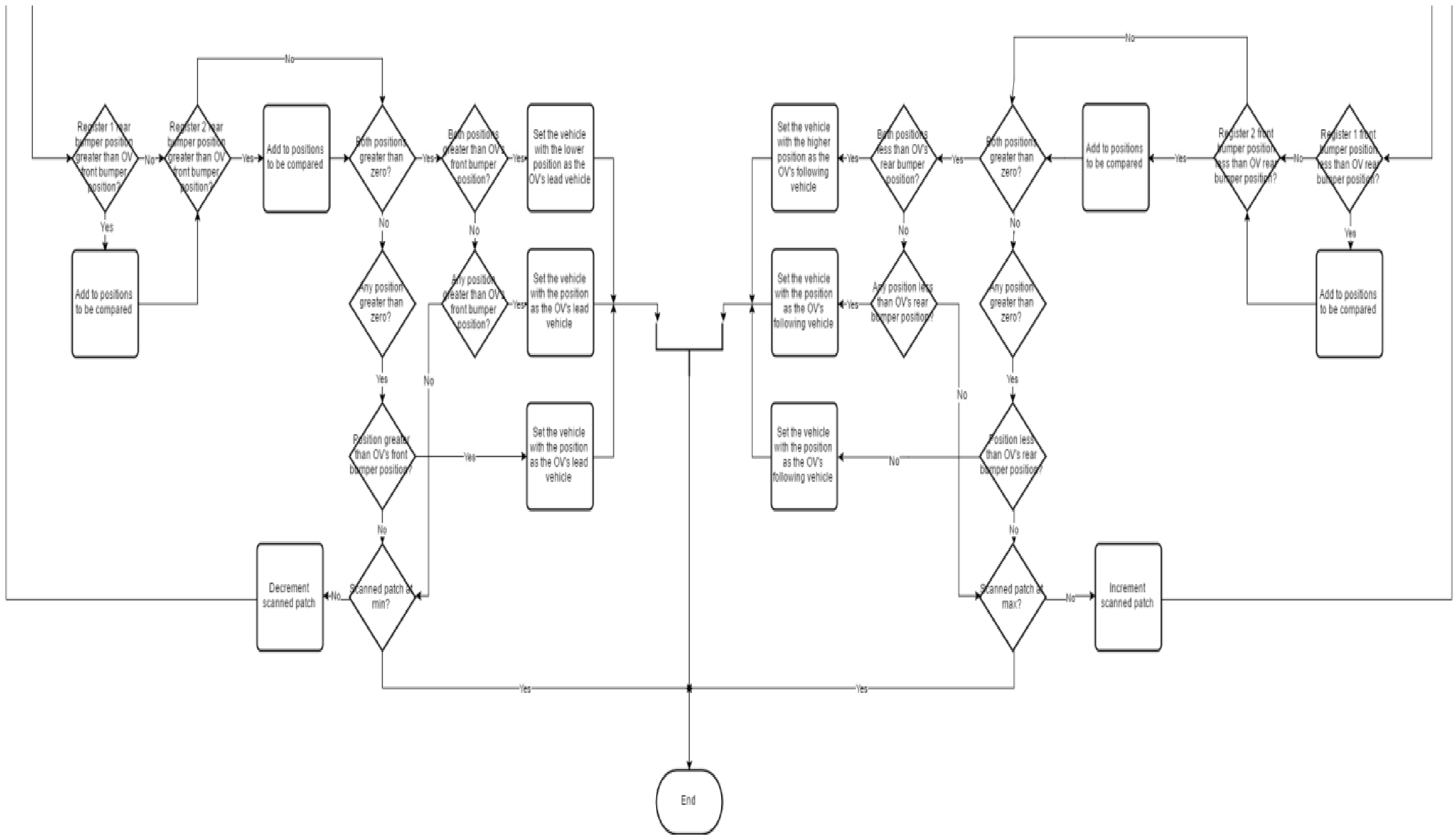


Figure 3.7: Flow chat of the reference DVU detection algorithm

3.2.6.2. Distance to patch convertor

The Patch Generator

This function was used to convert the distance covered by each DVU to patch variables. The length of the link to be featured was first divided into patches, each patch was 8 meters long and the total number of patches for any given link with a length being a multiple of 8 could be deduced as:

$$total\,patch = linklength/8 \qquad [3.7]$$

A look up table containing a range of distances from 1 to the link length (meters) split into groups (patches) was generated and fed into the patch generator function. For this research the link length was 1000 meters long hence there was a total of 125 patches. The distances were assigned to patches in descending order meaning 1m was assigned to patch 125 and 1000m assigned to patch 1.

Decimal positions were rounded up to higher integers, for example 8.1m was rounded up to 9m even though this would normally be rounded to 8m this was because 8.1m would be located on the 124th patch rather than the 125th patch which contained values from 1-8m also this way values less than 1m but greater than 0m were rounded up to 1m rather than assuming they were out of range.

After the positions to be searched were rounded to integers (i.e. the front bumper and the rear bumper positions of a DVU) they were searched for on the look up table and the corresponding column value of where they were located was assigned to their patch value. The patch generator code is shown in appendix 6. Figure 3.8 shows the flow chat of the distance to patch convertor algorithm. This section was explained in detail in appendix 2.

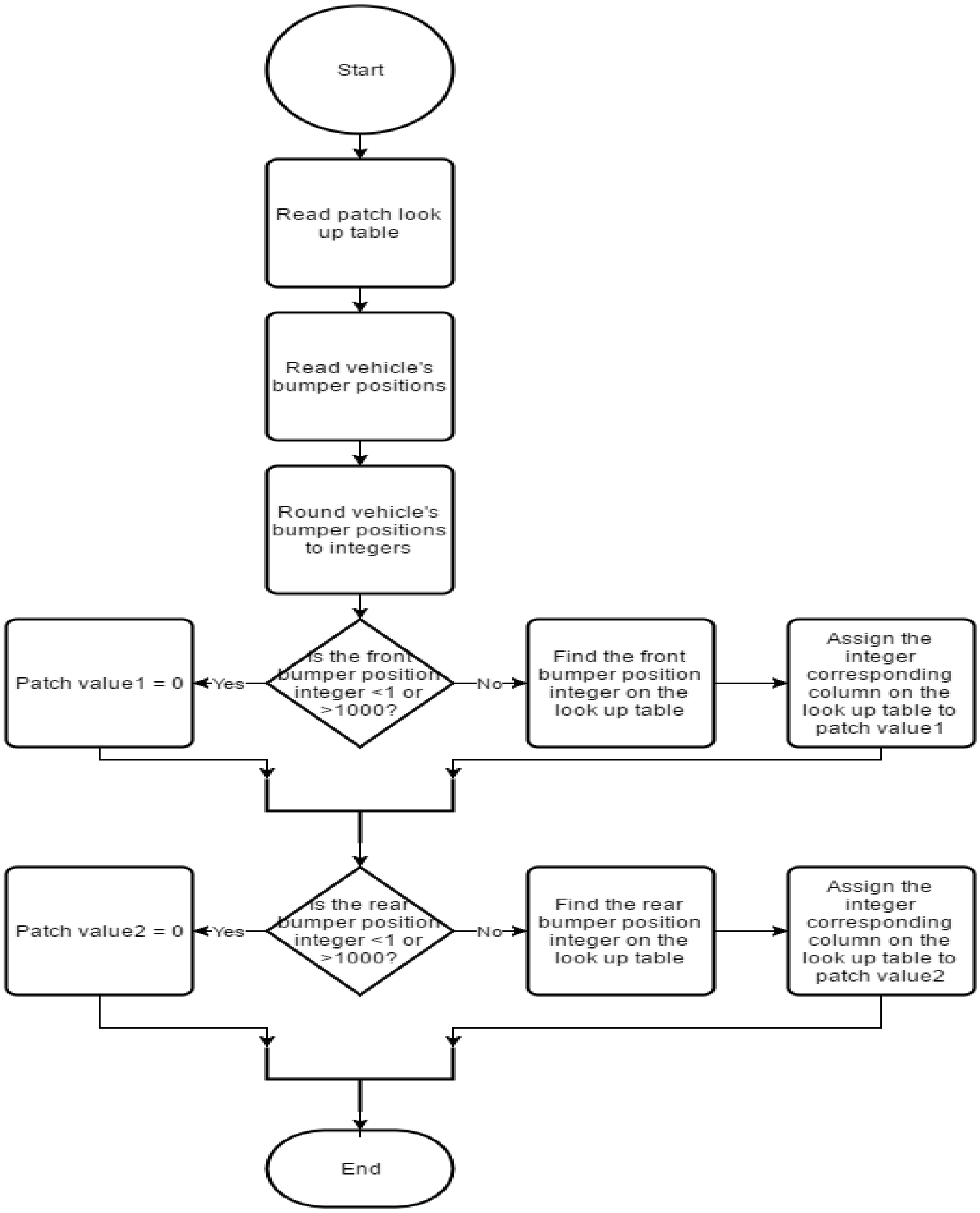


Figure 3.8: The flow chat of the distance to patch convertor algorithm

3.2.6.3. Collision detector

A collision detection function was used as a fail proof to avoid collisions in situations (if any) where Paramics vehicle following function failed and during DVU lane changing operation.

Paramics Technical report mentioned three modes of car following which are *braking*, *cruising* and *acceleration* modes. Detailed explanation of the braking and acceleration mode were not given except that a following driver would over compensate if it sensed its lead DVU was braking and would accelerate at a maximum rate if the lead DVU was perceived to be accelerating and was in a position greater than the following DVU's *safe stopping distance* away plus 2m which the minimum gap is as defined by Paramics (Duncan, 1998).

Mathew (2014) suggested a DVU looking to switch from its current lane to a different lane should determine if a collision would occur with the reference DVUs (lead and following DVUs) on the target lane before making the switch. This involved comparing the speeds of the individual DVUs to its current speed as well as determining if there would be enough time to respond by either itself or the reference DVUs to avoid a collision should any of the three DVUs suddenly start braking.

The collision detection function was used to calculate the stopping distances of both the lead and following DVUs and to determine if the following DVU's front bumper would be greater than the minimum gap based on its current speed. The list of formula used is shown below:

$$t = \Delta v / \Delta a \qquad [3.8]$$

$$db = 0.5 * v * t \qquad [3.9]$$

Where: t= stop time; Δv=change in speed; Δa=deceleration rate (maximum deceleration); db=distance covered while braking (Monster, 2003)

Equations 1&2 were used to calculate the distance covered while braking of the reference DVUs and the lead DVU. After the calculation was made it was then determined if the following DVU's front bumper was greater than the lead DVU's rear bumper minus a tolerance (average gap between DVUs during congestion) by adding their current bumper positions to their corresponding distance covered while braking and making a comparison between both resulting positions. The collision detector code is shown in appendix 6.

The stopping time and stopping distance

The first step was to calculate the stopping of the reference DVU which was calculated by dividing the speed of the DVU by its maximum deceleration rate. Similarly, the stopping time of the observed DVU was calculated by dividing the speed of the DVU by its maximum deceleration rate. The stopping distance of the reference DVU (lead or following) was calculated by multiplying the product of its speed and its stopping time by 0.5. Similarly, the stopping distance of the observed DVU was calculated by multiplying the product of its speed and its stopping time by 0.5.

The collision detector modes

The collision detector function was split into two modes. They were collision detector function:

- Used with the Lane changing function
- Used with Paramics car following function

Used with the lane changing function

A variable 'used_for_lane' was set to high when the function was being used along with the lane change function and set to low when it was used as a fail proof for the Paramics car following function. When it was used along with the lane change function, the displacement of the observed DVU was first calculated. This was done because the observed vehicle driver had to assume its vehicle in the target position and not its current position when determining if a collision would potentially occur. Although the response time of the driver was considered under Paramics car following function it was not considered under the collision detector function to reduce the complexity of the program. Ideally to take the driver's response time/awareness level into account, the driver of the current DVU should have some time delay when observing the parameters of the reference DVU hence it should observe the parameters at a few time steps behind the current time step. Since 1-time step equals 100 milliseconds (ms) a response time of 2 seconds would be equivalent to 20-time steps.

To determine if there would potentially be a collision the sum of the position of the observed DVU front bumper, its displacement for the current time as well as its stopping distance was compared to the sum of the reference DVU rear and its stopping distance minus the minimum traffic gap. A potential collision was flagged whenever the first equation was greater than or equals the second or if a collision had already occured, it was not flagged when the first equation was less than the second equation or when there was no collision.

It should be noted that the reference DVU here referred to the lead DVU while the observed DVU referred to the following DVU hence the reference DVU may be the observed DVU if it was observing the following DVU on the neighbouring lane.

Used with Paramics car following function

When the function was used alongside Paramics function the variable 'used_for_lane' was to low. The next step was then to determine if the gap (the gap plus the minimum gap between DVUs) between the lead and the observed DVU was wide enough for the observed DVU to accelerate at maximum rate (desired acceleration). The term desired acceleration was used because the maximum acceleration rate depended on the maximum rate the driver was comfortable with which was a percentage of the actual maximum acceleration rate of the DVU. This was further explained in a different function.

To determine if the gap was wide enough a threshold gap of 200m was chosen because it was at least 2 times wider than the stopping distance at maximum speed of the different DVUs featured. The gap between both DVUs was compared to this threshold and if the gap was wider it was assumed that the observed DVU could safely accelerate at maximum rate.

To determine if there would potentially be a collision the sum of the position of the observed DVU front bumper and its stopping distance was compared to the sum of the reference DVU rear and its stopping distance minus the minimum traffic gap. A potential collision was flagged whenever the first equation was greater than or equals the second or if a collision had already occurred, it was not flagged when the first equation was less than the second equation or when there was no collision.

It should be noted that the reference DVU here was always the lead DVU on the current lane while the observed DVU was always the actual observed DVU.

3.2.6.4. Paramics Car following function

Drivers controlled their speed under two main modes, the first mode was used when the driver was either the lead DVU or there was a sufficient gap between itself and the lead DVU where it accelerated at a desired maximum rate until it was at a distance from the intersection, the second mode was used when the driver was following a lead DVU and had to control its speed based on its perception of the lead DVU.

Paramics car following function was used for the second mode. When this function was operational drivers controlled their speed based on their perception of the speed of their corresponding lead DVU. Their speed variations were normally smooth but there were abrupt speed changes in cases where the lead DVU braked or started accelerating at a high rate. This function had three modes which were:

- Braking mode
- Acceleration mode
- Cruising mode

Braking mode

This mode was triggered when the stopping distance was greater than the safe stopping distance plus the minimum traffic gap plus a tolerance gap (note that as suggested by Duncan (1998) the following DVU always over compensated due to its reaction time). It was also triggered when the lead DVU rapidly lost speed within a time threshold. This situation had to occur at 5 consecutive time steps for the following DVU brake to be triggered. The driver of the following DVU also considered parameters of its lead DVU based on its awareness level. Braking mode triggers the maximum deceleration of the DVU. The condition that triggered the braking mode is shown in equation 3.10 while equation 3.11 is the equation for the maximum deceleration (braking).

$$SD > (SSD+minTG+TolG)OR(Lv_t-Lv_{t-1} = aDANDLv_{t-1}-Lv_{t-2} = aD...Lv_{t-4} - Lv_{t-5} = aD) \quad [3.10]$$

$$aD = md \quad [3.11]$$

where: SD is the stopping distance, SSD is the safe stopping distance, TolG is the tolerance gap of the DVU, minTG is the minimum traffic gap, md is the maximum deceleration rate of the DVU, Lv is the lead DVU's speed.

A function was designed to determine when the lead DVU was rapidly losing speed. This is shown in the code under appendix 6. The function was called in the main code as shown under appendix 6. This section was explained in detail in appendix 2.

Acceleration mode

This mode was triggered when the lead DVU was at a position much greater than the following DVU's safe stopping distance including all tolerances or in a situation where the lead DVU was accelerating with its speed being higher than the following DVU's speed and in a position greater than the following DVU's safe stopping distance including all tolerances. The condition that triggered the acceleration mode is shown in equation 3.12 while equation 3.13 is the equation for the maximum acceleration.

$$Lp > (p + SSD + minTG + TolG + 10) OR (Lp > (p + SSD + minTG + TolG) AND (Lv > v) AND (a = ma)) \quad [3.12]$$

aE=ma [3.13]

Where: Lp is the lead DVU's rear bumper position, v is the following DVU's speed and p is the position of the following DVU's front bumper

The maximum acceleration the driver is willing to utilise

The maximum acceleration of DVUs under various weather conditions was modelled using Rakha et al. (1999)'s vehicle dynamics model for estimating maximum vehicle acceleration levels based on vehicle's tractive effort and aerodynamic, rolling and grade resistance forces. Although Rakha et al. (1999) designed their model for trucks; Snare (2002) study showed that the model could also be effectively applied to lighter vehicles.

The Tractive Effort

The model constrained the maximum tractive force which was computed using Equation 3.14 using Equation 3.15 which was then demonstrated using Equation 3.16. The friction between the tyres of the vehicle's tractive axle and the road surface accounted for in Equation 3.15 while Equation 3.16 ensured that the tractive effort did not approach infinity while travelling at low speeds.

$$F_t = 3600\eta\frac{P}{V} \quad [3.14]$$

$$F_{max} = 9.8066 M_{ta} \upsilon \quad [3.15]$$

$$F = min(F_t, F_{max})$$ [3.16]

Where F_t : tractive effort (N); P:engine power (kW);V: truck speed (km/h);
n: transmission efficiency Typical transmission efficiencies range from 0.89 to 0.94; F_{max}: maximum tractive force (N); M_{ta}: vehicle mass on tractive axle (kg) such that M_{ta}=M.$perc_{ta}$; $perc_{ta}$: percent mass acting on tractive axle;µ: coefficient of friction between t ires and pavement; and F: tractive effort effectively acting on vehicle (N).

Rakha et al (2012) included a gear reduction factor to account for the impact of gear shift when trucks accelerate from a low speed. The factor is a linear function of vehicle speed with an intercept of 1/u_0 and a maximum value of 1.0 at u_0 (optimum speed or the speed at which the vehicle attains its full power). The tractive effort for trucks (HGVs) was calculated as:

$$F_T = 3600\beta\eta\frac{P}{v}$$ [3.17]

Where β is a gear reduction factor calculated as:

$$\beta = \frac{1}{\mu_0}[1 + min(\mu, \mu_0)(1 - \frac{1}{\mu_0})]$$ [3.18]

The intercept was used to guarantee that the vehicle had enough power to accelerate from a stop. The vehicle’s optimum speed was then calculated as a function of its weight to power ratio (ω) for ranges between 30 to 170 kg/kW. This is shown in equation 3.19:

$$\mu_0 = 1164\omega^{-0.75}$$ [3.19]

Where u_0 is the optimum speed

Rakha et al (2012) indicated that the gear shift parameter β is not required for the modelling of light-duty vehicle acceleration behaviour (weight-to-power is less than 30 kg/kW) hence equation 3.14 was used for cars while equation 3.17 was used for the heavier vehicles. In code the tractive force was obtained as shown in appendix 6.

The Resistance Forces

Rakha et al. (1999)’s model took three major types of resistance forces into account, which were aerodynamic, rolling, and grade resistance. The total resistance force was the determined as the summation of the three resistance components as shown in Equation 3.20.

$$R = R_a + R_r + R_g$$ [3.20]

Where R: total resistance (N); R_a: air drag or aerodynamic resistance (N); R_r: rolling resistance (N); and R_g: grade resistance (N).

Aerodynamic Resistance

The aerodynamic resistance was a function of the vehicle frontal area, the altitude, the vehicle drag coefficient, and the square of speed of the vehicle, as shown in Equations 3.21 and 3.22 (Rakha et al., 1999).

$$Ra = c_1 C_d C_h A V^2 \quad [3.21]$$

$$C_h = 1 - 1.85 \times 10^{-5} H \quad [3.22]$$

Where A: truck frontal area (m^2); V: truck speed (km/h); C_d: truck drag coefficient; C_h: altitude coefficient; c_1: constant equals to 0.047285; and H: altitude (m).

Rolling Resistance

The rolling resistance was a function of the vehicle mass and speed, as shown in Equation 3.23. Rolling coefficients (C_r) typical values as a function of the road surface type and condition can be found in Rakha et al. (1999). The rolling resistance coefficients (c_2 and c_3) as shown in Rakha et al. (1999) which vary based on the vehicle's tyre type were also considered.

$$R_r = 9.8066 C_r (C_2 V + C_3) \frac{M}{1000} \quad [3.23]$$

Where M: vehicle total mass (kg); Cr: rolling coefficient; and c2, c3: rolling resistance coefficients.

Grade Resistance

The grade resistance which was a constant depended on the vehicle's total mass and the percentage grade on which the vehicle travelled along, shown in Equation 3.24. The proportion of the vehicle's weight that resisted the vehicle's movement was accounted for by the grade resistance.

$$R_g = 9.8066 M i \quad [3.24]$$

Where i: percent grade (m/100 m)

In code the resistance forces were computed as shown in appendix 6.

The maximum vehicle acceleration

The maximum acceleration of the vehicle was then computed as the forces acting on the vehicle as shown in Equation 3.25.

$$a = \frac{F - R}{M} \quad [3.25]$$

Where a: maximum acceleration (m/s^2); F: tractive effort (N); R: total resistance force (N); and M: vehicle total mass (kg).

An average driver would normally only utilise a fraction of the maximum acceleration of their vehicle. Rakha et al indicated that field studies have shown this fraction to be around 0.65 (Snare (2002) and Rakha et al (2012)) and was accounted for in Equation 3.26.

$$a^0_{max} = f_p \frac{F - R}{M} \quad [3.26]$$

Where a^0_{max} is the maximum acceleration the driver is willing to utilise.

Equation 3.27 was then used to calibrate vehicle acceleration behaviour under *inclement weather condition*.

$$a_{max} = a^0_{max} - f_p g i \quad [3.27]$$

Where i is a rain adjustment factor

In code the maximum acceleration was computed as shown under appendix 6.

The maximum vehicle deceleration

Rakha et al (2012) indicated that that the maximum braking force acting on each axle of a vehicle can be derived as the product of the coefficient of roadway adhesion and the vehicle weight normal to the roadway surface. Actual optimal brake force is not often achieved in non-antilock braking systems hence a braking efficiency term is also accounted for when computing the maximum braking force as shown in equation 3.28.

$$d_{max} = \eta_b \upsilon_g \quad [3.28]$$

Where ηb is the braking efficiency, μ is the coefficient of roadway adhesion also known as the coefficient of friction, and g is the gravitational acceleration (9.8066 m/s^2).

For this research all vehicles were assumed to be equipped with antilock brake systems. With antilock braking system the braking efficiency approaches 100%.

Equation 3.29 was modified by Rakha et al (2012) to account for the effect of precipitation on driver/vehicle behaviour. The modified equation for computing the maximum vehicle deceleration shown in Equation 3.29 was adjusted using a rain adjustment factor which accounted for the impact of rain intensity on the deceleration behaviour.

$$d_{max} = \eta_b \upsilon_g (1.0 - 0.07759 i) \quad [3.29]$$

Where i is a rain adjustment factor

In code the maximum vehicle deceleration of was computed as shown under appendix 6.

Where n= μ, all vehicles where assumed to be fitted with anti-lock braking systems for this research therefore braking efficiency was assumed to be 100% hence E= ηb=1

Conditions and vehicles specifications

Both light and heavy vehicles were featured during this research, the specifications for the various light and heavy vehicles as well as pavement and tyre conditions were obtained from both Rakha et al. (1999) and Snare (2002). The featured heavy vehicles are abstract. This is summarised in Table 3.2 below:

Vehicle	1995 Acura Integra	Mazda 2001 Protégé	1995 BMW 740I	Semi-trailer and low mass	Semi-trailer with No aerodynamic aids and medium	Semi-trailer with Full aerodynamic aids and high mass
Power (hp)	142	130	282	349.71	349.71	349.71
% Mass Tractive Axle	0.515	0.525	0.515	0.40	0.40	0.40
Altitude (m)	599	599	599	599	599	599
Grade	0	0	0	0	0	0
Engine Efficiency	0.68	0.7	0.7	0.62	0.65	0.7
Coefficient friction	0.6	0.6	0.6	0.6	0.6	0.6
Cd	0.32	0.34	0.32	0.70	0.78	0.58
Ch	0.95	0.95	0.95	0.95	0.95	0.95
C1	0.047285	0.047285	0.047285	0.047285	0.047285	0.047285
C2	0.0328	0.0328	0.0328	0.0328	0.0328	0.0328
C3	4.575	4.575	4.575	4.575	4.575	4.575
Cr	1.25	1.25	1.25	1.25	1.25	1.25
Frontal Area (m^2)	1.94	2.04	2.27	6.8	7.0	10.0
Power (kW)	105.932	96.98	210.372	260.78	260.78	260.78
Mass (kg)	1670	1610	2370	22208	34263	43910

Table 3.2: Conditions and vehicles specifications

- Vehicle Engine Power: This is the maximum power that a given vehicle's engine can put out.
- Engine Efficiency: Internal friction and other factors result in power losses in the engine and they usually account for between 20-35% of the total engine losses for light duty vehicles hence typical efficiency values range between 0.65-0.80.
- Vehicle Mass: The total mass of the vehicle
- Percentage of Vehicle Mass on the Tractive Axle: Four-wheel drive vehicles often have 100% for this value while typical values for two-wheel drive vehicles often range between 50-65% for front wheel drives and 35-50% for rear wheel drives. Although not included in this thesis for simplicity, it should be noted that many modern 4-wheel drive light vehicles (such as the newer Honda CR-V models (Honda, 2019)) have 'intelligent' systems whereby they normally operate as 2-wheel drive (or nearly 2-wheel drive), but can vector torque to all wheels as condition vary.

- Pavement: Several constants are obtained using the pavement type and condition
- Coefficient of Friction: This value depended on the pavement type and condition.
- Altitude: The region of interest's altitude above sea.
- Air Drag Coefficient: Depending on the aerodynamic features of the vehicle, the values for light duty vehicles usually range from 0.30 to 0.35.
- Frontal Area: The frontal area of the vehicle which could be approximated as 85% of the height times the width of the vehicle if unknown
- Rolling Resistance Constants: The rolling resistance constants used in the model.
- Grade: The grade of the roadway is given as a decimal (m/100 m). The grade is often considered a constant for a given section of roadway. However, the gradient of the links featured were assumed to be 0.

In the code pavement conditions, the vehicle types and other parameters were defined in the code as shown in appendix 6.

Cruising mode

This mode was triggered when the conditions satisfying the braking and acceleration conditions were not met. This meant the lead and following DVUs were travelling without abrupt changes to their speeds (i.e. cruising). Paramics gave three secondary modes (or acceleration components) for the cruising mode. The modes are:

Target point overshot: This mode was triggered when the separation of the DVUs was less than the target point of the following DVU. The target point was calculated using the equation 2.3 while the acceleration for this secondary mode was calculated using equation 2.5. In equation 2.5 k_2 is a constant which equals 0.1

In code the target point was calculated in appendix 6 while the *target point overshot* acceleration component (aA), limited to the maximum acceleration and deceleration and called in the main code are also shown in appendix 6.

Lead vehicle pulling away: This mode was triggered when the separation of the DVUs increased with time. The separation was calculated using the equation 2.1 and was triggered when:

$$s_n > s_{n-a} \quad [3.30]$$

While the acceleration for this secondary mode was calculated using equation 2.6.

Where: s is the separation, n is the reaction time of the driver, a is the time used when contrasting by the driver.

In code the separation was calculated as shown in appendix 6, while the lead DVU pulling away acceleration component (*aB*), limited to the maximum acceleration and deceleration and called in the main code are shown in appendix 6.

Constant separation or coming together: This mode was triggered when the separation of the DVUs was constant or reduced with time.

$$s_n < s_{n-a} \quad [3.31]$$

The acceleration for this secondary mode was calculated using equation 2.7

In equation 2.7 c is a variable used to bring DVUs together rapidly. Its value reduces as DVUs approach the minimum gap of 2 meters. Its equation is shown in equation 2.4.

In code the bunching acceleration was written shown in appendix 6, while the *Constant separation or coming together* acceleration component (*aC*), limited to the maximum acceleration and deceleration and called in the main code are shown in appendix 6.

The flow diagram used for Paramics car following model is shown in figure 3.9 below. It should be noted that the separation and target point are as observed by the following driver sometime in the past. This time depends on the driver's awareness level. The following driver occasionally used a contrast time when attempting to reach a decision. This section was explained in detail in appendix 2.

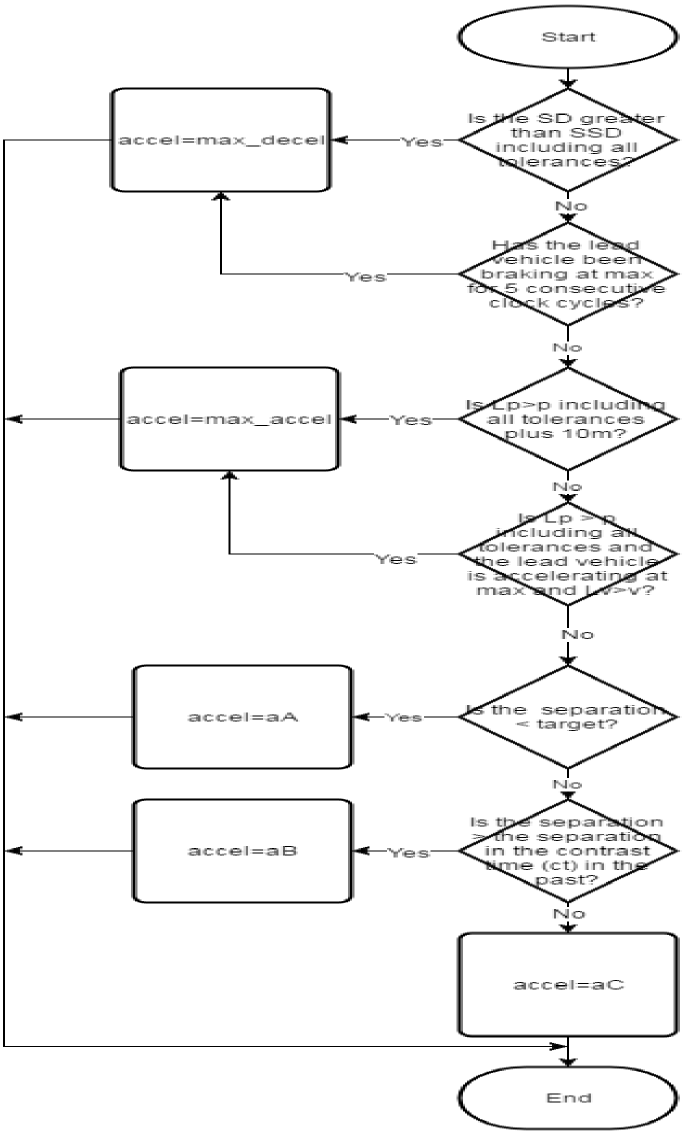


Figure 3.9: Paramics car following algorithm flow diagram

3.3. Simulating the Traffic Flow Model

3.3.1. The Primary code

This section of the program was responsible for simulating the entire program by calling functions and calculating various parameters of the driver-vehicle unit (DVU).

Weather conditions affect the DVU abilities such as the maximum acceleration/deceleration, top speed (the driver's maximum speed tolerance) and the headway. These parameters are exacerbated as the weather condition worsens with the headway increasing while top speed and maximum acceleration/deceleration decrease.

Due to the increased drag and the decrease in the coefficient of friction (roll resistance) between the road surface and the vehicle tyres as the vehicle speed increases the maximum acceleration of the vehicle reduces. At low speed the roll resistance is the main resistance force while at higher speeds the drag takes over in magnitude.

The *simulation main loop* was initiated immediately after the initialisation of the various parameters including various arrays whose sizes depended on the maximum allowed vehicle density on the link and the maximum simulation time both specified by the user. Every other aspect of the simulation occurred within this loop including function calls and calculations of DVUs parameters.

Initialisation

The model had a main menu with 7 user settings which the user was required to initialise before running the program. These options were:

- Traffic mode
- Signal mode
- Stop sign status
- Vehicle composition
- Vehicle Type
- Weather condition
- Number of lanes

This was written in the code as shown in appendix 6. After the user initialisation the initialisation of the various parameters including various arrays some of whose sizes depended on the maximum allowed vehicle density on the link and the maximum simulation time were carried out at the start of the simulation.

3.3.1.1. The first time step

The main simulation loop (the time loop) encapsulated every other loop within the simulation program. This loop ran from 1 to the maximum simulation time (time step) specified by the user. Within this loop was a second loop (the patch loop) which cycled from patch 1 to the maximum patch (patch 125) during each time step.

During the first time step, the first DVU entered the link and it was immediately given a DVU registration number. DVU registration numbers ranged from 1 to the link maximum density and were allocated based on availability with the lower values being favoured over the higher values. In this case the first DVU was allocated registration number 1. The registration numbers were used by DVUs to identify other DVUs in the traffic stream. From this point a DVU would be referred to by its registration number except otherwise stated.

DVU 1 lane was then initialised to lane 1 while its front bumper position was initialised to the minimum position of the link (0.1m) and its rear bumper's position was calculated by subtracting the vehicle's length from its front bumper's position.

$$p_r = p_f - VL \qquad [3.32]$$

Where p_r is the vehicle's rear bumper position, p_f is the vehicle's front bumper position and VL is the vehicle's length.

The DVU's position (distance covered) was then converted into a patch value which was done by calling a distance to patch conversion function explained in section 3.2.6.2. The DVU was then registered to the vehicle patch register. As mentioned earlier, this register showed the position of DVUs on patches. Its size was determined by the number of lanes and the length of the link. A patch was 8m long and the model's link length was 1000m long hence the vehicle patch register had a total of 125 patches. Depending on the number of lanes (up to 4 lanes) each patch had between 4 and 16 slots with 4 slots allocated to each lane. The first two slots of each lane were the front bumper registers while the last two were the rear bumper registers. The lead DVU in a patch always occupied the first bumper register while the following DVU occupied the second. The vehicle patch register was explained extensively in an earlier section.

The vehicle was given a vehicle type depending on the user's specified vehicle combination. A function which calculated the maximum acceleration and deceleration of the vehicle was then called and the acceleration of vehicle 1 was initialised based on its output.

Other variables were also taking into account such as the time step vehicle 1 entered the link (start time) which was later used to calculate the DVU's journey time by subtracting its start time from its finish time and also used to calculate the interval between vehicles entering the link and the density of the link was incremented. Figure 3.10 illustrates vehicle 1 entering the link at time step 1.

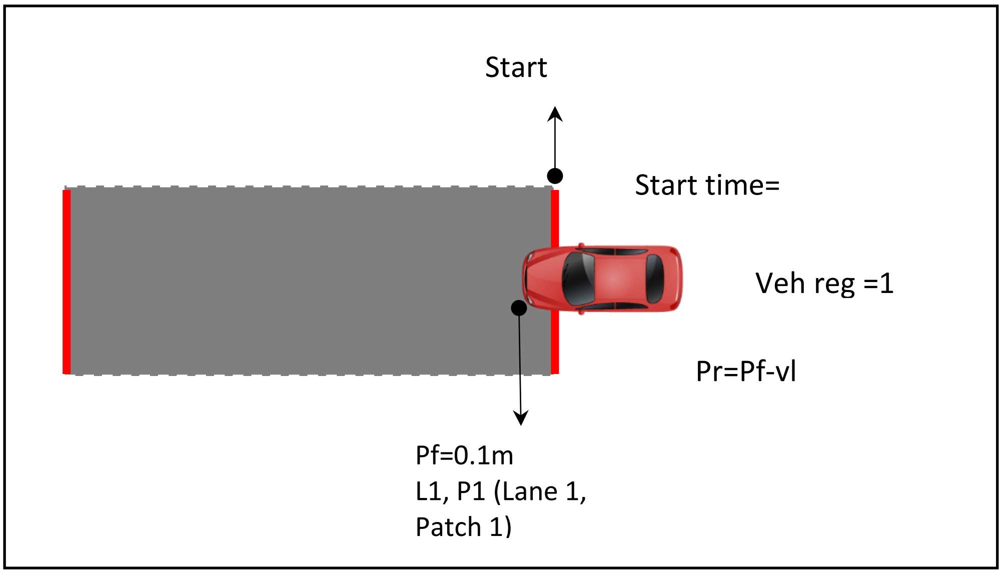


Figure 3.10: An illustration of vehicle 1 entering the link at time step 1

This was written in code as shown in appendix 6.

3.3.1.2. The other time steps

A second loop (i.e the patch loop) cycled through the patches; it encapsulated a third loop (i.e the lane loop) which cycled through each lane hence for each patch selected the lane loop made a complete cycle.

When the time step was greater than 1, the patch loop was incremented, and the lane loop was initiated. Vehicle patch register slots were allocated to each lane based on the lane number with lane 1 allocated slots 1 and 2 for front bumpers while 3 and 4 were allocated to rear bumpers, lane 2 was allocated slots 5 and 6 for front bumpers while 7 and 8 were reserved for rear bumpers etc. Table 3.3 shows an illustration of the vehicle patch register.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	1	5	1	0	2	6	2	0	3	19	3	0	4	0	4	0
2	7	0	5	0	8	0	6	0	22	0	19	0	26	30	26	0
3	9	0	7	0	10	0	8	0	21	0	22	0	34	0	30	0
4	11	0	9	0	25	0	10	0	29	0	21	29	38	0	34	0
5	12	0	11	12	18	0	25	18	33	37	33	0	42	0	38	42
6	13	14	13	0	20	17	20	0	41	0	37	0	46	49	46	0
7	15	0	14	0	23	0	17	0	50	0	41	0	27	0	49	0
8	16	0	15	0	28	0	23	0	24	0	50	0	47	0	27	0
9	31	0	16	31	44	0	28	44	35	0	24	35	45	0	47	45
10	32	36	32	0	48	43	48	0	40	0	40	0	0	0	0	0
11	39	0	36	0	0	0	43	0	0	0	0	0	0	0	0	0
12	0	0	39	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 3.3: The vehicle patch register

This register was generated when the simulation ran for 2000-time steps with a maximum density of 50 vehicles. For illustrative purpose the signal at the end of the link was set to constant red causing vehicles to stop at the end of the link. From the table vehicles had their bumpers registered on corresponding slots based on their positions.

A fourth loop (slot loop) located within the lane loop cycled through the front bumper slots of each lane. Each slot selected was tested to verify if a DVU registration number was present, whenever there was a DVU registration number this number was stored in a variable (veh_reg). The lane of the observed DVU (the DVU registration number stored in veh_reg) was then updated. This was done by calling the *lane change* function explained earlier depending on the output of the function the DVU then either stayed on its current lane or switched to a neighbouring target lane. The lane of each DVU for each time step was stored in an array, a portion of this array is shown Table 3.4.

	1	2	3	4	5	6	7	8	9
617	1	2	3	4	1	1	1	1	1
618	1	2	3	4	1	1	1	1	1
619	1	2	3	4	1	1	1	1	1
620	1	2	3	4	1	2	1	1	1
621	1	2	3	4	1	2	1	1	1
622	1	2	3	4	1	2	1	1	1
623	1	2	3	4	1	2	1	1	1
624	1	2	3	4	1	2	1	1	1
625	1	2	3	4	1	2	1	1	1
626	1	2	3	4	1	2	1	1	1
627	1	2	3	4	1	2	1	1	1
628	1	2	3	4	1	2	1	1	1

Table 3.4: A portion of the DVUs lanes for each time step

Whenever a DVU switched lanes its bumpers registration on the previous vehicle patch registration slots were cancelled then its bumpers were registered on their corresponding slots on the DVU's new lane. The portion in Table 3.4 shows a period when the vehicle stored in *vehicle handle* 6 changed its lane from lane 1 to lane 2 shown in time step 620. It should be noted that the vehicle was referred to as the vehicle stored in vehicle handle 6 rather than vehicle 6 because each vehicle is given a registration number upon entering the link and are referred to by their registration number rather than their handle number. The vehicle stored in each handle changed as the vehicle stored exited the link. This was written in code as shown in appendix 6. The switch_board function is also shown in code in appendix 6.

The next step was to detect the lead DVU of the observed DVU (if any), this was done by calling the *reference vehicle detector* function explained earlier and setting it to lead vehicle detection mode. The output of the function was 0 when there was no lead DVU detected or the lead DVU registration number when a lead DVU was detected. The reference vehicle detector called in the main code is shown in appendix 6.

The displacement of the DVU for the current time (D_i) step was first calculated to calculate the position of the DVU for the time step. The displacement was calculated using:

$$D_i = v_o * t + 1/2 * a_o * t^2 \qquad [3.33]$$

Each time step was equivalent to 0.1 second hence time (t) in the equation was equivalent to 0.1 second. The speed and the acceleration in the equation represent the initial speed (v_o) and acceleration (a_o) respectively of the DVU at the previous time step. A filter was used to ground displacements less than 0m to 0 m to prevent negative displacements (i.e. DVUs moving in reverse). This was written in code as shown in appendix 6.

The current position of the observed DVU front bumper (Pf_i) was then calculated by adding the initial position (Pf_o) (I.e. at the previous time step) to the current displacement (D_i) shown in equation 32.

$$p_{fi} = p_{fo} + D_i \quad [3.34]$$

The position of the rear bumper was then calculated using equation 30. The position, displacement, speed, acceleration and various other parameters of each registered DVU was logged at every time step. Table 3.5 shows a portion of the positions of various DVUs at various time steps. Again, it should be noted that the top horizontal numbers represent the vehicle handles not the actual vehicles registration numbers.

	24	25	26	27	28	29	30	31	32	33	34
610	240.5082	323.5470	320.4078	192.3712	229.6257	223.5876	220.5983	158.2022	127.9609	137.7529	135.3983
611	242.5096	326.6862	323.5470	194.3381	232.6745	226.5968	223.5876	160.0599	129.7384	140.1275	137.7529
612	244.5309	329.8253	326.6862	196.3249	235.7430	229.6257	226.5968	161.9150	131.5131	142.5220	140.1275
613	246.5495	332.9645	329.8253	198.3317	238.8314	232.6745	229.6257	163.7900	133.2852	144.9365	142.5220
614	248.5653	336.1037	332.9645	200.3358	241.9395	235.7430	232.6745	165.6849	135.0771	147.3709	144.9365
615	250.6012	339.2429	336.1037	202.3372	245.0675	238.8314	235.7430	167.5998	136.8664	149.8253	147.3709
616	252.6570	342.3821	339.2429	204.3585	248.2067	241.9395	238.8314	169.5346	138.6530	152.2996	149.8253
617	254.7327	345.5212	342.3821	206.3998	251.3458	245.0675	241.9395	171.4894	140.4595	154.7939	152.2996
618	256.8284	348.6604	345.5212	208.4610	254.4850	248.2067	245.0675	173.4641	142.2860	157.3080	154.7939
619	258.9440	351.7996	348.6604	210.5422	257.6242	251.3458	248.2067	175.4588	144.1324	159.8420	157.3080
620	261.0796	354.9388	351.7996	212.6433	260.7634	254.4850	251.3458	177.4735	145.9987	162.3957	159.8420
621	263.2351	358.0780	354.9388	214.7644	263.9026	257.6242	254.4850	179.5080	147.8851	164.9693	162.3957

Table 3.5: A portion of the positions of various vehicles at various time steps

It can be observed from table 3.5 that the position values are not in a descending order from left to right as would be expected of *the vehicle label-wise model* since every vehicle maintain a single lane in that model instead the positions are in an undefined order from left to right the reason being because the vehicles contained in the vehicle handles are not all on the same lane.

The position of the observed DVU's front bumper can also be calculated by integrating the speed of the observed DVU over time using Euler method for mathematical integration. This is shown in equation 33.

$$p_{fi} = p_{fo} + \Delta t * v \quad [3.35]$$

The new position of the DVU was then updated to the vehicle patch register using a method like the method used when the DVU's lane was changed except the registration was done on the same lane but depending on the new position of the DVU a different slot was selected if the DVU's new position was in a different patch.

When the DVU's position was greater than the link length its registration number was cancelled from the rear bumper vehicle patch registration slot and its finish time was updated. The vehicle's registration number was automatically released and free for use by a new DVU since no bumper of the vehicle was registered to any patch slot. This step was written in code as shown in appendix 6.

Other parameters such as the gap (g) and the bunching acceleration (c) which was used to bring vehicles together faster were calculated after the position of the vehicle was calculated. The gap between the lead and following DVU was calculated using equation 35.

$$g = p_{rl} - p_{ff} \qquad [3.36]$$

The gap (g) was calculated by subtracting the position of the following DVU front bumper (Pff) from the positon of the lead DVU rear bumper (Prl). The bunching acceleration '*c*' was calculated right after the gap was calculated and it was explained earlier.

The observed DVU's speed 'v_i' was then calculated by integrating acceleration overtime. The equation below was used to calculate the current speed. Again time 't' in the equation was equivalent to 0.1s.

$$v_i = v_o + a_o * t \qquad [3.37]$$

In Paramics drivers are given memories which hold their speed at some point in the past as well as their position, since their speed is based around the speed of the lead DVU they can decide what their current speed would be based on their memory of previous speed and position. Each driver is also given a *headway* which they try to attain by varying their speed. More aggressive drivers accept smaller headways while drivers with more awareness accept longer headways.

Headway parameters for various situations were identified on Paramics technical report (Duncan, 1998). The report identified 1.5 seconds as the average headway observed on a single-lane highway while 0.5 seconds was identified as the average headway during traffic jams (note: traffic jam was defined as a period where both the lead and following DVUs travelled at low speeds) and 2 metres was selected as the average gap between DVUs during congestion.

Paramics technical report didn't give a clear relationship between headway and weather conditions but rather a range of 1.1 to 3.0 seconds was given for various weather conditions.

Using 1.5 seconds for average vehicles travelling under dry conditions as specified by Paramics headways for various weather conditions were projected by relating the headway given by Paramics to the headway observed by. The headways used for the various weather conditions is summarised in Table 3.6.

The headways for the various weather conditions were then selected within this range as shown in Table 3.6. Agbolosu-Amison and Sadek (2004) observed the headways of vehicles travelling on a road in Vermont and indicated that there was a negligible difference in the headways of light snowy and light rainy conditions hence the same headway was assigned to both.

Weather condition	Headway (s)
Normal (Dry)	1.5
Light Rain	2
Light Snow	2
Heavy Rain	2.5
Heavy Snow	3

Table 3.6: Headways used for the various weather conditions

The separation, target and acceleration and braking components were then calculated for the observed DVU.

This process iterated until the time loop got to its maximum value after which the program was terminated.

In code the observed DVU's gap and speed were calculated using the codes in appendix 6. This section was explained in detail in appendix 2.

The acceleration control

DVUs' accelerations were controlled using Paramics car following logics along with various other logics such as the logic that was used to attempt to depict the interaction between the drivers and their environment (e.g. drivers and the stop line) as well as assumptions that were made in order to control the acceleration of DVUs in traffic streams under certain conditions (such as the collision detection and response).

The code used for DVUs acceleration control is shown in appendix 7 while the various logical steps of the code are explained in appendix 2. Basically, a lead DVU controlled its acceleration based on the current weather condition, its desired speed limit and its proximity to the end of the link. Following drivers used the same principle as the lead drivers but also controlled their acceleration with respect to their lead DVU whenever they were within a certain proximity from them. This section was explained in detail in appendix 2.

3.3.1.3. New DVU generation

New DVUs were generated on patch 125 of any lane depending on the conditions of the lane entry with the inner lane having higher priorities than the outer lanes. New DVUs were generated when the patch loop was at its maximum value and the link entry conditions were satisfied. The code used for generating new DVUs is shown on appendix 6. This section was explained in detail in appendix 2.

3.3.2. The Traffic Simulator Output Data

Various data such as the traffic flux, traffic density, the maximum traffic density, average traffic speed and average journey time were collected during the simulation. The average traffic speed was calculated using equation 3.38.

$$b_{tn} = \frac{\sum b_o}{r_{tn}} \qquad [3.38]$$

Where b_{tn} is the average speed from the start of the simulation up to the current time step, b_o is the average speed of each DVU that exited the link and r_{tn} is the total number of DVUs that had exited the link both during the same period.

The average speed of each DVU that exited the link (b_o) was calculated as the length of the link divided by the DVU's total journey time. This is shown in equation 3.39.

$$b_o = \frac{L}{t_v} \qquad [3.39]$$

The traffic mean speed during the traffic stable state (i.e. the period when DVUs entered and exited the link during the same time step) at the current time step was calculated using equation 3.40.

$$b_{stn} = \frac{\sum b_{so}}{r_{tsn}} \qquad [3.40]$$

Where b_{stn} is the average speed from the start of the stable state up to the current time step, b_{so} is the average speed of each DVU that exited the link and r_{stn} is the total number of DVUs that had exited the link both during the same period.

The traffic flux was computed from the start of the stable state and was calculated using equation 3.41.

$$FX_{tn} = b_o \times Q_{tn} \qquad [3.41]$$

Where FX_{tn} is the traffic flux from the start of the stable state to the current time and Q_{tn} is the current density.

The code used to compute and collect the simulation data is shown in appendix 6 while the entire main code is shown in appendix 2.

The flow diagram for the overview of the program is shown in figure 3.11.

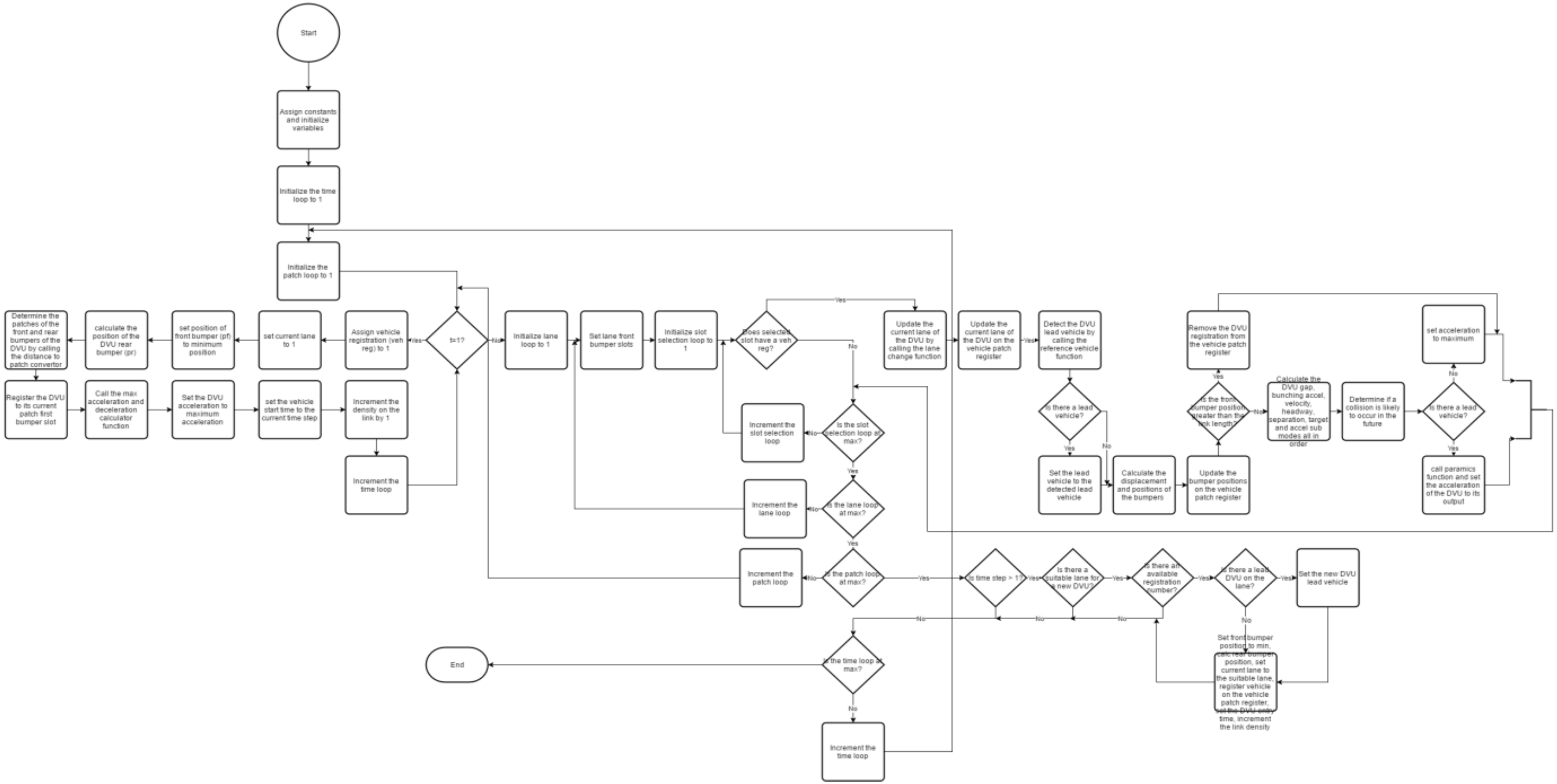


Figure 3.11: The Primary code overview

3.3.3. Testing the Traffic Simulator

3.3.3.1. The Car Following and Lane Changing Algorithm tests

To test the car following algorithm DVUs were made to queue up at the end of the link behind the stop line. This test was carried out using single lane and multiple lanes. Figure 3.12 shows a 2D position/time curve of a single lane 1000m link model. DVU 1 entered the link at 1ms and accelerated at maximum acceleration until it got to the end of the link where it decelerated until it came to an indefinite halt at approximately 2m from the stop line. Other DVUs entered the link at 3s intervals from their corresponding lead DVUs then utilised Paramics car following algorithm combined with a fail proof algorithm to *follow* their lead DVUs until they eventually came to a complete and indefinite halt at approximately 2m from their lead DVUs. Table 3.7 shows a portion of the spread sheet of the DVUs positions against time during a period where the DVUs were close to the end of the link while Table 3.8 shows the spread sheet of the gap between each DVU within the same time frame.

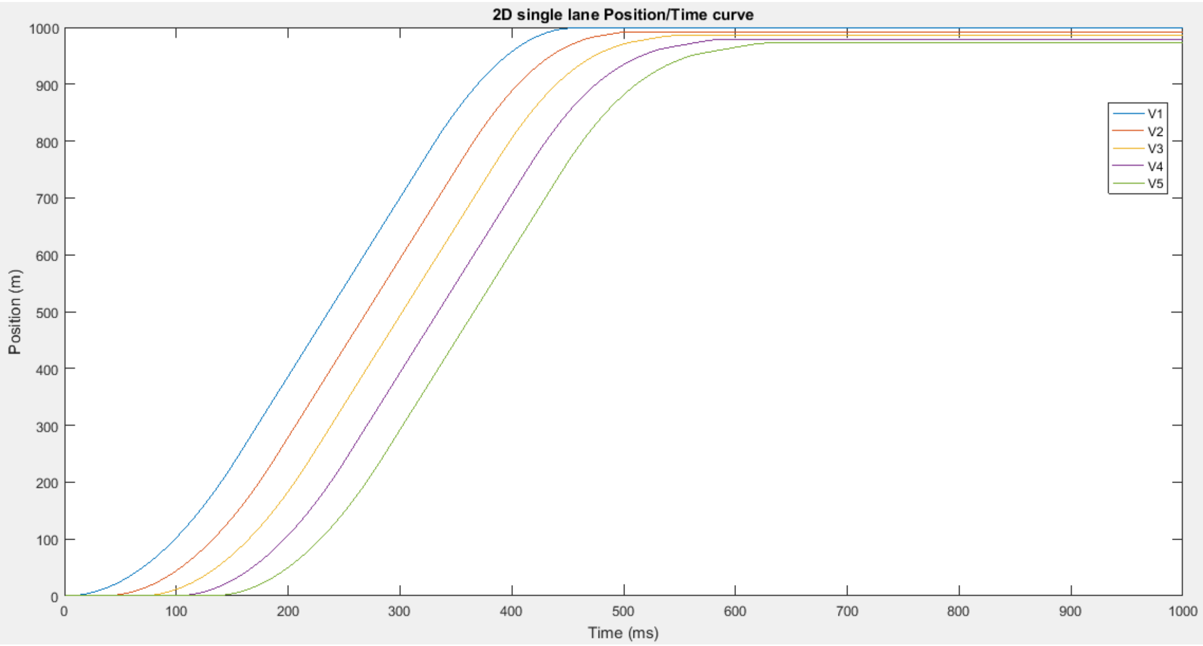


Figure 3.12: 2D single lane position/time curve

	1	2	3	4	5
623	998.5663	991.9546	985.4083	978.8812	971.8765
624	998.5663	991.9546	985.4083	978.8812	971.9941
625	998.5663	991.9546	985.4083	978.8812	972.0849
626	998.5663	991.9546	985.4083	978.8812	972.1490
627	998.5663	991.9546	985.4083	978.8812	972.1864
628	998.5663	991.9546	985.4083	978.8812	972.1971
629	998.5663	991.9546	985.4083	978.8812	972.1971
630	998.5663	991.9546	985.4083	978.8812	972.1971
631	998.5663	991.9546	985.4083	978.8812	972.1971
632	998.5663	991.9546	985.4083	978.8812	972.1971
633	998.5663	991.9546	985.4083	978.8812	972.1971
634	998.5663	991.9546	985.4083	978.8812	972.1971
635	998.5663	991.9546	985.4083	978.8812	972.1971
636	998.5663	991.9546	985.4083	978.8812	972.1971
637	998.5663	991.9546	985.4083	978.8812	972.1971
638	998.5663	991.9546	985.4083	978.8812	972.1971
639	998.5663	991.9546	985.4083	978.8812	972.1971
640	998.5663	991.9546	985.4083	978.8812	972.1971
641	998.5663	991.9546	985.4083	978.8812	972.1971
642	998.5663	991.9546	985.4083	978.8812	972.1971

Table 3.7: Table showing the DVUs positions against time

	1	2	3	4	5
623	0	1.9117	1.8463	1.8271	2.3047
624	0	1.9117	1.8463	1.8271	2.1872
625	0	1.9117	1.8463	1.8271	2.0964
626	0	1.9117	1.8463	1.8271	2.0322
627	0	1.9117	1.8463	1.8271	1.9948
628	0	1.9117	1.8463	1.8271	1.9841
629	0	1.9117	1.8463	1.8271	1.9841
630	0	1.9117	1.8463	1.8271	1.9841
631	0	1.9117	1.8463	1.8271	1.9841
632	0	1.9117	1.8463	1.8271	1.9841
633	0	1.9117	1.8463	1.8271	1.9841
634	0	1.9117	1.8463	1.8271	1.9841
635	0	1.9117	1.8463	1.8271	1.9841
636	0	1.9117	1.8463	1.8271	1.9841
637	0	1.9117	1.8463	1.8271	1.9841
638	0	1.9117	1.8463	1.8271	1.9841
639	0	1.9117	1.8463	1.8271	1.9841
640	0	1.9117	1.8463	1.8271	1.9841
641	0	1.9117	1.8463	1.8271	1.9841
642	0	1.9117	1.8463	1.8271	1.9841

Table 3.8: Table showing the DVUs gaps against time

Figure 3.13 shows the time/position/lane 3D curve of 10 vehicles in a 2 lane 1000m link. While most of the DVUs started their journeys using lane 1 because of lane 1 meeting the entry conditions during their attempted entry times, DVUs 2, 5 and 9 started their journeys on lane 2 because of lane 1 not meeting the lane entry conditions during their attempted entry times. DVU 2 maintained lane 2 throughout its journey because lane one did not show a more suitable driving condition than lane 2 throughout its journey while DVU 5 and 9 switched to lane 1 shortly after entering the link due to more suitable driving conditions detected on lane 1. DVU 5 switched its lane after just 3.9s into its journey covering just 15.26m deduced from figure 3.14. A portion of the vehicles lanes against time is shown on the spreadsheet in Table 3.9**.** The portion captures the period where DVU 5 switched lanes from lane 2 to lane 1. Various DVUs switched lanes during their journey as can be seen from the phase shift (referring to lanes) of some of the curves.

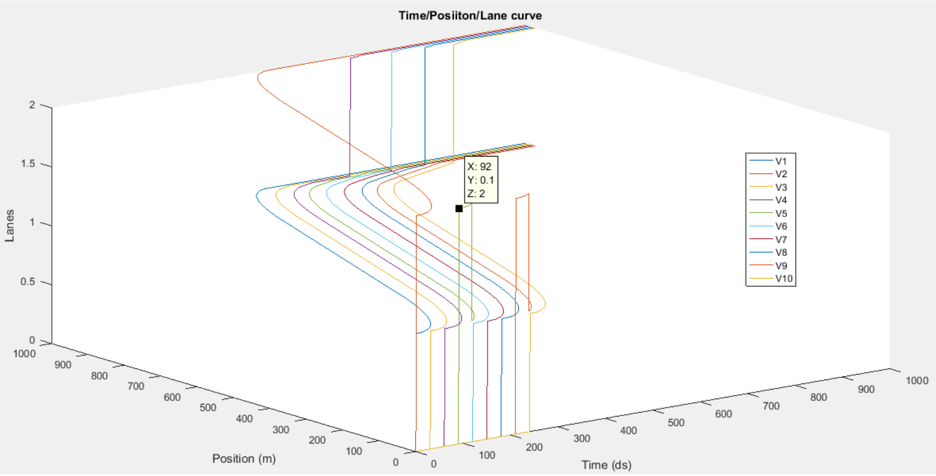


Figure 3.13: Time/position/lane 3D curve

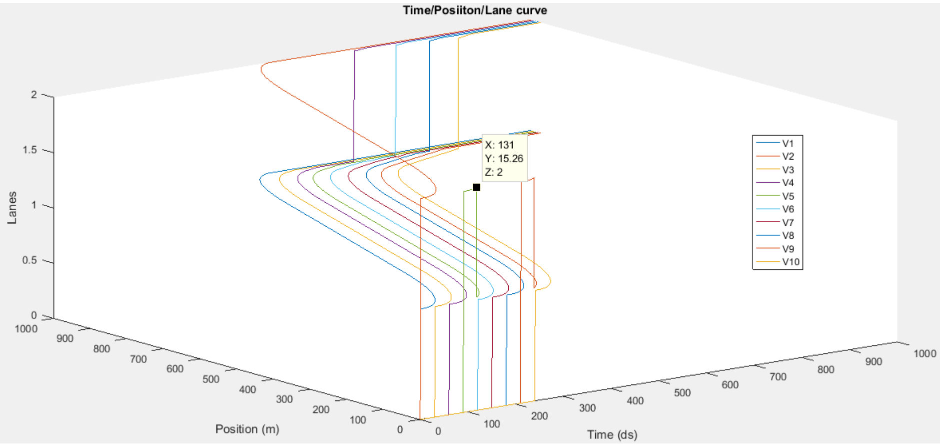


*Figure 3.14**:** Lanes switch on a 2 lanes 3D curve*

	1	2	3	4	5	6	7	8	9	10
126	1	2	1	1	2	1	0	0	0	0
127	1	2	1	1	2	1	0	0	0	0
128	1	2	1	1	2	1	0	0	0	0
129	1	2	1	1	2	1	0	0	0	0
130	1	2	1	1	2	1	0	0	0	0
131	1	2	1	1	2	1	0	0	0	0
132	1	2	1	1	1	1	0	0	0	0
133	1	2	1	1	1	1	0	0	0	0
134	1	2	1	1	1	1	0	0	0	0
135	1	2	1	1	1	1	0	0	0	0
136	1	2	1	1	1	1	0	0	0	0
137	1	2	1	1	1	1	0	0	0	0
138	1	2	1	1	1	1	0	0	0	0
139	1	2	1	1	1	1	0	0	0	0
140	1	2	1	1	1	1	0	0	0	0
141	1	2	1	1	1	1	0	0	0	0
142	1	2	1	1	1	1	0	0	0	0
143	1	2	1	1	1	1	0	0	0	0
144	1	2	1	1	1	1	0	0	0	0
145	1	2	1	1	1	1	0	0	0	0

Table 3.9: A portion of the DVUs lanes with time

Figure 3.15 shows the time/position/lane curves of 10 DVUs on a 4 lane 1000m long link. From the figure it can be seen the first four DVUs utilised the four lanes due to the entry conditions and driving conditions of neighbouring lanes. It should be noted that since all four DVUs entered the link at approximately the same time and travelled at a similar speed they travelled side by side to each other hence the driving conditions of neighbouring lanes were unfavourable throughout their journeys. Other DVUs followed these DVUs with more DVUs being on the first lane due to a section of the UK Highway Code being embedded into the program. The section of the Highway Code suggests drivers stick to the inner lanes for as long as the driving conditions remain favourable. Drivers were also programmed to always attempt starting their journeys on the inner lane if the entry conditions were met.

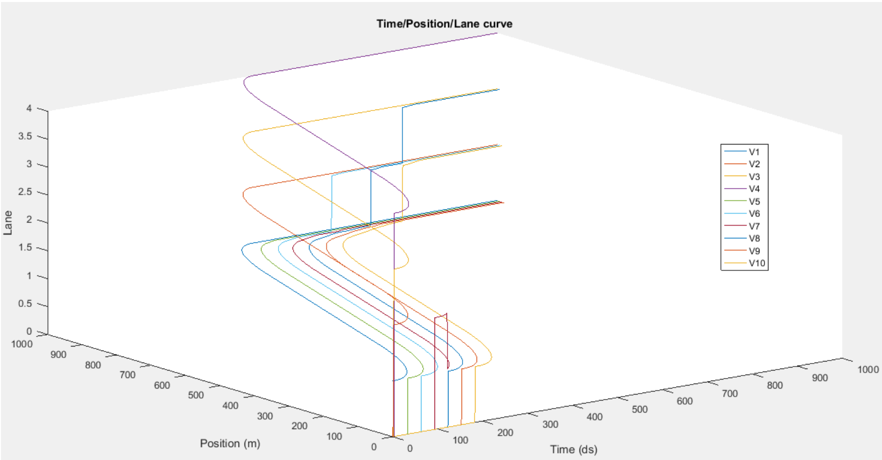


Figure 3.15: Four lanes time/position/lane curve

3.3.3.2. The impact of driving parameters on the journey times of the DVUs

To validate the impact of the main driving parameters featured in the model (acceleration, headway and speed), the observed variable was varied during a simulation while the other variables were left constant. The effect of the observed variable on the mean journey times of DVUs was then recorded.

Figure 3.16 represents the impact of acceleration on the journey times of DVUs when the maximum density on the link was set to 50, the number of lanes set to 4 and the maximum simulation period set to 3,000-time steps (i.e. 5 minutes) and other driving variables left constant. From figure 3.16 as the maximum acceleration of the DVUs increased the journey time reduced because of DVUs being able to attain higher speeds at progressively faster rates resulting in higher average speeds.

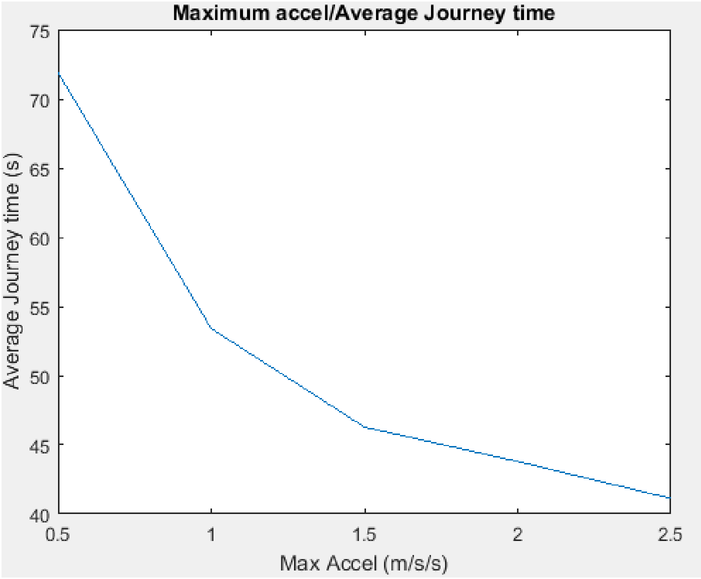


Figure 3.16: The impact of acceleration on the journey times of DVUs

Figure 3.17 represents the impact of the maximum speed of the DVUs on their journey times when the maximum density on the link was set to 50, the number of lanes set to 4 and the maximum simulation period set to 3,000-time steps (i.e. 5 minutes) and other driving variables left constant. From figure 3.17 as the maximum speed of the DVUs was increased the journey time reduced because of DVUs being able to attain higher maximum speeds also resulting in higher average speeds.

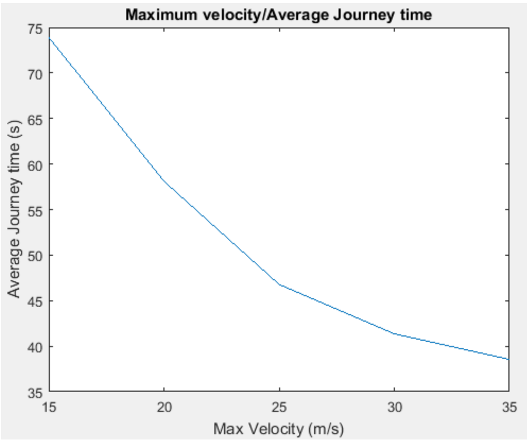


Figure 3.17: The impact of speed on the journey times of DVUs

The driving parameters where then selected into groups which were very good, good, moderate, poor, very poor conditions with the highest acceleration and highest maximum speed belonging to the very good condition while the lowest acceleration and lowest maximum speed belonging to the very poor condition. At later stages of the research these parameters were then referred to as dry, light rain, light snow, heavy rain and heavy snow conditions. It should be noted that the values used for the various parameters are not empirical values. Empirical values were later collected and used for the actual simulations.

Figure 3.18 represents the impact of the various driving conditions on the journey time of the DVUs. From the figure better driving conditions (lower headway, higher acceleration and maximum speed) resulted in lower journey times.

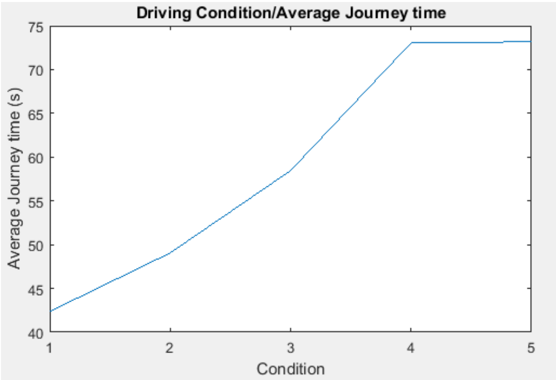


Figure 3.18: The impact of the various driving conditions on journey times

Congestion was then induced on the link by forcing the lead DVUs on each lane (leaders of the traffic stream on each lane) to brake down to 7m/s after covering 700m and maintain that speed until the end of their journey. This was done for all 5 conditions and the curve in figure 3.19 below shows the average journey time for all 5 conditions.

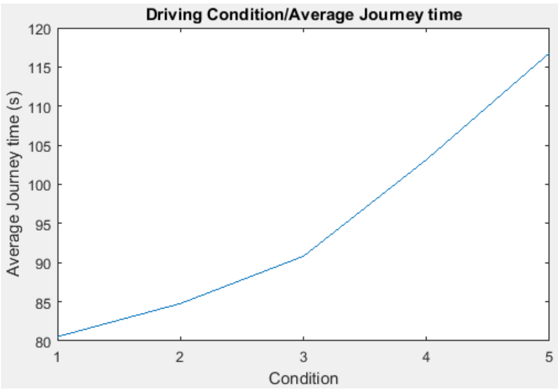


Figure 3.19: The impact of congestion on the journey times of the DVUs under various conditions

3.4. Simulation results, Traffic analysis and validation

Simulation was carried out on a 1-kilometre link featuring both HGVs and cars. The average length of cars and HGVs are 4.8m and 14m respectively (Nationwide Vehicle Contracts, 2017; Larsson, 2009) and these values were used for the simulation. For the mixed traffic flow simulation, the ratio of cars to HGVs was set to 16:1 this way there were 4 times as many cars on the link compared to HGVs which is a fair depiction of a real-world scenario and was a similar ratio in 2014 (DFT, 2016). Although the model can simulate single and up to 4 lanes only single and 3 lanes were simulated for this research. A Signal controlled traffic flow as well as a roundabout controlled traffic flow were both simulated. The maximum simulation time varied between 2,000-time steps and 40,000 time steps depending on the maximum density and weather condition featured in the simulation.

The speed limit of the link was set at 31.2928m/s (70mph) (GOV.UK, 2014) and drivers desired maximum speeds varied based on the weather condition and their vehicle type as explained in an earlier section, the maximum acceleration of each DVU depended on the vehicle type and the surface condition as explained in an earlier section and each time step was equivalent to 0.1second.

Simulations were carried out for both normal and precipitated conditions where drivers' behaviours such as their maximum speed, acceleration and deceleration rates and headway were affected. Weather conditions were simplified into light, moderate and heavy conditions (rain and snowfall).

The Federal Highway Administration (FHWA, 1977) in the US offered a weather classification scheme to the study of the impact of precipitation on motorway systems. The classification ranged between dry roads with a percentage speed reduction of 0% and snow packed road with a percentage speed reduction of 42%.

To validate the simulation output curves were compared to the fundamental curves of traffic flow for consistency. To simplify the validation process only the simulation outputs of a mixed traffic under normal condition were examined.

3.4.1. Traffic Analysis

The flow speed/density curve of a mixed traffic showing a signal and roundabout controlled traffic flow curves for a single and 3 lanes traffic flow under normal weather condition is shown in figures 3.20.

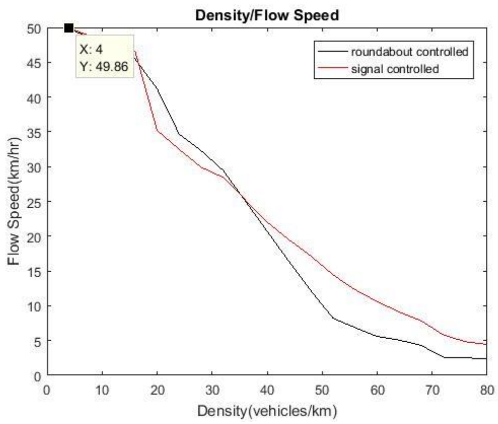


Figure 3.20a: Single lane free flow speed

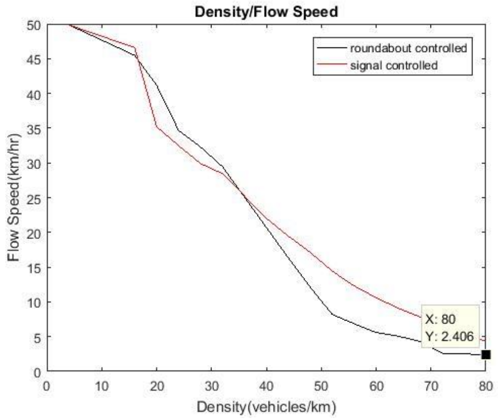


Figure 3.20b: Single lane saturated flow speed

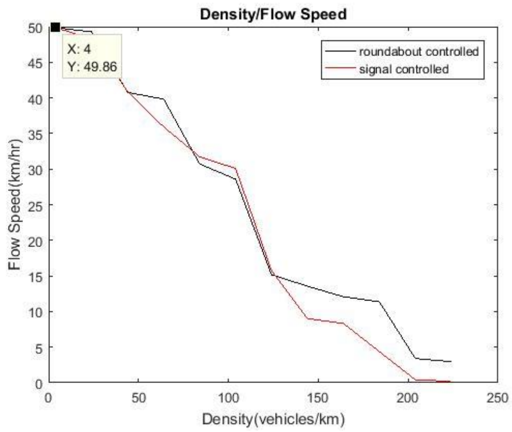


Figure 3.20c: 3 lanes free flow speed

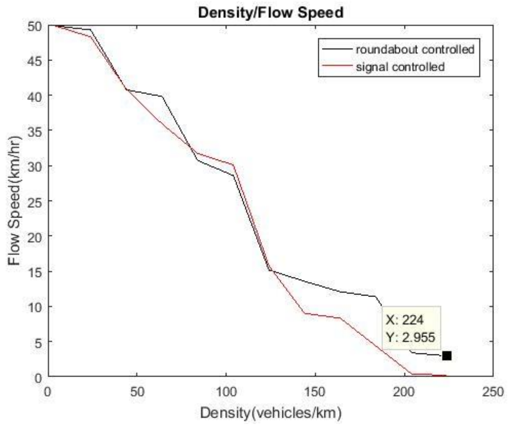


Figure 3.20d: 3 lanes saturated flow speed

Figure 3.20: The Flow speed/Density curves for a single and 3 lanes mixed traffic flow traffic flow under normal weather condition showing the curves for both signal controlled and roundabout controlled traffic flow

Free flowing traffic

Figure 3.20a shows that in the single lane traffic DVUs travelled at a maximum speed (uf) of 49.86km/hr for both the signal controlled and roundabout controlled traffic flow the density of the link at the maximum speed was 4vehicles/km in both cases as shown in figure 3.22a. The traffic flux under both control conditions was 199.4vehicles/hour as shown in figure 3.21b. Typically the free flow density would be 1vehicle/km but to save time the simulation started with a maximum link density of 4vehicles/km and successive simulations were carried out with 4 vehicles increase in their maximum allowed density.

For the 3 lanes flow the simulation started at a maximum allowed density of 4 vehicles as well but increased in steps of 20 vehicles for each successive simulation, the free flow speed (maximum speed) was also 49.86km/hr under both traffic control conditions as shown in figure 3.20c while the density during the free flow as well as the traffic flux were 4vehicles/km and 199.4 vehicles/hour as shown in figures 3.22d and 3.21d respectively.

Saturated traffic

Generally, when a link is in this state its traffic flux and mean speed would be close to zero because of the vehicles queuing and because of the maximum density k_j (jam density) of the link reached (Immers and Logghe, 2002). Figure 3.21a shows the minimum mean flow speed for a single lane traffic flow under both traffic control conditions as 2.622km/hr for the roundabout controlled traffic and 4.446km/hr for the signal-controlled traffic while the traffic flux was 192.5 vehicles/hour for the roundabout controlled traffic and 355.7 vehicles/hour for the signal-controlled traffic as shown in figure 3.22b. While figure 3.21c shows the minimum mean flow speed for a 3 lanes traffic flow under both traffic control conditions as 3.399km/hr for the roundabout controlled traffic and 0.409km/hr for the signal-controlled traffic while the traffic flux was 693.4 vehicles/hour for the roundabout controlled traffic and 83.42 vehicles/hour for the signal-controlled traffic as shown in figure 3.21c.

Capacity traffic

The capacity of a link is defined as its maximum traffic flux q_c for the single lane traffic this can be located on figure 3.24c as 942.87 vehicles/hour for the roundabout controlled traffic and 910.5 vehicles/hour for the signal-controlled traffic. The maximum traffic flux (q_c) had a corresponding capacity speed (u_c) which can be located on figure 3.21e as 29.46km/hr for the roundabout controlled traffic and 28.45km/hr for the signal-controlled traffic which are both below their corresponding maximum speed (u_f) and a capacity density (k_c) of 32 vehicles under both traffic control conditions as shown in figure 3.22c. While for the 3-lane traffic this is in figure 3.22f as 2973 vehicles/hour for the roundabout controlled traffic and 3129 vehicles/hour for the signal-controlled traffic. The maximum traffic flux (q_c) had a corresponding capacity speed (u_c) which can be located on figure 3.21f as 28.59km/hr for the roundabout controlled traffic and 30.09km/hr for the signal-controlled traffic which are also both below their corresponding maximum speed (u_f) and a capacity density (k_c) of 104 vehicles under both traffic control conditions as shown in figure 3.22f.

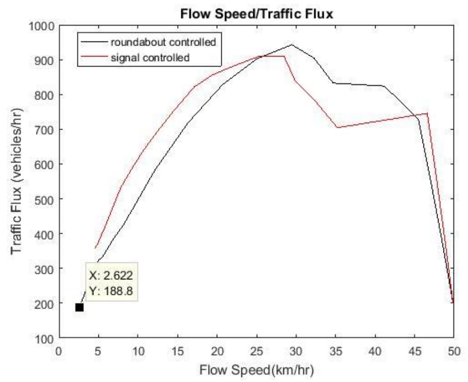


Figure 3.21a: The Single lane minimum flow speed

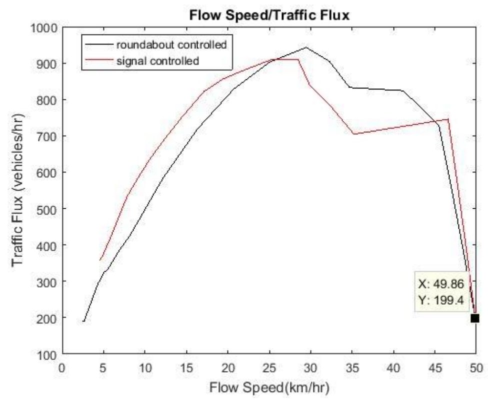


Figure 3.21b: The Single lane free flow traffic flux

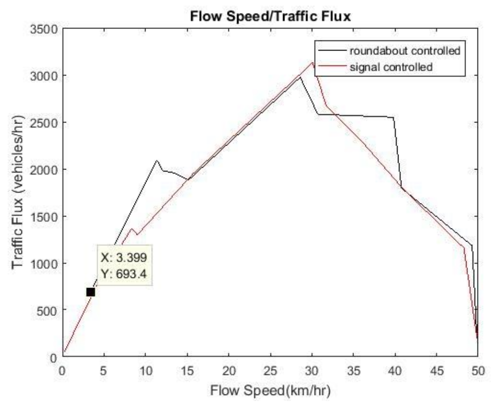


Figure 3.21c: The Single lane minimum flow speed

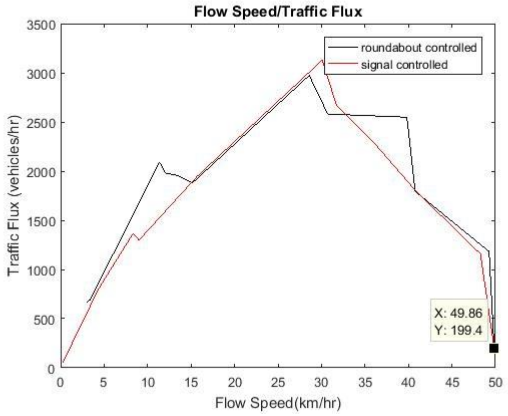


Figure 3.21d: The 3 lanes free flow traffic flux

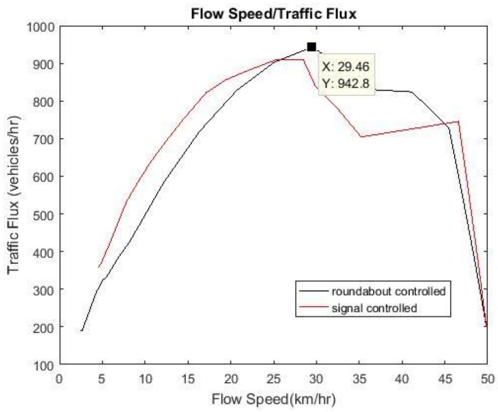


Figure 3.21e: The Single lane capacity speed

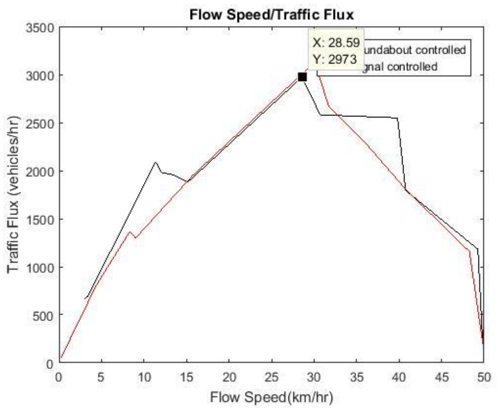


Figure 3.21f: The 3-lane capacity speed

Figure 3.21: The Flow Speed/Traffic Flux curves for a single and 3 lanes mixed traffic flow under normal weather condition showing the curves for both signal controlled and roundabout controlled traffic flow

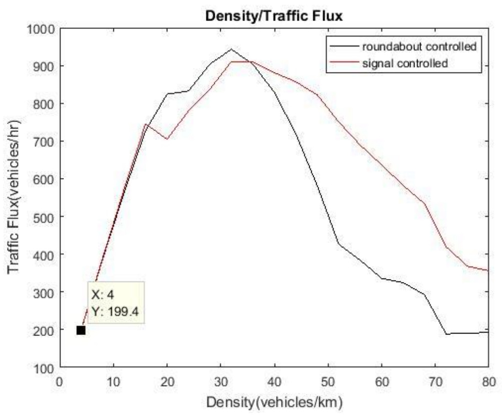


Figure 3.22a: The single lane free flow density

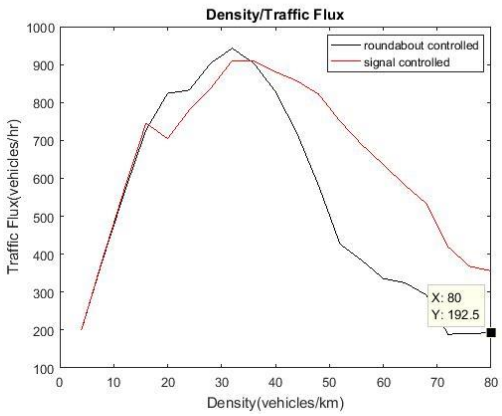


Figure 3.22b: The Single lane minimum traffic flux during congestion

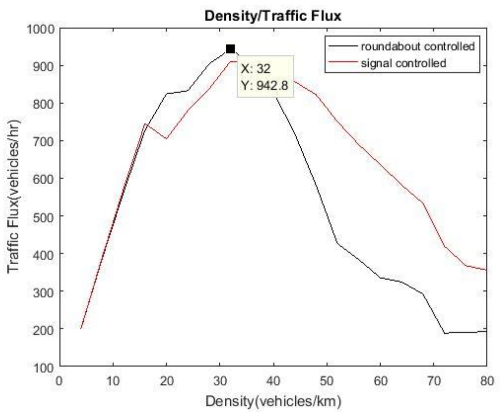


Figure 3.22c: The Single lane capacity density

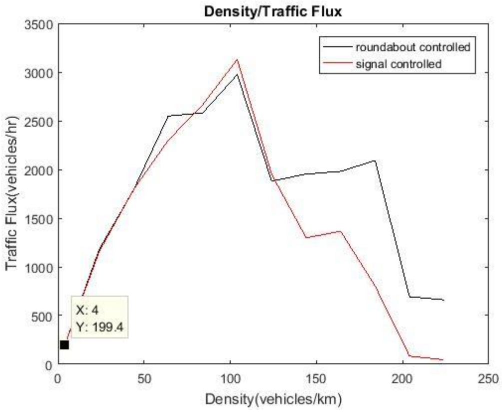


Figure 3.22d: The 3 lanes free flow density

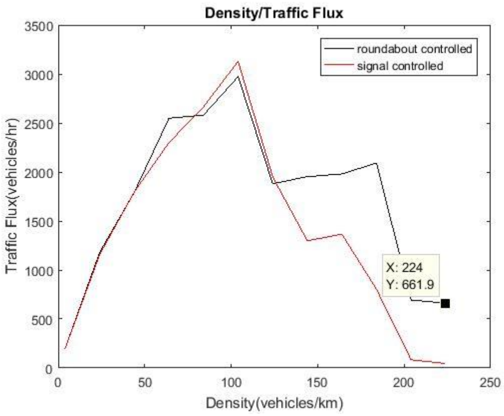


Figure 3.22e: The 3 lanes minimum traffic flux during congestion

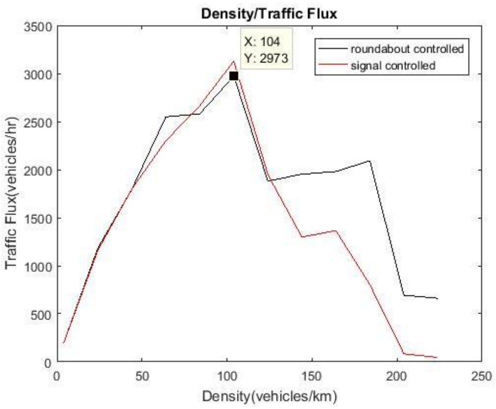


Figure 3.22f: The 3 lanes capacity density

Figure 3.22: The Density/Traffic Flux curves for a single and 3 lanes mixed traffic flow traffic flow under normal weather condition showing the curves for both signal controlled and roundabout controlled traffic flow

3.4.2. Discussion and Validation

Free flowing traffic

According to the fundamentals of traffic flow when a link is in this state vehicles travel freely at a maximum speed of u_f and are not impeded by other traffic. This can be observed in figures 3.20a and 3.20c where the density was minimum, and vehicles were not impeded by other traffic. The maximum speed depended on the speed limit for both traffic control conditions and the speed restriction towards the end of the link for roundabout controlled traffic and the frequency of the signal for signal-controlled traffic. The density and flux were also close to zero during this state.

Saturated traffic

According to the fundamentals of traffic flow when a link is in this state its traffic flux and mean speed would be close to zero because of the vehicles queuing and because of the maximum density k_j (jam density) of the link reached. Figures 3.21b and 3.21d shows that during this state the traffic flux and mean speed of the links were both close to zero.

Capacity traffic

The capacity of a link is defined as its maximum traffic flux q_c. The maximum traffic flux (q_c) has a corresponding capacity speed (u_c) which is located below the maximum speed (u_f) and a capacity density (k_c) which were shown in figures 3.22c and 3.22f.

3.4.2.1. The impact of weather conditions on the traffic parameters

Table 3.10a shows the traffic parameters for each weather condition for a roundabout controlled single lane traffic containing cars only.

Traffic Parameters	Normal (Dry)	Light Rain	Light Snow	Heavy Rain	Heavy Snow
Free flowing Traffic					
Max mean speed (m/s)	49.86	46.40	47.77	45.76	42.31
Max mean speed density (veh/km)	4	4	4	4	4
Max mean speed Traffic flux (veh/hr)	199.44	185.59	191.07	183.06	169.24
Saturated Traffic					
Min mean speed (m/s)	3.05	2.83	2.770	2.75	2.66
Min mean Traffic flux (veh/hr)	199.44	185.59	191.07	183.06	169.24
Capacity Traffic					
Maximum Capacity (veh/hr)	1020.50	956.92	929.95	917.11	826.96
Capacity speed (m/s)	31.89	29.90	29.06	28.66	22.97
Capacity Density (veh/km)	32	32	32	32	36

Table 3.10b shows the percentage reductions in the traffic parameters for each weather condition from the normal condition for a roundabout controlled single lane traffic containing cars only.

Traffic Parameters	Normal (Dry)	Light Rain	Light Snow	Heavy Rain	Heavy Snow
Free flowing Traffic					
Max mean speed (m/s)	0	-6.95	-4.20	-8.22	-15.14
Max mean speed density (veh/km)	0	0	0	0	0
Max mean speed Traffic flux (veh/hr)	0	-6.94	-4.20	-8.21	-15.14
Saturated Traffic					
Min mean speed (m/s)	0	-6.96	-9.02	-9.73	-12.71
Min mean Traffic flux (veh/hr)	0	-6.94	-4.20	-8.21	-15.14
Capacity Traffic					
Maximum Capacity (veh/hr)	0	-6.23	-8.87	-10.13	-18.97
Capacity speed (m/s)	0	-6.23	-8.87	-10.13	-27.97
Capacity Density (veh/km)	0	0	0	0	-12.50

Table 3.11a shows the traffic parameters for each weather condition for a signal controlled single lane traffic containing cars only.

Traffic Parameters	Normal (Dry)	Light Rain	Light Snow	Heavy Rain	Heavy Snow
Free flowing Traffic					
Max mean speed (m/s)	49.86	47.90	45.85	45.74	39.39
Max mean speed density (veh/km)	4	4	4	4	4
Max mean speed Traffic flux (veh/hr)	199.44	191.59	183.38	182.97	157.54
Saturated Traffic					
Min mean speed (m/s)	1.80	1.69	1.68	1.61	1.47
Min mean Traffic flux (veh/hr)	137.20	133.37	129	122.18	112.87
Capacity Traffic					
Maximum Capacity (veh/hr)	828.24	772.34	748.09	747.16	682.24
Capacity speed (m/s)	29.58	27.58	26.72	26.68	24.37
Capacity Density (veh/km)	28	28	28	28	28

Table 3.11b shows the percentage reductions in the traffic parameters for each weather condition from the normal condition for a signal controlled single lane traffic containing cars only.

Traffic Parameters	Normal (Dry)	Light Rain	Light Snow	Heavy Rain	Heavy Snow
Free flowing Traffic					
Max mean speed (m/s)	0	-3.94	-8.05	-8.26	-21.01
Max mean speed density (veh/km)	0	0	0	0	0
Max mean speed Traffic flux (veh/hr)	0	-3.936	-8.053	-8.258	-21.009
Saturated Traffic					
Min mean speed (m/s)	0	-6.48	-6.73	-10.70	-18.27
Min mean Traffic flux (veh/hr)	0	-2.79	-5.98	-10.95	-17.73
Capacity Traffic					
Maximum Capacity (veh/hr)	0	-6.75	-9.68	-9.79	-17.63
Capacity speed (m/s)	0	-6.75	-9.68	-9.79	-17.63
Capacity Density (veh/km)	0	0	0	0	0

Table 3.12a shows the traffic parameters for each weather condition for a roundabout controlled single lane traffic containing HGVs only.

Traffic Parameters	Normal (Dry)	Light Rain	Light Snow	Heavy Rain	Heavy Snow
Free flowing Traffic					
Max mean speed (m/s)	49.86	46.63	44.98	43.10	40.41
Max mean speed density (veh/km)	4	4	4	4	4
Max mean speed Traffic flux (veh/hr)	199.44	186.52	179.91	172.40	161.63
Saturated Traffic					
Min mean speed (m/s)	2.41	2.35	2.16	2.10	2.05
Min mean Traffic flux (veh/hr)	188.76	182.50	172.51	168.06	148.68
Capacity Traffic					
Maximum Capacity (veh/hr)	942.80	905.71	873.58	835.55	795.06
Capacity speed (m/s)	29.46	28.30	27.30	26.11	28.40
Capacity Density (veh/km)	32	32	32	32	28

Table 3.12b shows the percentage reductions in the traffic parameters for each weather condition from the normal condition for a roundabout controlled single lane traffic containing HGVs only.

Traffic Parameters	Normal (Dry)	Light Rain	Light Snow	Heavy Rain	Heavy Snow
Free flowing Traffic					
Max mean speed (m/s)	0	-6.48	-9.79	-13.56	18.96
Max mean speed density (veh/km)	0	0	0	0	0
Max mean speed Traffic flux (veh/hr)	0	-6.48	-9.79	-13.56	-18.96
Saturated Traffic					
Min mean speed (m/s)	0	-2.16	-10.36	-12.67	-14.79
Min mean Traffic flux (veh/hr)	0	-3.32	-8.61	-10.97	-21.23
Capacity Traffic					
Maximum Capacity (veh/hr)	0	-3.93	-7.34	-11.38	-15.67
Capacity speed (m/s)	0	-3.94	-7.34	-11.37	-3.62
Capacity Density (veh/km)	0	0	0	0	-12.50

Table 3.13a shows the traffic parameters for each weather condition for a signal controlled single lane traffic containing HGVs only.

Traffic Parameters	Normal (Dry)	Light Rain	Light Snow	Heavy Rain	Heavy Snow
Free flowing Traffic					
Max mean speed (m/s)	49.86	47.14	46.71	44.57	40.72
Max mean speed density (veh/km)	4	4	4	4	4
Max mean speed Traffic flux (veh/hr)	199.44	188.54	186.85	178.29	162.89
Saturated Traffic					
Min mean speed (m/s)	5.61	5.28	5.37	5.13	4.40
Min mean Traffic flux (veh/hr)	199.44	188.54	186.85	178.29	162.89
Capacity Traffic					
Maximum Capacity (veh/hr)	956.38	901.02	908.08	865.570	816.67
Capacity speed (m/s)	29.89	28.16	28.38	24.04	25.52
Capacity Density (veh/km)	32	32	36	32	32

Table 3.13b shows the percentage reductions in the traffic parameters for each weather condition from the normal condition for a signal controlled single lane traffic containing HGVs only.

Traffic Parameters	Normal (Dry)	Light Rain	Light Snow	Heavy Rain	Heavy Snow
Free flowing Traffic					
Max mean speed (m/s)	0	-5.46	-6.32	-10.61	-18.327
Max mean speed density (veh/km)	0	0	0	0	0
Max mean speed Traffic flux (veh/hr)	0	-5.47	-6.31	-10.61	-18.326
Saturated Traffic					
Min mean speed (m/s)	0	-5.96	-4.42	-8.58	-21.554
Min mean Traffic flux (veh/hr)	0	-5.47	-6.31	-10.61	-18.326
Capacity Traffic					
Maximum Capacity (veh/hr)	0	-5.79	-5.05	-9.50	-14.61
Capacity speed (m/s)	0	-5.79	-5.05	-19.55	-14.61
Capacity Density (veh/km)	0	0	-12.50	0	0

Table 3.14a shows the traffic parameters for each weather condition for a roundabout controlled single lane traffic containing mixed vehicles.

Traffic Parameters	Normal (Dry)	Light Rain	Light Snow	Heavy Rain	Heavy Snow
Free flowing Traffic					
Max mean speed (m/s)	49.86	47.33	46.49	46.18	44.14
Max mean speed density (veh/km)	4	4	4	4	4
Max mean speed Traffic flux (veh/hr)	199.44	189.31	185.97	184.70	176.54
Saturated Traffic					
Min mean speed (m/s)	0.96	0.90	0.86	0.85	0.77
Min mean Traffic flux (veh/hr)	76.48	72.35	68.47	67.78	61.60
Capacity Traffic					
Maximum Capacity (veh/hr)	735.82	710.18	679.91	658.43	636.65
Capacity speed (m/s)	26.28	25.36	24.28	23.52	22.74
Capacity Density (veh/km)	28	28	28	28	28

Table 3.14b shows the percentage reductions in the traffic parameters for each weather condition from the normal condition for a roundabout controlled single lane traffic containing mixed vehicles.

Traffic Parameters	Normal (Dry)	Light Rain	Light Snow	Heavy Rain	Heavy Snow
Free flowing Traffic					
Max mean speed (m/s)	0	-5.08	-6.76	-7.39	-11.48
Max mean speed density (veh/km)	0	0	0	0	0
Max mean speed Traffic flux (veh/hr)	0	-5.08	-6.75	-7.39	-11.48
Saturated Traffic					
Min mean speed (m/s)	0	-5.40	-10.47	-11.38	-19.46
Min mean Traffic flux (veh/hr)	0	-5.40	-10.47	-11.38	-19.46
Capacity Traffic					
Maximum Capacity (veh/hr)	0	-3.49	-7.60	-10.52	-13.48
Capacity speed (m/s)	0	-3.49	-7.60	-10.52	-13.48
Capacity Density (veh/km)	0	0	0	0	0

Table 3.15a shows the traffic parameters for each weather condition for a signal controlled single lane traffic containing mixed vehicles.

Traffic Parameters	Normal (Dry)	Light Rain	Light Snow	Heavy Rain	Heavy Snow
Free flowing Traffic					
Max mean speed (m/s)	49.86	48.16	46.086	43.26	40.77
Max mean speed density (veh/km)	4	4	4	4	4
Max mean speed Traffic flux (veh/hr)	199.44	192.63	184.350	173.03	163.09
Saturated Traffic					
Min mean speed (m/s)	4.45	4.31	4.19	3.92	3.65
Min mean Traffic flux (veh/hr)	199.44	192.63	184.35	173.03	163.09
Capacity Traffic					
Maximum Capacity (veh/hr)	910.45	885.08	857.97	818.51	782.09
Capacity speed (m/s)	28.45	27.66	25.58	23.83	24.44
Capacity Density (veh/km)	32	32	36	32	32

Table 3.15b shows the percentage reductions in the traffic parameters for each weather condition from the normal condition for a signal controlled single lane traffic containing mixed vehicles.

Traffic Parameters	Normal (Dry)	Light Rain	Light Snow	Heavy Rain	Heavy Snow
Free flowing Traffic					
Max mean speed (m/s)	0	-3.41	-7.57	-13.24	-18.23
Max mean speed density (veh/km)	0	0	0	0	0
Max mean speed Traffic flux (veh/hr)	0	-3.42	-7.57	-13.24	-18.23
Saturated Traffic					
Min mean speed (m/s)	0	-3.12	-5.84	-11.96	-17.89
Min mean Traffic flux (veh/hr)	0	-3.42	-7.57	-13.24	-18.23
Capacity Traffic					
Maximum Capacity (veh/hr)	0	-2.79	-5.76	-10.10	-14.10
Capacity speed (m/s)	0	-2.79	-10.10	-16.23	-14.10
Capacity Density (veh/km)	0	0	-12.500	0	0

Table 3.16a shows the traffic parameters for each weather condition for a roundabout controlled 3 lanes traffic containing cars only.

Traffic Parameters	Normal (Dry)	Light Rain	Light Snow	Heavy Rain	Heavy Snow
Free flowing Traffic					
Max mean speed (m/s)	49.86	48.05	47.74	43.17	42.06
Max mean speed density (veh/km)	4	4	4	4	4
Max mean speed Traffic flux (veh/hr)	199.44	192.19	190.96	172.67	168.22
Saturated Traffic					
Min mean speed (m/s)	2.48	2.36	2.37	2.23	1.94
Min mean Traffic flux (veh/hr)	199.44	192.19	190.96	172.67	168.22
Capacity Traffic					
Maximum Capacity (veh/hr)	3014.60	2918.70	2761.50	2730.30	2666.70
Capacity speed (m/s)	28.99	28.06	26.55	26.25	25.64
Capacity Density (veh/km)	104	104	104	104	104

Table 3.16b shows the percentage reductions in the traffic parameters for each weather condition from the normal condition for a roundabout controlled 3 lanes traffic containing cars only.

Traffic Parameters	Normal (Dry)	Light Rain	Light Snow	Heavy Rain	Heavy Snow
Free flowing Traffic					
Max mean speed (m/s)	0	-3.63	-4.25	-13.43	-15.65
Max mean speed density (veh/km)	0	0	0	0	0
Max mean speed Traffic flux (veh/hr)	0	-3.64	-4.25	-13.42	-15.65
Saturated Traffic					
Min mean speed (m/s)	0	-4.86	-4.63	-10.00	-21.88
Min mean Traffic flux (veh/hr)	0	-3.64	-4.25	-13.42	-15.65
Capacity Traffic					
Maximum Capacity (veh/hr)	0	-3.18	-8.40	-9.43	-11.54
Capacity speed (m/s)	0	-3.18	-8.40	-9.43	-11.54
Capacity Density (veh/km)	0	0	0	0	0

Table 3.17a shows the traffic parameters for each weather condition for a signal controlled 3 lanes traffic containing cars only.

Traffic Parameters	Normal (Dry)	Light Rain	Light Snow	Heavy Rain	Heavy Snow
Free flowing Traffic					
Max mean speed (m/s)	49.86	48.47	47.40	44.66	40.27
Max mean speed density (veh/km)	4	4	4	4	4
Max mean speed Traffic flux (veh/hr)	199.44	193.88	189.62	178.64	161.07
Saturated Traffic					
Min mean speed (m/s)	0.18	0.17	0.16	0.16	0.16
Min mean Traffic flux (veh/hr)	39.84	39.02	36.52	36.16	35.38
Capacity Traffic					
Maximum Capacity (veh/hr)	2036.10	1960.20	1924.30	1803.10	1614.20
Capacity speed (m/s)	31.82	30.63	30.067	28.17	36.69
Capacity Density (veh/km)	64	64	64	64	44

Table 3.17b shows the percentage reductions in the traffic parameters for each weather condition from the normal condition for a signal controlled 3 lanes traffic containing cars only.

Traffic Parameters	Normal (Dry)	Light Rain	Light Snow	Heavy Rain	Heavy Snow
Free flowing Traffic					
Max mean speed (m/s)	0	-2.79	-4.93	-10.43	-19.24
Max mean speed density (veh/km)	0	0	0	0	0
Max mean speed Traffic flux (veh/hr)	0	-2.79	-4.92	-10.43	-19.24
Saturated Traffic					
Min mean speed (m/s)	0	-2.07	-8.35	-9.25	-11.21
Min mean Traffic flux (veh/hr)	0	-2.063	-8.35	-9.24	-11.20
Capacity Traffic					
Maximum Capacity (veh/hr)	0	-3.73	-5.49	-11.44	-20.72
Capacity speed (m/s)	0	-3.73	-5.49	-11.45	-15.31
Capacity Density (veh/km)	0	0	0	0	-31.25

Table 3.18a shows the traffic parameters for each weather condition for a roundabout controlled 3 lanes traffic containing HGVs only.

Traffic Parameters	Normal (Dry)	Light Rain	Light Snow	Heavy Rain	Heavy Snow
Free flowing Traffic					
Max mean speed (m/s)	49.86	46.94	47.23	44.32	40.28
Max mean speed density (veh/km)	4	4	4	4	4
Max mean speed Traffic flux (veh/hr)	199.44	187.77	188.93	177.28	161.14
Saturated Traffic					
Min mean speed (m/s)	2.955	2.82	2.74	2.55	2.59
Min mean Traffic flux (veh/hr)	199.44	187.77	188.93	177.28	161.14
Capacity Traffic					
Maximum Capacity (veh/hr)	2973.40	2897.40	2733.10	2666.50	2440.80
Capacity speed (m/s)	28.59	27.86	26.28	25.64	23.47
Capacity Density (veh/km)	104	104	104	104	104

Table 3.18b shows the percentage reductions in the traffic parameters for each weather condition from the normal condition for a roundabout controlled 3 lanes traffic containing HGVs only.

Traffic Parameters	Normal (Dry)	Light Rain	Light Snow	Heavy Rain	Heavy Snow
Free flowing Traffic					
Max mean speed (m/s)	0	-5.85	-5.27	-11.11	-19.21
Max mean speed density (veh/km)	0	0	0	0	0
Max mean speed Traffic flux (veh/hr)	0	-5.85	-5.27	-11.11	-19.20
Saturated Traffic					
Min mean speed (m/s)	0	-4.48	-7.23	-13.81	-12.38
Min mean Traffic flux (veh/hr)	0	-5.85	-5.27	-11.11	-19.20
Capacity Traffic					
Maximum Capacity (veh/hr)	0	-2.56	-8.08	-10.32	-17.91
Capacity speed (m/s)	0	-2.55	-8.08	-10.32	-17.91
Capacity Density (veh/km)	0	0	0	0	0

Table 3.19a shows the traffic parameters for each weather condition for a signal controlled 3 lanes traffic containing HGVs only.

Traffic Parameters	Normal (Dry)	Light Rain	Light Snow	Heavy Rain	Heavy Snow
Free flowing Traffic					
Max mean speed (m/s)	49.86	47.55	47.44	45.44	39.12
Max mean speed density (veh/km)	4	4	4	4	4
Max mean speed Traffic flux (veh/hr)	199.44	190.18	189.74	181.76	156.50
Saturated Traffic					
Min mean speed (m/s)	2.96	2.89	2.83	2.63	2.62
Min mean Traffic flux (veh/hr)	199.44	190.18	189.74	181.76	156.50
Capacity Traffic					
Maximum Capacity (veh/hr)	2974.20	2832.90	2792.50	2614.20	2598.80
Capacity speed (m/s)	28.60	27.24	26.85	25.14	25
Capacity Density (veh/km)	104	104	104	104	104

Table 3.19b shows the percentage reductions in the traffic parameters for each weather condition from the normal condition for a signal controlled 3 lanes traffic containing HGVs only.

Traffic Parameters	Normal (Dry)	Light Rain	Light Snow	Heavy Rain	Heavy Snow
Free flowing Traffic					
Max mean speed (m/s)	0	-4.64	-4.86	-8.87	21.53
Max mean speed density (veh/km)	0	0	0	0	0
Max mean speed Traffic flux (veh/hr)	0	-4.64	-4.86	-8.87	-21.53
Saturated Traffic					
Min mean speed (m/s)	0	-2.29	-4.49	-11.25	-11.59
Min mean Traffic flux (veh/hr)	0	-4.64	-4.86	-8.87	-21.53
Capacity Traffic					
Maximum Capacity (veh/hr)	0	-4.75	-6.11	-12.10	-12.62
Capacity speed (m/s)	0	-4.75	-6.11	-12.11	-12.62
Capacity Density (veh/km)	0	0	0	0	0

Table 3.20a shows the traffic parameters for each weather condition for a roundabout controlled 3 lanes traffic containing mixed vehicles.

Traffic Parameters	Normal (Dry)	Light Rain	Light Snow	Heavy Rain	Heavy Snow
Free flowing Traffic					
Max mean speed (m/s)	49.86	48.75	44.40	43.63	40.67
Max mean speed density (veh/km)	4	4	4	4	4
Max mean speed Traffic flux (veh/hr)	199.44	194.98	177.58	174.52	162.70
Saturated Traffic					
Min mean speed (m/s)	0.142	0.132	0.13	0.12	0.12
Min mean Traffic flux (veh/hr)	31.72	29.54	28.54	27.60	26.84
Capacity Traffic					
Maximum Capacity (veh/hr)	2751.40	2595.20	2538.30	2503	2445.50
Capacity speed (m/s)	26.46	24.95	24.41	24.07	23.52
Capacity Density (veh/km)	104	104	104	104	104

Table 3.20b shows the percentage reductions in the traffic parameters for each weather condition from the normal condition for a roundabout controlled 3 lanes traffic containing mixed vehicles.

Traffic Parameters	Normal (Dry)	Light Rain	Light Snow	Heavy Rain	Heavy Snow
Free flowing Traffic					
Max mean speed (m/s)	0	-2.24	-11	-12.50	-18.42
Max mean speed density (veh/km)	0	0	0	0	0
Max mean speed Traffic flux (veh/hr)	0	-2.24	-10.96	-12.50	-18.42
Saturated Traffic					
Min mean speed (m/s)	0	-6.86	-10.04	-13.00	-15.38
Min mean Traffic flux (veh/hr)	0	-6.86	-10.04	-13	-15.38
Capacity Traffic					
Maximum Capacity (veh/hr)	0	-5.68	-7.75	-9.03	-11.12
Capacity speed (m/s)	0	-5.67	-7.74	-9.03	-11.11
Capacity Density (veh/km)	0	0	0	0	0

Table 3.21a shows the traffic parameters for each weather condition for a signal controlled 3 lanes traffic containing mixed vehicles.

Traffic Parameters	Normal (Dry)	Light Rain	Light Snow	Heavy Rain	Heavy Snow
Free flowing Traffic					
Max mean speed (m/s)	49.86	48.52	46.84	46.21	41.59
Max mean speed density (veh/km)	4	4	4	4	4
Max mean speed Traffic flux (veh/hr)	199.44	194.08	187.35	184.83	166.38
Saturated Traffic					
Min mean speed (m/s)	0.21	0.20	0.19	0.18	0.18
Min mean Traffic flux (veh/hr)	45.80	43.66	41.93	41.19	39.90
Capacity Traffic					
Maximum Capacity (veh/hr)	3129	3000.10	2846.20	2808.10	2650.60
Capacity speed (m/s)	30.09	28.85	27.37	27.00	25.47
Capacity Density (veh/km)	104	104	104	104	104

Table 3.21b shows the percentage reductions in the traffic parameters for each weather condition from the normal condition for a signal controlled 3 lanes traffic containing mixed vehicles.

Traffic Parameters	Normal (Dry)	Light Rain	Light Snow	Heavy Rain	Heavy Snow
Free flowing Traffic					
Max mean speed (m/s)	0	-2.69	6.07	-7.33	-16.58
Max mean speed density (veh/km)	0	0	0	0	0
Max mean speed Traffic flux (veh/hr)	0	-2.69	-6.06	-7.33	-16.58
Saturated Traffic					
Min mean speed (m/s)	0	-4.68	-8.45	-10.07	-12.89
Min mean Traffic flux (veh/hr)	0	-4.68	-8.45	-10.07	-12.89
Capacity Traffic					
Maximum Capacity (veh/hr)	0	-4.12	-9.04	-10.26	-15.29
Capacity speed (m/s)	0	-4.12	-9.04	-10.26	-15.29
Capacity Density (veh/km)	0	0	0	0	0

3.4.2.1.1. Discussion

The research carried out by Agarwal et al (2005) to quantify the impact of rain, snow and pavement surface conditions on traffic flow shows estimated relationship between highway capacity and traffic speed on congested freeways in the Minneapolis/St. Paul (the Twin Cities) metropolitan area. Freeway traffic in-pavement system detectors data collected from a four-year period, weather data from three Automated Surface Observing Systems (ASOS) and five RWIS sensors where utilised. Results from this research indicated that severe precipitation (mainly rain and snow) and visibility impairment resulted in the most significant speed and capacity reductions (Agarwal et al, 2005). The findings are summarised in the table 3.22. Table 3.23 shows the precipitation threshold values used for this research. This table is further discussed in chapter 5.

Weather Variable	Intensity (inch/hour)	Percentage reduction in capacity compared to Clear	Percentage reduction in speed compared to Clear
Rain	0	0	0
	0-0.0.01	2%	2%
	0.01-0.25	7%	4%
	>0.25	14%	6%
Snow	0		
	<=0.05	4%	4%
	0.06-0.1	9%	8%
	0.11-0.5	11%	9%
	>0.5	22%	13%

Table 3.22: Average impact of precipitation on speed and capacity (Agarwal et al, 2005)

Classification	Precipitation range (mm/hr)	Temperature range (° C)
Dry	0	N/A
Light Rain	> 0 < 2 or >0<0.08inch/hr	> 0
Light Snow	> 0 < 2 or > 0 < 0.08inch/hr	< 0
Heavy Rain	> 2 or > 0.08inch/hr	> 0
Heavy Snow	> 2 or > 0.08inch/hr	< 0

Table 3.23: Precipitation threshold values

The result of comparing Table 3.22 to Table 3.23 is shown in Table 3.24. The comparison shows how the precipitation classification used for this research lines up with the precipitation ranges used in the Agarwal et al, 2005.

Weather Variable	Intensity (mm/hour)	Intensity (inch/hour)	Our adjusted classification
Rain	0	0	Dry
	0-0.254	0-0.01	Light rain
	0.254-6.35	0.01-0.25	Light rain
	>6.35	>0.25	Heavy rain
Snow	0	0	Dry
	<=1.27	<=0.05	Light snow
	1.524-2.54	0.06-0.1	Light snow
	2.794-12.7	0.11-0.5	Light snow
	>12.7	>0.5	Heavy snow

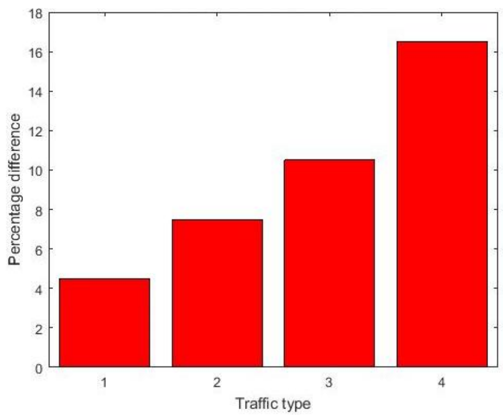
Table 3.24: Adjusted weather classification

Comparison of the output fluxes under the various weather conditions

Table 3.25 shows Agarwal et al (2005) midrange percentage reduction values of the traffic flux under the various weather conditions when compared to the normal (dry) condition, this is also shown in figure 3.23 for clarity. Comparing these values with those obtained from the model simulation shown in figures 3.24a to 3.27b the values obtained from the simulation output were within the range of the values specified by the Agarwal et al (2005). From the results of the simulation it can also be said that in most cases traffic conditions containing cars only appeared to show the least flux reductions while those containing HGVs only appeared to show the most flux reductions. The result of the simulation also showed that the saturated traffic conditions showed a fairly higher flux reduction under the various weather conditions compared to the capacity traffic conditions. It also showed that the signal-controlled traffic conditions induced higher flux reductions under the various weather conditions compared to the roundabout controlled traffic conditions.

Weather Variable	Percentage Capacity reduction range (%)	Percentage Capacity reduction midrange (%)
Light Rain	2-7	4.5
Light Snow	4-11	7.5
Heavy Rain	>7<14	10.5
Heavy Snow	>11<22	16.5

Table 3.25: Percentage Capacity reduction midrange



Legend	
s/n	Traffic type
1	Light Rain
2	Light Snow
3	Heavy Rain
4	Heavy Snow

Figure 3.23: Agarwal et al (2005) midrange percentage reduction values

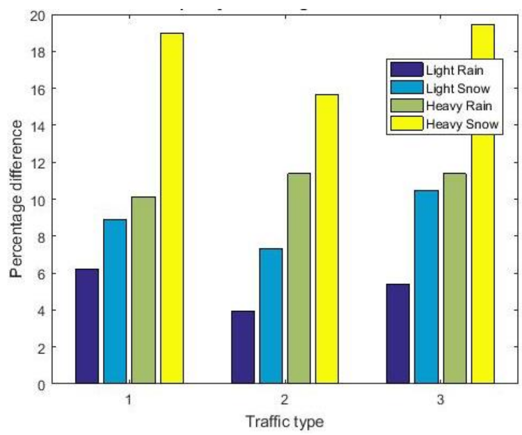
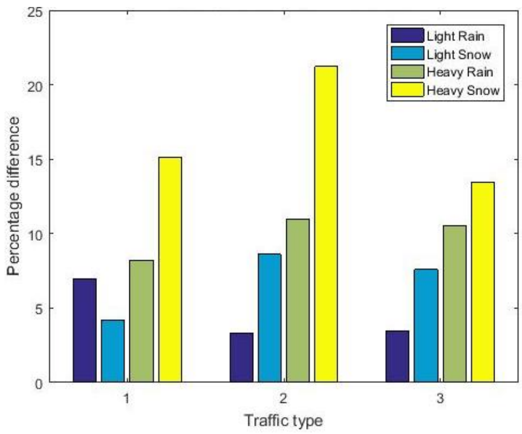


Figure 3.24a: Roundabout single lane saturated traffic



Legend	
s/n	Traffic type
1	Cars only
2	HGVs only
3	Cars and HGVs (ratio 16:1)

Figure 3.24b: Roundabout single lane capacity traffic

Figure 3.24: Single lane roundabout controlled saturated and capacity traffic flow validation

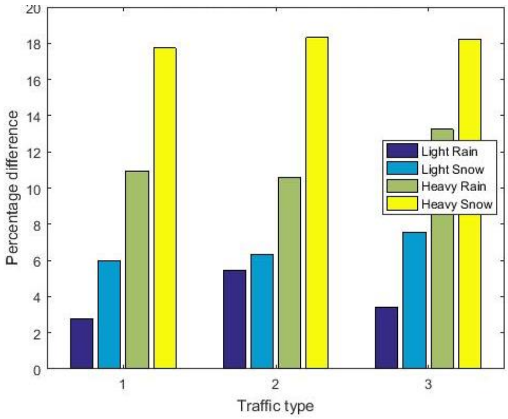
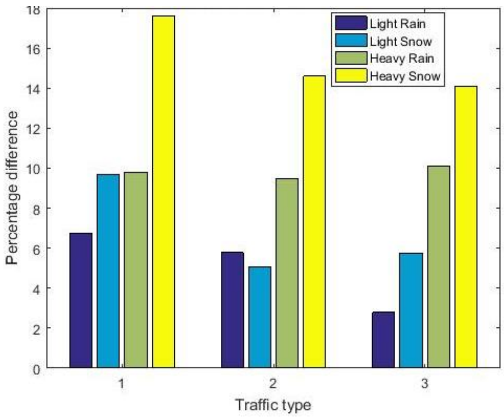


Figure 3.25a: Signal controlled single lane saturated traffic



Legend	
s/n	Traffic type
1	Cars only
2	HGVs only
3	Cars and HGVs (ratio 16:1)

Figure 3.25b: Signal controlled single lane capacity traffic

Figure 3.25: Single lane signal controlled saturated and capacity traffic flow validation

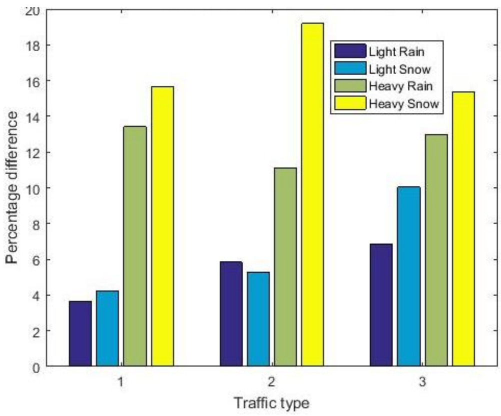
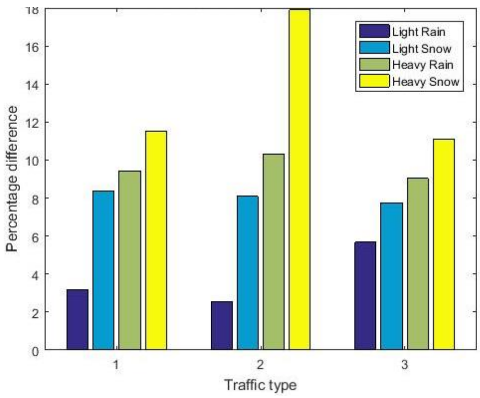


Figure 3.26a: Roundabout multiple lanes saturated traffic



Legend	
s/n	Traffic type
1	Cars only
2	HGV vehicles only
3	Cars and HGVs (ratio 16:1)

Figure 3.26b: Roundabout multiple lanes capacity traffic

Figure 3.26: Multiple lanes roundabout controlled saturated and capacity traffic flow validation

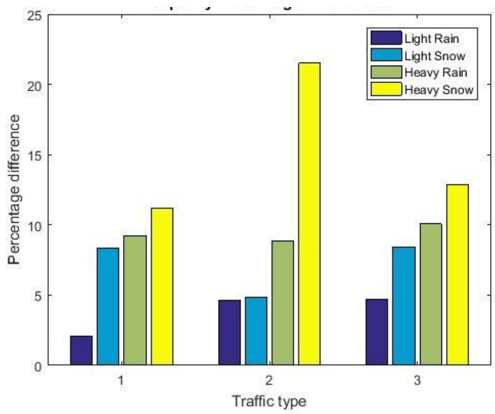
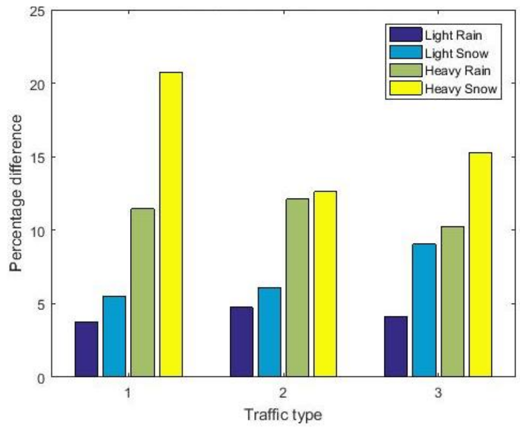


Figure 3.27a: Signal controlled multiple lanes saturated traffic



Legend	
s/n	Traffic type
1	Cars only
2	HGVs only
3	Cars and HGVs (ratio 16:1)

Figure 3.27b: Signal controlled multiple lanes capacity traffic

Figure 3.27: Multiple lanes signal controlled saturated and capacity traffic flow validation

3.5. Summary and Conclusion

This chapter discussed the design and implementation of the traffic flow model used for this thesis. The traffic flow algorithm was designed using MATLAB and it was based on the Paramics car following algorithm, the UK Highway code, an innovated lane changing model and the maximum acceleration of vehicles under various weather conditions was modelled using Rakha et al. (1999)'s vehicle dynamics model for estimating maximum vehicle acceleration levels. Although the model designed can simulate up to 4 lanes of traffic of a 1km link the methodology used could be used to design much longer and wider links. The links featured in this thesis were a single-lane 1km link and a 3-lane 1km link.

The main limitation of the model is that it could be very slow and simulating road transport peak periods in the UK which often lasts up to 3 hours (108,000-time steps) could take up to one week for a single simulation to be completed. Due to this limitation smaller time samples were simulated, and the result of the simulations were then used to extrapolate much larger time frames. This is discussed in a later chapter.

Validating the simulation output involved comparing the outputs to the fundamentals of traffic flow for consistency. To simplify the validation process only the simulation output of a mixed traffic under normal condition was focused on and examinations were done on both signal controlled and roundabout controlled traffic for both a single and 3 lane links.

Validating the impact of weather conditions on the output of the simulations involved comparing the outputs to the result of the research carried out by Agarwal et al (2005) to quantify the impact of rain, snow and pavement surface conditions on traffic flow. It was indicated after the comparison that the result of the simulation fell within the percentage capacity reduction range derived from Agarwal et al (2005) research.

The traffic flow model was used to simulate the interaction of drivers and drivers and their environment in traffic streams and the output of the simulations which were mainly the traffic flow rates, mean speed and density under free flow, capacity and saturated traffic states were later used as inputs to the IWIS along with the weather data as well as the user inputs discussed in chapter 5.

In the next chapter the weather generator and its output data which were later used as inputs to the IWIS will be discussed. The weather generator can make future weather projections under various emissions scenarios and its output data is important when making future impact projections on road traffic capacities.

Chapter 4 – Methodology: The Weather Generator and Its Output Data

4.1. Introduction

In the previous chapter the design and implementation of the traffic flow model used for the thesis as well as its limitations were discussed. The outputs of the traffic flow simulation were later used as inputs to the IWIS along with the weather data and user inputs. In this chapter the weather generator, its output weather data, its limitations as well as proposed methods to complement its limitations will be discussed.

Roads are generally busier during peak periods compared to other periods of the day and these periods are of most concern to investors and stakeholders as there is a lot of interest in optimising road usage. In the UK, Highways England are the primary investors and they are looking to double their investment to £30bn post 2020. Adequate planning which would include plans to optimise the flow of traffic as well as adaptation strategies would be required to ensure this increased investment is properly utilised (Construction News, 2018).

Weather conditions have been known to play an important role in road capacity. Dryer conditions have been known to increase the aggression of drivers resulting in higher accident rates (Jaroszweski et al, 2014) but they also generally positively impact capacity. On the other hand, precipitated conditions have been known to negatively impact capacity resulting in reductions in drivers' responsiveness with higher precipitation levels increasing accident rates with reduced severity when compared to dryer conditions. There is a notion of future hotter, drier summers; warmer, wetter winters, rise in sea level and increased frequency of extreme storms (Baker et al., 2010) but the impact of climate change on these seasons would depend greatly on the emission level between now and the period in focus with higher emission level expected to have a higher impact than medium and low emission. This notion has been explained extensively in literature review located in chapter 2.

In this chapter the impact of three emission scenarios on the precipitation level of both the summer and winter periods were examined. This examination was split into two categories; the first involved a general examination of precipitation disparities between the *control scenarios* climate and their corresponding projected 2050s climate with emphasis on the peak hours of the summer and winter months while the second involved an examination of heavy precipitation disparities between both scenarios.

The *Integrated Weather Impact Simulation Tool* (IWIS) described in chapter 5 was used for the data examination. It was designed in such a way that it could separate the weather data for both seasons in focus from weather data of the other months as well as their peak periods from the other hours of the seasons. It was also designed to perform statistical calculations based on the data and generate outputs in form of cumulative distribution functions (CDFs) based on the results of the calculations. The UKCP09 weather generator was used to generate weather conditions for this research. The weather generator has been deemed to have an issue with spatial correlation (Baker, 2013) which occurred when multiple adjacent grid squares were highlighted when using the WG, this was further discussed in section 4.3.1.5. Various possible methods were introduced to address the issue. It was recommended that for projections involving small areas or distances the default methods of the UKCP09 tool could be used as the limitations are not very significant for small distances. Two innovative methods were put forward in this chapter to address the issue faced when making projections for wider areas or longer distances. The first method involved extrapolating weather based on land altitude (BBC, 2019; on the snow, 2018) while the second involved complimenting the weather data from the UKCP09 tool with historical weather data (Smith, 2017). The steps taken to successfully generate weather data using the weather generator were explained including key terms such as the Emission scenarios as well as the change factors. The format of the outputs of the weather generator was explained and the outputs were examined against the general notion of future dryer summer months and wetter winter months with higher extremes.

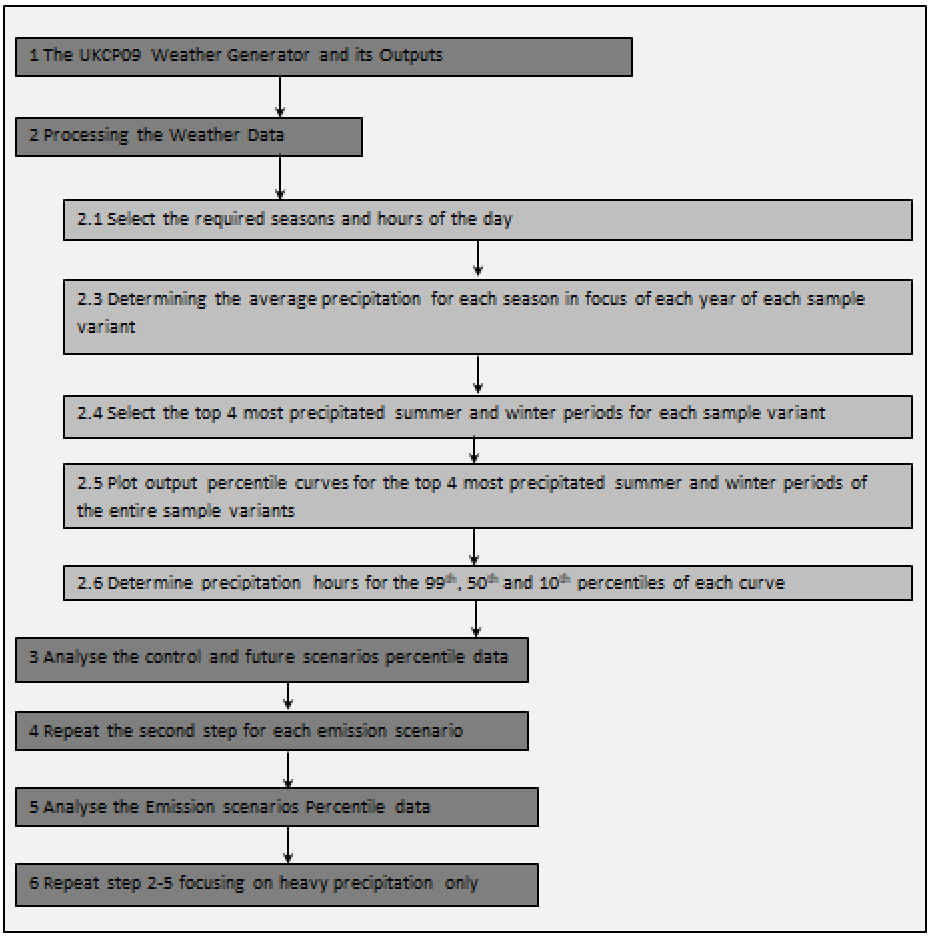


Figure 4.1: The weather data examination frame work

4.2. Overview

The frame work shown in figure 4.1 illustrates the key steps taken during the examination. The examination was started off by obtaining weather data from the UKCP09 weather generator. The various steps taken to achieve this, the issues faced when using the weather generator as well as innovative methods that may be used to compliment the issues when dealing with projections for wider areas were all discussed. The second step involved feeding the weather data into the Weather Impact Simulation tool (IWIS which will be discussed in chapter 5) which was designed to analyse weather data and generate precipitation percentile curves for the top 4 most precipitated years for each sample variants of the weather data as a part of its various outputs. The second step also involved determining the precipitation hours for the 99th, 50th and 10th percentiles. The third step involved analysing the percentile data obtained in 2.6 for the control and future weather data of the emission scenario being processed to determine if they were consistent with the future weather projection theory. The fourth step involved feeding the weather data for the remaining emission scenarios into the IWIS and obtaining their corresponding precipitation percentile curves like step two. The fifth step involved analysing the percentiles obtained in 2.6 for all the emission scenarios to verify if the emission levels had direct impacts on the precipitation levels. The sixth step involved repeating steps 2-5 but focusing on only heavy precipitation which the IWIS was designed to deal with.

4.3. The Weather Data Examination

4.3.1. The UKCP09 Weather Generator and its Outputs

4.3.1.1. Weather generators

Generally, available weather data as well as random number sampling are utilised by weather generators to generate statistically credible long time series of daily and hourly weather data.

4.3.1.2. The UKCP09 weather generator

The UKCP09 weather generator is a tool which utilises existing weather data and random number sampling to develop lengthy time series of statistically credible daily and hourly weather data. Statistical representation of a series of daily future climate possessing similar statistical properties as the *baseline* data they were derived from are developed by the UKCP09.Probabilistic projections are used to generate future daily and hourly time series. The UKCP09 weather generator basically uses the 5km, daily observed baseline of 1961-1990 (Met Office, 2010).

4.3.1.3. The UKCP09 weather generator Change factors

Stochastic/random processes are used to generate synthetic time series of weather variables by the UKCP09 weather Generator. Data were sampled from a given distribution based on the use of random numbers, these random numbers are referred to as change factors and they provide projections for the change between the baseline climate and the future climate. Generally, using this method the state of the system at one time (e.g. the weather today) does not totally define the state at the next time (e.g. tomorrow) (for more info visit Met Office, 2010).

4.3.1.4. Emission scenarios

The emission scenarios of the UKCP09 weather generator represented the future development of greenhouse gas emissions and were based on a coherent and internally consistent set of assumptions about driving forces (such as demographic and socio-economic development and technological change) (IPCC, 2001). The scenarios are based on The Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) where four different narrative storylines were developed to describe consistently the relationships between the forces driving emissions and their evolution and to add context for the scenario quantification (for more info see IPCC, 2001).

The emission scenarios featured in the UKCP09 tool ranged from low to high emission level and are explained below:

- *Low Emission Scenario*: The SRES B1 storyline was used for future emissions under this scenario. It conveys a converging world with a global population that peaks in mid-century and declines thereafter, where there are rapid changes in the economy structures that drives towards an economy where service and information are dominant, the availability of materials are reduced, and efficient and clean resource technologies are introduced.
- *Medium Emission Scenario*: The SRES A1B was used for future emissions under this scenario. Generally, storylines under the SRES A1 category tend to portray a future converging world with a global population that peaks in mid-century and declines thereafter, very rapid economic growth, and new and more efficient technologies are rapidly introduced. They are distinguished by their focus on fossil energy with the first two A1FI and A1T being fossil energy intensive and non-fossil energy intensive respectively while A1B attempts to strike a balance between fossil energy and non-fossil energy (for more info see IPCC, 2001).
- *High Emission Scenario*: The SRES A1FI explained under *Medium Emission Scenario* was used for future emissions under this scenario. Under this scenario fossil energy is mainly utilised.

4.3.1.5. The issue of spatial coherency when using the UKCP09 tool

When multiple adjacent square grids are highlighted when using the WG, weather for each grid square were not presented instead the average weather data for the entire highlighted grid squares were presented. Presenting the weather data this way may not represent a realistic weather projection of the individual grid squares since it did not account for the weather differences between high level areas and low-level areas. This was not really an issue for a short link but weather generation for longer links may result in unrealistic weather data for the individual grid squares.

When combining the methodology introduced in this research with the UKCP09 weather generator, various approaches have been introduced to compliment the issue of spatial correlation faced when using the UKCP09 weather generator tool.

The first is the default method featured when using the UKCP09 tool and the limitation is explained; this method was used during the research because although it has an issue with spatial correlation it is only evident when longer link stretches are being considered and since the research used a relatively small link sample this method was enough. The second approach is an alternative to the first and they are both suitable for small to medium Trunk Road stretches, the last two are drafted approaches for longer Trunk Road stretches where the limitation of the weather tool would be more evident. The approaches are:

- Average weather for square grids covered
- Centralised weather for square grids covered
- Extrapolating weather based on land altitude
- Complimenting UKCP09 weather data with historic data

1. Average weather for square grids covered: This is the default method when using the UKCP09 weather generator, the limitation of this is it did not account for the weather differences between high level areas and low-level areas. An assumption could be made that the highlighted sections are approximately at the same level if few adjacent square grids are selected at a time, only square grids containing sections of the Trunk Road stretch should be selected. This is illustrated in figure 4.2**,** assuming the curve within the square grids represents a very long stretch of Trunk Road between two junctions in the UK (the M11 j10-j9 southbound) which is 17.75miles (28.6km) and the square grids are each 5km.

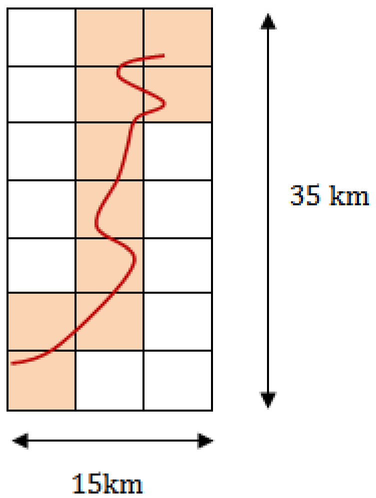


Figure 4.2: A stretch of a Trunk Road contained by square grids

The shaded square grids in figure 4.2 above represents the highlighted square grids containing sections of the Trunk Road stretch; these square grids will be considered during the weather generator tool averaging process while the unselected square grids will be ignored.

2. Centralised weather for square grids covered: The second option would require selecting an approximated mid-section of the Trunk Road stretch and then using the weather generated for this section for the entire grid squares containing sections of the Trunk Road stretch. This would mean assuming that the entire sections of Trunk Road stretch are approximately on the same level. This assumption may be valid for much shorter Trunk Road stretches compared to the example used for the previous option. This is illustrated in figure 4.3 below, assuming 8 miles (12.87km) Trunk Road stretch between two junctions.

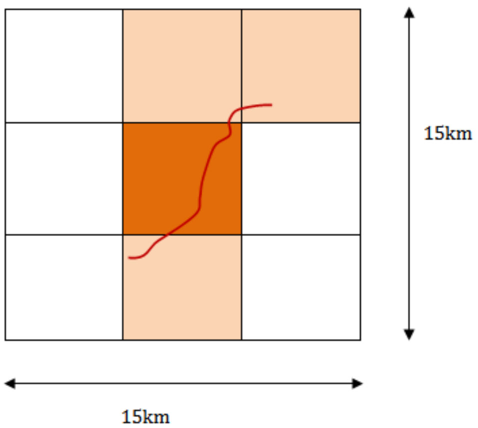


Figure 4.3: A short stretch of a Trunk Road contained by square grids

The dark shaded square grid in figure 4.3 above contains the mid-section of the Trunk Road stretch. Weather is generated for this square grid and is assumed for other square grids where sections of the Trunk Road stretch are contained.

3. Extrapolating weather based on land altitude: A third option that was proposed during this research involves using empirical factors (land altitude) to determine the weather variables could also be considered. It would be more suitable when applying the methodology featured in this research on longer Trunk Road stretches. This option involves generating weather for the square grid containing the mid-section of the Trunk Road and using empirical factors to extrapolate the weather for other square grids containing sections of the Trunk Road stretch. This is illustrated in figure 4.4 below, assuming a Trunk Road stretch between 4 junctions totalling 45km. It is generally known that the higher the altitude an area is the colder and more precipitated it is compared to other areas. An example of a land altitude in 499m above sea level feet but for illustrative purpose the altitude would be classified as very low, low, medium, high and very high. Table 4.1 represents the altitudes of the square grids shown in figure 4.4.

Square grid	Altitude (m)	Altitude class
A	499	Medium
B	590	High
C	690	High
D	730	Very high
E	810	Very high
F	920	Very high
G	330	Low
H	220	Low
I	130	Very Low
J	90	Very Low
K	40	Very Low

Table 4.1: Altitudes of square grids

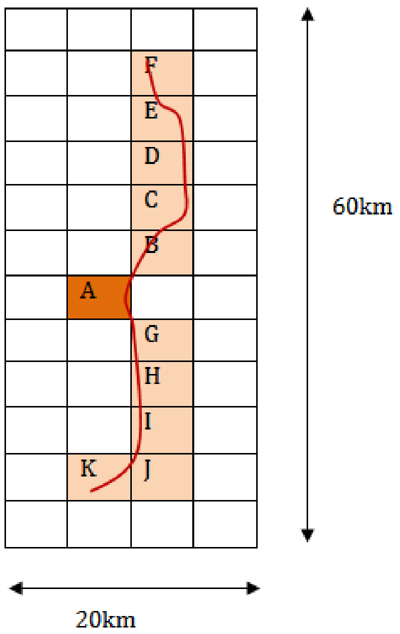


Figure 4.4: A long stretch of a Trunk Road contained by square grids

From figure 4.4 above assuming square grid A is the mid-section of the Trunk Road stretch and it happens to be located on a mid-altitude location with respect to the other square grids. Weather is generated for square grid A being the square grid containing the mid-section of the Trunk Road stretch, since square grid B has a high-altitude level it is then assumed that the temperature of B would be slightly lower than A while the precipitation level would be slightly higher. Square grid G would be assumed to have a slightly higher temperature than A since it is located on a slightly lower ground while its precipitation level would be slightly lower. The weather for C and H is then determined based on the weather of B and G respectively and so on. Without precipitation falling from the sky and the observer not being in a cloud, it is known that temperature decreases by 9.8^{o}C for every

1000m increase in altitude (i.e. -0.0098 °C/m) while when in cloud or with the presence of precipitation the temperature decreases by 6°C for every 1000m increase in altitude (i.e. -0.006 °C/m) (On the Snow, 2018). Table 4.2 shows the estimated temperatures for the other grid squares if grid A was 20°C.

Square grid	Altitude (m)	Altitude class	Estimated temperature without precipitation	Estimated temperature with precipitation
A	499	Medium	20	20
B	590	High	19.1082	19.454
C	690	High	18.1282	18.854
D	730	Very high	17.7362	18.614
E	810	Very high	16.9522	18.134
F	920	Very high	15.8742	17.474
G	330	Low	21.6562	21.014
H	220	Low	22.7342	21.674
I	130	Very Low	23.6162	22.214
J	90	Very Low	24.0082	22.454
K	40	Very Low	24.4982	22.754

Table 4.2: The grid squares estimated temperatures

In a paper by Sasaki and Kurihara (2008) the relationship between precipitation and elevation was investigated, it was concluded that the relationship between precipitation and elevation is brought about by atmospheric conditions and the characteristics of the topography. The results from the investigation indicated that the amount of precipitation increases with elevation, following the characteristics of the topography.

4.3.1.5.1. Other factors that may affect the Weather Condition of a Geographical Location

It is also imperative to note that land altitude is not the only factor that affects the weather condition of a given geographical location. Other factors include the direction of prevailing winds, the latitude, the distance from sea, the ocean currents and the directional side of a mountain and they should also be considered when utilising this method.

The Prevailing Winds

This is the dominant wind direction in a given geographical location. The origin of the air determines the temperature of the wind and partially the amount of rainfall. Winds blowing into the UK and travelling from warm inland geographical locations such as Africa will be warm and dry while those that travel into the UK from cooler locations such as central Europe will be cold and dry during winter. The most experienced (Prevailing) winds in the UK travels from a south westerly direction over the Atlantic. They are generally cool in the summer, wet in the winter and usually bring wet weather (UKECN, 2015; BBC, 2019).

The Latitude

The distance an area is from the equator affects its climate. The equator is located directly underneath the Sun hence geographical areas that are located on the equator receive the strongest solar energy (UK ECN, 2015; BBC, 2019). Areas such as Scotland which is in the Northern part of the UK experience less concentrated solar energy compared to areas in the south such as London.

The Distance from the Sea

The climate of an area is affected by the sea. Coastal areas are most affected by the sea and they are cooler and wetter than inland areas. It takes longer time to heat and cool down the sea compared to land hence during the winter the sea warms up the coastal areas while during the summer it cool them down (UK ECN, 2015; BBC, 2019). Coastal areas of the UK such as Crosby, Merseyside experience this effect.

When arm air from inland areas meets cool air from the sea clouds are formed. This effect affects the centre part of continents and they tend to experience a wide range of temperatures. Summer temperatures can be very hot and dry due to the evaporation of moisture from the sea before arriving the centre parts of the continent (UK ECN, 2015; BBC, 2019). In the UK areas in the Midlands such as Birmingham experience this effect.

The Ocean Currents

Ocean currents have the tendency to either increase or reduce temperatures depending on its own temperature. Although Britain is on the same latitude as Siberia and Russia, but it does not experience similar long, harsh winters which is mainly due to the Gulf Stream which is the main Ocean current that affects the UK. The Gulf Stream is a large Atlantic Ocean current of warm water from the Gulf of Mexico. Its air is quite moist because it travels over the Atlantic Ocean hence this is one of the reasons why Britain frequently experiences wet weather (UK ECN, 2015; BBC, 2019).

The directional side of a Mountain

The Windward side of a Mountain is the side which faces the prevailing wind (upwind). Air that is lifted along the windward side of a mountain cools as it rises (known as adiabatic cooling). This cooling usually gives rise to the formation of clouds which eventually results in precipitation fall on the Windward slope and at the summit. This entire process is known as orographic lifting (Means, 2018).

On the other hand, the Leeward side of a Mountain is the side sheltered from the prevailing wind by the Mountain's very elevation (downwind). Generally, winds in the mid-latitudes blow from the west hence the Leeward side can be said to be the eastern side of the mountain range. It should be noted that although this is often true, but it is not always the case. Compared to the windward side of a mountain, the leeward side usually has a dry, warm climate due to the air which rises along the windward side up to the summit losing most of its moisture before descending along the leeward side. As the dry air descends along the leeward side, it warms up and expands (known as adiabatic warming) causing clouds to disappear which adds up to the reduction in the possibility of precipitation in that area. This occurrence is known as rain shadow effect and has resulted in some of the driest places on the planet (Means, 2018).

Basically, the Windward side of a Mountain or slope experiences more precipitation compared to the Leeward side of the slope due to processes *orographic lifting* and *rain shadow effects* (Means, 2018).

In the UK, a rain shadow is created in Eastern Scotland resulting in Edinburgh experiencing only about half the rainfall that Glasgow experiences. Further up North, Aberdeen's rainfall is only about a third of what Fort William or Skye experiences (BBC, 2011).

4. Complimenting future weather data with historic data: A fourth idea which could be developed on would be to compliment future data using historic data. Basically, historic data which may be obtained from The Natural Environment Research Council (NERC, 2018) would be used to compliment the data generated by the UKCP09. This could mean analysing the weather data and developing relationships between the mid-section of the Trunk Road stretch being considered and the other sections of the Trunk Road. After relationships have been established weather could then be generated for the mid-section of the Trunk Road stretch and then extrapolated for the other sections using the developed relationships.

Various mathematical models could be used to process the data, establish relationships and make projections, a process often referred to as data mining. Data mining is the practice of examining large pre-existing databases to generate new information (Sejdinovic, 2015). Further, to projecting the information various methods of data mining could be used such as (Trivedi, 2018):

- Decision Tree
- Rule-based Methods
- Neural Networks
- Naïve Bayes
- Bayesian Belief Network
- Support Vector Machine

The most common data mining method is the decision tree. With a decision tree, information is viewed in a tree-like graph or model of decision and their possible outcomes, their possibilities of occurrence, overhead costs and utility. In the article by Trivedi (2018) an example of the decision tree was given. A similar method could be used to make more complex future projections.

4.3.1.6. Using the UKCP09 weather generator

Various steps were taken when attempting to use the *UKCP09 weather generator* to generate weather variables at hourly temporal resolution. These steps are shown on appendix 3.

4.3.1.7. The UKCP09 Weather Generator Hourly Output Data

The hourly data output of the UKCP09 Weather Generator (WG) was downloaded as large zip files containing CSV files. Each control and *future climate* run had a single CSV file and due to the number of *random sampling variants* specified there were a total of 100 files each. A description of the WG output data is shown in appendix 3.

4.3.2. Processing the Output Weather Data

This examination focused on the impact of the emission scenarios on future climate examining the impact of the emissions scenarios on:

- the general weather conditions frequency
- the individual weather conditions frequency

4.3.2.1. The impact of the emission scenarios on the general weather conditions frequency

It has been projected that *there will be hotter dryer summers and warmer wetter winters with more extreme conditions under future weather conditions* (Baker, 2013) but the degree of this impact would depend on the emission scenario between the control (control period) and the future climate in focus (2050s) with *high emission scenario* projected to have more impact than *medium* and *low emissions scenarios*.

Projections of regional changes across the UK were presented using maps by the METoffice (UK Climate Projections, 2009). It was indicated that a warmer atmosphere can hold more moisture, and globally water vapour increases by 7% for every degree centigrade of warming. It is likely that in a warmer climate heavy rainfall will increase and be produced by fewer more intense events. This could lead to longer dry spells and a higher risk of floods (Met Office and The Guardian, 2011). Basically, increase in the global temperature would result in hotter, drier summers and warmer, wetter winters with higher extremes. Maps showing the UKCP09 projected change for 2050s in both seasons mean precipitation for all the emissions scenarios with descriptions are shown in appendix 3.

Rainfall and Snowfall

Weather projections from the UKCP09 did not differentiate between rainfall and snowfall hence thresholds were used to make the differentiations for the traffic flow model. To make such differentiation, the precipitation level for each hour as well as their temperature level were used to estimate the weather condition for a given hour.

In the article by the University of Illinois (2010) it was mentioned that precipitation that falls to the ground usually starts as snow in the atmosphere. The snowflakes are formed when the air temperature is around 0^oC and starts falling to the ground as snow. The freezing level is located somewhere above the ground and beyond the freezing level the air becomes warmer where the snow melts and changes to rain before reaching the ground. In a situation where the air temperature on the ground is 0^oC or less the precipitation continues as snowfall until it reaches the ground. Occasionally, there may be a thin layer of warm air just above the ground which may result in temperatures being several degrees above 0^oC. Due to the thin layer of warm air, the snow may reach the ground without melting and becoming rain.

Webb (2012) mentioned that snow falls when the air temperature at the ground level is below 3^oC and it usually falls when it is between -2^oC and 2^oC. She stated that snow generally settles when the air temperature on the ground is below 0^oC which is in line with the University of Illinois (2010) suggestion. NSIDC (2012) statement is also in line with University of Illinois (2010) statement. They said that "Snow forms when the atmospheric temperature is at or below freezing (0 degrees Celsius) and there is a minimum amount of moisture in the air. If the ground temperature is at or below freezing, the snow will reach the ground."

All three papers mentioned above suggested that snow usually settles when the air temperature on the ground is below 0^oC. The temperature levels given by the MET office UKCP09 weather generator are air temperatures just above the ground (Met office, 2018; Met Office 2017). Although there are some rare cases where snow may reach the ground at positive air temperatures just above the ground as pointed out by NSIDC (2012) such cases were not considered in this thesis because they are rare. It was therefore assumed that temperatures below 0^oC would result in snowfall reaching the ground and settling if precipitation was experienced during the given hour while those greater than 0^oC would result in rainfall.

To model a somewhat realistic transition from one weather condition to another, pavement drainage characteristics were assumed in the model. This will be explained later in section 5.2.2.2.1.4.

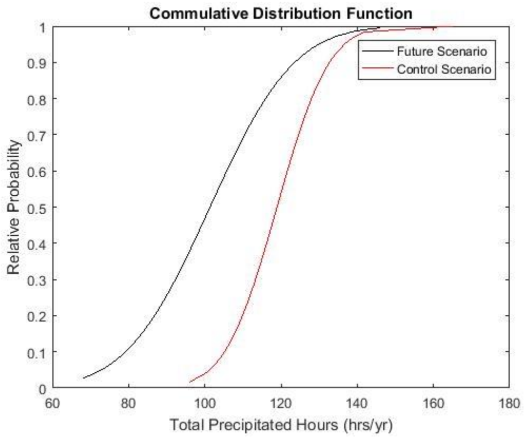
4.3.2.2. The impact of the emission scenarios on the general weather conditions frequency

The UKCP09 weather generating tool was used to generate weather conditions for all three emission scenarios as discussed in appendix 3; a traffic flow algorithm was designed as discussed in chapter 3 and integrated with the obtained weather data discussed later in chapter 5. Weather conditions are key elements when discussing the impact of emission levels on traffic flux, the higher the emission levels the higher the impact on climate change. The effects of climate change are currently occurring: loss of sea ice, accelerated sea level rise and longer more intense heat waves (GCC, 2019). Adefisan (2018) paper concluded that the higher the emission level, the higher the future temperature which may likely result in more rainfall and hence increased likelihood of flooding, increased frequency of heatwave and other high temperature related issues.

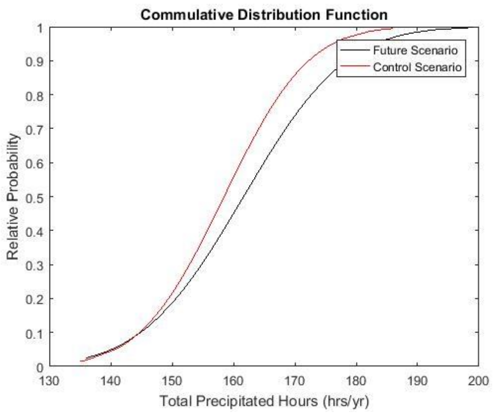
Without taking changes in accident rate because of changes in the aggression levels of the drivers into account, dryer hotter weather conditions are generally expected to mean better traffic flux due to increases in driving conditions such as traction while wetter colder conditions are expected to mean lower traffic flux as a result of lower driving conditions. Increase in the average temperatures may result in better driving conditions but increase in the maximum temperature may pose risks to the strategic network in the forms of increased irritability of drivers which could result in aggressive driving and damages to the infrastructure (such as rutting and shoving) as pointed out in section 2.1.

Although light rain and light snow conditions do not have much impact on traffic capacity and have been known to show reductions of between 4-7% as discussed in chapter 3, heavy rain and snow conditions are the main issues regarding capacity loss and they have been known to reduce traffic capacity by 10-16%. Increases in the frequency of heavy rain and snow conditions would result in higher increases in capacity loss.

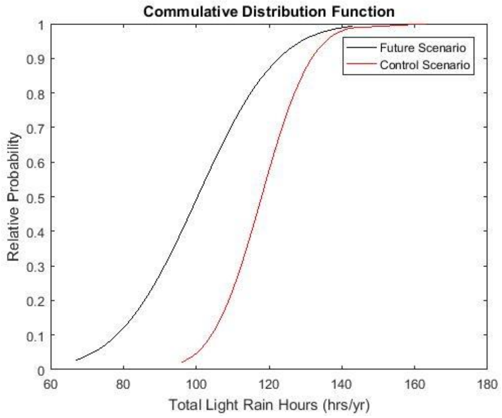
Figure 4.5 contains cumulative distribution function (CDF) curves showing the probability of experiencing precipitated conditions for each season under the high emissions scenario.



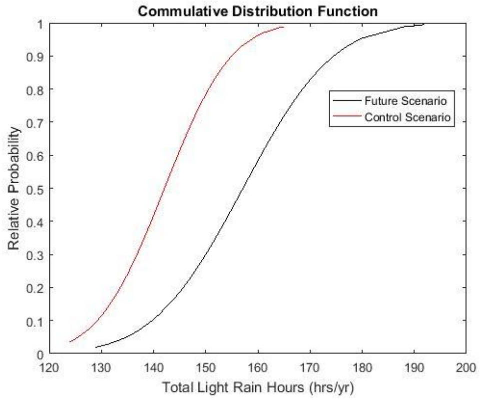
a. The probability of experiencing precipitated hours for the summer period



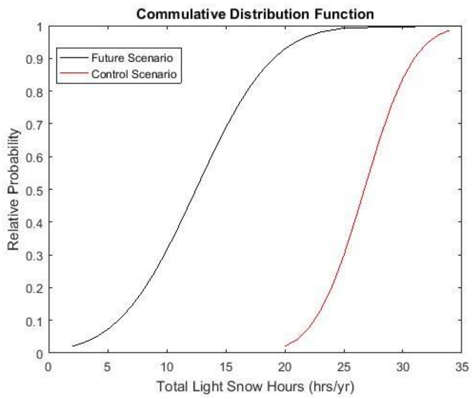
b. The probability of experiencing precipitated hours for the winter period



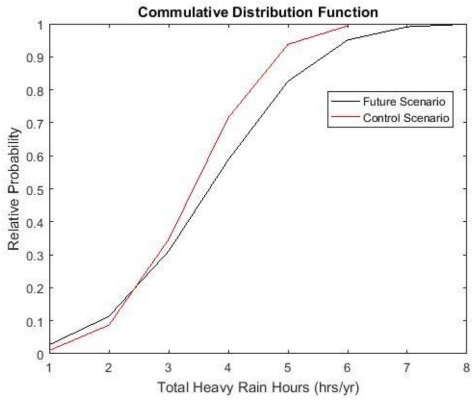
c. The probability of experiencing Light rain hours for the summer period



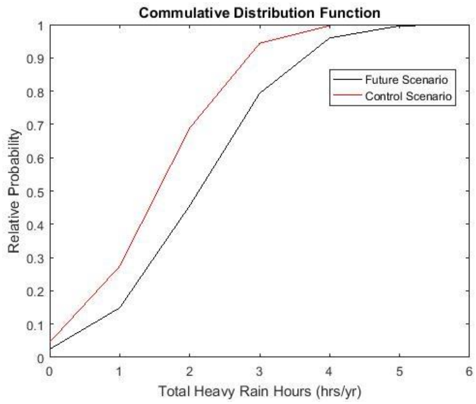
d. The probability of experiencing Light rain hours for the winter period



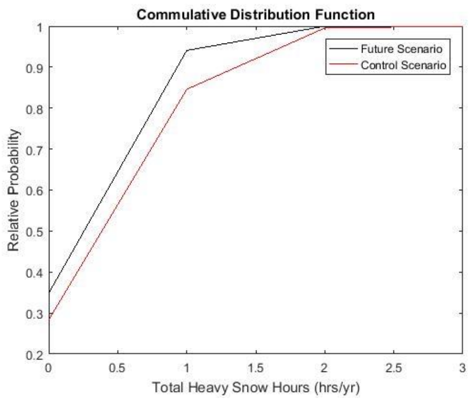
e. The probability of experiencing Light Snow hours for the winter period



f. The probability of experiencing Heavy Rain hours for the Summer period



g. The probability of experiencing Heavy Rain hours for the Winter period



h. The probability of experiencing Heavy Snow hours for the Winter period

Figure 4.5: The probability of experiencing the various precipitations conditions for each season of the high emissions scenario

Table 4.3 summarises the outputs from the high emissions scenario shown in figure 4.5.

	Percentile						Difference (%)		
	Control			Future			Future vs Control		
	10%	50%	90%	10%	50%	90%	10%	50%	90%
Summer									

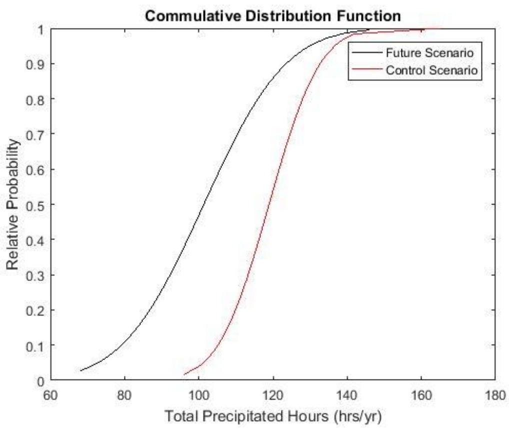
All Precipitation	106	119	133	80	101	123	-32.50	-17.82	-8.13
Light Rain	79	118	132	104	101	122	-31.65	-16.83	-8.20
Light Snow	0	0	0	0	0	0	0	0	0
Heavy Rain	2.1	3.3	4.9	1.9	3.6	5.8	-10.53	8.33	15.52
Heavy Snow	0	0	0	0	0	0	0	0	0
Winter									
All Precipitation	145	158	172	145	161	179	0	1.86	3.91
Light Rain	129	142	155	140	157	175	7.86	9.55	11.42
Light Snow	23	27	31	6	13	19	-283.33	-107.69	-63.16
Heavy Rain	0.2	1.5	2.8	0.7	2.3	3.6	71.43	34.78	22.22
Heavy Snow	0	0.3	1.56	0	0.4	0.9	0	-33.33	-73.33

Table 4.3: The weather condition probabilities for High Emissions scenario

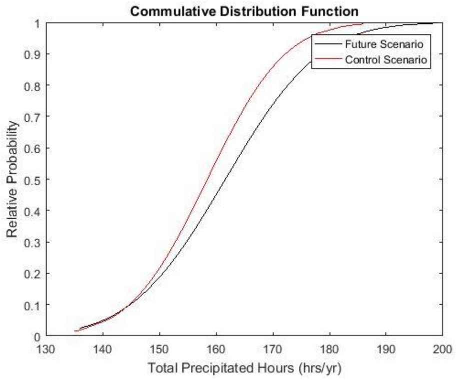
From table 4.3 it can be seen that:

- The future scenario showed lower precipitation compared to the control scenario during the summer period, while for the winter period the future scenario showed more rainfall both light and heavy compared to the control scenario. Basically, the future weather became drier during the summer and wetter during the winter period.
- More heavy rain conditions were observed during the future scenario compared to the control scenario during the summer and winter period which is in line with the general observation mentioned earlier.
- No light or heavy snow conditions were observed during the summer period.
- Light Rain appeared to be the dominant precipitated weather condition for the summer and winter periods of both scenarios.

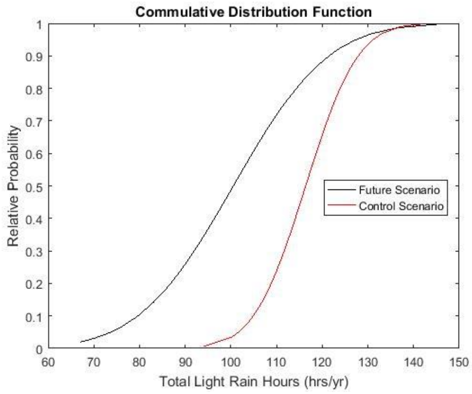
Figure 4.6 contains cumulative distribution function (CDF) curves showing the probability of experiencing precipitated conditions for each season under the medium emissions scenario.



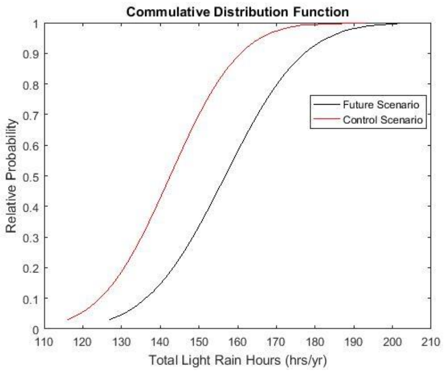
a. The probability of experiencing precipitated hours for the summer period



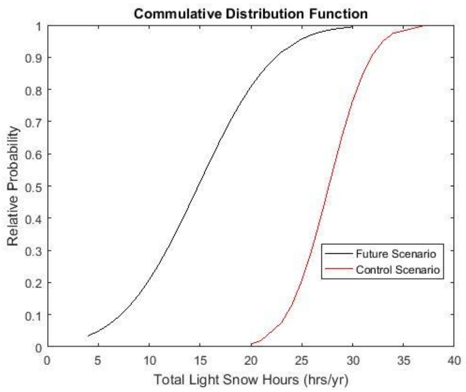
b. The probability of experiencing precipitated hours for the winter period



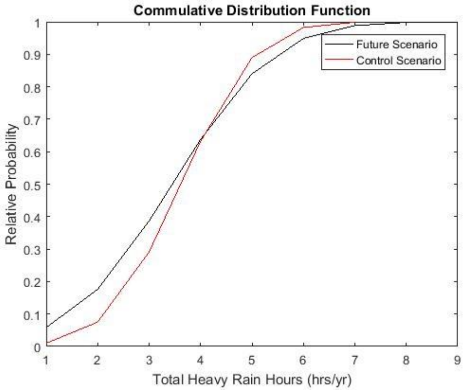
c. The probability of experiencing Light rain hours for the summer period



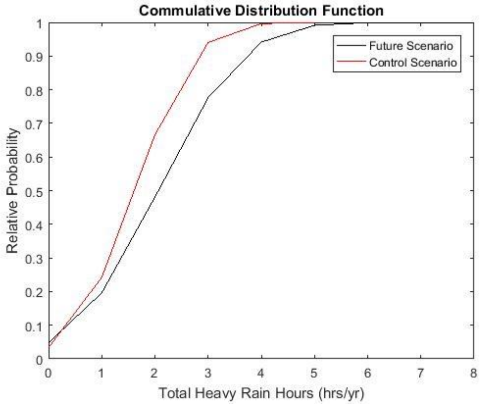
d. The probability of experiencing Light rain hours for the winter period



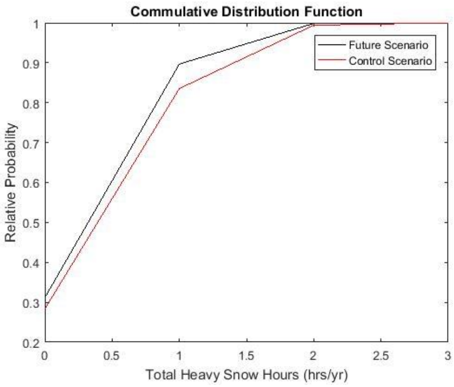
e. The probability of experiencing Light Snow hours for the winter period



f. The probability of experiencing Heavy Rain hours for the Summer period



g. The probability of experiencing Heavy Rain hours for the Winter period



h. The probability of experiencing Heavy Snow hours for the Winter period

Figure 4.6: The probability of experiencing the various precipitations conditions for each season of the medium emissions scenario

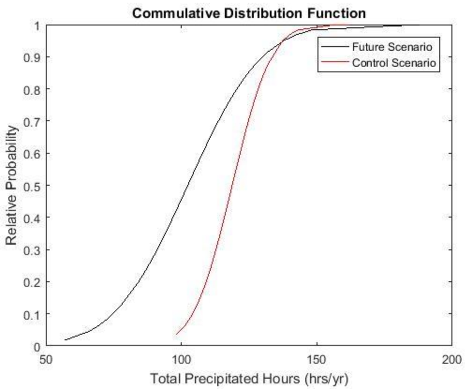
	Percentile						Difference (%)					
	Control			Future			Future vs Control			Medium emissions VS High emissions		
	10%	50%	90%	10%	50%	90%	10%	50%	90%	10%	50%	90%
Summer												
All Precipitation	106	118	129	81	101	123	-30.86	-16.83	-4.88	-1.64	-0.99	-3.25
Light Rain	106	117	129	81	101	123	-30.86	-15.84	-4.88	-0.79	-0.99	-3.32

Light Snow	0	0	0	0	0	0	0	0	0	0	0	0
Heavy Rain	2.2	3.6	5.1	1.3	3.4	5.6	-69.23	-5.88	8.93	58.7	14.21	6.59
Heavy Snow	0	0	0	0	0	0	0	0	0	0	0	0
Winter												
All Precipitation	141	159	176	144	163	183	2.08	2.45	3.83	-2.08	-0.59	0.08
Light Rain	125	142	159	137	157	178	8.76	9.55	10.67	-0.9	0	0.75
Light Snow	24	27	32	7	15	23	-242.86	-80	-39.13	-40.47	-27.69	-24.03
Heavy Rain	0.3	1.6	2.4	0.3	2.1	3.6	0	23.81	33.33	71.43	10.97	-11.11
Heavy Snow	0	0.4	1.3	0	0.3	0.9	0	-33.33	-44.44	0	0	-28.89

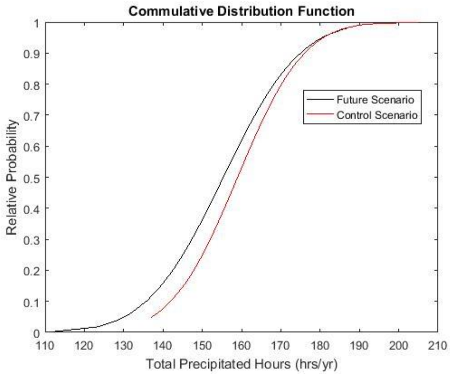
Table 4.4: The weather condition probabilities for Medium Emissions scenario

Table 4.4 was drawn from figure 4.6, from the table the precipitation hours percentage differences were like the high emission scenario because the summer period experienced drier conditions during the future scenario when compared to the control scenario. More heavy rainfall hours were also experienced, the winter period appeared to be wetter during the future scenario compared to the control scenario and the frequency of heavy rainfall was a bit higher. But due to higher temperature rises for the high emission scenario, the impact on the medium emission scenario was a bit lower compared to the high emission scenario hence lower precipitated hour percentage differences between the control and future scenario were experienced in the medium emission scenario. This can be observed when the future vs control columns for both scenarios are compared as shown in the last 3 columns to the right of table 4.10.

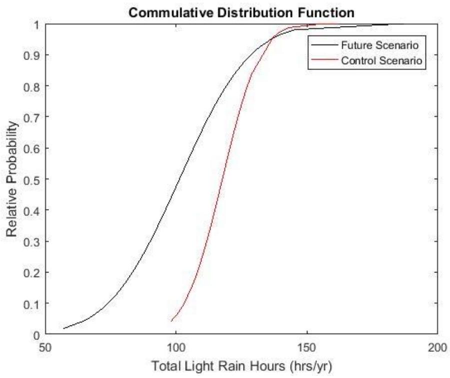
Figure 4.7 contains cumulative distribution function (CDF) curves showing the probability of experiencing precipitated conditions for each season under the low emissions scenario.



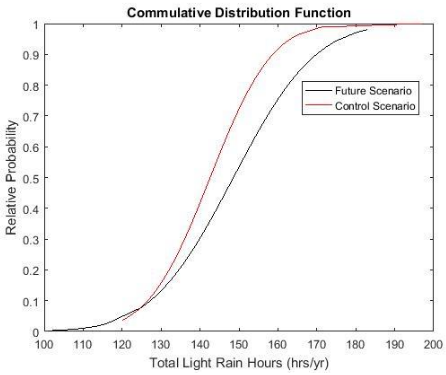
a. The probability of experiencing precipitated hours for the summer period



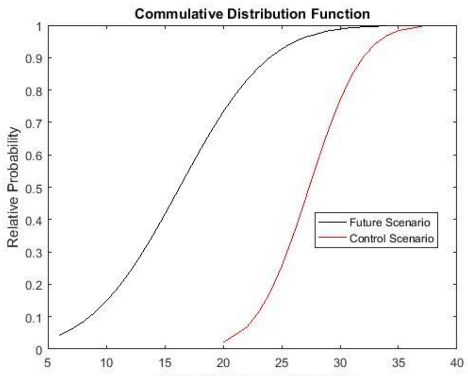
b. The probability of experiencing precipitated hours for the winter period



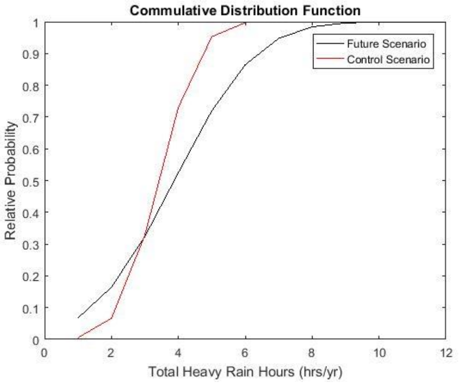
c. The probability of experiencing Light rain hours for the summer period



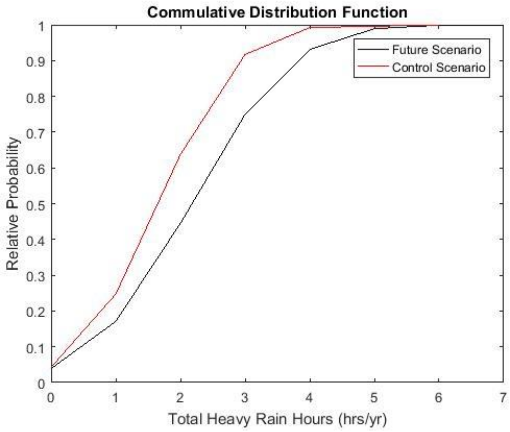
d. The probability of experiencing Light rain hours for the winter period



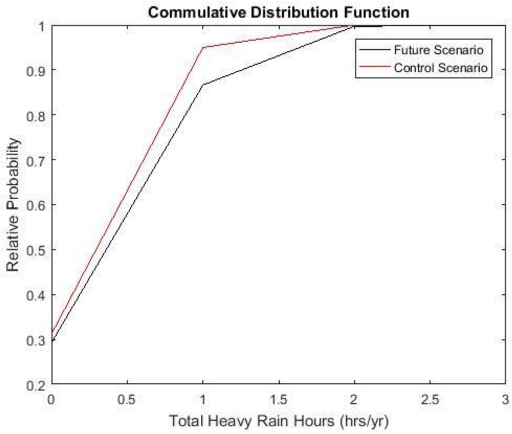
e. The probability of experiencing Light Snow hours for the winter period



f. The probability of experiencing Heavy Rain hours for the Summer period



g. The probability of experiencing Heavy Rain hours for the Winter period



h. The probability of experiencing Heavy Snow hours for the Winter period

Figure 4.7: The probability of experiencing the various precipitations conditions for each season of the low emissions scenario

	Percentile						Difference (%)					
	Control			Future			Future vs Control			Low emissions VS Medium emissions		
	10%	50%	90%	10%	50%	90%	10%	50%	90%	10%	50%	90%
Summer												
All Precipitation	105	119	133	79	101	123	-32.91	-17.82	-8.13	2.05	0.99	3.25
Light Rain	103	118	134	74	101	129	-39.19	-16.83	-3.88	8.33	0.99	-1

Light Snow	0	0	0	0	0	0	0	0	0	0	0	0
Heavy Rain	1.2	3.4	4.9	1.4	3.9	6.7	-57.14	12.82	26.87	-12.09	-18.7	-17.94
Heavy Snow	0	0	0	0	0	0	0	0	0	0	0	0
Winter												
All Precipitation	145	158	172	145	161	178	0	1.68	3.37	2.08	0.77	0.46
Light Rain	128	143	159	129	149	170	0.78	4.03	6.47	7.98	5.52	4.2
Light Snow	23	27	32	9	16	24	-155.56	-68.75	-33.33	-87.3	-11.25	-5.8
Heavy Rain	2.2	3.2	4.9	1.2	3.9	6.4	-83.33	17.95	23.44	83.33	5.86	9.89
Heavy Snow	0	0.3	0.8	0	0.4	1.3	0	25	38.46	0	-58.33	-82.9

Table 4.5: The weather condition probabilities for Low Emissions scenario

Table 4.5 was deduced from figure 4.7 and it can be observed from the last 3 columns on the right-hand side that the low emissions scenario showed similar characteristics to the high and medium emissions scenario, the precipitation hours differences between the control and future scenarios were smaller compared to the medium and high emissions scenario due to lower temperature rise. This meant that the lower the emissions level the lower the precipitation hours differences between the control and future scenarios hence lower changes in the climatic conditions.

4.4. Summary and Conclusion

The UKCP09 weather generator has been deemed to have an issue with spatial correlation (Baker, 2013) which occurred when multiple adjacent square grids were highlighted when using the WG. Weather for each square grid were not presented instead the average weather for the entire highlighted square grids were presented which may not represent a realistic weather projection of the individual grid squares since it did not account for the weather differences between high level areas and low-level areas. This issue was addressed with various methods (such as *complimenting future weather data with historic data and extrapolating weather based on land altitude*) proposed to compensate for the issue.

The UKCP09 weather generator was successfully used to generate weather data for the three emission scenarios. Generally, each emission scenario appeared to have certain degrees of impact on the future climate with high emission having the most impact. Reductions in summer precipitated hours and rises in winter precipitated hours for the future scenarios indicated that the weather data was consistent with the general projection of future dryer summers months and wetter winters months which was later reinforced by the result of examining heavy precipitation only which indicated rises in extremely precipitated hours with potential rises in extremely high temperature for summer hours if observed.

In this chapter the weather generator, its output weather data, its limitations as well as proposed methods to complement its limitations were discussed. Although none of the methods proposed to compensate for the issue of spatial coherency was featured during the impact projection since the link length used was only 1km long, longer road stretches could feature these methods or their variations because the limitation becomes more significant when larger areas are considered. The weather outputs of each emissions scenario were later fed as inputs into the Integrated Weather Impact Simulator (discussed in the next chapter). Since this thesis is mainly focused on the impact of precipitation on traffic flux, during the IWIS simulation only the precipitation and temperature levels for each hour were considered and they were combined to determine the precipitation level and type (rainfall or snowfall) for each hour.

Chapter 5 –Methodology: The Integrated Weather Impact Simulator (IWIS)

5.1. Introduction

In chapter 3 the design and implementation of the traffic flow model and its outputs which were mainly the traffic flow rates, mean speed and density under free flow, capacity and saturated traffic states were discussed while chapter 4 discussed the weather generator and its output weather data. In this chapter the design and implementation of the Integrated Weather Impact Simulator (IWIS) will be discussed. The IWIS was a model designed due to the simulation speed limitation of the traffic flow model and it was used to integrate the traffic data, weather data and user inputs to make weather impact projections of traffic streams. The user inputs were options available to the user which included the number of lanes, traffic type, vehicle type (fleet), traffic condition and the emissions level to be simulated.

The output data from the UKCP09 weather generator was made up of 100 baseline scenarios and 100 future projected scenarios each in comma-separated values (CSV) format and each made up of up to 30 years with 1-hour intervals. The aspects of the weather data that were extracted were the hours as well as the temperature and precipitation level of each hour. The weather data was discussed in chapter 4.

The traffic flow simulator designed for this research was capable of processing 1 hour of traffic flow within 30 minutes, comparing its performance to the output of the UKCP09 revealed that it would take approximately 43,800 hours to process a single scenario (i.e. 1,460 hours per year) assuming only the peak periods of each day were taken into consideration. It was then decided that the traffic flow model and the UKCP09 data would have to be integrated in such a simplified way that the time overhead would be significantly reduced. The designed traffic flow simulator was discussed in chapter 3.

Simulations were carried out at various densities and it was discovered that the traffic flux of a given traffic stream under a given density remained at approximately the same rate during the stable state of the flow (a state where the vehicles input to the link was equivalent to the vehicles output) and multiple iterations of the simulation showed similar rates. An assumption was therefore made that for a given traffic condition/weather condition combination, simulations ran within the stable state of the flow would exhibit similar output data for every iteration. Therefore, instead of running the integrated weather impact simulator (IWIS) continuously through the peak hours of the entire 30 years period for each scenario, sample simulations under various traffic and weather conditions combinations and various densities were ran with their output data saved after each run. The preliminary simulations were done as one-offs and their output data were saved as part of the simulator's package.

5.2. The Integrated Weather Impact Simulator Components

The simulator was divided into three main parts:

- The Inputs
- The processes
- The outputs

The Inputs: The inputs were the information passed on to the system for processing. They included:

- The Output data from the UKCP09 weather generator
- The Output data from the traffic simulator and
- The User inputs

The processes: The processes were the various actions the IWIS took based on the inputs. The processes include peak hour filtration, traffic condition selection, weather transition, flux assignment etc.

The output: The outputs were basically the results of the simulation after the simulator acted on the input variables. The outputs were mainly the curves generated at the end of each simulation. They included the various output curves pertaining to the impact of weather conditions on traffic flux.

Figure 5.1 shows an overview of the integrated weather impact simulation

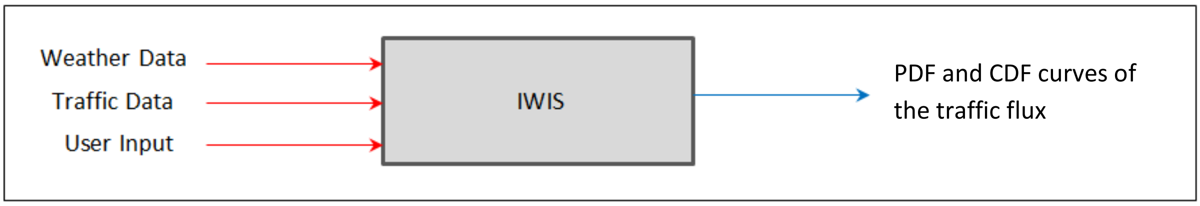


Figure 5.1: An overview of the integrated weather impact simulator

5.2.1. The Inputs

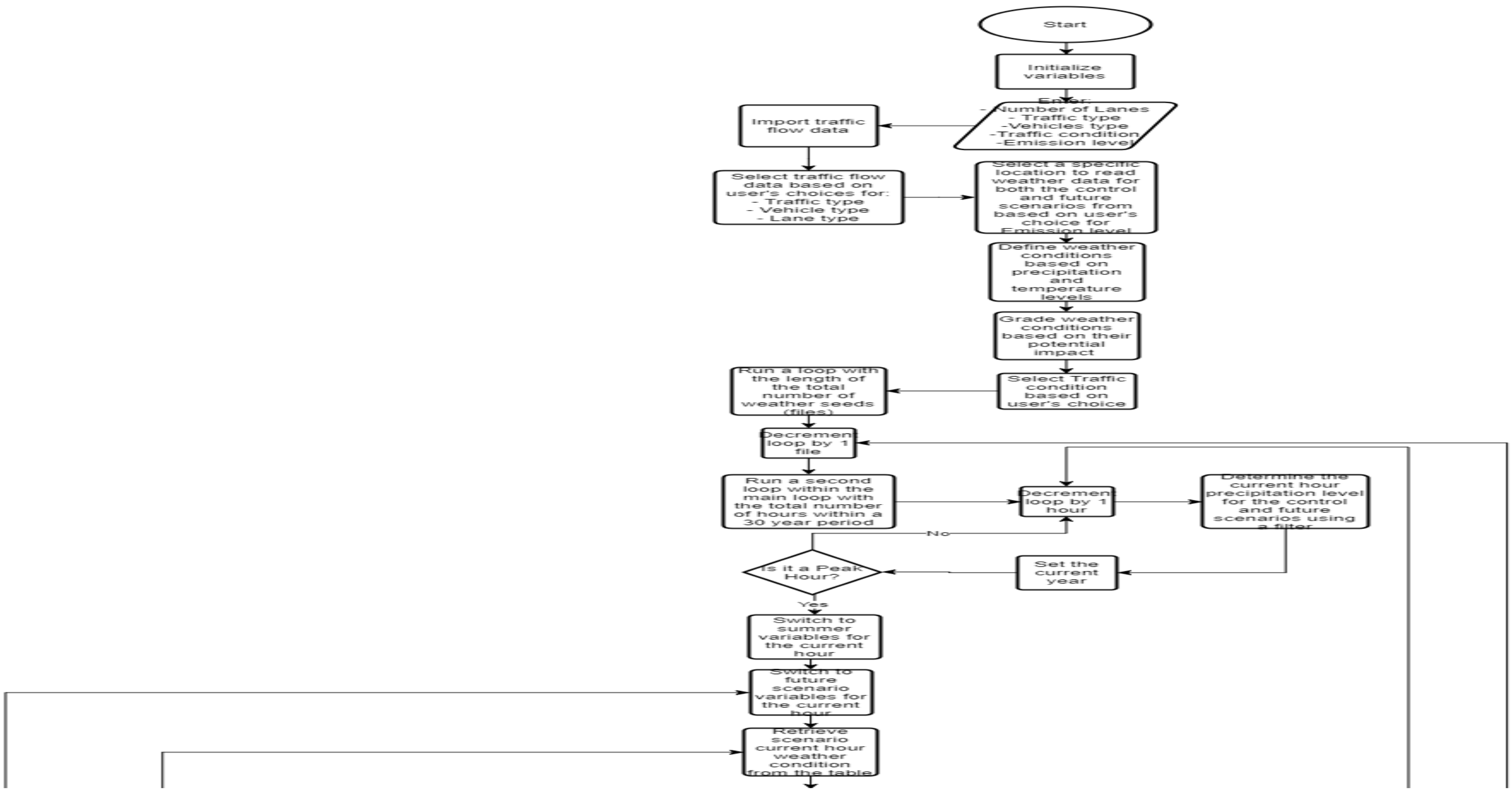

Start
Initialize variables
Enter:
- Number of Lanes
- Traffic type
-Vehicles type
-Traffic condition
-Emission level
Import traffic flow data
Select traffic flow data based on user's choices for:
- Traffic type
- Vehicle type
- Lane type
Select a specific location to read weather data for both the control and future scenarios from based on user's choice for Emission level
Define weather conditions based on precipitation and temperature levels
Grade weather conditions based on their potential impact
Select Traffic condition based on user's choice
Run a loop with the length of the total number of weather seeds (files)
Decrement loop by 1 file
Run a second loop within the main loop with the total number of hours within a 30 year period
Decrement loop by 1 hour
Determine the current hour precipitation level for the control and future scenarios using a filter
Set the current year
Is it a Peak Hour?
No
Yes
Switch to summer variables for the current hour
Switch to future scenario variables for the current hour
Retrieve scenario current hour weather condition from the table

Figure 5.2: The Integrated Weather impact simulator flow chart

Figure 5.2 above shows the flow chart of the IWIS. The simulator was split into 3 main stages:

- The initialisation stage
- The impact simulation stage
- The Analysis stage

5.2.1.1. The Initialisation stage

On the flow chart the initialisation process begins from ‘initialise variables’ to ‘select traffic condition based on user’s choice’.

5.2.1.1.1. Initialise variables

This stage generally assigned initial values to the variables to be used so that the compiler knew their initial values before the execution began. This is shown in appendix 4. The sizes of arrays as well as their initial contents were defined.

The User Inputs (Options)

The user options included:

- Number of lanes
- Traffic type
- Vehicle type
- Traffic condition
- Emission level

The IWIS had a menu of functions which the user could select depending on the required traffic condition to be simulated. Table 5.1 shows the various functions available which includes up to four lanes, traffic light at the end of the link or very slow traffic at the end (congestion), uniform vehicle type which could be either cars or HGVs and traffic condition which could be maximum (optimum) or minimum (worst) possible flux. When the user selected an emission level, the corresponding weather data set obtained from the UKCP09 weather generator for the selected emission level was used.

Functions	Options		
Lanes	1-4		
Traffic Type	Traffic light	Congested end	
Vehicle type	Uniform (Cars or HGVs)	Mixed	
Traffic condition	Optimum	Worst	
Emission level	High	Medium	Low

Table 5.1: The weather impact simulator menu

Depending on the user’s selection from the menu a matching data set like table 5.1 was selected, if optimum traffic condition was selected the maximum traffic flux for each weather condition was used as opposed to the minimum traffic flux being used for worst traffic condition. The User’s various options in code are shown in appendix 4.

5.2.1.1.2. Import traffic flow data

As mentioned in paragraph 4 of section 5.1, preliminary traffic flow simulations were ran as one-offs and their output data were saved as part of the simulator's package, this greatly reduced the IWIS simulation time.

Doing so meant the traffic flow data had to be automatically imported during each simulation run of the IWIS. The traffic flow data was saved in comma-separated values (CSV) format hence the MATLAB specific MATLAB functions were used to import the files. A portion of the written code for the importation of the traffic flow data is shown in appendix 4.

The files were imported using a MATLAB function called csvread and saved to arrays. Specific identifiers were selected using a specific format when saving each data after each preliminary simulation. The format for the identifiers is as follows:

- Each identifier had *'WE'* for easy sorting
- Traffic Type (*'Conj'* or *'Traffic'*)
- Vehicle Combination (*'Uni'* or *'Mixed'*)
- Vehicle Type ('*Small'* or *'Large'*)
- Number of lanes (*'Single'* or *'Multi'*)

Table 5.2 shows a portion of the output data of mixed vehicles, single lane, and congested traffic simulation. The first 5 rows show the output data of dry weather condition, rows 6-12 shows the output data for light rain, rows 13-19 shows the output data for heavy rain and the rest shows heavy snow condition. The 2nd row of each weather condition represents its average journey time (s), the 3rd row represents its average speed (km/h) while the eight row represents the traffic flux (vehicle/hr). The fourth row from the top shows the various densities, each column represents a density level. It should be noted that table 5.2 is a portion of the actual data content and the actual data contained more density levels and all the weather conditions corresponding traffic parameters.

13.8500	26.8680	39.0420	50.3620	58.2550	63.0840	63.7790	70.8670
72.2020	74.4390	76.8400	79.4250	85.8300	95.1110	109.7500	112.8900
49.8600	48.3620	46.8500	45.3280	41.9440	37.8500	32.8010	31.8900
4	8	12	16	20	24	28	32
199.4400	386.9000	562.2000	725.2400	838.8700	908.4100	918.4200	1.0205e+03
13.4840	26.4850	38.4090	49.1050	57.2090	62.4390	63.2390	70.4130
73.2050	74.5060	77.7610	80.7590	87.2870	97.4270	110.4500	114.7600
47.4380	46.6300	44.0170	43.5930	39.6390	35.8950	30.5630	30.9320
2.6394	1.4221	1.6211	2.4959	1.7954	1.0224	0.8467	0.6404
1.3896	0.0898	1.1987	1.6800	1.6979	2.4351	0.6366	1.6608
0.8235	0.6856	2.2664	1.6971	1.4332	2.3942	0.7515	1.5772
189.7500	373.0400	528.2100	697.4800	792.7800	861.4700	855.7600	989.8300
12.9340	25.3430	36.2930	46.7560	53.9100	59.8800	60.3940	65.3690
76.6660	77.5260	80.6480	84.1980	90.9300	99.8360	114.1000	117.3300
46.2150	45.8830	44.4550	42.6630	38.0430	34.7220	29.2690	28.8880
6.6171	5.6742	7.0425	7.1611	7.4585	5.0785	5.3080	7.7587
6.1818	4.1463	4.9558	6.0094	5.9421	4.9678	3.9556	3.9373
4.8119	2.2629	3.2982	2.9520	2.9093	4.5121	3.7367	4.1809
184.8600	367.0700	533.4600	682.6100	760.8600	833.3400	819.5200	924.4300

Table 5.2: A sample output data of a preliminary simulation

When the IWIS was ran the output data of a given conditions combination (i.e. weather condition and traffic condition) was then substituted whenever a similar condition combination was met. After the one-off preliminary stage of running each condition combinations, it was revealed that the time overhead for each scenario simulation was less than 10 minutes.

5.2.1.1.3. Traffic flow data selection

Filters were used to select the required traffic flow data depending on the user's traffic mode selections. A selection was made from the various arrays holding the imported data which was then saved into a different array for further processing. A section of the filter's code is shown in appendix 4. The code shows the filer selected the required data based on the traffic type, vehicle combination type and lane type.

5.2.1.1.4. Importing the Weather Data

The weather data for the various emission levels for both the control and future scenarios were saved in different folders and the compiler needed to read data from the required folder when necessary.

The first step towards achieving this was to select the address of the required folder based on the user's choice. The next step was to save the names of all the CSV files as a vector; the third step was to extract the file names. The final step occurred inside the main loop where the full file name and partial name of each file was created, and the required CSV file was read when the loop called its corresponding number as located in the vector. This was done for both the control and future scenarios and is shown in appendix 4.

5.2.1.1.5. Classifying the weather conditions

The precipitation classification method featured was based on the MET office classification method. This method used colour bands to represent precipitation levels and blue representing minimum precipitation (0.01-0.5mm/hr) and grey representing maximum precipitation (>32mm/hr), yellow band was used to represent moderate precipitation (2-4mm/hr) (Met Office, 2017). Bands between the minimum level band and the moderate level band were assumed to be light precipitation bands while bands between the moderate level band and the maximum level band were assumed to be heavy precipitation bands. During traffic analysis precipitation is often grouped into light and heavy precipitation levels with moderate precipitation level split between both groups (e.g. HCM) this made validating any traffic flow under moderate weather conditions difficult hence the moderate precipitation level band was split into halves with precipitation equals or less than 2mm/hr considered light precipitation while greater than 2mm/hr considered heavy precipitation.

Temperature levels were used to distinguish between snowfall and rainfall, an assumption was made that precipitation at temperatures equals or less than 0 degrees Celsius was snow while those over zero degrees Celsius was rain as shown on table 5.3. The justification for this assumption is shown in section 4.3.2.1.

Classification	Precipitation range (mm/hr)	Temperature range (° C)
Dry	0	N/A
Light Rain	> 0 < 2	> 0
Light Snow	> 0 < 2	< 0
Heavy Rain	> 2	> 0
Heavy Snow	> 2	< 0

Table 5.3: Precipitation classification

The adjusted weather classification deducted by comparing data from Agarwal et al (2005) to table 5.3 is shown in table 5.4. This output was explained in chapter 3.

Weather Variable	Intensity (mm/hour)	Intensity (inch/hour)	Our adjusted classification
Rain	0	0	Dry
	0-0.254	0-0.01	Light rain
	0.254-6.35	0.01-0.25	Light rain
	>6.35	>0.25	Heavy rain
Snow	0	0	Dry
	<=1.27	<=0.05	Light snow
	1.524-2.54	0.06-0.1	Light snow
	2.794-12.7	0.11-0.5	Light snow
	>12.7	>0.5	Heavy snow

Table 5.4: Adjusted weather classification

The section of the code that shows how the weather condition definition and grading were done is shown in appendix 4.

5.2.1.1.6. Traffic condition selection

The traffic condition was selected based on the user's choice, the two options available were optimum (capacity) and worst (saturated). With the capacity traffic condition selected the compiler chose the maximum possible flux from the traffic data being used while with the saturated traffic condition selected the minimum possible flux from the traffic data being used was selected. The code showing how the traffic condition was selected based on the user's choice is shown in appendix 4.

5.2.2. The Processes

5.2.2.1. Initialise the first loop (main loop)

The first loop was the main loop of the simulation, scenario files were sequentially selected under this loop and since it contained the second loop most processes apart from majority of the analysis section ran under this loop.

The loop was set to have a minimum value of 1, a maximum value of the total scenario files (i.e. 100) and to increase its values in steps of 1 for all iterations. This is shown in appendix 4.

5.2.2.2. Initialise the second loop (secondary loop)

The second loop ran through the file selected by the first loop, it ran through each row of the file hence had a minimum value of 1 and a maximum value of the width of each file which was equivalent to the total number of hours in a 30yr period (262968 hours). The loop value represented the current hour of the file. This is shown in appendix 4. Most of the processes such as determining the precipitation level of the current hour for both scenarios from the weather data were done within the second loop.

5.2.2.2.1. The Processes within the second loop

5.2.2.2.1.1. The current hour weather condition

As the second loop ran through the hours of the selected files (control and scenario) sequentially, the weather condition of the file's current hour was selected based on its precipitation and temperature levels, this was explained in paragraph 2 of section 5.2.1.1.5.

5.2.2.2.1.2. Summer and Winter months filters

Since the summer and winter months were filtered from the other months as they were the focus of the research. Winter months were defined as January, February and March while the summer months were defined as June, July and August. This is shown in code in appendix 4.

5.2.2.2.1.3. Peak hours filter

After the weather condition of the *current hour* was determined a check was then used to determine if the hour was a *peak hour*, peak hours were chosen as hours between 7am to 10am and 3pm to 6pm. The weather data was passed through a filter shown in appendix 4 and whenever the conditions for peak period was true the weather condition of the *current hour* was then selected for further processing. The *weather condition* was then passed through a series of filters to determine the actual weather condition based on *the weather transition table*.

5.2.2.2.1.4. Weather transitions and flux assignments

To model a somewhat realistic transition from one weather condition to another, pavement drainage characteristics were assumed in the model. This was done to ensure that rather than an abrupt transition from a higher inclement weather condition to a lower one there was a time delay during the transition which represented the drying period during the change.

The model was designed to allow a minimum transition time to elapse before a higher inclement weather condition could be replaced by a lower one. For example, a 12 hour transition time was assigned to heavy snow condition; this condition may be switched to a different condition except dry condition after 10 hours had elapsed. Each inclement condition was designed to switch to light rain condition within the final 2hrs of their transition time and it is during this final 2hrs period that the weather condition may switch to a lower weather condition. It was designed that if the weather condition for the next hour is a higher inclement weather condition it may replace the lower one the next hour regardless of the current state of the transition time of the lower condition. The transition time of a given inclement weather condition was designed to reset at the next hour if it gets featured again at any time during its transition time count down. Table 5.5 shows examples of various weather transitions.

Current weather	Max transition time (Hrs)	Transition time left (Hrs)	Next hour weather from UKCP09	Determined next hour weather
Heavy Snow	12	7	Heavy Rain	Heavy Snow
Heavy Snow	12	2	Heavy Rain	Heavy Rain
Heavy Rain	8	8	Heavy Snow	Heavy Snow
Heavy Rain	8	2	Dry	Light Rain
Light Snow	6	4	Light Rain	Light Snow
Light Rain	4	2	Dry	Light Rain
Light Rain	4	1	Dry	Dry

Table 5.5: Various weather transitions

After the *actual weather condition* was selected the current flux was then selected based on the weather condition. For example, heavy rain was assigned heavy rain flux from the traffic flow data.

The weather transition and flux assignment code are shown in appendix 4.

5.2.3. The Outputs

5.2.3.1. Data collection and analysis

5.2.3.1.1. The Total precipitated hours

The total precipitated hours for the summer and winter months of each year were considered and this was done for each precipitated weather condition. The required data were filtered from the weather data using filters. A filter was used to separate the summer and winter months from the other months as explained earlier while a second filter was used to determine the number of hours experienced a given precipitation level. The code showing how this stage was performed is shown in appendix 4.

5.2.3.1.2. Calculating the average fluxes

Individual year total fluxes for each season of each scenario (control and future scenarios) were collected. This was done by integrating the determined flux for each hour of the given season of the year being processed; the results were then saved in various arrays. This was repeated for both scenarios. This is shown in the equation 5.1.

$$TF = TF + CF \qquad [5.1]$$

Where TF represents the total traffic flux for any scenario season of a given year (e.g. summer period of year one of the control scenario) and CF represents the current hour flux.

After a given year for both scenarios had been processed, the mean fluxes for both seasons were then taken. This was done by dividing the total flux of a given season by the total number of hours of the season. This is shown in equation 5.2. The code is shown in appendix 4.

The average flux (mean flux) was obtained because it showed the typical flow rate for the given season and the flow rate of each hour of the season lie around the average value. The average value was therefore a good indicator of the flow rate for the season in general. The average flow rate indicates that there is some variability around this single value within the original data (University of Leicester, 2009). The difference between the average traffic flow rate for an ideal season (a season without precipitation although in reality this may be unlikely) and a given season would therefore be an indicator of the impact of precipitation on the flow rate of the season as explained later in section 5.2.3.1.4.2.

$$AF = \frac{TF}{TH} \qquad [5.2]$$

Where AF represents the average traffic flux for any scenario season of a given year and TH represents the total hour for any scenario season of a given year.

5.2.3.1.3. The Total peak hours of each season

Only the peak hours (i.e. 7am-10am and 3pm-6pm) for each season were processed and considered. This was done by using a filter on the weather data to select only the peak hours while other hours were omitted. The total peak hour was incremented only when the condition for peak hours was met. This is shown in appendix 4.

5.2.3.1.4. The simulation results

The simulation results were presented as both probability density functions (PDF) and cumulative distribution functions (CDF). Assuming a variable x, the CDF(x), would simply tell us the odds of measuring any value up to and including x while the PDF(x) magnitude would be some indication of the relative likelihood of measuring x. CDF takes into consideration the slope of the curve while PDF takes the area underneath the curve into consideration.

5.2.3.1.4.1. Traffic Flux data sorting

The first step towards plotting the PDF and CDF curves was to sort the data in ascending order. For each file (scenario) the years were sorted in ascending order based on their fluxes, the top 4 years with the most fluxes were selected for each file and the files were sorted in ascending order based on the fluxes of the selected years. A portion of a sorted data is shown in table 5.6. In the data the columns represent the years while the rows represent the files. The code used to execute this step is shown in appendix 4.

1.0053e+03	1.0078e+03	1.0087e+03	1.0088e+03
1.0066e+03	1.0080e+03	1.0087e+03	1.0095e+03
1.0069e+03	1.0084e+03	1.0088e+03	1.0095e+03
1.0069e+03	1.0085e+03	1.0093e+03	1.0096e+03
1.0070e+03	1.0086e+03	1.0093e+03	1.0097e+03
1.0071e+03	1.0086e+03	1.0093e+03	1.0098e+03
1.0075e+03	1.0086e+03	1.0093e+03	1.0098e+03
1.0075e+03	1.0086e+03	1.0095e+03	1.0099e+03

Table 5.6: A portion of a Flux data for each year of the scenario sorted in ascending order

5.2.3.1.4.2. The impact of weather on the average traffic fluxes

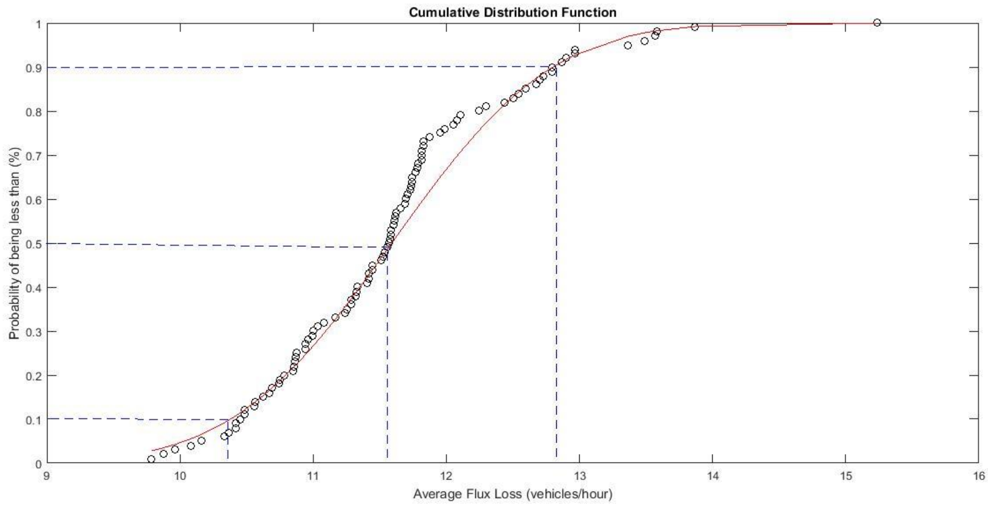
Since precipitation has a negative impact on traffic flux an ideal year was assumed to be a year without any precipitated hour, although in reality this may be unlikely. This meant that the average flux for an ideal year was the flux reserved for dry weather condition. The impact of weather on the traffic flux of a given year was then assumed to be the difference between the average flux of an ideal year and the average flux of the year. The table 5.7 shows a portion of a data sheet showing the impact of weather on the top 4 highest flux years of each scenario. The code is shown in appendix 4.

9.7842	9.3674	9.2093	9.0010
9.8785	9.4177	9.3258	9.0482
9.9619	9.5010	9.3589	9.0757
10.0844	9.5311	9.4091	9.1174
10.1592	9.5758	9.4508	9.2008
10.3345	9.5844	9.4839	9.2063

Table 5.7: The impact of weather on the traffic fluxes of various years

Figure 5.3 shows a CDF curve and the resulting normal CDF curve of the average lost flux of the lowest flux year of a congested single lane traffic operating at maximum capacity in a high emission scenario featuring only cars. From the curve it can be seen that 50% of the data is at or below approximately 11.57veh/hr which is consistent with the mean which is 11.57veh/hr. Theoretically if the data follows a normal distribution or something akin to it within 1 standard deviation from the mean (the STD of the data was 0.95 hence 0.95 to the right and 0.95 to the left) should lay approximately 70% of the data while ±2 STD should contain approximately 95% of the data. Figure 5.3 is in line with this general rule hence it could be said that the data is normally distributed. Since the data was normally distributed, the mean and the standard deviation were then used to construct normal distribution curves for the sample data as shown in figures 5.3. The generated flux data for each scenario were also all normally distributed around their mean hence normal probability distribution curves were used to simplify the data curves for the average lost flux data. The code used to generate the curves is shown in appendix 4.

(a)



(b)

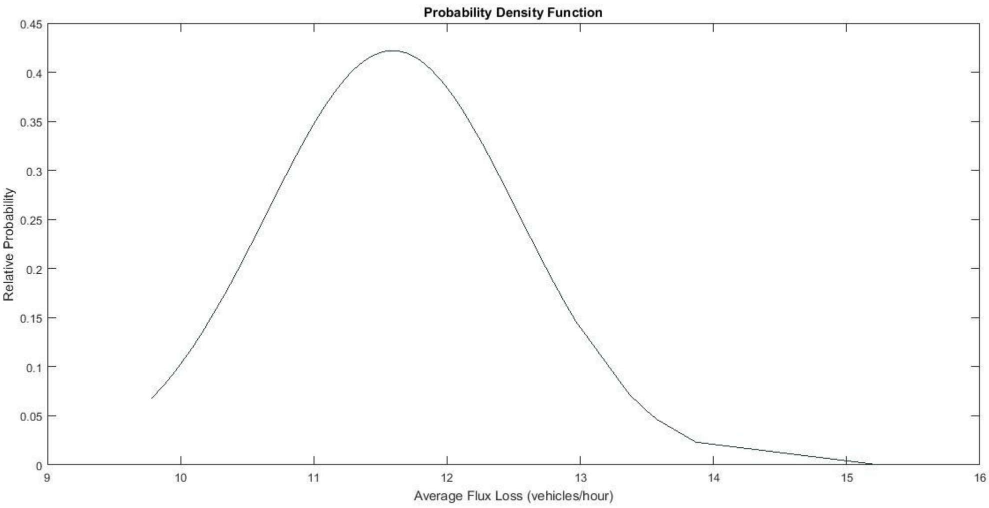


Figure 5.3: Graphs showing the cumulative distribution function (a) and probability density function (b) of a scenario average traffic flux loss

From the CDF the central estimate for the average flux loss is 11.57veh/hr, with a 10% probability of the loss being less than 10.4veh/hr and a 90% probability of less than 12.8veh/hr. It can also be said that there is a 10% probability of the average flux loss being more than 12.8veh/hr. This information would be useful when discussing the impact of climate change on traffic flux in chapter 6.

5.3. Summary and Conclusion

In this chapter discussed the design and implementation of the Integrated Weather Impact Simulator (IWIS). The IWIS was a model designed due to the simulation speed limitation of the traffic flow model and it was used to integrate the traffic data, weather data and user inputs to make weather impact projections of traffic streams. The user inputs were options available to the user which included the number of lanes, traffic type, vehicle type (fleet), traffic condition and the emissions level to be simulated. The IWIS was designed to filter the weather data for the peak hours of each day for simulation while excluding the other hours of the day this was because when considering road usage optimisation, investors and stakeholders are usually more concerned with the performance of roads during peak periods because they experience the most traffic fluxes during these hours.

The outputs of the IWIS were presented in Cumulative Distribution functions (CDF) and Probability Density functions (PDF). The CDF was used to determine the probability of measuring any value up to and including a given value (e.g. a given traffic flux) while the PDF magnitude would be some indication of the relative likelihood of measuring the given traffic flux.

The analysis of the output data of the IWIS will be used to investigate the impact of weather on traffic performance discussed in chapter 6. This investigation will cover various aspects such as the impact of the future projected weather conditions on traffic flow rate under the Conventional Development System of the UK (CDSU), possible changes to the CDSU, technological advancements as well as different geographical locations of the UK.

Chapter 6 – Methodology: The Effect of Weather on Traffic Performance

6.1. Introduction

In the previous chapter the Integrated Weather Impact Simulator (The IWIS) was discussed, where the method used to combine the weather data with the traffic flow data obtained from the various simulations was explained. The outputs of the IWIS were presented in Cumulative Distribution functions (CDF) and Probability Density functions (PDF). The analysis of the output data of the IWIS will be used to investigate the impact of weather on traffic performance. This investigation will cover various aspects such as the impact of the future projected weather conditions on traffic flow rate under the Conventional Development System of the UK (CDSU), possible changes to the CDSU, technological advancements as well as different geographical locations of the UK.

This chapter focuses on various socio-economic scenarios, the impact of technological advancement (autonomous vehicles) and the effect of geographical location on the traffic performance. It starts off by discussing the factors affecting the future of road transport which were grouped into independent and dependent factors, after which the region of interest which was an area between Winwick and Croft, Greater Manchester was discussed. The traffic stream was then discussed where two different link types both containing 3 lanes were discussed. The first link type was roundabout controlled while the second link type was signal controlled.

The socio-economic values may have an impact on the nature of vehicles featured in the traffic stream of a link with a more consumeristic nature featuring more privately-owned vehicles (i.e. small vehicles) while a more community driven nature featuring more public vehicles (i.e. large vehicles). The government nature may affect the emission level with a more interdependent government featuring a lower emission level than an autonomous government which may feature a high emission level.

The impact of the various emissions scenarios on both link types under the summer and winter seasons were then discussed under the conventional development system of the UK (the CDSU), a more consumeristic oriented scenario and a more community-oriented scenario. The CDSU favours more of consumerism than community meaning more private consumption than public consumption. This generally means that individuals will rather utilise their own private properties instead of public properties resulting in more private vehicles on the road network. It was indicated on DFT (2016) that as of 2014 the ratio of cars to HGVs on the UK road was 16:1. For a more consumeristic oriented scenario it was assumed that the ratio of cars to HGVs would be more in favour of the cars while for a community-oriented scenario it was assumed that the ratio would be less than the CDSU.

Various ratio values were tested to determine the sensitivity and combinations that reasonably impacted the traffic flow rate of the CDSU. The value of ±8 was eventually selected for the consumeristic and community-oriented scenarios because with this value the traffic fluxes of each scenarios showed reasonable disparities from each other due to its impact on the vehicle fleet combinations. This meant that a ratio of 24:1 and 8:1 were used for the consumeristic and community-oriented scenarios respectively.

For all the socio-economic scenarios it was found out that the future scenarios showed higher traffic flux compared to their control scenarios under each emissions scenario for both seasons. The higher the emissions level was the greater the difference was between the average traffic fluxes of both scenarios. Although the consumeristic socio-economic scenario showed the highest average traffic flux compared to the other scenarios, it also showed the most sensitivity to weather conditions due to higher vehicle density hence more drivers making decisions while the community oriented socio-economic scenario showed the least average traffic flux but with lower sensitivity to weather conditions due to lower vehicle density.

The impact of autonomous vehicles on the traffic flux in both seasons under the CDSU was then discussed. Three different percentages of the composition of autonomous vehicles on the traffic stream were investigated which were 33%, 67% and 100%. The presence of autonomous vehicles generally resulted in rises in the traffic flux and these rises increased with increasing percentage composition. The sensitivity of the traffic stream to weather conditions also dropped with increases in the number of autonomous vehicles in the stream.

The effect of geographical location on traffic performance was investigated. In terms of climatic conditions two distinct locations were investigated which were Northern Scotland and Southern England. It was found that geographical location is projected to impact future traffic performances and that the changes in precipitation and temperature levels observed between the control and future scenarios in the 2050s would most likely result in higher flux gain in the southern region during the summer period as a result of higher reductions in precipitation, higher increases in temperature and generally dryer conditions compared to the northern region while during the winter period the reverse would be the case.

6.1.1. The Factors affecting the future of road transportation

To project the shape of future (2050s) road transportation in the UK it is important to consider various factors that are likely to affect the outcome of the transportation system. These factors could be grouped into:

- Fundamental/Independent Factors
    - The Nature of Governance
    - The Social and Political Values
- Dependent Factors

- Economic growth
- Demographic growth
- Technological advancement

6.1.1.1. The Fundamental/Independent Factors

Using axes is a simplified way of having an insight into the relationship of the two dimensions of change as various possible scenarios could be explored by adjusting the proportion of contribution of each axis.

The horizontal axis captures two different socio-economic values which are consumerism where private consumption is primary and community where everyone works together for a common goal. The vertical axis captures two different government natures which are interdependent government which is geared towards unions and an autonomous government where decision making depends entirely on its own laws. Figure 6.1 shows four socio-economic scenarios, and a *conventional development system* for the UK. Factors affecting change were discussed extensively in chapter 2.

Figure 6.1: The UKCIP socio-economic scenarios (Jaroszweski, 2010)

6.1.1.2. The socio-economic scenarios

In this section the effect of switching the orientation of the economy in focus will be explored. The conventional development system for the UK (CDSU) as well as other possible development systems will be focused on.

6.1.1.2.1. The conventional development system for the UK (CDSU)

6.1.1.2.1.1. Socio-economic Values

In terms of socio-economic values, the current CDSU favours more of consumerism than community as shown on figure 6.1 which means private consumption and personal freedom are primary values. Generally, this means individuals would seek to utilise privately owned properties rather than public properties meaning more privately-owned vehicles are expected to be on the road. It was indicated on DFT (2016) that as of 2014 the ratio of cars to HGVs on the UK road was 16:1.

6.1.1.2.1.2. Government Nature

In terms of governance, the current CDSU is more interdependent than autonomous as shown in figure 6.1 and this is evident from the UK being a part of various unions such as the European Union (EU) which works towards sustainable growth of the region as well as being one of the countries in the Paris agreement which has a long-term goal of keeping the increase in global average temperature to well below 2 °C above pre-industrial levels; and aims to limit the increase to 1.5 °C which would result in significantly reducing risks and the impacts of climate change.

Modifications in the UK governance system may result in significant impacts on the environment. Currently the UK has voted to leave the EU, this decision may result in negative impacts on the environment if some of the EU regulations aimed at carbon emissions reduction within the region (such as EC (2010)) are not incorporated into the British law. The US recently pulled out of the Paris climate accord this impact may be exacerbated should the UK choose to also pull out in the future.

Balanced Government

This sort of governance may feature very rapid economic growth with new and more efficient technologies being rapidly introduced. The economy may strike a balance between fossil energy and non-fossil energy intensive. The government works fair closely with other country's government towards sustainable growth, may belong to fewer unions driven towards sustainability and strike a balance between efficiency and sustainability. The impact of a government of this nature on the environment would most likely be a medium emission level of greenhouse gases.

Interdependent Inclined Government

This sort of governance may feature rapid changes in the economic structures that drives towards an economy where service and information are dominant, the availability of materials are reduced, and efficient and clean resource technologies are introduced. The government works very closely with other country's government towards sustainable growth, may belong to more unions driven towards sustainability and they prioritise sustainability over efficiency. The impact of a government of this nature on the environment would most likely be a low emission level of greenhouse gases.

Autonomy Inclined Government

This sort of governance may be like a balanced government except fossil energy is the primary energy source and they prioritise efficiency over sustainability meaning that they prioritise short term economic gain (GDP and/or sales growth) over sustainability. This would most likely result in a high emission level of greenhouse gases in the environment. Efficiency over sustainability in this context means that they prioritise short term economic gain (GDP and/or sales growth) over sustainability.

6.1.1.3. The Impact of the Socio-economic scenarios on the traffic stream

As explained in the previous sections the socio-economic values may have an impact on the nature of vehicles featured in the traffic stream of a link with a more consumeristic nature featuring more privately-owned vehicles (i.e. cars) while a more community driven nature featuring more public vehicles (i.e. HGVs). The government nature may affect the emission level with a more interdependent government featuring a lower emission level than an autonomous government which may feature a high emission level.

6.1.2. Technological Advancement

6.1.2.1. Vehicle Platooning

Vehicle platooning involves the formation of platoons by two or more in-lane vehicles maintaining close headway which is facilitated using radar and vehicle-vehicle (V2V) communications that control their longitudinal and lateral movement. In order minimise the chances of collision and disruption of platoons, dedicated lanes for vehicles moving in platoons was suggested by Kavathekar (2012).

Factors affecting the inter-vehicle space setting controller of a following vehicle were explained in chapter 2. In this thesis only, the estimated braking ability of each vehicle (i.e. the weather condition and the brake condition) and the traffic conditions (i.e. speed of the traffic stream) were used to determine the headway between the lead and following vehicles in a platoon. Figure 2.9 in chapter 2 shows that autonomous vehicles are capable of significantly increasing the capacity of a link. Vehicle platooning was explained in detail in chapter 2.

6.1.3. The Region of interest (ROI)

The links used in this thesis were hypothetical 1km trunk roads containing 3 lanes with one link containing a signal-controlled link end while the other contained a roundabout controlled link end. The link ends types used in this thesis were selected to explore the most common junction types used in the UK (VisitBritain, 2012; Gov.UK, 2015).

The weather data for an area in Greater Manchester, North-West England was utilised. Greater Manchester experiences a temperate maritime climate, like most of the British Isles, with relatively cool summers and mild winters. The region's average annual rainfall is 806.6mm compared to the UK average of 1,125.0mm, and its mean rain days are 140.4mm per annum, compared to the UK average of 154.4mm which places it just below the average for the UK. The mean temperature is slightly above average for the United Kingdom. The Urban areas within the region do not often experience snowfall due to *urban warming* while areas outside the urban region which was where the hypothetical trunk roads were based tend to experience more snowfall and roads sometimes get closed due to heavy snowfall (Revolvy, 2016). This region was selected for the hypothetical trunk roads because it is of a very high economic importance hosting sections of the M6 such as J21A, the croft interchange which is one of the main traffic feeds for the M6 southbound and carries traffic from Liverpool the second largest city within 70miles of the M6 (Route6, 2012). It also hosts the Winwick link road which is a trunk road containing a large roundabout as its link end. The Winwick link road is the main approach to Warrington town centre from the north (Owens, 2003). Note that:

- the traffic demand for the selected region was not used during the simulation instead the simulation was carried out using various vehicle densities including free flow, capacity and saturated densities,
- The length of the hypothetical trunk roads were 1km,
- the link end conditions were roundabout and signalised link ends,
- The weather data generated was based on an area between Winwick and Croft outside the urban areas of Greater Manchester.

Figure 6.2 shows the region used for the weather data on a map which was between Winwick and Croft while figure 6.3 shows the location of Greater Manchester on the map of England.

Figure 6.2: The area used for the weather data

Figure 6.3: The location of Greater Manchester on the map of England

6.1.4. A summary of the Development System Scenarios to be investigated

Table 6.1 summarises the input parameters to the traffic simulator and weather generator for the various development scenarios to be investigated.

Development Scenario	Vehicle Type	Vehicle Ratio (cars: HGVs)	Ratio of Manual to autonomous	Location	Comments
1 The CDSU	Manual	16:1	N/A	An area between Winwick and Croft, Greater Manchester	This scenario features more cars compared to HGVs. It is the base development scenario and the results of simulating the other development scenarios will be compared to its results for contrast
1.1 The CDSU	Manual & autonomous	16:1	3:1	An area between Winwick and Croft, Greater Manchester	Including autonomous vehicles moving in platoons is expected to have a significant increase in the traffic flux due to better traffic parameters such as higher mean speed of the flow
1.2 The CDSU	Manual & autonomous	16:1	3:2	An area between Winwick and Croft, Greater Manchester	It is expected that more vehicles moving in platoons in the traffic stream would result in better traffic parameters including reductions in headway
1.3 The CDSU	Manual & autonomous	16:1	3:3	An area between Winwick and Croft, Greater Manchester	As explained in an earlier section autonomous vehicles produce better traffic parameters compared to human drivers hence a fully autonomous traffic stream is expected to produce the best traffic flux
1.4	Manual	16:1	N/A	Thurso, North Scotland and London, South England	Higher rises in temperature and precipitation loss in South England is expected to result in higher impact on traffic flux within the region compared to North Scotland
2 consumerism	Manual	24:1	N/A	An area between Winwick and Croft, Greater Manchester	This scenario features more cars compared to the CDSU. Generally, cars travel faster than HGVs and due to their smaller size, they produce higher density compared to HGVs therefore they're expected to produce higher traffic flux as a result since flux is the product of speed and density of the flow.
3 Community	Manual	8:1	N/A	An area between Winwick and Croft, Greater Manchester	This scenario features less cars compared to the CDSU and a negative impact on the traffic flux is expected due to reduced speed and density as a result of more HGVs in the traffic stream.

Table 6.1: Summary of the various development scenarios simulator's input parameters

6.1.5. The traffic streams

Two different link endings were featured at the end of the link; the first exhibited a roundabout where vehicles were expected to reduce their speed towards a given speed limit before exiting the link there by inducing traffic congestion towards the end of the link. For this link ending, the headway between vehicles was a major parameter in the traffic flux since during the stabled state of the traffic stream vehicles maintained headways from their lead vehicle that was dependent on the weather condition.

The second link ending was signalised where a traffic light periodically alternated between a Stop (red) and Go (green) signal and vehicles were periodically expected to stop and continue their journey towards the end of the link. With this link ending feature, the acceleration of each vehicle as well as the drivers' reaction time under the various weather conditions played a major role in the traffic flux. Quicker acceleration meant the start-up loss time was reduced when vehicles started accelerating on the Go signal.

Start-up lost time happens when a traffic signal changes from red to green. Some amount of time elapses between the signal changing from red to green and the first queued vehicle moving through the intersection. There is then an additional amount of time for the next vehicle to begin moving and pass through the intersection, and so on. The total time taken for all waiting drivers to react and accelerate is the start-up lost time.

6.2. Projecting the future impact of weather on the traffic stream under the conventional development system of the UK

The traffic flux of a traffic stream responds to the emission level of a given scenario. During summer periods higher emission levels where the weather appears to be drier would show higher traffic flux, this is because without taking other factors such as increased accident rate due to increased drivers' aggression lower precipitated hours show lower flux loss.

6.2.1. The Impact of the emissions scenarios on the traffic flow of a roundabout controlled link

If we considered a roundabout controlled 3 lanes link, as mentioned earlier the main drivers' parameter that would affect the traffic flux would be the headway parameter since during the stabled state of the traffic stream vehicles maintained headways from their lead vehicle that was dependent on the weather condition.

6.2.1.1. The Impact of the emissions scenarios on the average headway of a roundabout controlled link

The headways for each emissions scenario were obtained similarly to the traffic flux, the average headways for each weather condition were first obtained during the traffic flow simulation then they were integrated with the weather data using the IWIS which then generated the average headway for each year and then each emissions scenario. Table 6.2 shows the target headways of the drivers under each weather conditions which were derived in chapter 3, while table 6.3 shows the average headways of the traffic stream under each weather condition obtained after the simulations.

Weather Condition	Headway (s)
Normal (Dry)	1.5
Light Rain	2
Light Snow	2
Heavy Rain	2.5
Heavy Snow	3
Traffic Jam all conditions	0.5

Table 6.2: The target headways of drivers under each weather conditions

Weather Condition	Average Headway
Dry	1.65
Light Rain	1.79
Light Snow	1.84
Heavy Rain	2.32
Heavy Snow	2.55

Table 6.3: The average headways of the traffic stream under each weather condition

Table 6.4 shows a comparison between the average headway of both scenarios for each of the emissions scenarios during the summer period when the link was at capacity and under the CDSU. The link being at capacity basically meant the link was at its optimal traffic flux.

	Control Scenario			Future Scenario			Headway Differences		
	10%	50%	90%	10%	50%	90%	10%	50%	90%
High	1.76	1.85	1.91	1.67	1.74	1.82	0.09	0.11	0.09
Medium	1.77	1.87	1.94	1.71	1.78	1.89	0.06	0.09	0.05
Low	1.79	1.9	1.98	1.76	1.88	1.97	0.03	0.02	0.01

Table 6.4: The average headways for the various emission scenarios for a roundabout controlled 3 lanes link during the summer periods under the CDSU

Table 6.4 shows that the weather conditions resulting from the emissions scenarios did have an impact on the average headway on the link with the headway reducing with increasing emission level during the summer periods. It shows where 10% 50% and 90% of the average headway for both scenarios of each emissions scenario fall.

The high emission level showed the highest differences in the average headway between both scenarios with the future scenarios showing lower average headways compared to the control scenarios. Table 6.5 summarises the average headway reductions for each emissions scenario.

	Average Headway Reductions (%)		
Percentile	Low	Medium	High
10%	1.68	3.39	5.11
50%	1.05	4.81	5.95
90%	0.51	2.58	4.71

Table 6.5: The average headway reductions for each emission level for a roundabout controlled 3 lanes link during the summer periods under the CDSU.

Considering the same roundabout controlled 3 lanes link but in the winter periods where the weather appeared to get wetter with higher emission levels, table 6.6 shows the average headways of each emissions scenario under the CDSU.

	Control Scenario			Future Scenario			Headway Differences		
	10%	50%	90%	10%	50%	90%	10%	50%	90%
High	2.21	2.26	2.38	1.99	2.18	2.29	0.22	0.08	0.09
Medium	2.21	2.36	2.42	2.05	2.3	2.32	0.16	0.06	0.1
Low	2.19	2.24	2.4	2.01	2.16	2.24	0.19	0.08	0.16

Table 6.6: The average headways under the various emission levels for a roundabout controlled 3 lanes link during the winter periods under the CDSU.

Table 6.6 shows that during the winter periods the weather conditions resulting from emissions scenario did have a positive impact on the average headway on the link with the headway reducing as the emission level increased. It was expected that higher emissions level would result in higher headway differences between the control and future scenarios, but the low emissions scenario showed a higher difference compared to the other scenarios. The reason for this was discussed under a later section. Table 6.7 summarises the average headway raises for each emission level.

	Average Headway Raises (%)		
Percentile	Low	Medium	High
10%	8.68	7.24	9.96
50%	3.57	2.54	3.54
90%	6.67	4.13	3.78

Table 6.7: The average headway raises under each emissions scenario for a roundabout controlled 3 lanes link during the winter periods under the CDSU.

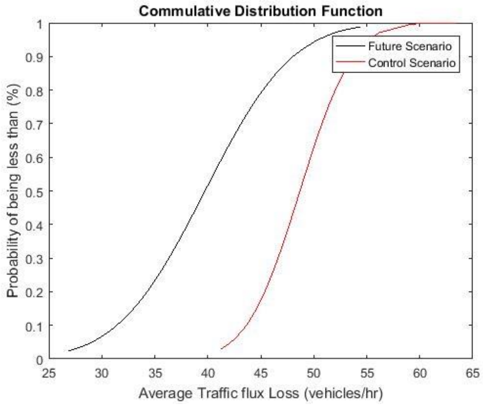
Generally, it was observed that the average headway reduced as the emission level was increased during the summer and winter periods. This was because the summer periods experienced drier weather conditions as the emission level was increased providing better driving conditions while during the winter period snowy conditions reduced for rainy conditions because of higher temperature and since rainy conditions provide better driving conditions the traffic flux was improved as a result.

6.2.1.2. The Impact of the emission levels on the traffic flux of a roundabout controlled link

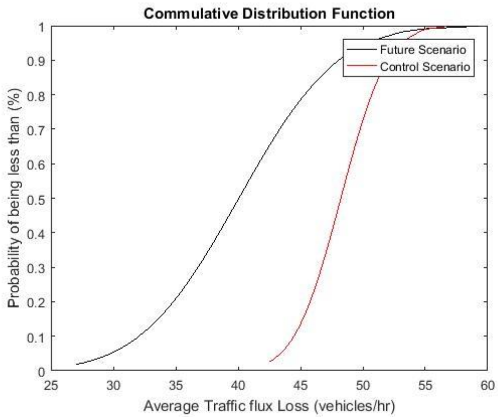
Since precipitation has a negative impact on traffic flux an ideal year was assumed to be a year without any precipitated hour. This meant that the average flux for an ideal year was the flux reserved for dry weather condition. The impact of weather on the traffic flux of a given year (or the flux loss for the year) was then assumed to be the difference between the average flux of an ideal year and the average flux of the year. This was further explained in chapter 5.

The headway played a key role in the traffic flux of the roundabout controlled traffic flow since when the traffic was saturated vehicles moved at steady speeds rather than having to rapidly accelerate or decelerate. Therefore, an impact on the average headway had a significant impact on the entire traffic flux.

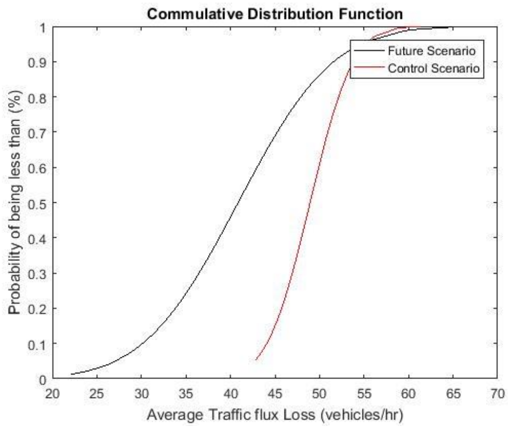
Considering the various emission level scenarios for a roundabout controlled traffic flow at capacity during the summer periods under the CDSU, figure 6.4 shows the CDF curves for its average traffic flux loss.



a. The CDF curve for the average traffic flux loss under the high emission scenarios



b. The CDF curve for the average traffic flux loss under the medium emission scenarios



c. The CDF curve for the average traffic flux loss under the low emission scenarios

Figure 6.4 CDF curves showing the average traffic loss under the various emission scenarios for a roundabout controlled 3 lanes link during the summer periods under the conventional development system for the UK.

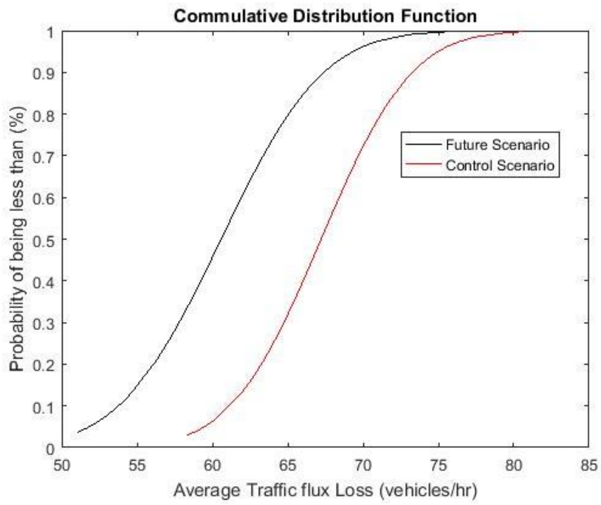
From the CDF curves shown in figure 6.4 the future scenarios for each emission level showed higher traffic flux this was because in each case the weather became drier in the future scenarios and the degree of dryness depended on the emission level with high emission level exhibiting more dry weather conditions and therefore lower traffic flux loss. Table 6.8 summarises the outputs made from figure 6.4.

	Control Scenarios			Future Scenarios			Percentile Differences			Percentile Differences (%)		
Percent	10%	50%	90%	10%	50%	90%	10%	50%	90%	10%	50%	90%
Summer												
High	43.74	48.68	54.04	31.16	39.77	48.13	-12.58	-8.92	-5.91	-28.76	-18.32	-10.93
Med	44.47	48.25	52.03	31.85	40.08	48	-12.63	-8.17	-4.03	-28.40	-16.93	-7.75
Low	43.98	49.02	53.62	30.38	40.73	52.03	-13.59	-8.29	-1.60	-30.90	-16.91	-2.98

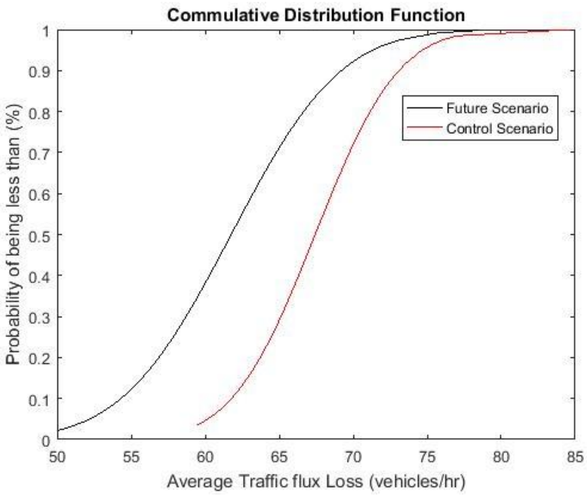
Table 6.8: Traffic flux loss probabilities under the various emission scenarios for a roundabout controlled 3 lanes link during the summer periods under the conventional development system for the UK.

From table 6.8 generally the future emissions scenarios showed lower flux loss compared to their control scenarios for each emissions scenario. Also, higher flux differences were experienced under the high emission scenarios which had traffic flux loss central probability projection of -18.32% compared to -16.93% and -16.91% for medium and low respectively.

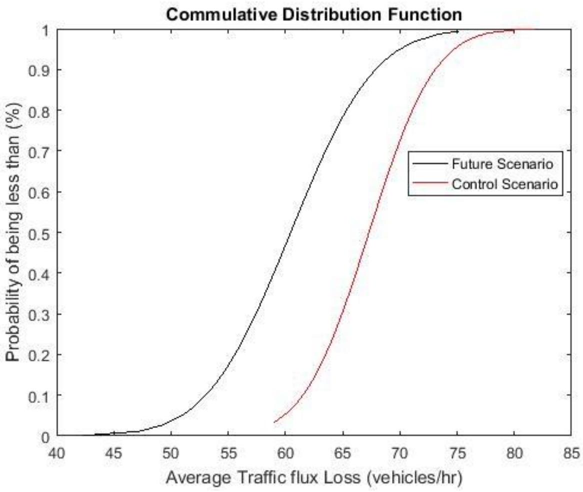
The CDF curves for the average traffic flux loss under the various emissions scenarios for the same link type during the winter periods under the CDSU is shown in figure 6.5.



a. The CDF curve for the average traffic flux loss under the high emission scenarios



b. The CDF curve for the average traffic flux loss under the medium emission scenarios



c. The CDF curve for the average traffic flux loss under the low emission scenarios

Figure 6.5 CDF curves showing the average traffic loss under the various emission scenarios for a roundabout controlled 3 lanes link during the winter periods under the conventional development system for the UK.

The CDF curves shown in figure 6.5 shows that the future scenario also showed higher traffic flux compared to the control scenario this was because rises in temperature resulted in wetter conditions instead of the colder temperatures featured in the control scenario which resulted in icy/snowy conditions and it is known that wetter conditions show less traffic flux drop compared to icy/snowy conditions. This rise in temperature is not necessarily ideal for road transport because rises in temperature result in more hours of heavy rainfall with increasing intensities which may result in flooding depending on the quality of the drainage systems which may result in entire roads closures. Table 6.9 summarises the outputs made from figure 6.5.

	Control Scenarios			Future Scenarios			Percentile Differences			Percentile Differences (%)		
Percent	10%	50%	90%	10%	50%	90%	10%	50%	90%	10%	50%	90%
Winter												
High	61.78	67.21	73.38	53.78	60.56	67.35	-8	-6.65	-6.03	-12.95	-9.89	-8.22
Med	61.67	67.43	73	54.27	61.76	69.24	-7.40	-5.67	-3.76	-12	-8.41	-5.15
Low	61.53	67.33	73.02	52.92	60.43	67.65	-8.60	-6.91	-5.37	-14	-10.26	-7.35

Table 6.9: Traffic flux loss probabilities under the various emission scenarios for a roundabout controlled 3 lanes link during the winter periods under the conventional development system for the UK.

From table 6.9 for all 3 emissions levels the future scenario showed lower traffic flux loss compared to the control scenario which was a similar characteristic to the summer period, but the low emissions scenario appeared to show higher flux differences between both scenarios (i.e. control and future scenario) compared to both the medium and high emissions scenarios. The reason for this can be observed in figures 4.5-4.7 and in tables 4.3-4.5 where the low emissions level showed lower number of heavy rainfall hours compared to both the medium and high emissions scenarios and the higher the emissions scenario the higher the number of heavy rainfall hours.

6.2.2. The Impact of the emission levels on the traffic flow of a signalised link

If we considered a signalised 3 lanes link, as mentioned earlier the main parameters affecting the traffic flux would be the driver's response time and the acceleration parameters. Quicker acceleration meant the start-up loss time was reduced when vehicles started accelerating on the Go signal. The total time taken for all waiting drivers to react and accelerate is the start-up lost time.

6.2.2.1. The Impact of the emission levels on the average acceleration and drivers' response time of a signalised link

The driver's response time and the acceleration parameters were obtained similarly to how the headway was obtained for the roundabout controlled link after which they were integrated with weather data using the IWIS which then generated the average acceleration and average drivers' response time for each year and then each emissions scenario. Table 6.10 below shows the average acceleration and drivers' response time for each weather condition. The response time for each weather condition used in the simulation were obtained from Copradar (2015).

Weather Condition	Average Acceleration (m/s^2)	Average Response time (s)
Dry	0.60	1.0
Light Rain	0.54	1.5
Light Snow	0.52	1.5
Heavy Rain	0.33	2.5
Heavy Snow	0.19	3.0

Table 6.10: The average acceleration and drivers' response for each weather condition

Table 6.11 below shows the average acceleration for each season of the emissions scenarios for their 10^{th}, 50^{th} and 90^{th} percentiles.

	Average Acceleration (m/s^2)					
	Control Scenario			Future Scenario		
Percentile	10%	50%	90%	10%	50%	90%
Summer						
High	0.50	0.52	0.55	0.55	0.57	0.58
Medium	0.52	0.54	0.55	0.55	0.56	0.57
Low	0.53	0.55	0.56	0.54	0.55	0.56
Winter						
High	0.42	0.49	0.51	0.47	0.52	0.54
Medium	0.47	0.51	0.52	0.49	0.52	0.55
Low	0.46	0.53	0.55	0.48	0.55	0.58

Table 6.11: The average acceleration for each season of the emissions scenarios

Table 6.11 shows that the weather conditions resulting from the emissions level did have an impact on the average acceleration on the link with the acceleration increasing with increasing emissions level during the summer periods due to drier conditions hence better traction. This was also the case during the winter period since warmer temperatures resulted in less snowy conditions and more rainy conditions as discussed in chapter 3 resulting in better traction. The table shows where 10%, 50% and 90% of the average acceleration for both scenarios of each emission level fall. It should be noted that the table should be read across rather than downwards. For example, for the high emissions scenario, the 10th percentile of the Control scenario should be compared to the 10th percentile of the future scenario.

From the table the high emission level showed the highest differences in the average acceleration between both scenarios while low emission was slightly higher than medium emission level; during both seasons the future scenarios showed higher acceleration compared to the control scenarios for all the emissions scenarios.

Table 6.12 summarises the average acceleration percentage differences for each emissions scenario. The positive values indicate rises in the average acceleration levels.

	Average Acceleration rises (%)		
Percentile	10%	50%	90%
Summer			
High	10	9.62	5.46
Medium	5.77	3.70	3.64
Low	1.89	0	0
Winter			
High	11.91	6.12	5.88
Medium	4.26	1.96	5.77
Low	4.35	3.77	5.46

Table 6.12: The average acceleration percentage differences for each emission level for a signalised 3 lanes link under the conventional development system for the UK

Table 6.13 below shows the average rivers’ response time for each season of the emissions scenarios for their 10th, 50th and 90th percentiles

	Average Drivers' response time (s)					
	Control Scenario			Future Scenario		
Percentile	10%	50%	90%	10%	50%	90%
Summer						
High	1.33	1.35	1.39	1.28	1.32	1.35
Medium	1.29	1.34	1.36	1.27	1.33	1.34
Low	1.27	1.35	1.36	1.27	1.34	1.35
Winter						
High	1.44	1.47	1.48	1.39	1.42	1.44
Medium	1.40	1.44	1.47	1.39	1.43	1.45
Low	1.42	1.46	1.48	1.40	1.45	1.47

Table 6.13: The average drivers' response time for each season of the emissions scenarios

Table 6.13 shows that the weather conditions resulting from the emissions scenarios did have an impact on the average drivers' response time on the link. The response time reduced with increasing emissions level during both seasons due to warmer conditions hence higher aggression as discussed in chapter 2.

From the table the high emission level showed the highest differences in the average drivers' response time between both scenarios; during both seasons the future scenarios showed lower response time compared to the control scenarios for all the emissions scenarios.

Table 6.14 summarises the average drivers' response time percentage differences for each emission level. Positive percentages indicate reductions in the average response times.

	Average Response time reductions (%)		
Percentile	10%	50%	90%
Summer			
High	3.76	2.22	2.88
Medium	1.55	0.75	1.47
Low	0	0.74	0.74
Winter			
High	3.47	3.40	2.70
Medium	0.71	0.69	1.36
Low	1.40	0.69	0.67

Table 6.14: The average drivers' response time percentage differences for each emissions scenario for a signalised 3 lanes link during under the conventional development system for the UK

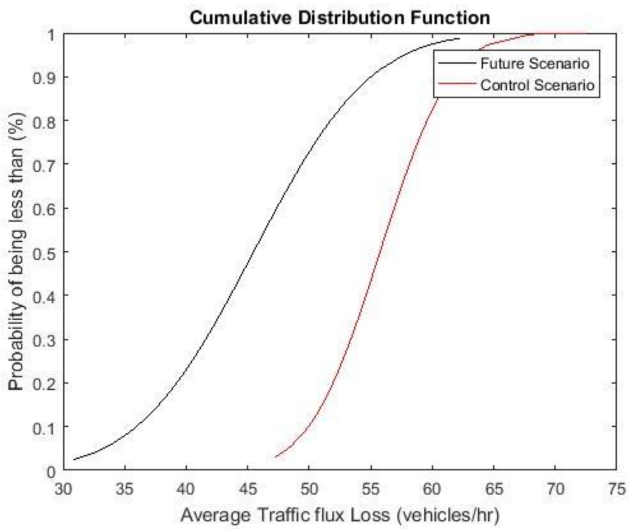
In summary, from the percentage differences between both scenarios (future and control scenarios) of the emissions scenarios, it was observed that the average acceleration increased as the emissions level was increased during the summer and winter periods. This was because rises in temperature resulted in drier conditions during the summer season and less snowy conditions and more wet conditions during the winter season hence better traction in both cases.

The drivers' response times also reacted positively to increased emissions level during both seasons due to increased aggression of the drivers because of higher temperatures.

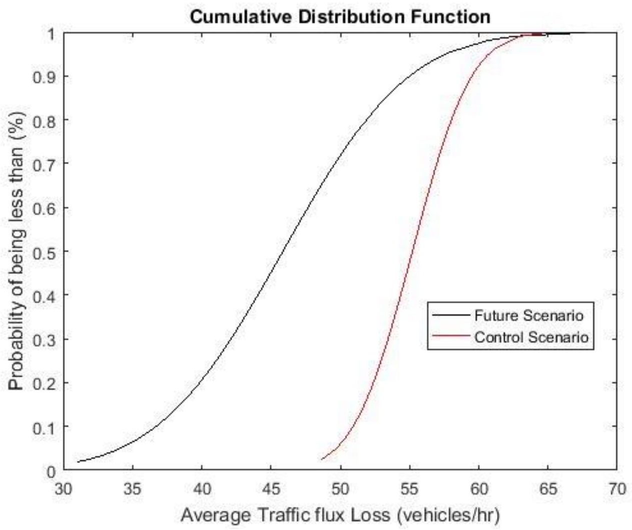
6.2.2.2. The Impact of the emissions levels on the traffic flux of a signalised link

The vehicles' accelerations and drivers' response time were important factors in the traffic flux of the signalised traffic flow because drivers had to stop and move their vehicles periodically based on the signal. The start-up loss time was explained in an earlier section; basically, quicker accelerations meant the start-up loss time was reduced when vehicles started accelerating on the Go signal. Also, quicker response times reduced the start-up loss time because drivers were able to recognise the change in the traffic state and start accelerating quicker.

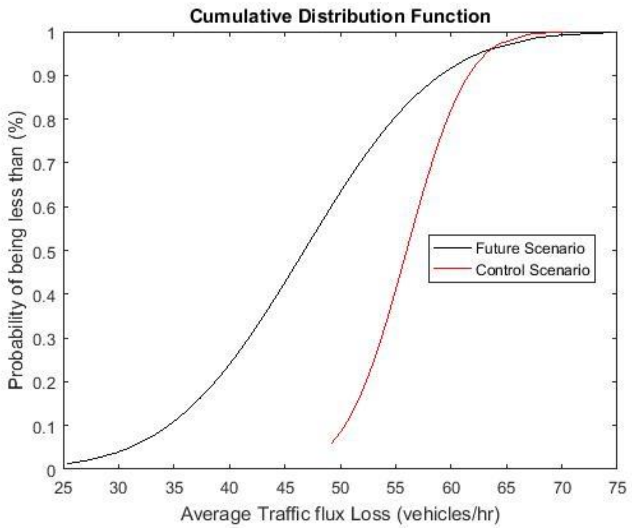
Considering the various emissions scenarios for a signalised traffic flow at capacity during the summer periods under the CDSU, figure 6.6 shows the CDF curves for its average traffic flux loss.



a. The CDF curve for the average traffic flux loss under the high emission scenarios



b. The CDF curve for the average traffic flux loss under the medium emission scenarios



c. The CDF curve for the average traffic flux loss under the low emission scenarios

Figure 6.6: CDF curves showing the average traffic loss under the various emission scenarios for a signalised 3 lanes link during summer period under the conventional development system for the UK

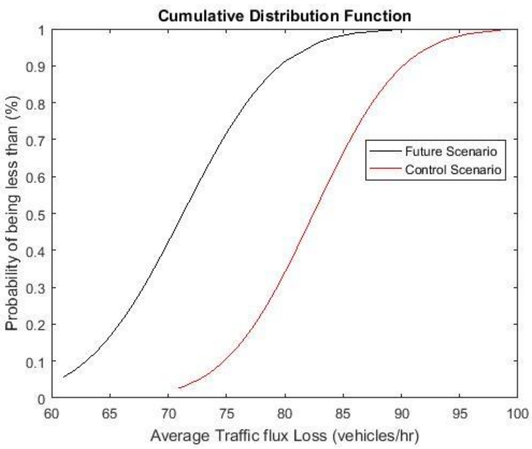
In this case the CDF curves shown in figure 6.6 also shows lower traffic flux loss for the future scenario under each emission level this was because drier conditions meant better traction hence quicker acceleration also the quicker drivers' response times due to increased aggression as mentioned earlier. Higher emissions level resulted in drier conditions hence lower traffic flux loss. Table 6.15 summarises the outputs made from figure 6.6. In figure 6.6c there appear to be errors above the 95th percentile but the essence of both curves can be seen between the 10th percentile and the 90th percentile.

	Control Scenarios			Future Scenarios			Percentile Differences			Percentile Differences (%)		
Percent	10%	50%	90%	10%	50%	90%	10%	50%	90%	10%	50%	90%
Summer												
High	49.81	55.88	61.88	35.62	45.49	55.03	-14.20	-10.38	-6.84	-28.51	-18.58	-11.05
Med	50.83	55.24	59.57	36.55	45.79	54.95	-14.28	-9.45	-4.62	-28.09	-17.11	-7.76
Low	50.41	56.08	61.55	34.69	46.63	58.52	-15.72	-9.45	-3.03	-31.18	-16.85	-4.92

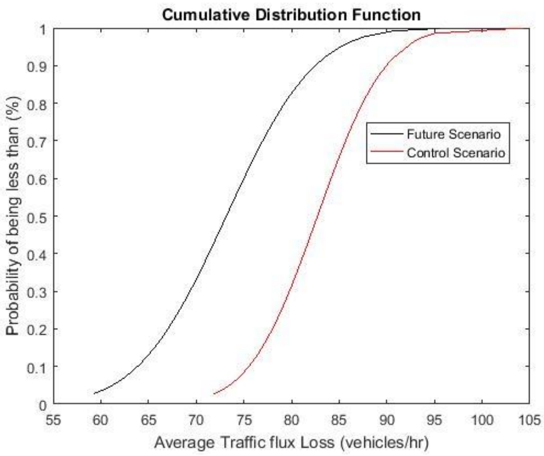
Table 6.15: Traffic flux loss probabilities under the various emission scenarios for a signalised 3 lanes link during the summer periods under the conventional development system for the UK

From table 6.15 generally the future emissions scenarios showed lower flux loss compared to their control scenarios for each emissions scenario. Also, higher flux differences were experienced under the high emission scenarios which had traffic flux loss central probability projection of -18.58% compared to -17.11% and -16.85% for medium and low respectively.

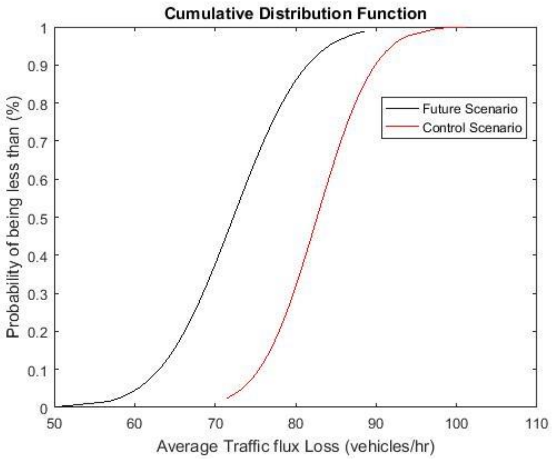
The CDF curves for the average traffic flux loss under the various emissions scenarios for the signalised link type during the winter period under the CDSU is shown in figure 6.7.



a. The CDF curve for the average traffic flux loss under the high emission scenarios



b. The CDF curve for the average traffic flux loss under the medium emission scenarios



c. The CDF curve for the average traffic flux loss under the low emission scenarios

Figure 6.7 CDF curves showing the average traffic loss under the various emission scenarios for a signalised 3 lanes link during the winter period under the conventional development system for the UK

From the CDF curves shown in figure 6.7 the future scenarios also showed lower traffic flux loss during the winter period because of wetter conditions and less snowy conditions when compared to the control scenarios because wetter conditions resulted in less traction loss compared to snowy conditions and the drivers were more responsive during the wetter conditions than in the snowy conditions. Table 6.16 summarises the outputs made from figure 6.7.

	Control Scenarios			Future Scenarios			Percentile Differences			Percentile Differences (%)		
Percent	10%	50%	90%	10%	50%	90%	10%	50%	90%	10%	50%	90%
Summer												
High	74.45	82.51	89.99	62.77	71.26	79.68	-11.68	-11.24	-10.32	-15.69	-13.63	-11.47
Med	75.54	82.85	90.35	63.89	73.19	82.45	-11.66	-9.66	-7.90	-15.44	-11.66	-8.74
Low	75.67	82.62	90.28	63.12	72.24	81.36	-12.55	-10.38	-8.92	-16.59	-12.56	-9.88

Table 6.16: Traffic flux loss probabilities under the various emission scenarios for a signalised 3 lanes link during the winter periods under the conventional development system for the UK.

From table 6.16 for all 3 emissions levels the future scenario showed lower traffic flux loss compared to the control scenario which was a similar characteristic to most of the other analysis. From the central probabilities, the high emissions scenario showed higher traffic flux increase compared to the medium emissions and low scenarios, but the low emissions scenario showed a higher increase compared to the medium scenario. The reason why low emissions showed a higher flux increase is as discussed earlier less heavy rainfall hours were experienced compared to the other scenarios resulting in better driving conditions for the drivers.

6.3. Projecting the future impact of weather on the traffic stream under the consumeristic and community oriented socio-economic scenarios

A ratio of 16:1 for cars to HGVs has been used so far for the conventional development system of the UK. In this section other possible development systems will be explored. Basically, the socio-economic values will be adjusted and then subjected to the various forms of governance (emissions scenarios) as was previously done with the CDSU.

A more consumeristic socio-economic value is expected to feature more privately-owned vehicles (i.e. cars) as opposed to a more community socio-economic value where more publicly owned vehicles (i.e. HGVs) would be featured. To explore these options, the ratio of cars to HGVs was adjusted with the ratio being increased to 1:24 for consumeristic while in the case of community it was reduced to 1:8. The illustrated interactions between the various government natures and socio-economic values is shown in appendix 5.

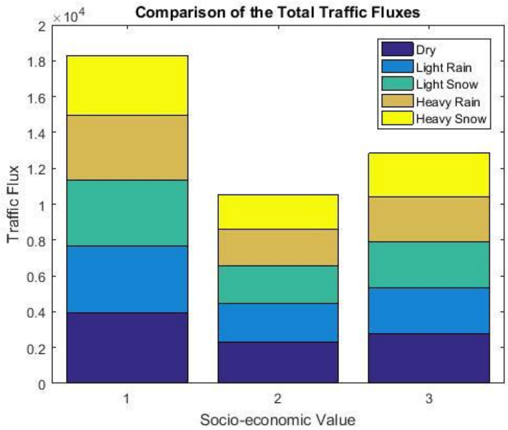
6.3.1. Procedure

The entire processes used for the CDSU were repeated for these two development systems. The first process was to carry out traffic flow simulations where the ratio of cars to HGVs were adjusted from 1:16 to 1:24 for consumeristic and 1:8 for community, this process was done for the CDSU in chapter 3.

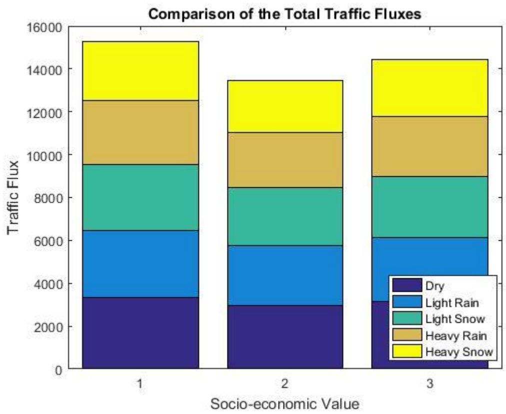
The consumeristic development system generally showed higher traffic fluxes for both link types since cars on the traffic stream meant higher maximum capacity due to increased speed of the flow and higher density since flux is the product of flow speed and the density. Table 6.17 below shows the maximum traffic capacity results obtained by simulating both development systems as well as the results of the CDSU shown in chapter 3 while figure 6.8 compares these results.

Traffic Parameters	Normal (Dry)	Light Rain	Light Snow	Heavy Rain	Heavy Snow
Roundabout Controlled Link					
	Maximum Capacity (veh/hr)				
Consumeristic	3931.7	3740.3	3659.7	3596.7	3355.2
Community	2292.3	2194.9	2071.5	2048.9	1911.1
The CDSU	2751.4	2595.2	2538.300	2503	2445.5
Signal Controlled Link					
	Maximum Capacity (veh/hr)				
Consumeristic	3317.9	3126.2	3107.6	2966.9	2766
Community	2940.2	2822.6	2708.5	2572.1	2397.8
The CDSU	3129	3000.1	2846.2	2808.1	2650.6

Table 6.17: The maximum traffic capacity under each development system



a. Comparison of the total traffic fluxes for the roundabout controlled link



b. Comparison of the total traffic fluxes for the Signal controlled link

Legend	
S/N	Socio-Economic Value
1	Consumeristic
2	Community
3	The CDSU

Figure 6.8: Comparison of the total traffic fluxes of the socio-economic values

Figure 6.8 shows a comparison of the total traffic fluxes of the socio-economic values shown in table 6.14. From the chart the consumeristic value showed the highest combined traffic flux for all its weather conditions since it featured the lowest number of HGVs while the community value showed the least total traffic flux since it featured the highest number of HGVs. Table 6.18 examines the percentage differences of the consumeristic and community traffic fluxes under each weather condition from those of the CDSU.

Traffic Parameters	Normal (Dry)	Light Rain	Light Snow	Heavy Rain	Heavy Snow
Roundabout Controlled Link					
	Percentage differences from the CDSU (%)				
Consumeristic	0.43	0.44	0.44	0.44	0.37
Community	-0.17	-0.15	-0.18	-0.18	-0.22
Signal Controlled Link					
	Percentage differences from the CDSU (%)				
Consumeristic	0.06	0.04	0.09	0.06	0.04
Community	-0.06	-0.06	-0.048	-0.08	-0.10

Table 6.18: The Consumeristic and Community traffic flux percentage differences from the CDSU

In table 6.18 the positive percentages show increases in flux values when compared to the CDSU while the negative percentages indicate reductions in flux values. In all weather conditions the consumeristic value showed the highest fluxes indicated by the positive percentages under each weather conditions while the community showed the lowest fluxes indicated by the negative percentages under each weather condition.

The next step in the process was to combine the traffic flux data with the weather data generated from the UKCP09. Table 6.19 shows the traffic flux loss probabilities under the various emissions scenarios for both link types (roundabout controlled and signalised) under the consumeristic and community socio-economic values scenarios. The CDF curves where each table was derived from can be seen in appendix 5.

	Control Scenarios			Future Scenarios			Percentile Differences			Differences from high (%)		
Percent	10%	50%	90%	10%	50%	90%	10%	50%	90%	10%	50%	90%
Summer												
High	62.41	69.44	76.98	44.60	56.82	68.39	-17.81	-12.61	-8.58	0	0	0
Med	63.19	68.98	74.25	45.77	57.212	68.53	-17.42	-11.77	-5.72	2.20	6.70	33.34
Low	62.80	70.02	77.24	43.17	58.51	73.34	-19.64	-11.51	-3.90	-10.22	8.77	54.58
Winter												
High	81.32	88.73	96.46	75.15	84.10	92.69	-6.17	-4.63	-3.76	0	0	0
Med	81.84	88.89	96.23	75.01	85.03	94.95	-6.83	-3.86	-1.28	-10.65	16.57	65.98
Low	81.21	88.90	95.95	72.38	82.49	92.70	-8.82	-6.41	-3.25	-43	-38.44	13.75

a. Traffic flux loss probabilities under the various emissions scenarios for a roundabout controlled 3 lanes link under a consumeristic socio-economic values scenario.

	Control Scenarios			Future Scenarios			Percentile Differences			Differences from high (%)		
Percent	10%	50%	90%	10%	50%	90%	10%	50%	90%	10%	50%	90%
Summer												
High	62.76	69.80	77.35	44.80	57.04	68.50	-17.97	-12.76	-8.85	0	0	0
Med	63.81	69.40	74.49	46.09	57.30	68.76	-17.72	-12.10	-5.73	1.39	5.15	35.27
Low	63.03	70.28	77.36	43.24	58.34	74.04	-19.79	-11.94	-3.32	-10.15	6.44	62.54
Winter												
High	77.21	84.76	91.02	74.28	82.89	92.32	-2.92	-1.88	1.30	0	0	0
Med	76.96	84.66	91.58	73.66	83.52	92.92	-3.30	-1.15	1.34	-13.06	38.86	-3.21
Low	77.68	84.69	91.54	70.65	80.70	91.15	-7.03	-3.99	-0.39	-140.59	-112.83	130.27

b. Traffic flux loss probabilities under the various emissions scenarios for a signalised 3 lanes link under a consumeristic socio-economic values scenario.

	Control Scenarios			Future Scenarios			Percentile Differences			Differences from high (%)		
Percent	10%	50%	90%	10%	50%	90%	10%	50%	90%	10%	50%	90%
Summer												
High	32.42	36.12	39.83	23.29	29.51	35.73	-9.13	-6.61	-4.1	0	0	0
Med	32.82	35.86	38.64	23.95	29.64	35.47	-8.87	-6.22	-3.17	2.85	5.90	22.68
Low	32.69	36.39	39.97	21.97	30.37	38.51	-10.72	-6.02	-1.46	-17.42	8.93	64.39
Winter												
High	46.62	51.79	56.64	40	45.05	50.47	-6.62	-6.74	-6.17	0	0	0
Med	47.14	51.86	56.37	40.33	46.17	51.95	-6.81	-5.69	-4.42	-2.87	15.58	28.36
Low	47.29	51.75	56.59	39.72	45.48	51.37	-7.57	-6.27	-5.22	-14.35	6.97	15.40

c. Traffic flux loss probabilities under the various emissions scenarios for a roundabout controlled 3 lanes link under a community socio-economic values scenario.

	Control Scenarios			Future Scenarios			Percentile Differences			Differences from high (%)		
Percent	10%	50%	90%	10%	50%	90%	10%	50%	90%	10%	50%	90%
Summer												
High	39.75	44.42	49.05	28.73	36.49	43.78	-11.02	-7.93	-5.27	0	0	0
Med	40.36	44.07	47.74	28.92	36.59	43.94	-11.44	-7.48	-3.8	-3.81	5.68	27.89
Low	40.27	44.86	49.46	27.48	37.50	47.71	-12.79	-7.36	-1.75	-16.06	7.19	66.79
Winter												
High	54.54	59.88	65.13	47.58	53.80	60.17	-6.96	-6.08	-4.96	0	0	0
Med	54.72	59.95	64.67	48.31	54.75	61.34	-6.41	-5.2	-3.33	7.90	14.47	32.86
Low	54.49	59.82	64.96	47.20	53.88	60.51	-7.29	-5.94	-4.45	-4.74	2.30	10.28

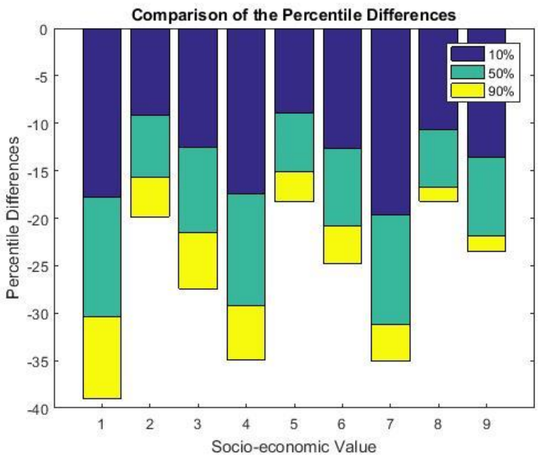
d. Traffic flux loss probabilities under the various emissions scenarios for a signalised 3 lanes link under a community socio-economic values scenario.

Table 6.19: The Traffic flux loss probabilities under the various emissions scenarios for both link types under the consumeristic and community socio-economic values scenarios

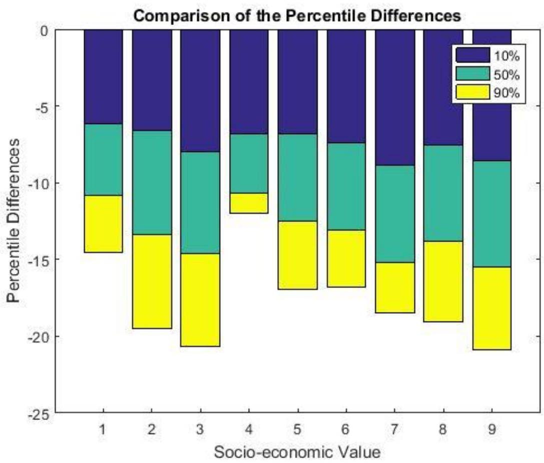
Table 6.19 the traffic flux of the control and future scenarios of the two link types under the consumeristic and socio-economic values scenarios were compared. From the percentile differences tab of both socio-economic values scenarios on both link types for both scenarios the future scenario showed lower flux loss (hence higher flux) compared to the control scenario indicated by the negative signs.

Comparing the traffic flux differences under all three emissions scenarios, on each link for both socio-economic values the high emissions scenario showed the highest flux differences between the control and future scenarios (all three emissions scenarios showed flux rises in the future scenario) indicated by the positive percentage differences shown under the last 3 columns to the right of each table.

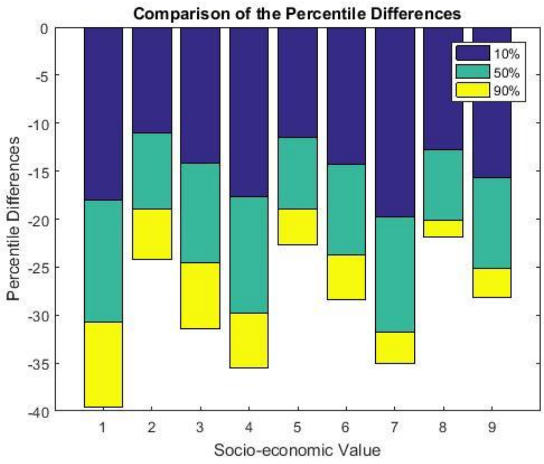
Figure 6.9 compares the traffic flux percentile Differences of the consumeristic, community and the CDSU for both link types under each season.



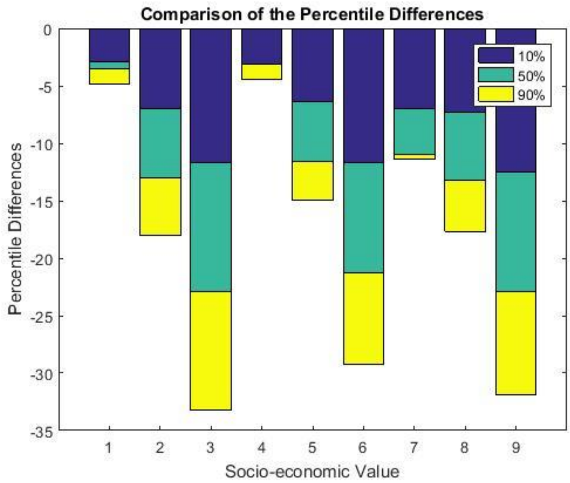
a. Comparison of the traffic flux percentile Differences of the consumeristic, community and the CDSU for the roundabout controlled link type under the summer season.



b. Comparison of the traffic flux percentile Differences of the consumeristic, community and the CDSU for the roundabout controlled link type under the winter season.



c. Comparison of the traffic flux percentile Differences of the consumeristic, community and the CDSU for the signalized link type under the summer season



d. Comparison of the traffic flux percentile Differences of the consumeristic, community and the CDSU for the signalized link type under the winter season

Legend	
S/N	Socio-Economic Value
1:3	High
1	Consumeristic
2	Community
3	The CDSU
4:6	Medium
4	Consumeristic
5	Community
6	The CDSU
7:9	Low
7	Consumeristic
8	Community
9	The CDSU

Figure 6.9: Comparison of the traffic flux percentile Differences of the socio-economic values and the CDSU for the various link types under the various seasons

Figure 6.9 was adapted from tables 6.19a & b for consumeristic, tables 6.19c & d for community and tables 6.8, 6.9, 6.15 & 6.16 for the CDSU. The negative bars indicate rises in the future scenarios traffic flux fluxes for each case and the longer the bars the more the traffic flux gained. From figure 6.9a & c during the summer period the consumeristic socio-economic value showed the highest increase in traffic flux while the community value showed the least increase for both link types while for the winter period the CDSU showed the highest increase in traffic flux while the consumeristic value showed the least increase.

These results indicate that higher vehicle densities in a traffic stream are more prone to weather conditions than lower vehicle densities since both consumeristic and the CDSU had higher vehicle densities compared to the community value which had more HGVs hence less density. Since the consumeristic value and the CDSU were more sensitive to changes in weather conditions, the summer period experienced higher fluxes compared to the community value because of drier conditions, while during the winter period the reverse was the case due to wetter conditions. They also indicate that the emissions levels had an impact on the traffic fluxes, with higher emissions levels showing higher vulnerability to changes in traffic fluxes compared to lower levels. This was observed from the traffic flux differences between the control and future scenarios where high emissions levels showed higher flux differences when compared to medium and low emissions levels as shown in table 6.19 and figure 6.9.

6.4. Projecting the future impact of weather on traffic streams containing autonomous vehicles

Autonomous vehicles are being designed to move in platoons, each platoon could be seen as an HGV since the vehicles in each platoon accelerate and decelerate at the same rate while maintaining a constant headway. In this section the impact of the weather conditions resulting from the different emissions scenarios on autonomous vehicles will be examined.

6.4.1. Modelling autonomous vehicles on the traffic links

The traffic flow model designed in chapter 3 was edited to accommodate autonomous vehicles. Various steps were carried out when including autonomous vehicles in the design and have been fully described in appendix 6 including the edited sections of the code and the entire edited code.

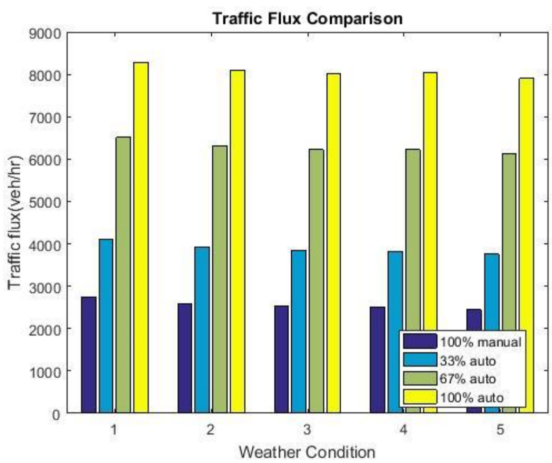
In summary of the autonomous vehicles traffic flow design, for simplicity only 3 lane traffic was designed to accommodate autonomous vehicles, the designed autonomous vehicles were assigned designated lanes on the link, the traffic flow was designed to feature either 33%, 67% or 100% (i.e. 1/3, 2/3 or 3/3) autonomous vehicles on the link. The percentage was from 1 lane, 2 lanes or 3 lanes allocation to autonomous vehicles where the autonomous vehicles were assigned lanes from the inner lanes to the outer lanes. Figure 2.9 shown in chapter 2 illustrated the relationship between autonomous vehicles speed and their distances from their lead vehicles and this was compared to the distances human drivers attempt to maintain from their lead vehicles at the same speed range. The graph presented was used in this thesis to derive a relationship between the speed of autonomous vehicles and their target distances from their lead vehicle.

6.4.2. The impact of weather conditions on traffic streams containing autonomous vehicles

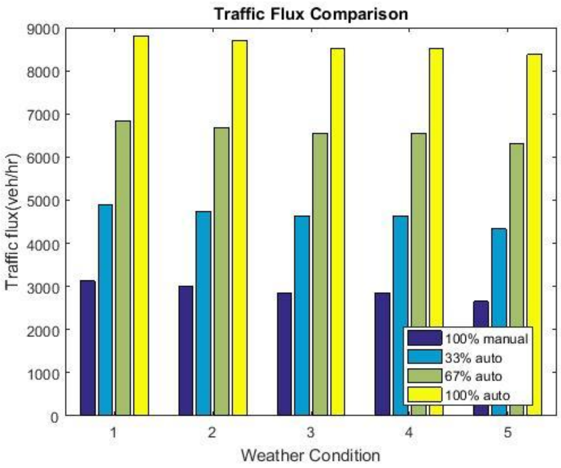
Just like the original model traffic flow simulations were carried out under each weather condition on both traffic link types containing 33%, 67% and 100% autonomous vehicles. The simulations were all carried out based on the conventional development system of the UK ratio of cars to HGVs previously used in this thesis (i.e. 16:1). Table 6.20 shows the output traffic fluxes of all the autonomous vehicles percentage compositions on both link types as well as 100% manual vehicles while figure 6.10 shows a comparison between the fluxes.

Traffic Parameters	Normal (Dry)	Light Rain	Light Snow	Heavy Rain	Heavy Snow
Roundabout Controlled Link					
Autonomous percentage	Maximum Capacity (veh/hr)				
100% Manual	2751.4	2595.2	2538.3	2503	2445.5
33%	4101	3924.66	3850.84	3826.23	3760.62
67%	6515	6313.04	6221.83	6228.34	6130.62
100%	8288	8105.66	8022.78	8039.36	7906.75
Signal Controlled Link					
Autonomous percentage	Maximum Capacity (veh/hr)				
100% Manual	3129	3000.1	2846.2	2808.1	2650.6
33%	4889	4737.44	4634.77	4507.66	4336.54
67%	6838	6687.56	6557.64	6468.75	6297.80
100%	8813	8707.24	8522.17	8548.61	8381.16

Table 6.20: The maximum traffic capacity under each autonomous vehicle percentages on the links



a. Traffic Flux Comparison for the roundabout controlled link



b. Traffic Flux Comparison for the signal-controlled link

Legend	
S/N	Weather Condition
1	Normal (Dry)
2	Light Rain
3	Light Snow
4	Heavy Rain
5	Heavy Snow

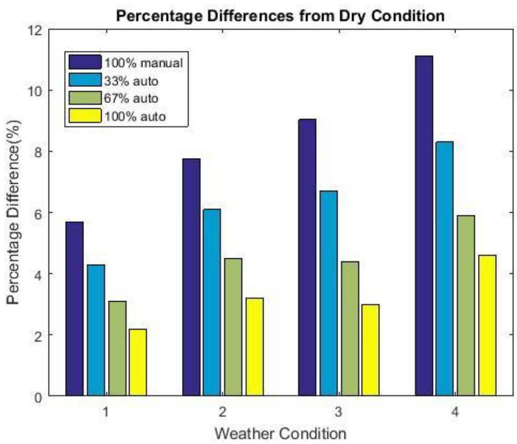
Figure 6.10: The traffic flux comparison for various autonomous vehicle compositions and all manual vehicles for both link types

From figure 6.10 above it can be seen that autonomous vehicles did have positive impacts on the traffic flux of both links. While 100% manual vehicles showed the lowest fluxes under all weather conditions, 100% autonomous vehicles showed the most fluxes with the fluxes increasing with increases in the percentage of autonomous vehicles on both links.

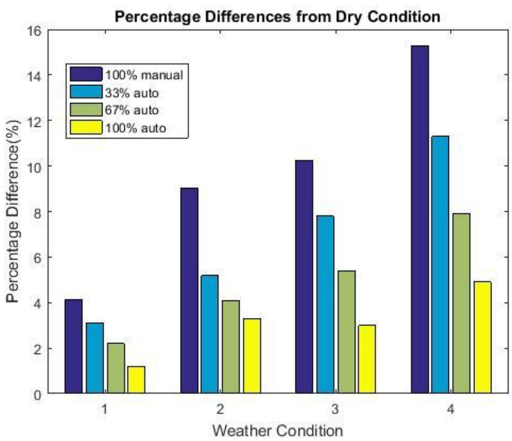
In section 6.3.1 it was indicated that traffic fluxes for the community driven socio-economic values were the least prone to the impact of weather conditions due to more HGVs on the traffic stream resulting in less vehicle density and fewer drivers making decisions while consumeristic were the most prone due to having the highest vehicle density and the most drivers making decisions. Autonomous vehicles in platoons somewhat behaved like HGVs in the traffic streams since the vehicles accelerated and decelerated at virtually the same time this meant drivers were not required to make decisions hence traffic parameters such as the headway between vehicles, response times and accelerations were less prone to weather conditions. Table 6.21 shows the percentage differences between the dry condition fluxes and the other weather conditions while figure 6.11 shows a comparison of the weather conditions flux percentage differences from the dry condition fluxes for both link types.

Traffic Parameters	Normal (Dry)	Light Rain	Light Snow	Heavy Rain	Heavy Snow
Roundabout Controlled Link					
Autonomous percentage	Percentage difference (%)				
100% Manual	0	-5.68	-7.75	-9.03	-11.12
33%	0	-4.3	-6.1	-6.7	-8.3
67%	0	-3.1	-4.5	-4.4	-5.9
100%	0	-2.2	-3.2	-3	-4.6
Signal Controlled Link					
Autonomous percentage	Percentage difference (%)				
100% Manual	0	-4.12	-9.04	-10.26	-15.29
33%	0	-3.1	-5.2	-7.8	-11.3
67%	0	-2.2	-4.1	-5.4	-7.9
100%	0	-1.2	-3.3	-3	-4.9

Table 6.21: The percentage differences between the dry condition fluxes and the other weather conditions



a. Comparison of the weather conditions flux percentage differences from the dry condition fluxes for the roundabout controlled link



b. Comparison of the weather conditions flux percentage differences from the dry condition fluxes for the roundabout controlled link

Legend	
S/N	Weather Condition
1	Light Rain
2	Light Snow
3	Heavy Rain
4	Heavy Snow

Figure 6.11: Comparison of the weather conditions flux percentage differences from the dry condition fluxes for both link types

Figure 6.11 since each bar represents the output traffic flux percentage difference of the corresponding weather condition from their corresponding dry condition, the height of each bar is hence an indication of the traffic stream sensitivity to the given weather condition. In both traffic link types 100% manual vehicles showed the highest bars hence the most sensitivity and the sensitivity reduced with increased autonomous vehicles in the traffic stream with 100% autonomous vehicles showing the least sensitivity.

6.4.2.1. The impact of weather conditions on the target headways of autonomous vehicles

As mentioned in a previous section the average headway was one of the main factors affecting the traffic parameters on the roundabout controlled link. By referring to Hee et al. (2015) curves (fig 2.9) showing the average safe inter-vehicle distance, the target headways for autonomous vehicles under various weather conditions were deduced from the target headways of drivers (manual vehicles) shown in table 6.22.

Weather Condition	Headway (s)
Normal (Dry)	1.5
Light Rain	2
Light Snow	2
Heavy Rain	2.5
Heavy Snow	3
Traffic Jam all conditions	0.5

Table 6.22: The target headways of drivers (manual vehicles) under each weather conditions

This was done by first taking sample data from Hee et al. (2015) curves of the 100% manual vehicles and the 100% autonomous vehicles and taking the average of each curve shown in table 6.23. The safe inter-vehicle distances samples were taken at 15, 50, 80 & 120 Km/hr respectively.

	Samples				Averages
Vehicle type	Sample 1	Sample 2	Sample 3	Sample 4	
Vehicle speed (km/hr)	15	50	80	120	
Manual	5	15	24	37	20.25
Autonomous	1	2	4	6	3.25

Table 6.23: The averages of the sample data from the average safe inter-vehicle distance for both 100% autonomous and 100% manual vehicles

The next step was then to establish a relationship between the averages obtained and the target headways. The target headways for the manual vehicles were already knowns so these were used to derive the target headways for the autonomous vehicles. Equation 6.1 below was used.

$$\upsilon = \frac{\tau}{\alpha} \times \beta \qquad [6.1]$$

Where τ is the target headway of manual vehicles, α is the average safe inter-vehicular spacing of the manual vehicles, β is the average safe inter-vehicular spacing of the autonomous vehicles and υ is the target headway of autonomous vehicles.

Table 6.24 shows the derived target headways for autonomous vehicles under each weather condition and a comparison with the manual vehicles target headways.

Weather Condition	Autonomous Vehicles Headway (s)	Manual Vehicles Target Headway (s)	Percentage Differences (%)
Normal (Dry)	0.24	1.5	84
Light Rain	0.32	2	84
Light Snow	0.32	2	84
Heavy Rain	0.40	2.5	84
Heavy Snow	0.48	3	84
Traffic Jam all conditions	0.08	0.5	84

Table 6.24: The derived target headways for autonomous vehicles under each weather condition

It should be noted that the target headways are only for illustration and analysis and were not used during the design of the car following algorithm for the autonomous vehicles and since vehicles moved in platoons target distances from their lead vehicles were set based on their current speed, these distances were derived from Hee et al. (2015) curve for the safe inter-vehicle distances. See appendix 6 for the full explanation and implementation.

6.4.2.2. The impact of weather on the average acceleration and response time of traffic streams containing autonomous vehicles

It was explained in chapter 3 that an average driver would only utilise approximately 65% of their vehicle's maximum acceleration rate, this in some cases may be the case of vehicles driving in a platoon since the lead vehicle of a platoon which may be driven by a human driver would probably utilise the same percentage. In some cases, some vehicles in a platoon such as the HGVs may have to utilise their maximum potential to keep up with the platoon. For simplicity it was assumed that the leader of each platoon operated like a human driver and utilised only 65% of the vehicle's maximum potential. Vehicles had to meet a minimum threshold distance from their lead vehicles before the platoon feature could be enabled, and vehicles that were left behind due to low acceleration or top speed were automatically disengaged from the platoon which automatically resulted in their following vehicles being disengaged as well. An alternative could be to use the maximum acceleration of the slowest vehicle in the platoon as the maximum acceleration of the platoon but since it was assumed that the leader of each platoon behaved like a human driver this method was not used.

Since each platoon on the traffic streams operated somewhat like a train it was assumed that the response of each vehicle would depend on the response of the cooperative adaptive cruise control (CACC) fitted in the vehicle and since this response would most likely be less than 0.1s and each time step in the code was equivalent to 0.1s it was assumed that the response time of each autonomous vehicle was immediate without anytime delay as opposed to human drivers.

The average acceleration of vehicles and their response times on a signalised link containing 100% autonomous as well as a signalised link containing 100% manual vehicles (from chapter 6) under the various weather conditions is shown in table 6.25.

	100% Autonomous		100% Manual		
Weather Condition	Average Acceleration (m/s^2)	Average Response time (s)	Average Acceleration (m/s^2)	Average Response time (s)	Average acceleration percentage difference (%)
Dry	1.32	0	0.60	1.0	54.55
Light Rain	1.30	0	0.54	1.5	58.46
Light Snow	1.29	0	0.52	1.5	59.69
Heavy Rain	1.20	0	0.33	2.5	72.5
Heavy Snow	1.09	0	0.19	3.0	82.57

Table 6.25: The average acceleration of vehicles and their response times on a signalised link under the various weather conditions

Table 6.25 the traffic streams containing 100% autonomous vehicles showed higher accelerations compared to the traffic streams containing 100% manual vehicles. Various factors contributed to this increase such as reduced response time and less vehicles switching lanes which may result in alteration of the speed of the traffic stream. Autonomous vehicles travelling under heavy snow conditions experienced the highest acceleration increase due to a massive reduction in the response time.

The next step was to combine the traffic flux data for the traffic streams containing the various percentages of autonomous vehicles with the weather data generated from the UKCP09. Table 6.26 shows the traffic flux loss probabilities under the various emissions scenarios for both link types (roundabout controlled and signalised) under the various autonomous vehicles percentage combinations in traffic streams. The CDF curves where each table was derived from can be seen in appendix 5.

	Control Scenarios			Future Scenarios			Percentile Differences			Differences from high (%)		
Percent	10%	50%	90%	10%	50%	90%	10%	50%	90%	10%	50%	90%
33% Autonomous Vehicles												
Summer												
High	56.77	63.69	70.55	40.61	51.86	62.76	-16.17	-11.82	-7.79	0	0	0
Med	57.97	63.00	67.91	41.68	52.22	62.64	-16.29	-10.78	-5.27	-0.76	8.82	32.34
Low	57.49	63.94	70.18	39.53	53.18	66.71	-17.96	-10.76	-3.47	-11.09	8.95	55.45
Winter												
High	76.20	83.24	90.38	69.35	77.62	85.99	-6.85	-5.62	-4.39	0	0	0
Med	76.73	83.68	90.32	69.66	78.92	88.16	-7.06	-4.77	-2.17	-3.16	15.13	50.66
Low	76.52	83.32	90.00	67.09	76.56	86.22	-9.43	-6.75	-3.78	-37.65	-20.27	13.96
67% Autonomous Vehicles												
Summer												
High	65.25	73.01	80.88	46.58	59.48	71.91	-18.67	-13.53	-8.98	0	0	0
Med	66.69	72.18	77.87	47.76	59.83	71.83	-18.94	-12.35	-6.04	-1.43	8.71	32.74
Low	65.87	73.32	80.42	45.40	60.93	76.49	-20.47	-12.40	-3.92	-9.63	8.38	56.31
Winter												
High	85.06	93.41	101.65	79.00	88.13	97.76	-6.06	-5.29	-3.89	0	0	0
Med	85.42	93.78	101.46	79.15	89.56	100.18	-6.27	-4.22	-1.29	-3.45	20.22	66.99
Low	85.68	93.80	100.73	75.71	86.80	97.72	-9.96	-7.00	-3.01	-64.33	-32.35	22.59
100% Autonomous Vehicles												
Summer												
High	58.91	65.89	73.00	42.04	53.68	64.90	-16.87	-12.20	-8.11	0	0	0
Med	60.19	65.14	70.28	43.10	54.00	64.83	-17.09	-11.15	-5.45	-1.33	8.67	32.78
Low	59.45	66.18	72.57	40.98	54.99	69.04	-18.46	-11.19	-3.54	-9.50	8.30	56.39
Winter												
High	76.47	83.60	90.42	71.24	79.37	87.95	-5.23	-4.24	-2.47	0	0	0
Med	77.36	83.72	90.83	71.19	80.52	89.91	-6.17	-3.20	-0.92	-18.05	24.45	62.70
Low	77.09	83.83	90.64	68.13	78.05	87.97	-8.95	-5.78	-2.67	-71.35	-36.41	-8.06

a. Traffic flux loss probabilities under the various emissions scenarios for a roundabout controlled 3 lanes link containing the various percentages of autonomous vehicles.

	Control Scenarios			Future Scenarios			Percentile Differences			Differences from high (%)		
Percent	10%	50%	90%	10%	50%	90%	10%	50%	90%	10%	50%	90%
33% Autonomous Vehicles												
Summer												
High	49.25	54.82	60.67	35.25	44.92	54.17	-14.02	-9.90	-6.50	0	0	0
Med	50.05	54.42	58.72	36.07	45.32	54.18	-13.98	-9.10	-4.53	0.27	8.07	30.24
Low	49.65	55.35	61.18	34.19	46.16	57.91	-15.46	-9.19	-3.27	-10.29	7.17	49.65
Winter												
High	72.49	80.09	87.54	61.85	69.66	77.64	-10.63	-10.42	-9.89	0	0	0
Med	73.32	80.32	87.46	62.40	71.27	80.72	-10.91	-9.06	-6.74	-2.64	13.10	31.88
Low	73.20	80.17	87.54	61.81	70.64	79.39	-11.39	-9.53	-8.15	-7.17	8.54	17.62
67% Autonomous Vehicles												
Summer												
High	49.32	54.77	60.73	35.19	44.79	53.74	-14.14	-9.98	-6.99	0	0	0
Med	49.91	54.55	58.56	36.25	44.97	53.99	-13.66	-9.60	-4.57	3.36	3.77	34.56
Low	49.49	55.12	60.69	33.92	45.81	58.28	-15.57	-9.31	-2.41	-10.12	6.67	65.49
Winter												
High	74.16	81.90	89.91	61.80	70.19	78.57	-12.36	-11.71	-11.34	0	0	0
Med	74.94	82.27	89.69	62.61	72.05	81.35	-12.33	-10.22	-8.34	0.23	12.69	26.44
Low	74.48	82.14	89.70	61.86	71.45	80.57	-12.63	-10.69	-9.14	-2.18	8.68	19.42
100% Autonomous Vehicles												
Summer												
High	35.43	39.50	43.67	25.65	32.31	39.24	-9.77	-7.19	-4.42	0	0	0
Med	35.90	39.10	42.37	26.02	32.49	38.74	-9.88	-6.611	-3.63	-1.076	8.01	17.96
Low	35.76	39.89	43.88	24.73	33.28	42.26	-11.03	-6.61	-1.62	-12.84	8.00	63.45
Winter												
High	52.60	58.40	63.76	43.79	49.88	55.80	-8.81	-8.52	-7.96	0	0	0
Med	52.97	58.34	63.63	44.52	51.21	57.77	-8.45	-7.14	-5.85	4.14	16.21	26.51
Low	53.48	58.33	63.18	43.98	50.70	57.01	-9.50	-7.63	-6.17	-7.80	10.37	22.52

b. Traffic flux loss probabilities under the various emissions scenarios for a signal controlled 3 lanes link containing the various percentages of autonomous vehicles.

Table 6.26: Traffic flux loss probabilities under the various emissions scenarios for both link types containing the various percentages of autonomous vehicles

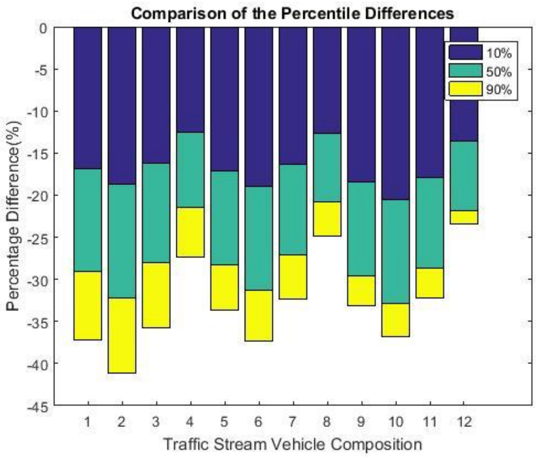
Table 6.26 the traffic flux of the control and future scenarios of the two link types under the various autonomous vehicles combinations traffic streams were compared. From the percentile differences tabs of the various autonomous vehicles combinations traffic streams, on both link types for all the autonomous vehicles percentage combinations, the future scenario showed lower flux loss (hence higher flux) compared to the control scenario indicated by the negative signs.

Comparing the traffic flux differences under all three emissions scenarios, on each link all the various autonomous vehicles combinations traffic streams the high emissions scenario showed the highest flux differences between the control and future scenarios (all three emissions scenarios showed flux rises in the future scenario) indicated by the positive percentage differences shown under the last 3 columns to the right of each table.

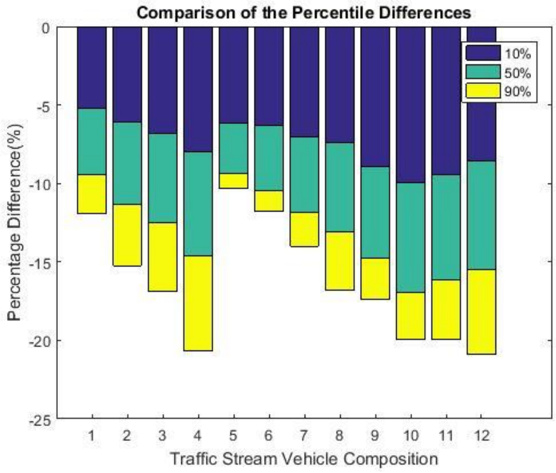
Table 6.27 shows the percentile differences of the various autonomous vehicles combinations and the CDSU for both link types under each season while figure 6.12 compares the traffic flux percentile differences. The data for the CDSU were extracted from tables 6.8, 6.9, 6.15 & 6.16 while the data for the various autonomous vehicles combinations was extracted from tables 6.26a & b.

Percentile differences												
	100%			67%			33%			CDSU		
Roundabout Controlled												
Summer												
	10%	50%	90%	10%	50%	90%	10%	50%	90%	10%	50%	90%
High	-16.87	-12.20	-8.11	-18.67	-13.53	-8.98	-16.17	-11.82	-7.79	-12.58	-8.92	-5.91
Medium	-17.09	-11.15	-5.45	-18.94	-12.35	-6.04	-16.29	-10.78	-5.27	-12.63	-8.17	-4.03
Low	-18.46	-11.19	-3.54	-20.47	-12.40	-3.92	-17.96	-10.76	-3.47	-13.59	-8.29	-1.60
Winter												
High	-5.23	-4.24	-2.47	-6.06	-5.29	-3.89	-6.85	-5.62	-4.39	-8	-6.65	-6.03
Medium	-6.17	-3.20	-0.92	-6.27	-4.22	-1.29	-7.06	-4.77	-2.17	-7.40	-5.67	-3.76
Low	-8.95	-5.78	-2.67	-9.96	-7.00	-3.01	-9.43	-6.75	-3.78	-8.60	-6.91	-5.37
Signal Controlled												
Summer												
	10%	50%	90%	10%	50%	90%	10%	50%	90%	10%	50%	90%
High	-9.77	-7.19	-4.42	-14.14	-9.98	-6.99	-14.02	-9.90	-6.50	-14.20	-10.38	-6.84
Medium	-9.88	-6.611	-3.63	-13.66	-9.60	-4.57	-13.98	-9.10	-4.53	-14.28	-9.45	-4.62
Low	-11.03	-6.61	-1.62	-15.57	-9.31	-2.41	-15.46	-9.19	-3.27	-15.72	-9.45	-3.03
Winter												
High	-8.81	-8.52	-7.96	-12.36	-11.71	-11.34	-10.63	-10.42	-9.89	-11.68	-11.24	-10.32
Medium	-8.45	-7.14	-5.85	-12.33	-10.22	-8.34	-10.91	-9.06	-6.74	-11.66	-9.66	-7.90
Low	-9.50	-7.63	-6.17	-12.63	-10.69	-9.14	-11.39	-9.53	-8.15	-12.55	-10.38	-8.92

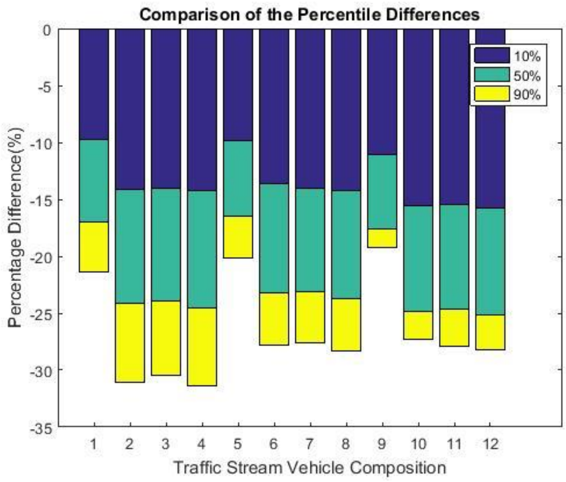
Table 6.27: The percentile differences of the various autonomous vehicles combinations and the CDSU for both link types under each season



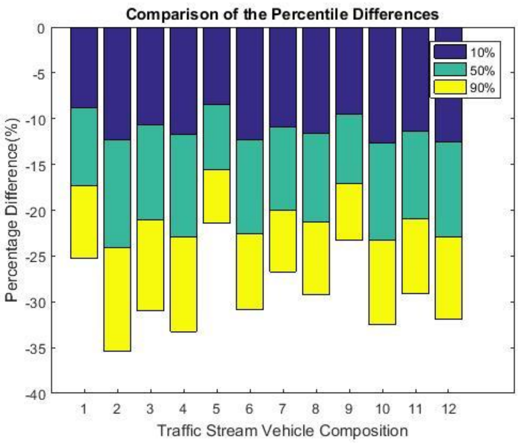
a. Comparison of the traffic flux percentile Differences of the various autonomous vehicles combinations and the CDSU for the roundabout controlled link type under the summer season.



b. Comparison of the traffic flux percentile Differences of the various autonomous vehicles combinations and the CDSU for the roundabout controlled link type under the winter season.



c. Comparison of the traffic flux percentile Differences of the various autonomous vehicles combinations and the CDSU for the signalized link type under the summer season



d. Comparison of the traffic flux percentile Differences of the various autonomous vehicles combinations and the CDSU for the signalized link type under the winter season

Legend	
S/N	Socio-Economic Value
1:4	High
1	100% Autonomous
2	67% Autonomous
3	33% Autonomous
4	The CDSU
5:8	Medium
5	100% Autonomous
6	67% Autonomous
7	33% Autonomous
8	The CDSU
9:12	Low
9	100% Autonomous
10	67% Autonomous
11	33% Autonomous
12	The CDSU

Figure 6.12: Comparison of the traffic flux percentile Differences of the various autonomous vehicles combinations and the CDSU for the various link types under the various seasons

From figure 6.12 in most cases the percentile differences reduced as the emissions scenario moved from high to low which can also be observed from the narrowing of the gap between the control and future scenario curves on the CDF curves for the traffic flux differences shown in appendix 5. The length of each bar is an indication of the sensitivity of the traffic stream to the emissions scenarios. Shorter bars indicate lower sensitivity and from figure 6.12 generally as the percentage of autonomous vehicles contained in the traffic stream increased the sensitivity of the stream to climatic conditions reduced, this is more obvious on the bar chats for the roundabout controlled traffic flow in the winter season.

6.5. The Effect of Geographical Location on Traffic Performance

The regional climates summaries of Northern Scotland and Southern England (London) were obtained from Met Office (2018) and are discussed below; their focus is on the latest 30-year averaging period of 1981-2010.

6.5.1. Weather conditions in Northern Scotland and Southern England

6.5.1.1. Temperatures in Northern Scotland and Southern England

Northern Scotland generally has a mean annual temperature of 7°C-9°C at low altitudes but significantly lower temperatures at higher altitudes such as in places like Cairngorm Summit where the mean annual temperature is just below 1°C. The coldest month is usually January or February where the mean daily minimum temperature varies from 2°C on west-facing coasts and in the western and northern Isles to less than -1°C on higher ground. The warmest month is usually July or August where the mean daily maximum temperatures at low altitudes is 19°C in areas close to Moray Firth while the higher grounds and the Islands is mean daily maxima is 16°C (Met Office, 2018).

In Southern England, the mean annual temperature varies from about 11.5^{o}C in in Central London and along the south coast to around 9.5^{o}C over higher ground well inland. The coldest month is usually January with mean daily minimum temperatures varying from over 3^{o}C in London and over the coast to about 0.5^{o}C over the higher ground. Extreme temperatures are known to often occur in December or January where the temperature has been known to drop to as low as -18.2^{o}C. The warmest month is usually July where the mean daily maximum temperatures in the London area is 23.5^{o}C which is the highest in the UK while in higher grounds and along the south coast of the same region the mean maxima are close to 21^{o}C. Extreme temperatures have been known to occur in July or August and are usually associated with heat waves which lasts several days, and the highest temperature ever recorded which is also the highest temperature ever recorded for the UK was 38.5^{o}C at Faversham, Kent (Met Office, 2018).

6.5.1.2. Precipitation in Northern Scotland and Southern England

In Northern Scotland, there is an average annual rainfall of 1700mm for most of the western half of Northern Scotland with its wettest region which is located over the higher, west facing slopes (northwest of Fort William) experiencing over 4000mm per year while the lower lying islands experience annual averages of less than 1600mm. Winter periods (December to February), experiences an average of fewer than 40 wet days (rainfalls total of 1mm or over) in areas close to Moray Firth while areas in the western half and in Shetland sometimes experience over 60 wet days, periods of prolonged rainfall can lead to widespread flooding, especially in winter and early spring when soils are usually near saturation and snowmelt can be a contributing factor. During summer (June to August) the Moray Firth area has about 30 wet days and the western areas over 45 wet days (Met Office, 2018).

In Southern England, the wettest areas are South Downs and the higher parts of Dorset with a mean rainfall of over 950mm per year while the driest region, the Thames Valley London and north Kent coast normally receives an average rain of less than 650mm per year and less than 550mm around the Thames Estuary. Winter period (December to February) usual have a mean of 35 to 40 wet days over Downs and higher parts of the west and this drop to below 30 days around the Thames Estuary while summer period (June to August), have a mean of 25 wet days.

Snowfall generally depends on temperature with snowfall usually occurring when the temperature is 4 °C or less but for snow to lay for any length of time the temperature must be considerably less than this. In this thesis it was assumed that for snow to lay the temperature must be below 0°C, only laid snow was considered since the vehicles' traction was one of the main factors prone to weather condition. In northern Scotland snowfall normally occurs between November to April, averagely the number of days with snow vary from 30 days per year along the west coast to over 100 days per year over the Grampians with snow usually lying for between 6 to 50 days. Heavy snowfalls have been known to cause disruptions to road transport (Met Office, 2018). In southern England the mean number of snowfall days is about 12-15 per year over the lower lying areas while over the higher ground of the Chilterns, North Downs and Weald it is about 20 days. Areas close to the English Channel are the least places prone to snow with less than 10 days of snowfall. Snow usually lay for 5 days per year in most inland areas but over 10 days on the higher ground (Met Office, 2018).

6.5.1. The Effect of Geographical location on Traffic flux

Rises in the global temperature have been projected to result in hotter, dryer summers and warmer, wetter winters with higher extremes with dry areas being projected to become dryer and wet areas projected to become wetter. The probability of changes in the temperature level for the various regions in the UK including Northern Scotland and Southern England for the 2050s period was graphically illustrated in appendix 3. From the figure Southern England is a lot more prone to rises in temperature compared to Northern Scotland also *it can be seen that southern England is more prone to reductions in precipitation levels compared to northern Scotland during the summer period while during the winter period the northern region shows higher susceptibility to precipitation loss*. When this is related to the changes in traffic flux from the control scenarios to the future scenarios, *this would most likely result in higher flux gain in the southern region during the summer period because of higher reductions in precipitation, higher increases in temperature and generally dryer conditions compared to the northern region while during the winter period the reverse would be the case*. Table 6.28 represents the traffic flux loss probabilities from an ideal year (dry all year) under the various emissions scenarios for both link types located in the Northern and Southern regions of the UK under the conventional development system of the UK (the CDSU). The regions of interest were Thurso, North Scotland and London, South England. The CDF curves can be seen in appendix 5.

	Control Scenarios			Future Scenarios			Percentile Differences			Differences from high (%)		
Percent	10%	50%	90%	10%	50%	90%	10%	50%	90%	10%	50%	90%
North UK												
Summer												
High	56.92	61.91	66.98	45.94	53.26	60.03	-10.98	-8.65	-6.96	0	0	0
Med	67.53	71.98	76.62	54.36	62.78	71.96	-13.18	-9.20	-4.66	-20	-6.35	32.97
Low	69.70	74.27	79.25	57.10	66.80	76.75	-12.60	-7.47	-2.51	-14.71	13.65	63.89
Winter												
High	103.83	112.66	121.16	88.91	98.67	108.63	-14.91	-13.99	-12.53	0	0	0
Med	110.18	119.88	129.98	95.67	106.92	118.74	-14.52	-12.96	-11.24	2.65	7.36	10.32
Low	101.91	110.75	119.73	91.34	100.20	109.42	-10.57	-10.55	-10.31	29.10	24.61	17.72
South UK												
Summer												
High	36.24	40.81	45.77	25.31	34.09	42.71	-10.93	-6.72	-3.062	0	0	0
Med	37.52	42.06	46.85	22.88	30.93	38.95	-14.64	-11.13	-7.90	-33.96	-65.64	-158.04
Low	37.57	41.93	46.54	24.16	33.73	43	-13.41	-8.20	-3.53	-22.70	-22.07	-15.22
Winter												
High	57.10	62.50	67.96	51.75	59.04	66.98	-5.35	-3.46	-0.99	0	0	0
Med	59.77	66.83	73.44	53.90	60.98	67.79	-5.87	-5.86	-5.65	-9.60	-69.23	-474.08
Low	58.93	66.01	72.98	55.26	61.45	68.17	-3.67	-4.56	-4.81	31.45	-31.83	-388.58

a. The average traffic flux loss probabilities under the various emissions scenarios for a roundabout controlled 3 lanes link located in the Northern and Southern regions of the UK.

	Control Scenarios			Future Scenarios			Percentile Differences			Differences from high (%)		
Percent	10%	50%	90%	10%	50%	90%	10%	50%	90%	10%	50%	90%
North UK												
Summer												
High	65.33	71	76.67	52.72	60.86	68.90	-12.60	-10.14	-7.77	0	0	0
Med	77.51	82.55	87.59	62.39	71.96	82.22	-15.12	-10.59	-5.37	-20	-4.40	30.9
Low	79.97	85.10	89.90	65.54	76.67	88.01	-14.43	-8.43	-1.89	-14.53	16.85	75.74
Winter												
High	132.69	143.90	155.06	106.95	121.44	136.18	-25.74	-22.46	-18.88	0	0	0
Med	139.64	153.29	166.30	114.51	132.24	150.10	-25.13	-21.05	-16.20	2.35	6.27	14.21
Low	127.30	138.49	149.61	108.18	120.87	134.17	-19.12	-17.62	-15.44	25.73	21.57	18.25
South UK												
Summer												
High	41.59	46.63	52.21	28.90	39.07	48.82	-12.69	-7.56	-3.39	0	0	0
Med	42.76	48.10	53.56	26.26	35.50	44.53	-16.51	-12.60	-9.03	-30.03	-66.67	-166.34
Low	43.06	47.89	53.26	27.73	38.65	49.36	-15.33	-9.24	-3.90	-20.81	-22.22	-15.05
Winter												
High	68.50	75.36	82.09	60.54	68.99	77.94	-7.96	-6.37	-4.15	0	0	0
Med	71.93	80.12	87.75	62.38	70.93	79.44	-9.55	-9.19	-8.31	-20.07	-44.32	-100.37
Low	70.43	78.89	87.19	64	71.92	79.61	-6.42	-6.97	-7.58	19.25	-9.43	-82.75

b. The average traffic flux loss probabilities under the various emissions scenarios for a signal controlled 3 lanes link located in the Northern and Southern regions of the UK.

Table 6.28: The average traffic flux loss probabilities under the various emissions scenarios for both link types located in the Northern and Southern regions of the UK

From table 6.28 under the percentile differences tab it can be seen that for both link types during the summer period the southern region showed higher increases in the average traffic fluxes between the control and future scenarios indicated by the absolute value of the traffic flux loss (since in each case the traffic flux loss was negative) compared to the northern region, while for the winter period the northern region showed higher increases in the average traffic fluxes between both scenarios. Note that the traffic flux loss is the loss from the ideal year which was a year with no precipitation.

This result is consistent with the observation made earlier which summarises as "*the changes in precipitation and temperature levels observed between the control and future scenarios in the 2050s would most likely result in higher flux gain in the southern region during the summer period as a result of higher reductions in precipitation, higher increases in temperature and generally dryer conditions compared to the northern region while during the winter period the reverse would be the case.*"

6.6. Summary and Conclusion

In this chapter the data obtained in chapter 3-5 were analysed to investigate the effect of weather on traffic performance and to ultimately project the shape of future (2050s) road transportation in the UK. To project the shape of future road transportation in the UK it was important to consider factors that are likely to affect the outcome of the transportation system. These factors were grouped into the Independent factors (the nature of governance, and social and political values) and the Dependent factors (the economic and demographic growth, and technological advancement). The Nature of governance, and Social and Political values were used as determining factors for the emissions level and consumption nature of the society respectively. In the UK, technological advancements would likely result in connected and autonomous vehicles becoming dominant modes of road transport in the 2050s resulting in vehicles being able to drive in platoons among other features. The impact of demographic and economic growth could be an extension to this research where they may impact the density, accident rate and general traffic flow on the road network.

The interrelationships between the Independent factors were expressed using the axis of change where the Conventional Development System of the UK (the CDSU) was identified. Possible changes to this development system which were a more consumeristic system and a more community oriented socio-economic scenarios were also addressed. The emissions levels (High, medium and low) were affected by the nature of government and a government that was biased towards autonomy was deemed to likely result in higher emissions level than a government biased towards interdependency.

The links used in this thesis were hypothetical 1km trunk roads containing 3 lanes. One of the links contained a signal-controlled link end while the other contained a roundabout controlled link end. The link ends types used in this thesis were selected to explore the most common junction types used in the UK. Their weather data was based on the weather data for an area in Greater Manchester, North-West England except for the links featured in section 6.5.1 which were based on the weather data of Thurso, North Scotland and London, South England.

The impact of weather on traffic performances under the CDSU, a more consumeristic and a more community oriented socio-economic scenarios were then discussed. This discussion covered topics such as the impact of weather on the various emissions scenarios on both link types. It was found that during the summer period, the future scenario showed higher capacity under each emissions scenario due to increases in drier conditions. This resulted in better traction hence quicker acceleration and quicker drivers' response times due to increased aggression. The future scenarios also showed increased capacity during the winter periods. This was because of wetter conditions and less snowy conditions when compared to the control scenarios. The reason for this was wetter conditions resulted in less traction loss compared to snowy conditions. The drivers were also more responsive during the wetter conditions than in the snowy conditions. In both seasons, higher emissions scenario resulted in higher differences in traffic capacity between the control and future scenario. This was due to higher rises in temperature and overall changes in the climatic conditions.

An insight into the impact of weather on traffic performances under each socio-economic scenario revealed that for both seasons, a more consumeristic oriented socio-economic value resulted in higher traffic capacity on both link types under each emissions scenario than the CDSU. While a more community oriented socio-economic scenario showed the least traffic capacity. The reason was because the consumeristic oriented socio-economic value scenario featured more cars (privately owned) hence experienced higher traffic density and speed compared to the CDSU. While the community oriented socio-economic value scenario featured the highest number of HGVs hence the lowest traffic density and speed. In terms of responsiveness to weather conditions, the consumeristic oriented socio-economic value scenario showed the highest response to weather conditions. This was due to it experiencing the highest traffic density hence more drivers making independent decisions on the link when responding to the weather conditions. The community oriented socio-economic value scenario on the other hand, showed the least sensitivity due to experiencing the least traffic density hence less drivers making independent decisions when responding to the weather conditions. The emissions levels had an impact on the traffic fluxes, with higher emissions levels showing higher vulnerability to changes in traffic fluxes compared to lower levels. This was observed from the traffic flux differences between the control and future scenarios where high emissions levels showed higher flux differences when compared to medium and low emissions levels.

The impact of autonomous vehicles on the traffic flux in both seasons under the CDSU was then discussed. Three different percentages of the composition of autonomous vehicles on traffic streams were investigated which were 33%, 67% and 100%. The presence of autonomous vehicles generally resulted in rises in the traffic flux and these rises increased with increasing percentage composition in the traffic stream. The sensitivity of the traffic stream to weather conditions also dropped with increases in the number of autonomous vehicles in the stream. This was due to more vehicles moving in platoons hence fewer independent decisions being made in response to the weather conditions.

The Effect of geographical location on traffic performance was investigated. It was observed that during the summer periods, Southern England appeared to observe higher rises in traffic flux between the control and the future scenarios than Northern Scotland which is a relatively wetter and colder location. While during the winter period, Northern Scotland showed higher rises in traffic flux compared to Southern England. Generally, it is expected that during summer periods dryer locations would show higher rises in traffic flux compared to wetter locations while during winter periods the reverse would be the case.

In conclusion, without taking other factors such as increased accident rates and damages to road infrastructure such as rutting, shoving and flooding into consideration higher emissions scenarios are expected to result in increased Trunk Road traffic capacity due to reductions in precipitation during summer periods and snowfall hours being replaced by rainfall hours during winter periods due to rises in temperature. It should be noted that increase in the average temperatures may result in better driving conditions. But increase in the maximum temperature may pose risks to the strategic network in the form of increased irritability of drivers. This could result in aggressive driving and damages to the infrastructure as pointed out in section 2.1. The presence of autonomous vehicles would generally result in rises in traffic capacity and reduced sensitivity of the traffic stream to weather conditions. Geographical location is projected to impact future traffic performances. Dryer locations are expected to show higher capacity rises compared to wetter locations during summer periods and the reverse is expected during winter periods.

A possible extension to this research may include an insight into possible rises in accident rates and frequency of infrastructure damages in the future as this may compliment the results obtained in this thesis.

In the next chapter there will be a general discussion on the results and key findings of this research, the limitations of the methodologies used and how they influenced the results as well as possible future researches related to this topic.

Chapter 7 – Conclusion

7.1. Summary

This section summarises the thesis including key methods featured in the paper.

The aim of the thesis was to investigate how future weather conditions would affect traffic capacity on the UK Trunk Road network. To achieve this aim, four main objectives had to be met. These objectives were:

- To investigate the impact of projected future weather conditions on the UK road network under the Current Development system of the UK.

  How would changes in the weather conditions affect the traffic flux?

- To investigate the impact of changes in the Current Development System of the UK on the future traffic flux

  Would changes in the current government nature and socio-economic values have an impact on the future traffic flux under future climate?

- To investigate the impact of technological advancements in the UK on future traffic flux

  Would the introduction of autonomous vehicles on the UK road network have a significant impact on the future traffic flux?

- To investigate how the traffic fluxes of different geographical locations of the UK may be affected by future weather conditions

  How would the future traffic flux of various geographical locations in the UK respond to changes in the weather condition?

To fill the knowledge gaps when attempting to meet these objectives, initial reviews on related topics were carried out. This began by reviewing the impact of weather conditions on road networks. The result of this review revealed that precipitation is the main weather factor affecting road traffic flow. It affects the flow by influencing drivers' behaviours and road infrastructure. Capacity reductions in the range of 2-14% were identified for rainy conditions with speed reductions in the range of 2-6% while capacity reductions of 4-22% were identified for snowy conditions and speed reductions in the range of 4-13%.

The thesis therefore focused on the future impact of precipitation on traffic flow. A traffic flow model was required to analyse this impact. Developing a traffic flow model is often an important step when analysing a real-world traffic system. To determine the resilience of a road to future climatic conditions it was important to have in place a traffic flow model of the road to be observed which was then subjected to various future weather conditions generated from the UKCP09 weather generator to determine their effects on traffic performance.

Traffic flow modelling was therefore discussed covering its various classifications which were macroscopic, mesoscopic and microscopic traffic flow models. The various classifications have their pros and cons when utilising them for various applications but for this research the microscopic model was chosen. This was because detail interactions between drivers and drivers and their environment were required when investigating intrinsic factors of traffic streams. These can only be investigated by considering the behaviours of drivers such as the average acceleration and start-up loss times. Microscopic traffic flow models are generally split into two parts which are the car following model and the lane changing model.

Car following models may be classified into three categories depending on the logic they are based on which are Gazis-Herman-Rothery models (GHR), Safety-distance models, Psycho-physical car-following models. The psycho-physical car following model category which utilises thresholds for various parameters such as the minimum speed difference between follower and leader perceived by the follower, appeared to be the most realistic modelling method and was therefore used in the microscopic traffic flow model designed. Paramics car following model is an example of the psycho-physical car following model. It utilises thresholds for various parameters such as separation between the leader and the follower as perceived by the follower. It was featured in the traffic flow model designed.

Lane change modelling is an integral aspect of multiple lane microscopic traffic simulation and it involves complex decision making by the model drivers which often rely on several objectives that sometimes conflict. In most cases lane change durations often range between 4-6 seconds.

This thesis introduced a new timing method which is a derivation of the conventional lane change timing method (expressed in seconds) used in previous works. In this method, time expressed in seconds was replaced with interest levels. The interest level of a driver may increase or decrease by one level or remain unchanged during each time-step. The levels ranged from 0 to 50, the maximum level 50 was adopted from the average lane change duration utilised by other works. This model was designed based on the UK Highway Code and drivers looking to switch lanes for better driving conditions took this into account when deciding.

The next step was to review the fundamentals of traffic flow where it was revealed that road traffic is characterised by the traffic flux (flow rate), the density and the mean speed. The road traffic flow fundamental diagrams showed the states of a given traffic which are usually of major concern. The states were identified as free flowing traffic where vehicles travel freely without being impeded by other traffic, saturated traffic where vehicles queue and move at very low speeds because of the maximum density reached and capacity traffic which is the maximum flow rate on the link. The fundamentals of traffic flow were used to validate the simulation output which involved comparing them to outputs of the simulation for consistency.

The factors affecting the future of road transport were then investigated. They were grouped into independent and dependent factors. The independent factors constitute the nature of governance and the social and political values of a given society while the dependent factors constitute the economic and demographic growths as well as the technological advancement of the society. The nature of governance of the society may be interdependent or autonomous while its social and political values may be consumeristic or community oriented. Emissions levels were drawn from the nature of governance of the society while the social and political value of the society was used to identify the nature of the vehicle fleets on the road network. The conventional development system of the UK (CDSU) was defined in terms of the interactions between the independent factors and these interactions were used to define possible changes to the CDSU.

Technological advancement was the only dependent factor that was considered in this thesis. The introduction of autonomous and connected vehicles is one of the main factors that are likely to impact the UK road network by the 2050s.

Socially, even with the advancement in vehicle technologies an average driver in the UK still spends an average of 235 hours driving because 100% concentration is still required. In terms of safety, over 90% of road accidents have been attributed to human error. Connected and autonomous vehicles have the potential to change the dynamics of the UK roads. Its impact could change the basics of motoring improving various factors such as improved road safety and social inclusion, reduced emission and ease congestion which could result in significant economic, environmental and social benefits.

Vehicle platooning is an important innovation in the automotive industry which involves the formation of platoons by two or more in-lane vehicles which possess at least level 2 automation enabling them to maintain close headways. Vehicle platooning has the potential of reducing traffic congestion and increasing road capacity by up to 300%. Vehicle platooning was featured in the thesis to show the impact of autonomous vehicles moving in platoons on traffic capacity.

The next step was then to design and implement the traffic flow model used for the thesis. The traffic flow model was designed using MATLAB and it was based on Paramics car following model, the UK Highway code, an innovated lane changing model and the maximum acceleration of vehicles under various weather conditions was modelled using Rakha et al. (1999)'s vehicle dynamics model for estimating maximum vehicle acceleration levels. The introduced methodology used in the model is so robust that it can be used to design traffic flow models containing any number of lanes, vehicle density and road length pending the computational power of the platform the simulator is to be run on. The roads featured in this thesis were a roundabout and a signalised 3 lanes trunk roads which were both 1km long.

The traffic flow model was used to simulate the interaction of drivers and drivers and their environment in traffic streams. The output of the simulations which were mainly the traffic flow rates, mean speed and density under free flow, capacity and saturated traffic states were later used as inputs to the Integrated Weather Impact Simulator (IWIS) along with the weather data and the user inputs.

Validating the simulation output involved comparing the outputs to the fundamentals of traffic flow for consistency. While validating the impact of weather conditions on the output of the simulations involved comparing the outputs to the result of the research carried out by Agarwal et al (2005) to quantify the impact of rain, snow and pavement surface conditions on traffic flow. The 3-lane link had a capacity of 2973 vehicles/hour for the roundabout controlled traffic and 3129 vehicles/hour for the signal-controlled traffic under dry condition. For the roundabout controlled traffic, a capacity reduction of 5.7%, 7.6%, 9% and 11.3% were experienced under light rain, light snow, heavy rain and heavy snow conditions respectively. While for the signal-controlled traffic, a capacity reduction of 4.6%, 9.8%, 11% and 15.9% were experienced under light rain, light snow, heavy rain and heavy snow conditions respectively. The percentages obtained were all within the percentage ranges established by Agarwal et al (2005).

The next step was then to discuss the weather generator and its output data which were later used as inputs to the IWIS. The weather generator can make future weather projections under various emissions scenarios and its output data was important when making future impact projections on traffic capacities.

The UKCP09 weather generator has been deemed to have an issue with spatial correlation which occurred when multiple adjacent square grids were highlighted when using the weather generator (WG). Weather for each square grid were not presented instead the average weather for the entire highlighted square grids were presented which may not represent a realistic weather projection of the individual square grids since it did not account for the weather differences between high level areas and low-level areas. This issue was addressed in this thesis by introducing various methods proposed to compensate for the issue.

The weather data generated using the WG showed that each emission scenario had a certain degree of impact on the future climate with high emission having the most impact. Reductions in summer precipitated hours and rises in winter precipitated hours for the future scenarios indicated that the weather data was consistent with the general projection of future dryer summers months and wetter winters months. This was later reinforced by the result of examining heavy precipitation only which indicated rises in extremely precipitated hours with potential rises in extremely high temperature for summer hours when observed. The weather outputs of each emissions scenario were later fed as inputs into the IWIS.

The next step was to discuss the design and implementation of the IWIS. The IWIS was a model designed due to the simulation speed limitation of the traffic flow model. It was used to integrate the traffic data, weather data and user inputs in order to make weather impact projections of traffic streams.

The precipitation classification method featured was based on the MET office method. Although the MET classification did not distinguish between snowfall and rainfall, the temperature levels given by the UKCP09 weather generator were air temperatures just above the ground. Various authors noted that snow forms when the atmospheric temperature is at or below freezing (0 degrees Celsius) and there is a minimum amount of moisture in the air. If the ground temperature is at or below freezing, the snow will reach the ground. It was also mentioned that snow usually settles when the air temperature on the ground is below 0^oC. Therefore, in this thesis it was assumed that precipitation fall at temperatures at or below 0^oC resulted in snowfall which settled while others resulted in rainfall.

The outputs of the IWIS were presented in Cumulative Distribution functions (CDF) and Probability Density functions (PDF). The CDF was used to determine the probability of measuring any value up to and including a given value (e.g. a given traffic flux) while the PDF magnitude would be some indication of the relative likelihood of measuring the given traffic flux.

The next was to discuss the outcomes of investigating various socio-economic scenarios including the conventional development system of the UK, the impact of technological advancement (autonomous vehicles) and the effect of geographical location on the traffic performance. These investigations were intrinsic to the objectives of the research.

The impact of the various emissions scenarios on the two link types (signalised and roundabout controlled) under the summer and winter seasons were discussed under the conventional development system of the UK (the CDSU), a more consumeristic oriented scenario and a more community-oriented scenario.

The impact of autonomous vehicles on the traffic flux in both seasons under the CDSU was also discussed. Three different percentages of the composition of autonomous vehicles on the traffic stream were investigated which were 33%, 67% and 100%.

The effect of geographical location on traffic performance was discussed. In terms of climatic conditions two distinct locations were investigated which were Northern Scotland and Southern England.

7.2. Result Discussions

The outcome of addressing the objectives of this thesis showed that:

Objective 1

To investigate the impact of projected future weather conditions on the UK road network.

How would changes in the weather conditions affect the traffic flux?

The traffic fluxes of each traffic streams responded to the emissions levels of the scenarios. During summer periods higher emission levels where the weather appeared to be drier showed higher traffic fluxes. This was because without taking other factors into account such as rises in traffic demand, accident rate and damages to road infrastructure, the projected future weather conditions which are relatively warmer than their base conditions under each emissions scenario generally resulted in better driving conditions hence better traffic flux. It should be noted that increase in the average temperatures may result in better driving conditions but increase in the maximum temperature may be where the real threat lies. Two link end conditions (signalised and roundabout controlled) were used for this investigation and the projections of the headway, acceleration, response time and traffic flux are shown in table 7.1.

Headway	Headway reductions range (%)	Headway reductions central projection (%)	Acceleration rise range (%)	Acceleration rise central projection (%)	Response time reduction (%)	Response time reduction central projection (%)	Traffic flux loss range (-%)	Traffic flux loss central projection (%)
Roundabout								
Summer								
High	4.71-5.95	5.95	N/A	N/A	N/A	N/A	10.93-28.76	-18.32
Medium	2.58-4.81	4.81	N/A	N/A	N/A	N/A	7.75-28.40	-16.93
Low	0.51-1.68	1.05	N/A	N/A	N/A	N/A	2.98-30.90	-16.91
Winter								
High	3.54-9.96	3.54	N/A	N/A	N/A	N/A	8.22-12.95	-9.89
Medium	2.54-7.24	2.54	N/A	N/A	N/A	N/A	5.15-12	-8.41
Low	3.57-8.68	3.57	N/A	N/A	N/A	N/A	7.35-14	-10.26
Signalised								
Summer								
High	N/A	N/A	5.46-10	9.62	2.22-3.76	2.22	11.05-28.51	-18.58
Medium	N/A	N/A	3.64-5.77	3.70	0.75-1.55	0.75	7.76-28.09	-17.11
Low	N/A	N/A	0-1.89	0	0-0.74	0.74	4.92-31.18	-16.85
Winter								
High	N/A	N/A	5.88-11.91	6.12	2.70-3.47	3.40	11.47-15.69	-13.63
Medium	N/A	N/A	1.96-5.77	1.96	0.69-1.36	0.69	8.74-15.44	-11.66
Low	N/A	N/A	3.77-5.46	3.77	0.67-1.40	0.69	9.88-16.59	-12.56

Table 7.1: Future projections for various traffic variables

The summary of table 7.1 is future summer periods would experience drier conditions which would provide better traction resulting in better acceleration, reduced headway and increased response times of the drivers due to higher drivers' aggression. Similarly, future winter periods would also experience this effect as snowy conditions will be reduced and rainy conditions will be increased resulting in better traction, increased response time and reduced headways. Furthermore, although during the winter period there was no clear relationship between the emissions levels and traffic performance, generally it could be said that higher emissions levels are projected to result in higher rises in traffic fluxes. This is because of higher rises in temperature and precipitation loss.

Objective 2

To investigate the impact of changes in the current UK development system on the future traffic flux

> *Would changes in the current government nature and socio-economic values have an impact on the future traffic flux under future climate?*

Table 6.18 examined the percentage differences of the consumeristic and community-oriented scenarios traffic fluxes under each weather condition from those of the CDSU.

From the table, the consumeristic scenario showed rises in flux where the rise ranged from 0.37% to 0.43% for the roundabout controlled road and 0.04% to 0.06% for the signalised road. While the community showed the flux reductions ranging from -0.17% to -0.22% for the roundabout controlled road and -0.06% to -0.10% for the signalised road.

Figure 6.9: compared the traffic flux percentile differences of the socio-economic scenarios and the CDSU for the various link types under the various seasons. The results obtained indicated that higher vehicle densities in a traffic stream were more prone to weather conditions than lower vehicle densities. This was because both the consumeristic and the CDSU had higher vehicle densities compared to the community value which had more HGVs hence less density.

Since the consumeristic scenario and the CDSU were more sensitive to changes in weather conditions the summer period experienced higher fluxes compared to the community scenario because of drier conditions while during the winter period the reverse was the case due to wetter conditions. The figure also indicated that the emissions levels had an impact on the traffic fluxes, with higher emissions levels showing higher vulnerability to changes in traffic fluxes compared to lower levels. This was observed from the traffic flux differences between the control and future scenarios where high emissions levels showed higher flux differences when compared to medium and low emissions levels as shown in table 6.19 and figure 6.9.

In summary, an insight into the impact of weather on traffic performances under each socio-economic scenario revealed that for both seasons a more consumeristic oriented socio-economic value resulted in higher traffic capacity on both link types under each emissions scenario compared to the CDSU. While a more community oriented socio-economic scenario which showed the least traffic capacity. The reason was because the consumeristic oriented socio-economic scenario featured more cars (privately owned) hence experienced higher traffic density and speed compared to the CDSU. While the community oriented socio-economic value scenario which featured the highest number of HGVs showed the lowest traffic density and speed.

In terms of responsiveness to weather conditions the consumeristic oriented socio-economic value scenario showed the highest response to weather conditions. This was due to experiencing the highest traffic density hence more drivers making independent decisions on the road when responding to the weather conditions. While the community oriented socio-economic value scenario showed the least sensitivity due to experiencing the least traffic density hence less drivers making independent decisions when responding to the weather conditions.

Objective 3

To investigate the impact of technological advancements on future traffic flux

Would the introduction of autonomous vehicles on the UK road network have a significant impact on the future traffic flux?

The impact of autonomous vehicles on the traffic flux in both seasons under the CDSU was investigated. Three different percentages of the composition of autonomous vehicles on the traffic streams were investigated, which were 33%, 67% and 100%. The presence of autonomous vehicles generally resulted in rises in the traffic flux and these rises increased with rises in the percentage composition as shown in table 7.2.

Traffic Parameters	Normal (Dry)	Light Rain	Light Snow	Heavy Rain	Heavy Snow
Roundabout Controlled Link					
Autonomous percentage	Maximum Capacity (veh/hr)				
100% Manual	0	0	0	0	0
33%	49.05	51.23	51.71	52.87	53.78
67%	136.80	143.26	145.12	148.84	150.69
100%	201.23	212.33	216.07	221.19	223.32
Signal Controlled Link					
Autonomous percentage	Maximum Capacity (veh/hr)				
100% Manual	0	0	0	0	0
33%	56.25	57.91	62.84	60.53	63.61
67%	118.54	122.91	130.40	130.36	137.60
100%	181.66	190.23	199.42	204.43	216.20

Table 7.2: Percentage increases in the traffic capacity under each autonomous vehicle percentages on the roads

From table 7.2 increases in the number of autonomous vehicles on both road types resulted in increases in the flux. Traffic streams containing autonomous vehicles also showed lower vulnerability to changes in the weather conditions. This can be observed in the progressive rises in the percentage increases in the traffic capacity from dry condition to heavy snow condition for both link types. This could also be observed when the traffic flux percentage differences of each weather condition were compared to the dry condition as shown in table 6.21. From the table the 100% manual vehicles fleet showed the highest vulnerability to weather conditions. This was because it showed the highest traffic flux reductions as the severity of the weather condition increased. Its traffic flux reduction ranged from -5.68% to -11.12% for the roundabout controlled link and -4.12% to -15.29% for the signalised link. While the 100% autonomous vehicles traffic stream showed the least vulnerability with a reduction range of -2.2% to -4.6% for the roundabout controlled link and -1.2% to -4.9% for the signalised link.

Under each emissions scenario, figure 6.21 indicated that in most cases the traffic flux percentile differences for each fleet composition reduced as the emissions scenario moved from high to low. This can also be observed from the narrowing gap between the control and future scenario CDF curves for the traffic flux differences shown in appendix 5. The length of each bar was an indication of the sensitivity of the traffic stream to the emissions scenarios. Shorter bars indicated lower sensitivity and from figure 6.12 generally as the percentage of autonomous vehicles contained in the traffic stream increased the sensitivity of the stream to climatic conditions reduced.

In summary, the presence of autonomous vehicles generally resulted in rises in the traffic flux and these rises increased with rises in the percentage composition. The vulnerability of the traffic stream to weather conditions also dropped with increase in the number of autonomous platooning vehicles. This resulted in less independent decisions being made in response to the weather conditions.

Objective 4

To investigate how the traffic fluxes of different geographical locations of the UK may be affected by future weather conditions

> *How would the future traffic flux of various geographical locations in the UK respond to changes in the weather condition?*

The Effect of geographical location on future traffic performance was investigated. In terms of climatic conditions two distinct locations were investigated which were Northern Scotland and Southern England.

Analysis of the future weather conditions for both regions showed that Southern England is more prone to rises in temperature compared to Northern Scotland. Also, during summer periods, southern England is more prone to reductions in precipitation levels compared to northern Scotland. While during winter periods, the northern region showed higher susceptibility to precipitation loss. This resulted in southern England observing higher increases in traffic flux between the control and the future scenarios during summer periods compared to northern Scotland which is a relatively wetter and colder location. While during the winter period northern Scotland showed higher rises in traffic flux compared to southern England.

Generally, it is expected that during summer periods dryer locations would show higher rises in traffic flux compared to wetter locations while during winter periods the reverse would be the case.

7.3. Conclusion

Future climatic conditions are expected to result in rises in accident rates, damages to road infrastructures such as rutting, shoving and flooding but without taking these factors into consideration, higher emissions scenarios are expected to result in increased trunk Road traffic capacity. This is evident due to reductions in precipitation during summer periods and snowfall hours being replaced by rainfall hours during winter periods due to rises in temperature. This generally means better driving conditions for the drivers such as improved vehicle traction, higher reaction times, reduced headways etc. Generally, increase in the average temperatures may result in better driving conditions but increase in the maximum temperature may pose a threat to the strategic road network. This could be in the form of increased irritability of drivers which could result in aggressive driving as well as damages to the infrastructure.

The presence of autonomous vehicles would generally result in rises in traffic capacity and reduced sensitivity of the traffic stream to weather conditions. Rises in the traffic capacity levels are experienced because autonomous vehicles can move in platoons. This enables them to maintain close headways at high speeds with relatively higher reaction times compared to human drivers. The sensitivity of the traffic streams to weather conditions reduce because fewer independent decisions are made when vehicles move in platoons hence more consistency in the traffic stream.

Geographical locations influence traffic performance with dryer locations showing higher flux rises compared to wetter locations during summer periods and the reverse being the case during winter periods.

The findings of this research may be used by policymakers as well as stake holders when planning future adaptation strategies for climate change. For example, policymakers may want to determine the impact of implementing changes to vehicle excise duty (VED) on traffic flux. Generally, rises in VED would result in more people being swayed towards public transport hence reductions in private vehicles on the road network and increases in public vehicles (HGVs). This would mean a reduction in the traffic flux of the road network but reduced traffic stream sensitivity to weather conditions. It may also be used when planning to implement HGV restrictions on certain routes. The findings may also be used to determine the impact of introducing autonomous vehicles into the UK road network. The result of this research has shown that autonomous vehicles are capable of increasing traffic capacity by over 200% while also reducing its sensitivity to weather conditions. Policymakers and stakeholders may want to work towards promoting the use of autonomous vehicles on the UK road by reducing VEDs for such vehicles, insurance premiums as well as revising regulations to support the R&D of such vehicles. They may also want to restrict the number of manually driven vehicles on areas that are the most prone to climatic changes by promoting the use of autonomous vehicles in such regions using various incentives such as insurance subsidy for autonomous vehicles in those regions.

Highways England, which was formerly referred to as the Highways Agency is the UK government owned entity in charge of operating and improving the 4,300 miles of motorway and major A-roads forming the strategic road network which is one of the country's most important infrastructure assets. A resilient and effective strategic road network is an important aspect of a strong growing economy. Climate change poses a major threat to the operation of the UK strategic road network which is why Highways England is currently engaged in minimising the causes and managing the risks involved with it. Among other activities, doing so involves carrying out research projects related to resilience, adaptability and sustainability of the network. This thesis provides valuable knowledge in these core areas to both Highways England and their partner stakeholders which include owners of other UK infrastructure systems, freight organisations, local authorities, technology and innovation partners, sustainability and environmental bodies and motorway service operators.

The results found in this thesis may also be viewed as an initial stage for future researches that may be carried out in similar fields where factors such as the impact of demographic and economic growth and changes in accident rate may be considered.

7.4. Limitations

The main limitation of the model was that it was very slow and simulating road transport peak periods in the UK which often lasts up to 3 hours (108,000 time steps) would have taken unreasonably long periods of time to simulate. Due to this limitation smaller time samples were simulated, and the result of the simulations were then used to extrapolate much larger time frames.

The drawback of this method is each hour observing the same weather condition would have a homogeneous traffic flux. This is different compared to the traffic flux output being heterogeneous if the traffic flow simulator simulated the entire hours of each weather data resulting in richer projected impacts on the future traffic flux. An alternative method would have been to set up thresholds for the temperature or precipitation levels which could be 2 or more thresholds for each weather conditions (dry, light rain, light snow, heavy rain and heavy snow).

For example, the dry condition may have various level of dryness based on the number of thresholds used. Various simulations may then be carried out for dry weather conditions. During the stabled state of the simulation, under the same conditions the outputs of the simulation will be somewhat similar but not entirely. There will be certain variations in the traffic flux but these variations were not taking into consideration during this research. Considering these variations may be used to create a somewhat heterogeneous simulation. This could be done by using the highest output of the simulation as the upper band of the threshold and the lowest output as the lower band. Dry weather condition would then have multiple traffic flux levels and dry conditions with temperatures within the upper band may be set to experience the highest flux and those within the lowest band may be set to experience the least traffic flux for the dry weather conditions. The precipitated weather conditions could also be given sublevels by considering the temperature levels or the precipitation levels or even both variables. This method would result in a more heterogeneous output.

The limitation of this method is the timescale required to carry out multiple traffic flow simulations under each weather condition. For example, if three threshold values were used for each weather condition then running the entire simulation would be 3 times longer than using a single value for each weather condition. For this reason, only a single value was used for each weather condition.

7.5. Future Research

A possible extension to this research may include an insight into possible rises in accident rates, demographic and economic growth in the future as this may compliment the results obtained in this thesis. In her paper, Hooper (2013) identified how accidents occurring during wet weather impact on traffic speed and flow at a local scale in the UK. It was found that speed reductions can last for up to three hours after an accident and that the recovering time after an accident in wet weather condition is significantly higher than in dry conditions.

The behaviour or drivers and accident rates could be linked. Generally, higher temperatures (especially the maximum temperatures) result in rises in accident rates and the severity of the accidents while lower temperatures also result in increased accident rates but reduced severity. The complexity of the model could be increased by including accident occurrences and recoveries. Accidents could be accounted for in this traffic flow model by periodically including bottle-necks on the links during simulations where lanes may be forced to temporarily merge. Recovery times may be varied by the severity of the accident. More severe accidents would be expected to require more time for recovery than the less severe ones. Lane sections where an accident occurred may remain closed until the recovery time has elapsed.

Furthermore, a more complex traffic flow model capable of processing multiple simulations within relatively short periods of time may result in more sophisticated traffic flow outputs. The new point-based system for lane changing introduced in this thesis was proven to be effective and simple to implement hence it may be featured in a more complex model.

As mentioned in section 7.4, using multiple sublevels for each weather conditions may provide richer simulation output. The more the sublevels used the more heterogeneous and richer the output would be. A reasonable trade-off between the quality of the result and the timescale available for the research would be essential.

This research assumed that designated lanes would be assigned to autonomous vehicles. While this has its advantages in terms of safety and promoting vehicle platooning which in turn improves capacity, a research that explores cases where there are no regulations that promote platooning lanes may be investigated. Such cases may investigate the implications of having manually driving vehicles mixing up with autonomous vehicles where platoon may be interrupted. Safety measures that may be in place to avoid crashes between vehicles moving in platoons as well as manually driven vehicles that may interrupt these platoons may also be considered.

A wider research focused on the effect of geographical location on traffic performance may also be investigated. This research focused on just two distinct locations of the UK which were Northern Scotland and Southern England. It could be expanded to take other regions of the UK into account such as west midlands. This would provide a clearer picture of how traffic performance may be affected in the different regions.

The methodology featured in this thesis can feature a wide range of lane numbers containing either roundabout or signalised link end depicting various link types in the UK. These links could then be subjected to the projected weather conditions for the various regions of the UK to investigate the resilience of a link in that region to future weather conditions. The links featured in this thesis were 1km long, but the method used for the design could be used to design longer links for researches focused on individual corridors such as London to Carlisle (via M1 and M6), featured in Hooper (2013) paper. For longer links the methodology introduced in chapter 4 used to extrapolate weather conditions based on land altitude from sea level could be used to compliment the issue of spatial coherency when using the UKCP09 to generate weather data for the location.

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Appendices

1. Weather and Road Transportation

Inclement weather and Road Transportation

There is a significant support that the frequency of extreme weather events will increase over the next century (Katz et al., 2002; Wagner, 1999; Leavesley, 1994). This increase would be due to the continuous increase in the global temperature which would lead to continuous extreme weather out of the ordinary being experienced. Increase in the global temperature would result in hotter, drier summers; warmer, wetter winters; and increased frequency of extreme storms (Baker et al., 2010). It is generally accepted that inclement weather has negative effects on transportation (Koetse and Rietveld, 2009). Satterthwaite (1976) assessment of weather and seasonal effects on motorway accidents in California showed that weather was a major factor indicating that accident frequency during very wet days was twice the rate during dry days. The Federal Highway Administration (FHWA) Road Weather Management program defines weather-related crashes as those that occur in the presence of *inclement weather* and/or *slick pavement* such as wet, snowy/slushy, and icy pavements (Pisano et al, 2007). There have been several studies on the impact of weather on road accidents (such as Keay and Simmonds, 2006; Andrey and Yagar, 1993; Aguero-Valverde and Jovanis, 2006; Andreescu and Frost, 1998). Most of these studies related accident count for the region of study to meteorological data from either road weather information system (RWIS) or meteorological station and they mostly expressed the impact of weather on accident rate in relative accident rate (RAR) derived from the comparison of the accident count during a period of inclement weather conditions to a corresponding period which is usually a close period to the period of inclement weather conditions (perhaps a day or a week from or before the conditions) known as matched pairs. Regression method was also used by other studies; it involved comparing the amount of precipitation to accident counts including more information about other factors involved such as traffic volumes (Eisenberg, 2004; Jaroszweski et al, 2014).

Although the effect of weather conditions on transport has been studied extensively, only a few studies have investigated the effect in the UK (e.g. Hooper, 2013) but with the recent availability of Highways England Traffic Information System (HATRIS) data more studies in this area can now be carried out in the UK. According to the USDOT (2014) weather affects vehicle performances (such as traction, manoeuvrability, and stability), driver capabilities, pavement friction, crash risk, roadway infrastructure, agency productivity and traffic flow through precipitation, visibility impairments, high winds and temperature extremes. Jaroszweski et al (2014) split these effects into two main categories which are those that occur as a result of behavioural changes to driver/agent due to the stress induced by weather such as speed reductions due to rain (Hooper et al., 2012) and those that are influenced by physical failure of the infrastructure or by the set off of natural disasters such as low temperature induced potholes. Highways England (Highways England, 2016) which is a government owned entity, is devoted to understanding, assessing and taking appropriate management actions to mitigate the risks faced by strategic road networks due to changing climate. They do this by following a climate change strategy and adaptation framework which provides a consistent approach to assessing and understanding the risks faced by the strategic road network. In their paper (Highways England, 2016) Highways England identified various trends that England will experience up to 2080 under a high emissions scenario from the UKCP09.

The Impact of extreme weather on the UK Road networks

Precipitation

Intense precipitation is particularly expected to occur more frequently due to the increase in global temperature (Fowler and Hennessy, 1995). It is recognised as the major weather factor which affects road transportation due to its influences on congestion and safety (Koetse & Rietveld, 2009). In several studies, it has been shown that precipitation in the form of rain and snow has led to more *accidents* (Codling, 1974; Satterthwaite, 1976; Sherretz and Farhar, 1978; Brodsky and Hakkert, 1988; Fridstrøm et al., 1995; Levine et al., 1995a; Edwards, 1999; Eisenberg, 2004). There are also evidences that wet or snowy weather especially when accompanied by severe storm could discourage drivers from embarking on journeys leading to a reduction in traffic volume (Knapp and Smithson, 2000). In the UK precipitation is a major hazard on road networks because it tends to occur all year round (Hooper, 2013).

Effects of Precipitation on Road Networks

Precipitation being the main weather factor affecting road transport has been known to affect it through various ways. These include behavioural changes to drivers/agents such as speed reduction due to visibility impairment, and physical failure of infrastructures such as temperature induced potholes. Its impacts which affect driver capabilities (such as visibility), pavement friction, crash risk, roadway infrastructure, productivity and traffic flow have been split into three main categories:

- Traffic Congestion and Speed reduction
- Traffic Safety
- Roadway Infrastructure

Traffic Congestion and Speed reduction

Traffic flow and speed are affected by precipitation leading to increase in journey times which would most likely be exacerbated in the future should there be rises in precipitation levels. A study by (Keay and Simmonds, 2005) on Melbourne roads, Australia showed that rainfall especially during winter and spring had the greatest impact on traffic volumes. A similar study by Akin et al. (2011) on urban motorways in Istanbul showed a similar result. These studies along with studies by Hooper et al. (2012) and El Faouzi et al. (2010) also pointed out that inclement weather especially rainfall led to significant speed reductions and increased traffic congestion while snow led to a significant reduction in the demand for the road hence a reduction in traffic volume. Khattak and Knapp (2001) examined Iowa motorway data and discovered that traffic volumes on the motorway reduced by 30% during snowy conditions compared to normal dry conditions and rainy conditions. This was also discovered by ElDessouki et al (2004) during an examination on accident risk on Connecticut motorways. While most studies concentrated on motorways Keay and Simmonds (2005) study was focused on an urban area in Melbourne while Hooper et al. (2012) study although was more focused on a motorway between London and Glasgow in the UK it included several sections which passed through urban areas. It was discovered in both urban studies that increased rainfall led to reduction in speeds and increased traffic congestion, this result is like the studies carried out on motorways, but the speed reductions are less significant on the motorways as pointed out in a literature review by Pisano and Goodwin (2004) regarding weather effects on urban arterials.

Other studies involving the relationship between precipitation and speed include Stern et al. (2004) study on metropolitan Washington DC where travel time data was combined with weather data to analyse the effect of weather on travel times. The method used is like the one used by Hooper et al. (2012) because they both featured weather radar; Ibrahim and Hall (1994) study on the impact of bad weather conditions on driving on motorway, which study showed that when it rained slightly the driving speed decreased by approximately 2km/h, when it snowed slightly the driving speed decreased by approximately 3km/h, when it rained heavily the driving speed decreased by between 5km/h to 10km/h and when it snowed heavily the driving speed decreased by between 38km/h to 50km/h. The figures by Ibrahim and Hall (1994) are in line with the figures on the Highway Capacity Manual (2010) which indicated that highway speed is reduced by between 2% and 17% if more than 6mm/h. It was also indicated in the manual that highway capacity declines by 15% which is in line with Agarwal et al's (2005) study which indicated capacity reduction of up to 17% and Chung et al. (2006) study which indicated up to 7% for light rain and 14% for heavy rain.

Ways in which Precipitation affects Traffic congestion

Precipitation has been known to influence traffic congestion through:

- Visibility impairment
- Reduced traction
- Flooding

Visibility impairment: Road authorities in the UK have had major concerns about the reduction of drivers' visibility due to precipitation which is usually through heavy rainfall, mist, fog and blizzard. Drivers often travel at lower speeds in low visibility conditions to anticipate traffic and other road obstructions sometimes resulting in traffic congestion and increased journey times. Maze et al. (2006) discovered that when visibility was less than 0.25 miles, a 12% reduction in speed occurred in the Minneapolis / St. Paul area over a four-year study period. Kyte et al. (2001) explicitly defined a critical visibility distance of 0.3 km (0.18 mile), below which speed was reduced by 0.77 km/hr (0.48 mph) for every 0.01 km (0.0062 mile) reduction in visibility. Visibility is severely reduced during heavy precipitation events because of both the transparency of the windscreen being reduced and as a result of vehicles creating clouds as they pass through snow or wet surfaces (Edward, 2002). Ishimoto and Yoshifumi (1993) carried out a study involving vehicle snow spray on roads and discovered that as the temperature of a road surrounding drops snow particles on the surface of the road are easily blown up due to reduction in cohesion of the snow particles leading to a reduction in visual range. They also discovered that larger vehicles created larger snow clouds and the extent of the snow cloud depended on the size of the vehicle.

Splash and spray occur due to various factors and various methods have been introduced to reduce their effect by retrofitting devices on vehicles (especially heavy vehicles) that alter their aerodynamics (Pilkington II, 1982). Altering various characteristics of the highway pavement such as pavement geometry, drainage, texture and porosity have also been considered. Rungruangvirojn and Kanitpong (2009) investigated the impact of splash and spray on visibility for porous asphalt (PA), stone mastic asphalt (SMA) and conventional dense graded asphalt pavements. Two different approaches were used for the investigation which were light reduction method (LMR) and colour changing method (CCM). Their result revealed that pavement characteristics affect visibility loss. Visibility loss on conventional dense grade asphalt pavement was 1.4 times higher than SMA and PA.

Traction: Inclement weather conditions on the roads cause road friction reduction (Rowland et al., 2007). Traction shows the magnitude of the frictional force that is present between the tires and the pavement during the execution of a given response by the driver such as accelerating, steering and decelerating. As the amount of precipitation on a road pavement increases vehicle manoeuvrability becomes increasingly difficult up to a point where vehicles become completely uncontrollable (FHWA, 2009). Ice and snow have been shown to affect vehicle traction, driver capability and behaviour (Rowland et al. 2007). Eriksson and Lindqvist (2001) suggested that road icing usually occurs during a shift from a period of cold and stable weather to warmer weather. This shift is usually accompanied by rainfall or wet snow on the road surface and since the air around the road surface warms up faster than the road itself it leads to icing of the road.

Drivers often reduce their speed when driving on surfaces with high precipitation to maintain vehicle traction. This speed reduction sometimes results in traffic congestion and increase in journey times. In some cases, entire roads get shut down due to slippery conditions. The Federal Highway Administration (FHWA, 1977) in the US offered a weather classification scheme to the study of the impact of snow and ice on motorway systems. The classification ranged between dry roads with a percentage speed reduction of 0% and snow packed road with a percentage speed reduction of 42%.

Flooding: Among all the precipitation factors flooding has been known to have the greatest impact on road traffic congestion. It occurs because of overflowing rivers commonly known as fluvial flooding (river flooding), heavy rainfall over a short time period commonly known as pluvial flooding (flash flooding) or an unusual inflow of sea water into land commonly known as ocean flooding which are sometimes caused by storms, high tides or seismic events. Pluvial flooding has been referred to as the most problematic type of flooding (Hooper, 2013). Flooding is expected to increase especially along river valleys and in coastal communities due to sea level rise and increased frequency of storms and hurricanes because of increase in precipitation (Penning-Roswell et al., 1996; Weijers and Velinga, 1995, Clarke et al., 2002). Knox (2000) paper on Sensitivity of modern and Holocene floods to climate change shows that small changes in average temperature (between 1-2^{o}C) and annual rainfall could lead to changes in the magnitude and frequency of flood. Increase in journey times or in worst cases entire trips being cancelled could occur due to flooding because of sections of the road network being flooded. Increase in journey times could occur because of diversions being implemented from for example high capacity roads such as motorways and A roads into lower capacity roads that are not designed to handle high traffic volumes leading to traffic congestion. Trip cancellation could occur because of either the origin location or the destination location being flooded or flooding of links made it impossible for the traveller to get from their origin to destination.

Traffic Safety

Precipitation has been known to have a negative impact on traffic safety and is the most problematic weather factor on road transportation (Theofilatos and Yannis, 2014). As the amount of precipitation on a road network increases the safety of the network reduces, as a result accident rate on the road network increases. The effect of precipitation on road networks is quite consistent and generally leads to increased accident frequency (Andrey and Yagar, 1993, Scott, 1986; 1993; Fridstrøm et al., 1995; Theofilatos and Yannis, 2014; Edwards, 1996; Caliendo et al., 2007; Chang and Chen, 2005; Smith, 1982). Some precipitation factors have been known to be more dangerous than others. Precipitation factors which changes the general condition of road pavements (such as snow, ice and rainfall) making them more slippery than usual are generally the most problematic.

Although no statistical difference was found between heavy and moderate *rainfall* as they have similar effects a positive effect of rainfall on accident rate was found by Haghighi-Talab (1973). Andrey and Yagar (1993) study of crashes during and after rain events in Calgary and Edmonton, Canada led to a conclusion that during rainfall accident risk was 70% higher than accident risk under normal conditions. They mentioned that a combination of both low friction and visibility impairment resulted in rises of the risk levels during these conditions; they also suggested that even though the poor friction of the road due to wet condition was compensated by the drivers, visibility impairment reduces the overall safety of the road and increases crash risk. They observed that accident risk is reduced to regular levels just after rainfall events. Brodsky and Hakker (1988) used data from the United States and Israel to analyse accident risk during rainy conditions. They discovered that injury accident risk during rainy conditions was approximately 2-3 times higher compared to dry conditions. Few authors have argued that rainfall has little impact on the safety of some roads. Jones et al. (1991) argued that the safety of the freeways of Seattle is not very much influenced by rainfall but indicated that wet surface conditions has a consistent positive relationship with the safety. A 5-year analysis by Aguero-Valverde and Jovanis (2006) on injury and fatal crashes in Pennsylvania, US resulted in a conclusion that though total precipitation had a positive linear relationship in the traditional negative binomial models (certainty in modelling) it was not statistically significant in the hierarchical full Bayesian models (uncertainty or probability in modelling).

Some authors suggested that the more drivers are exposed to precipitation on road networks the lower the risk would be when the condition arises due increased risk awareness. This was suggested by Karlaftis and Yannis (2010) using Athens, Greece 21 years accumulated daily data count for accident. They discovered that increase in precipitation amount on the road networks could reduce the accident count. Since the precipitation levels of Greece are relatively low compared to other areas used for other studies this may be significant as drivers may become more cautious during wet conditions. Bergel-Hayatet al. (2013) found a similar result in Athens. Other studies (Khattak et al., 1998; Andrey and Yagar, 1993) have indicated drivers' compensation in inclement weather conditions. A parameter was contributed by Brodsky and Hakkert (1988) and later emphasised on by Eisenberg (2004) and Keay and Simmonds (2006). It is known as the lagged effect of rain which basically indicates that as the time from the last precipitation event increases accident risk increases as well. Their results which also applied for non-fatal crashes indicated that after two days from the last precipitation event has passed 1 cm of precipitation raises the fatal crash rate by approximately 3% and after 20 days by 9%. Theofilatos and Yannis (2014) suggested that the effect of snowfall may also show the lagged effect. The idea of lagged effect was however disputed by Brijs et al. (2008) and instead suggested that the intensity of rain was very significant.

Snowfall has been known to have a negative effect on the safety of road networks because of the hazardous conditions it leads to. Although accident rate has been known to increase by snowfall several studies (including Hooper et al. (2012)) and Khattak and Knapp (2001) indicated that fewer injuries were involved in accidents during snowy conditions compared to accidents without snowy conditions. Fridstrøm et al. (1995) suggested that as snowfall duration increases (in days) accident rate reduces implying that the most dangerous snow day is often the first day (Eisenberg and Warner, 2005). This is related to Elvik's (2006) law of accident causation which states that the rate at which a hazard occurs is proportional to its relative accident rate, with drivers getting more familiar with conditions that they are frequently exposed to. Fridstrøm et al. (1995) study showed that accident rate reduced by approximately 1.2% for each additional snow day in Denmark. This is in line with the risk compensation by drivers discussed earlier which suggested that as drivers become more exposed to precipitation on road networks they become more aware and cautious of the risk involved. Brude and Larson's (1980) also discovered this phenomenon in their study conducted in Sweden stating that areas less prone to snowy or icy conditions experienced more accident rates during the conditions than areas more prone to the conditions. Maze and Hans (2006) concluded that accident risk is 3.5 times more at the start of a winter season than at its end. Although a significant number of researchers agree with Elvik's (2006) law several researchers such as Andreescu and Frost (1998) and El-Basyouny and Kwon (2012) have disputed it insisting that snow fall actually increases accident rate as its intensity increases regardless of its frequency.

One of the fundamental prerequisites for road safety is being able to see and being seen (Peden et al, 2004). Road accident risk is exacerbated by poor visibility for all road user types. Most of the increased risk during rainfall seems to be attributed to visibility since accident rate rapidly reverses to close to the normal rate just after the rainfall even with the roads remaining wet (Andrey et al. 1993). *Visibility* contribution to road accidents varies between countries with low income countries known to be the most prone to visibility related accidents due to inadequate safety amenities such as street lights and reflective equipment. Countries prone to precipitation induced visibility impairment also suffer a lot from visibility related accidents. In the state of Victoria, Australia low visibility contributed to 65% of accidents involving vehicles only and the only contributor in 21% of them (Peden et al, 2004). Only a few studies so far have focused on the effect of visibility on traffic safety. Al-Ghamdi (2007) mentioned that the injury and fatality rates due to fog related accidents are remarkably high. The impact of visibility due to fog and smoke was studied by Abdel-Aty et al (2011) and they discovered that injury severity in conditions with low visibility was relatively high with head-on and rear-end collisions being the most common accident types.

Infrastructure

When infrastructures are exposed to adverse weather conditions that are beyond their design specifications they get affected (Jaroszweski et al., 2014). Higher temperature has been known to increase the stress on bridge joints and cause pavement softening and expansion (Nemry and Damirel, 2012). This could lead to rutting and the formation of potholes because they allow snow and rainwater to flow into the layers under the Hot Mix Asphalt (HMA) containing dirt and gravel. When the temperature drops, the water freezes and expands which leads to some of the dirt and gravel being pushed out, this leaves a hole when the water eventually melts (referred to as freeze-thaw weathering). This is especially in areas with high traffic density as continuous traffic over these unseen holes applies even more stress on the thin asphalt layer covering them leading to the asphalt layer over these divots collapsing causing potholes on the roadway (Erlingsson, 2012). Construction activities could be affected negatively due to heat waves especially in very humid areas. With climatic changes, building and maintaining roads and motorways could become more expensive (NRC, 2008, USGCRP, 2009). Certain areas that usually experience snowfall may experience a reduction in this cost and improvement in mobility as result of a reduction in snowfall due to warmer winters and therefore a reduction in salting requirements as well as snow and ice removal (NRC, 2008, USGCRP, 2009). Climate change is projected to cause an increase in rainfall which may result in flooding which could lead to the disruption of traffic flow, delay construction activities or weaken or erode the soil culverts that give support to road, bridges and tunnels (NRC, 2008; USGCRP, 2009). Motorways and roads life expectancy are shortened by excessive snow and flooding. Water and snow are known to cause damage to the infrastructures increasing the maintenance frequency as well as repairs and rebuilding (Nemry and Damirel, 2012). Road infrastructures located in coastal regions are the most prone to frequent and permanent flooding due to rise in sea level and storm surges (Nemry and Damirel, 2012). In the polar region and very cold regions degradation of roads built on permafrost has been observed in recent years (Serreze et al., 2000, Zhang et al., 2008). In the Europe road infrastructures at risk of frequent or permanent inundation are 4.1% of the coastal infrastructures with a value of approximately £14.7 billion (Nemry and Damirel, 2012). Some locations in the UK (such as the South) are projected to experience more winter precipitation to fall as rain instead of snow due to warmer temperatures this may lead to an increase in the frequency of winter flooding if the frozen ground becomes unable to absorb precipitation. Landslides and washouts especially on roadside slopes are projected to occur more frequently in the UK as already saturated soils are exposed to more rainfall (He et al., 2011, Schmidt and Glade, 2003). Slope failures are mainly expected to be triggered by short heavy storms that sometimes occur during summers and winters (Jaroszweski et al., 2014). Drought which usually occurs once every 5-10 years in the UK especially in the south east of the country may become more frequent leading to detrimental effects on roads and infrastructures because of soil shoving due to shrinkage during drought (Met Office, 2013).

Other Weather Factors effects on road networks

Wind Speed

The impact of wind speed on transportation has only been studied by a few researchers (Baker & Reynolds, 1992; Levine et al., 1995a, b, Edward, 1992 and Lian et al., 1998). This is perhaps due to the difficulties faced in collecting and collating readily available consistent and coherent data over a reasonable period. In the UK for example, the Department of transport does not publish wind related accident totals.

Wind speed has been known to have a negative effect on road transportation in both direct and indirect effect of air in rapid motion (Edwards, 1994). Damage caused by wind on structures or vegetation when the magnitude of wind exceeds the strength of the structures is a direct effect of wind while the hazards caused when wind indirectly induces an effect such as blowing snow into drifts, blowing down trees or even walls or panels being blown over are indirect effects of wind. Edward (1994) carried out a research on wind hazard and its effects on accident occurrence in England and Wales using police road accident data for the period of 1980-1990. A conclusion was made that high winds significantly increases accident risk but the occurrence of high winds in England and Wales is low compared to other regions hence the weather hazard has a slight impact on the total number of accidents compared to other regions. This is clearly not in-line with Elvik's (2006) law of accident causation discussed earlier. Other studies (Andrey & Yagar, 1993, Baker & Reynolds, 1992) mentioned that the effect of wind on road accidents is almost insignificant except for heavy storms and large vehicles.

Problems such as the structure and steering geometry of vehicles being altered could arise from vehicles in strong wind conditions depending on the type of vehicle and condition of the wind. High-sided vehicles have the tendency to be completely blown over by high cross winds while smaller vehicles such as cars could be forced to deviate significantly from their orientation. Motorcycles could either be forced to deviate from their orientation of have their riders completely blown off in certain situations. The location of the UK in the mid-latitude westerlies makes it one of the windiest countries in the world (Perry, 1981) with the areas located on the coast of the extreme north and west suffering the windiest conditions while the counties located inland such as the East Midlands and South-East England are the least windy (Edwards, 1996). Wind hazard on transportation is exacerbated in the UK because many of the main routes such as the M1 and M6 motorways are positioned northwest - southeast through the country mainly due to the geometry and orientation of the mainland. This positions the general traffic movement at right angles to the prevailing south-westerly winds although the situation is made complicated by turbulence and vehicle speed (Edwards, 1994).

Although high-wind accidents account for only a small percentage of the overall accident totals their significance is increased (especially in the western counties) between the periods of October to February during which the greatest frequency of gales in the UK occurs (Edwards, 1996). Although it is believed that the windiness in the UK is on the decline, there are barely any winters that pass without gale causing damages to vehicle and sometimes causing traffic obstructions (Perry and Symons, 1994). The two of the most severe gales on record in the UK occurred on October 1987 and January 1990 (Perry and Symons, 1994). There was a death toll of 46 during the 1990 storm with most of the incidents related to transportation accidents. In the south of the UK high-sided vehicles and trees were blown over some of which obstructed roads and motorways which lead to their closure for several hours (Thornes, 1991). Around 47% of the total accidents that occurred involved vehicle overturning, course deviation made up for 19% and accidents involving trees made up for 16% of the total wind induced accidents. Baker et al (1992) discovered that high-sided vehicles were the most vulnerable as they were involved in 66% of the accidents with only 27% involving cars. A positive relationship between wind variation and the total number of accidents that occurred in the United Kingdom during the 1990 storm was observed. It was discovered that a side wind of 13m/s is enough to cause a considerable change of route for standard buses and a gust of 20m/s could result in tipping over of vehicles which is the most common wind-induced accident. The impact of wind is exacerbated on bridges. The Forth Road Bridge located in Scotland has vehicle restrictions and speed limit for various wind speeds. The speed limit on the bridge is lowered to 40m/h when there is a gust greater than 35m/h. High sided vehicles such as double-decked buses which are the most vulnerable to wind speed are restricted from using the bridge when there is a gust greater than 40m/h. Pedestrians, three wheeled vehicles and Light vehicles such as bikes and bicycles are restricted from using the bridge when there is a gust greater than 50m/h. The bridge becomes open to just cars when there is a gust greater that 65m/h with a speed restriction of 30m/h and it becomes completely shut when there is a gust greater that 80m/h (Forth Road Bridge, 2014). The speed restrictions on the bridge sometimes lead to traffic congestion and diversions from the bridge to other routes that are not designed to handle as much traffic sometimes leading to traffic congestions on those routes.

Extreme temperature

Extreme temperatures both high and low have been known to have negative impact on road transportation affecting infrastructures, drivers' behaviours and vehicles' performances. Rise in the frequency of freeze-thaw weathering cycles have been known to cause early deterioration of road pavements (Haas et al. 1999). With the global temperature on the rise a record-high temperature of 38.5C was recorded in the UK on august 2003 near Faversham, Kent (Met Office, 2012). High temperatures when sustained long enough could lead to the expansion of concrete which could result in the cracking, buckling, rutting, shoving or shattering of the concrete. Buckling of motorways in Illinois and Missouri occurred at a temperature index of ≥ 38°C (for several hours) during the 1999 heat wave in the US leading to their closure for hours (Palecki et al. 2001). The performance of vehicles could deteriorate over time as they continue to bump over these holes and cracks. Although not as severe as concrete, cracking has been known to occur on asphalt; its vulnerabilities are quite different from concrete. It is more prone to deformation in high temperature compared to concrete as it is less stiff causing roads to become very uneven, unpleasant and dangerous to use. Asphalt has been known to come off roads and stick to tyres in very extreme temperatures. Accidents due to these road irregularities could occur as drivers veer to avoid these obstacles which may result in loss of control of their vehicles. Accidents caused by potholes are regularly reported in the UK. Accidents recorded over the past 5 years showed that 502 reported accidents recorded from Scotland alone were due to drivers hitting or attempting to avoid potholes (Daily record, 2013). Potholes and other forms of road irregularities often lead to increased traffic on the roads since drivers tend to lower their speed to avoid these irregularities. Explosions have also been known to occur with concrete putting nearby individuals at risk as chunks of concrete are lifted. Predicting where these irregularities or explosions will occur is perhaps the biggest issue with heat related damage. Shoving which is a longitudinal displacement of a localized area of the pavement surface usually occurs because of braking or accelerating vehicles under high temperature which tends to soften the asphalt. They are often found on hills, curves, or at intersections and sometimes have associated vertical displacement (FHWA, 2017; Zhao et al, 2018). Rutting is one of the main distresses in asphalt pavements, especially in higher summer temperatures and/or under heavy loads (Zhang Q et al.). It is a longitudinal surface depression in the wheel path and sometimes have associated transverse displacement (FHWA, 2017, Zhao et al., 2018).

High temperatures have been found to increase fatigue (Zohar, 1980) and affect the irritability (such as aggression) of drivers (Anderson, 1989; Boyanowski et al., 1981). Viteles & Smith (1946) mentioned that drivers' mental performance reduces in hot conditions. Weiner & Hutchinson (1945) suggested an increase in drivers' reaction time while Stern & Zehavi (1990) suggested a reduction due to loss of concentration leading to crashes. Studies (Welch et al., 1970; Cantilli, 1974; McDonald, 1984) have shown that temperature over 25ºC can cause fatigue and crashes especially among bus drivers. Hermans et al. (2006) discovered that heatwaves in France have a strong influence on injury crashes. It is probably because drivers prefer to schedule their planned journeys for early mornings of late evenings which could disturb the sleeping pattern of the drivers and most likely result in tiredness.

Drought

Researchers have suggested that a continuous rise in the temperature of the northern hemisphere may lead to a rise in the frequency and severity of hot days and a reduction in the number of extremely cold days (Barrow & Hulme, 1996; Katz & Brown, 1992; Houghton et al., 2001). This could lead to an increase in the number of dry days and an increase in the severity of *droughts* if precipitation convection increases with a rise in extreme weather events and a fall in average rainfall. Evaporation level increase due to higher temperature could exacerbate the problem (IPCC, 2007). Although climate change is expected to result in more rainfall at the global level, the distribution and timing of the rainfall event is expected to change leading to an increase in the possibility of drought in some regions. Predicting the details is however difficult due to regional climate impact relying highly on large-scale atmospheric circulation patterns such as jet streams which are difficult to model in climate simulations. Regions such as the Mediterranean, Central America and Western Australia are expected to experience reduced rainfall due to climate change the UK may also experience a reduction in precipitation. In 2011 the southern parts of the UK experienced meteorological drought which eventually led to hydrological drought (The Guardian, 2012).

A summary on the Impact of weather conditions on road networks

Precipitation and road traffic

Traffic flow and speed are affected by precipitation leading to increase in journey times which would most likely be exacerbated in the future should there be rises in precipitation levels. A study by Keay and Simmonds (2005) on Melbourne roads, Australia showed that rainfall especially during winter and spring had the greatest impact on traffic volumes. A similar study by Akin et al. (2011) on urban motorways in Istanbul showed a similar result.

These studies along with studies by Hooper et al. (2012) and El Faouzi et al. (2010) also pointed out that inclement weather especially rainfall led to significant speed reductions and increased traffic congestion while snow led to a significant reduction in the demand for the road hence a reduction in traffic volume. Khattak and Knapp (2001) examined Iowa motorway data and discovered that traffic volumes on the motorway reduced by 30% during snowy conditions compared to normal dry conditions and rainy conditions. This was also discovered by ElDessouki et al (2004) during an examination on accident risk on Connecticut motorways. While most studies concentrated on motorways Keay and Simmonds (2005) study was focused on an urban area in Melbourne while Hooper et al. (2012) study although was more focused on a motorway between London and Glasgow in the UK it included several sections which passed through urban areas. It was discovered in both urban studies that increased rainfall led to reduction in speeds and increased traffic congestion, this result is similar to the studies carried out on motorways, but the speed reductions are less significant on the motorways as pointed out in a literature review by Pisano and Goodwin (2004) regarding weather effects on urban arterials.

Studies from all over the world (Ibrahim and Hall, 1994; Maze et al., 2006) including the UK (Hooper, 2013; Smith K., 1982) have shown that inclement weather conditions have negative effects on traffic flow. Their effects were split into two main categories by Jaroszweski et al (2014) which are those effects that occur because of behavioural changes to driver due to the stress induced by weather and those that are influenced by physical failure of the infrastructure or by the set off of natural disasters such as low temperature induced potholes. The behavioural changes may include reduced speed, acceleration, start-up times and wider gaps between moving vehicles in a traffic stream (Agbolosu-Amison, 2004). These behaviours are due to factors that occur during inclement weather conditions such as reduced traction and visibility.

Several studies (Ibrahim and Hall, 1994, Agarwal et al., 2005, Kyte et al., 2001) have been carried out to determine the degree of speed reductions under several inclement weather conditions at various intensities. Ibrahim and Hall (1994) study on a motorway showed that there was a speed reduction of approximately 2km/hr when it rained slightly and 3km/hr when it snowed slightly while when it rained heavily there was a speed reduction of up to 10km/hr while heavy snow resulted in speed reduction up to 50km/hr. A summary of Ibrahim et al’s findings is shown in the table 8.1. The Federal Highway Administration (FHWA, 1977) in the US offered a weather classification scheme to the study of the impact of precipitation on motorway systems. The classification ranged between dry roads with a percentage speed reduction of 0% and snow packed road with a percentage speed reduction of 42%. Maze et al. (2006) discovered that when visibility was less than 0.25 miles, a 12% reduction in speed occurred in the Minneapolis / St. Paul area over a four-year study period. A summary of the FHWA data is shown in the table 8.2. Kyte et al. (2001) explicitly defined a critical visibility distance of 0.3 km (0.18 mile), below which speed was reduced by 0.77 km/hr (0.48 mph) for every 0.01 km (0.0062 mile) reduction in visibility.

Agarwal et al (2005) quantified the impact of rain, snow and pavement surface conditions on traffic flow. They estimated a relationship between highway capacity and traffic speed on congested freeways in the Minneapolis/St. Paul (the Twin Cities) metropolitan area where they utilised freeway traffic in-pavement system detectors data collected from a four-year period, weather data from three Automated Surface Observing Systems (ASOS) and five RWIS sensors. Results from this research indicated that severe precipitation (mainly rain and snow) and visibility impairment resulted in the most significant speed and capacity reductions (Agarwal et al., 2005). The findings are summarised in the table 8.3.

Agbolosu-Amison (2004) referred to a report by Bernardin Lochmueller and Associates, Inc. (1995), the report was the result of an assessment on the speed variations and saturation flows during inclement weather conditions on a network containing 24 signals. Measurements of several traffic parameters (such as startup lost times, speed and saturation flow) were taken during average summer conditions and average winter conditions. Their report showed that the signalling time used for summer conditions were not satisfactory for winter conditions (inclement weather conditions). They suggested that travel time during inclement weather conditions could be reduced by up to 13% and average delay by up to 23% if purposely designed signalling times were used during inclement weather conditions (Agbolosu-Amison, 2004).

Weather Events		Speed Reduction
Rain	Light rain	1.2 mi/h (free-flow speeds) 10% at a flow rate of 2,400 veh/h
	Heavy rain	3 to 4 mi/h (free-flow speeds) 16% at a flow rate of 2,400 veh/h
Snow	Light snow	0.6 mi/h (free-flow speeds)
	Heavy snow	38%

Table 8.1: Speed reduction in inclement weather (Ibrahim and Hall, 1994)

Pavement Condition	Speed Reduction (%)
Dry	0
Wet	0
Wet and snowing	13
Wet and slushy	22
Slushy in wheel paths	30
Snowy and sticking	35
Snowing and packed	42

Table 8.2: Speed reduction in inclement weather (FHWA, 1977)

Weather Variable	Intensity (inch/hour)	Percentage reduction in capacity compared to Clear	Percentage reduction in speed compared to Clear
Rain	0	0	0
	0-0.0.01	2%	2%
	0.01-0.25	7%	4%
	>0.25	14%	6%
Snow	0		
	<=0.05	4%	4%
	0.06-0.1	9%	8%
	0.11-0.5	11%	9%
	>0.5	22%	13%

Table 8.3: Average impact of precipitation on speed and capacity (Agarwal et al., 2005)

Precipitation and acceleration

Precipitated conditions (such as rainfall and snow) result in slippery road surfaces which tends to reduce the friction between road surfaces and tires hence drivers tend to decelerate or accelerate at a lower rate compared to dry conditions specially to avoid skidding. Asamer et al. (2011) pointed out that lower acceleration is expected of moving vehicles compared to vehicles accelerating from the stop line. It is agreed that there is a relationship between maximum acceleration and weather conditions although no paper has explicitly identified these relationships (FHWA, 2004). Hoogendoorn et al. (2011) identified a relationship between the speed of the lead vehicle, the action point (i.e. response point of the following vehicle) of the following vehicle and the acceleration of the following vehicle. He concluded that following vehicles are less sensitive to speed changes of their lead vehicle under foggy conditions because of low visibility affecting their perception of their lead vehicle.

Although explicit relationships between weather conditions and driver's maximum acceleration have not been identified by any author the relationship between start-up loss time and weather conditions have been analysed. FHWA (2009) indicated that the start-up loss time increases significantly with the severity of the road conditions with the highest start-up loss times occurring when slush accumulates on the pavement surface. Increase in start-up loss time has been known to occur during reduced visibility, and reduced pavement friction. Lieu and Lin (2004) identified a 20% increase in start-up loss time during wet and slushy weather conditions while Maki (1999) identified a start-up loss time increase of 2-3sec under inclement weather conditions after an experiment.

Mitigating the Impact of extreme weather on the UK road network

Due to the potential effects of climate change on several transport modes several reports have pointed out why it is important to mitigate the impact of climate change (e.g. Gamaut, 2008; RAENG, 2011). Transportation networks are generally very valuable assets to economies and are required to keep them functioning. The UK transportation network is not an exception. In 2005 the UK road network alone was valued as the government's single most valuable assert having an approximate value of £62 billion (Hooper, 2013). The importance and value of road networks to an economy means they must be properly maintained. The impact of climatic changes is a major problem to the UK road networks with the impact not being limited to just pavements alone but other infrastructures on the network such as bridges as well. The impact can already be seen from the damages done by extreme flooding and other effects of extreme weather conditions. Unfortunately, things are most likely going to get worse before they start getting better and not much can really be done in the short term (Highfield, 2018; Black, 2000). As things get worse it may become more difficult to make the necessary changes that need to be made to mitigate the effects of climate change. There will be rises in temperatures and the frequency of high temperatures will increase which will have a negative impact on transport. Efforts to mitigate and prevent infrastructural damages from both extreme storms and extreme heat will cost a lot of money. Nevertheless, it is very important that both long term and short-term strategies are being made to mitigate the impact of climate. Short term strategies may include promoting greener forms of transportation (such as walking and cycling), creating awareness of the dangers of driving in heavily precipitated conditions and giving advices on how the risks could be reduced (such as installing snow tires); upgrading drainage systems on road sections prone to flooding, adjusting road specifications to allow higher traffic volumes and investing in more environmental friendly ways of removing snow from road pavements since salting of roads has been known to have negative effects on the environment especially on vegetation (Black, 2000). Long term strategies may include investing on cleaner energy, afforestation, building more drainage systems, more adaptive features that will aid in improving the resilience of road networks could be considered when considering upgrades and future developments as this would reduce costs on maintenance and repairs (Hooper, 2013) and the introduction of policies to control urban development in regions extremely prone to the impact of climatic changes (such as coastal regions).

There are currently large-scale global computer models based on sophisticated algorithms which can be used to predict climatic changes. These models could be used by stakeholders and policymakers when planning adaptation strategies for climate changes. In the UK, the UK Climate Impacts programme has developed climate projection tools which are UKCIP02 and its successors the UKCIP09 and UKCIP18 (released 2018) (Baker et al., 2010, Met Office 2019). These tools make predictions based on different emission scenarios and for each scenario average climate variables are predicted on definite square grids at definite time intervals. The UKCIP02 average climate variables are presented on 50km square grids at 30years time interval while the UKCIP09 being a finer version presents on 25km square grids at 30years time interval (Baker et al., 2010). The limitations of these tools are they do not account for the urban heat island or possible changes in urban activities and shape; and since they are statistical tools they do not take large scale meteorological dynamics such as blocking into consideration hence they are not optimised for predicting possible future scenarios where colder winters could become more frequent (Jaroszweski et al, 2014). Note that although 25km square grids were used to present the climate change information, 5km square grid for the weather generator was used to account for changes in local topology which is based on observations. These changes in the local topology have been spatially interpolated onto the same 5km grid but they do not present more climate information that was not presented by the 25km grid (for more info visit Eames et al., 2011).

However, only proposing adaptation strategies and implementing these strategies would not be enough to adequately curb global warming especially in future scenarios where extreme weather events becomes so severe that most adaptation strategies either become too expensive to be implemented or become virtually impossible to implement. It is therefore important to address the source of the problem and come up with strategies to mitigate it rather than just adapting to its effects. There is now a general agreement that the high emission of greenhouse gases is the main reason for the rise in global temperature and the rise in global temperature is the main reason for extreme weather events, it is therefore important to control the amount of greenhouse gases being released into the atmosphere. Various programs are now being promoted to reduce the amount of greenhouse gas released to the atmosphere. Recycling items such as paper, plastic, glass and aluminium is now being promoted in the UK to reduce the amount of greenhouse gases such as nitrous oxide and carbon dioxide being released into the atmosphere when these items are being made. Approximately 82% of the world's energy comes from burning fossil fuel such as coal for producing electricity (EIA, 2011). Burning of fossil fuel has been known to lead to high emission of carbon dioxide which is a greenhouse gas, energy conservation programs are now in place to reduce energy consumption and thereby reduce the amount of fossil fuel being burnt. This is being promoted in various institutions and homes in the UK using energy efficient devices such as bulbs and fuel-efficient vehicles. The UK government now promotes the use of low emission vehicles by taxing vehicle owners based on the emission level of their vehicles. Renewable energy (such as wind, ocean power, bio-fuel, solar and hydroelectric) which are often referred to as clean energy due to their zero carbon emission is becoming more popular in the UK as a result of the UK and EU aims to reduce carbon emissions and to promote renewable electricity power generation through commercial incentives such as Feed in tariffs (FITs) and the Renewable Obligation Certificate scheme and also by promoting renewable heat through the renewable Heat incentive (Energy saving Trust, 2014, ofgem, 2014).

Most of the UK was once covered by forest but due to deforestation for fuel, timber and agriculture by 1900 the forest and woodland area was reduced to about 5% of its original size. The demand for timber during the First World War led to the creation of the Forestry Commission in 1919 to build up a strategic timber reserve (POST, 2007). Today, the promotion of afforestation in the UK now helps in converting atmospheric carbon dioxide to wood thus acting as a sink and reservoir for carbon. Woodland and trees contribute to the reduction of greenhouse gases in the atmosphere by taking up and retaining atmospheric carbon (sequestration). Production of materials such as steel and concrete leads to high emission of carbon dioxide but by using wood as a source of bio-energy carbon dioxide emission is reduced especially when used in the production of products with a long-life span (POST, 2007). Carbon sequestration by trees alone would not be enough to adequately mitigate the impact of greenhouse gases because for example in the UK it was estimated that at least three quarters of the national land area would be required for forestry to counter the amount of greenhouse emissions by UK drivers (Broadmeadow and Matthews, 2003). It is therefore important that other additional strategies are setup to adequately mitigate the impact of greenhouse gas emission.

Moving away from the source of the problem, precipitation especially flooding which is the main adverse weather factor currently affecting the UK road network, would probably become exacerbated before the conditions start improving. Although strategies are currently being employed to control flooding in the UK, it may become worse in the future if global warming is not adequately addressed. Flooding is currently being controlled in the UK through:

Building of Dams and reservoirs: The amount of discharge by a river is often controlled by building dams along its course. Dams help to control flooding by holding back water and releasing it in a controlled manner. Reservoirs are often built behind these dams to store water which could be used for hydroelectric power generation, irrigation and recreational activities. Flood protection dams are typically designed to reduce flood peaks by 30-50% allowing time for further mitigation actions to be taking. There are currently 486 dams in the UK of which 168 are large dams i.e. higher than 15m and can hold more than 3 million cubic meters of water (The British Dam Society, 2014; European Environment Agency, 2014). The largest reservoirs in the UK currently are Kielder reservoir, Rutland Water and Hawes Water.

Adjusting river channels: Widening or deepening a river channel would allow the river to carry more water, straightening the channel would allow the water travel faster along the course. The impact of river flooding could be mitigated by diverting floodwaters away from settlements by altering the river channel course. River channel alteration may lead to a higher risk of flooding downstream because water gets transported there at a faster rate hence adequate planning and preparation is required before such a project is to be carried out. Some river adjustment projects have been carried out in the UK. An example is the project which was performed on river Valency channel which flows through a steep sided and narrow valley where Boscastle village is located. In 2004 the river was flooded causing an extensive damage to the village. The only feasible way of reducing future flooding and improve the water capacity was to enlarge the river channel (The river restoration centre, 2010).

Afforestation: Trees could be planted close to rivers with a risk of flooding which could eventually develop into riparian woodland. The roots of the trees and other vegetation in the riparian woodland would aid in the binding and strengthening of the river banks reducing erosion, siltation, lowering the river discharge and increasing the interception of rainwater (Forest Research, 2014). This is a relatively cheaper option which would also support global warming mitigation.

Factors affecting the future of road transport

Global warming

Global warming currently has a huge influence in today's environmental factors and this would potentially be the case for the next few decades. It's been known for a while now that global warming is currently on the rise due to anthropogenic activities associated with the emission of Greenhouse gases (GHG) hence various mitigation and adaptation strategies are being put forward to curb its impact. According to IPCC (2014) CO_2 was the highest Greenhouse gas emitted between 1970 and 2010 this is quite evident due to the world's dependence on fossil fuel within the period. Figure 8.1 shows the Total Annual Anthropogenic GHG Emissions by Groups of Gases 1970 – 2010. From the figure GHG emission was on the rise within this period. IPCC (2014) indicated that globally, the main factors influencing the rise in CO_2 emissions from fossil fuel combustion are economic and population growth.

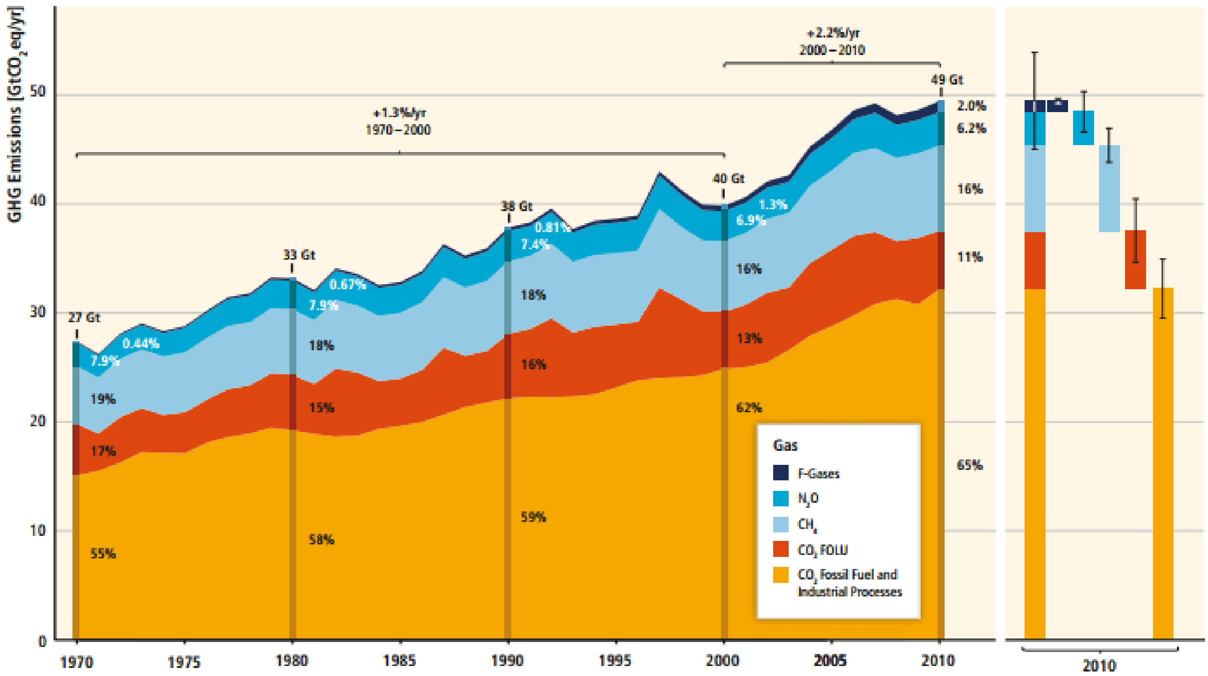


Figure 8.1: Total Annual Anthropogenic GHG Emissions by Groups of Gases 1970 – 2010 (IPCC, 2014)

Figure 8.2 below shows Greenhouse gas emissions by economic sectors for the period of 1970-2010. From the chat transport is a big player in greenhouse gas emission making up 14% of the total direct emissions and 0.3% of indirect emissions. *Emissions that occur from sources owned or controlled by the reporting entity are known as direct GHG emissions while* *emissions that occur because of activities of the reporting entity but occur at sources owned or controlled by a different entity are referred to as indirect emissions* (Jones, 2010).

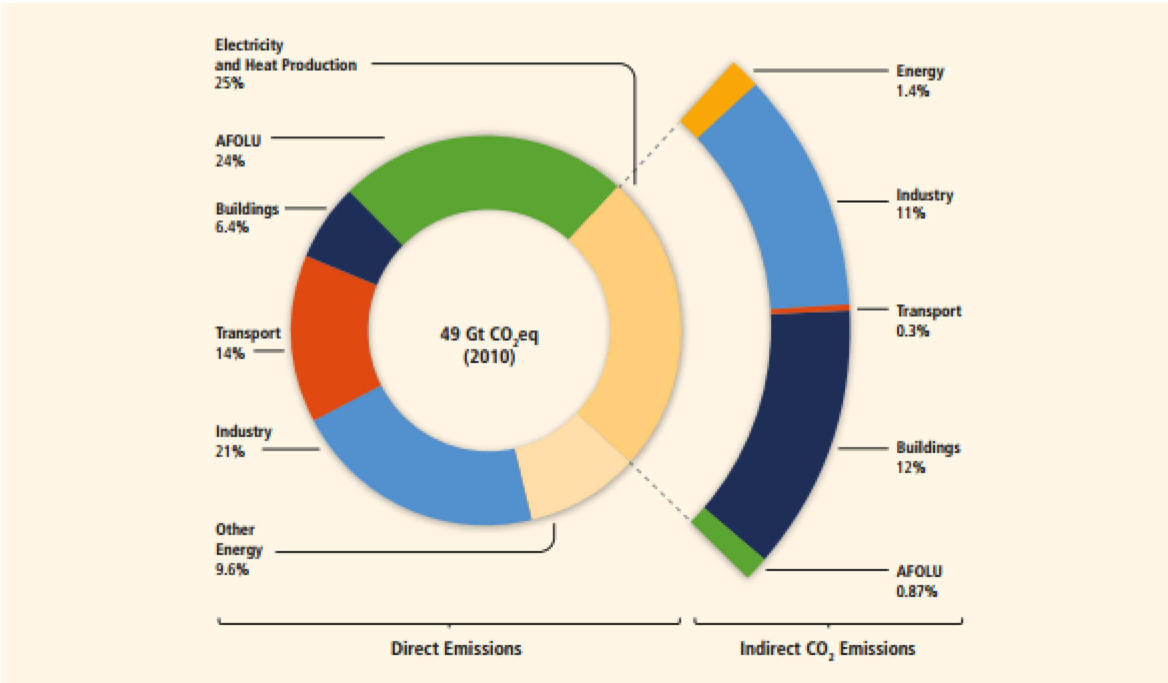


Figure 8.2: Greenhouse Gas Emissions by Economic Sectors IPCC (2014)

A report by the Department of Energy and climate change (DECC, 2015) on Greenhouse gas emissions shows that progress is being made in controlling greenhouse gas emission in the UK. The report showed that there was a decline in CO_2 gas emission between the periods of 1990-2013 and an overall decrease in GHG emission within the same period as shown in Figure 8.3. The report indicated that in 2013, CO_2 made up 82% of the total GHG gas emissions in the UK as shown in figure 8.4 and transport sector made up for a huge percentage as shown in figure 8.5.

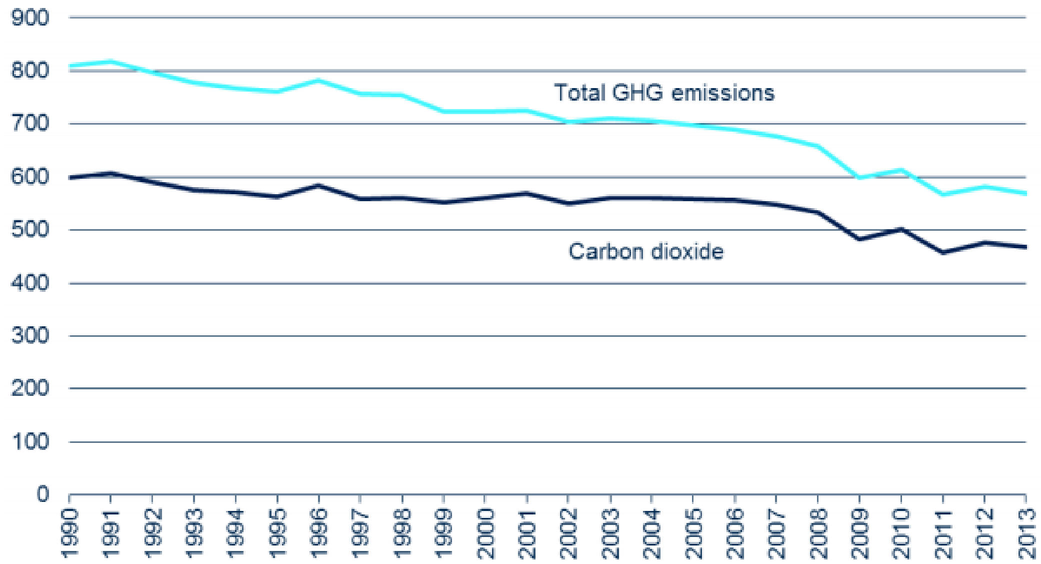


Figure 8.3: Emissions of greenhouse gases, UK and Crown Dependencies 1990-2013 ($MtCO_2e$) (DECC, 2015)

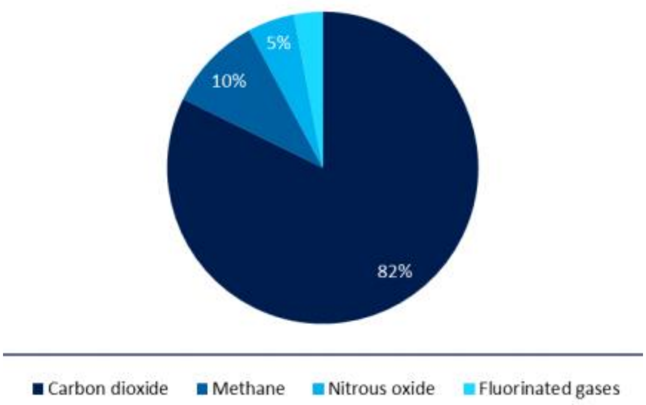


Figure 8.4: Greenhouse gas emissions by gas, UK and Crown Dependencies 2013 (%) (DECC, 2015)

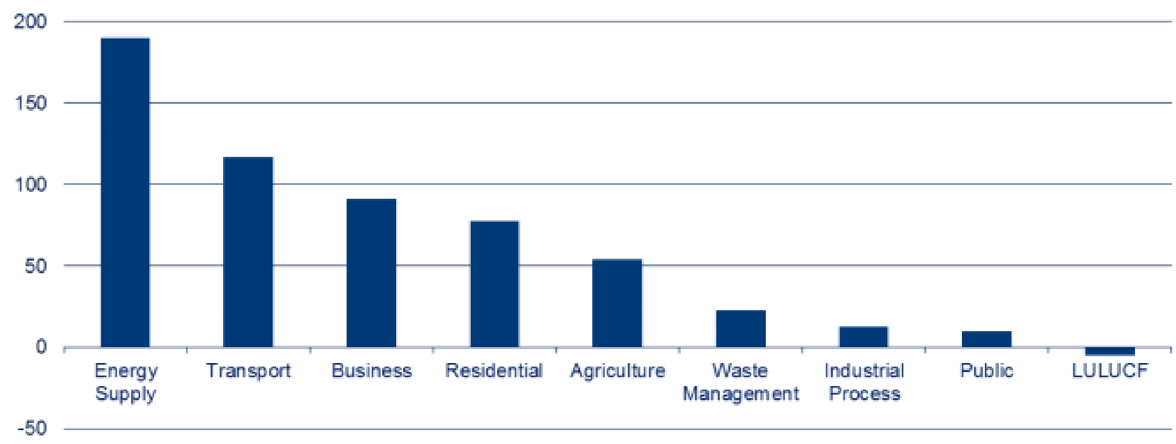


*Figure 8.5**:** Greenhouse gas emissions by source sector (excluding LULUCF), UK and Crown Dependencies 2013 (MtCO2e) (DECC, 2015)*

A review by Stern (2006) estimated that if no action is taken to reduce the impact of global warming, by 2035 the carbon dioxide concentration would be doubled in the atmosphere compared to pre-industrial levels. Regardless of the impact of anthropogenic activities on temperature rise, there may be a surge in temperature up to more than 2^{O}C above preindustrial levels. This would most likely still occur regardless of whether large scale greenhouse gas mitigation activities were to commence now or not (IPCC, 2007). Global warming is currently impacting every sector of our socio-economic life from reductions in the social inclusion of individuals to reductions in the productivity of industries, impacting through adverse weather conditions. Mitigation strategies such as CO_2 emission legislation, recycling programme and afforestation are currently being utilised by the UK to curb global warming. However, regardless of whether these strategies are adhered to and practiced thoroughly worldwide or not, the weather impact of global warming would still be exacerbated before improvement commences (IPPC, 2007). Technological advancements such as improved road infrastructures, vehicle autonomy and advancements in other transportation modes are resulting in better road transport adaptation to global warming impacts in the UK (HM government, 2011).

Various weather factors associated with global warming such as increased heavy rainfall and snowfall, and extreme temperatures are expected to have negative impacts on road transport. Heavy snowfall results in reduced visibility and slippery road surfaces which negatively affects acceleration, headway, response time and traffic speed resulting in higher journey times and reduced traffic capacity (Asamer, 2011; Chung et al., 2006; Agbolosu-Amison, 2004). Slippery conditions and general increased hazardous conditions on the other hand can result in drivers seeking alternative transportation means (such as mass transit) to get to their destinations to avoid accidents (Maze et al., 2006; Asamer, 2011). Traffic safety may decrease under adverse weather conditions. Increase in the average temperatures may result in better driving conditions but increase in the maximum temperature may result in poorer driving conditions as pointed out in section 2.1. For example, high temperatures have been found to increase fatigue (Zohar, 1980) and affect the irritability (such as aggression) of drivers (Anderson, 1989; Boyanowski et al., 1981). Weiner & Hutchinson (1945) suggested an increase in drivers' reaction time while Stern & Zehavi (1990) suggested a reduction due to loss of concentration leading to crashes. However according to Elvik's (2006) law of accident causation which states that "*the rate at which a hazard occurs is proportional to its relative accident rate, with drivers getting more familiar with conditions that they are frequently exposed to*" drivers will potentially adapt to driving under adverse weather conditions as the frequency of their exposure to such conditions increases. Hence when extrapolating future accident rates and traffic parameters in general during inclement weather conditions it is important to consider the possibilities of drivers adapting to future weather conditions. Fridstrøm et al. (1995) study showed that accident rate reduced by approximately 1.2% for each additional snow day in Denmark. This is in line with the risk compensation by drivers discussed earlier which suggested that as drivers become more exposed to precipitation on road networks they become more aware and cautious of the risk involved. Maze and Hans (2006) concluded that accident risk is 3.5 times more at the start of a winter season than at its end. Mobility is negatively affected during inclement weather conditions as people feel less inclined towards travelling resulting in reduced social inclusion (Hooper et al., 2012 and El Faouzi et al., 2010). Some vehicle manufacturers and OEMs feeling under pressure to meet certain legislations that have been put in place to reduce CO_2 emission (e.g. EU CO_2 emission legislation (DFT, 2016)).

Demographic and Economic growth

Transport has an important role to play in supporting a sustainable economic growth and its investment is even more important in times of economic challenges to secure sustainable growth and international competitiveness (DFT, 2013). Transportation development and economic growth could be viewed as two interdependent factors since the growth of one factor positively influences the growth of the other. Factors of a community such as its productivity, employment, property values, business activities, investment and tax revenues could be impacted by transportation development. General economic growth could result in increased business activities which may influence the demand for transportation and economic revenue hence potentially more funding for transportation development. Forecasts by various organisations indicate a fairly stable UK economy between now and 2020. A long term forecast by OECD (Knoema, 2016) shown in figure 8.6 shows a steady economic decline after 2020. Depending on the actual outcome the UK economic growth would have an influence on its transportation development.

Demographic growth of the UK would have a significant impact on the UK's future road transport network and this impact would depend on the demographic composition. A composition that supports economic growth would potentially have a positive influence in the state of the transport network since a higher economic growth would potentially result in higher transportation development. In a paper by ONS (2015) the projected demographic growth of the UK is shown. It shows projected demographic growths based on fertility, migration and life expectancy. The projection indicates that the UK population is expected to increase by 9.7 million over the next 25 years. It would be important to consider age factor of the population when considering economic growth (as well as other factors such as literacy) as the demographic composition would influence the economic growth.

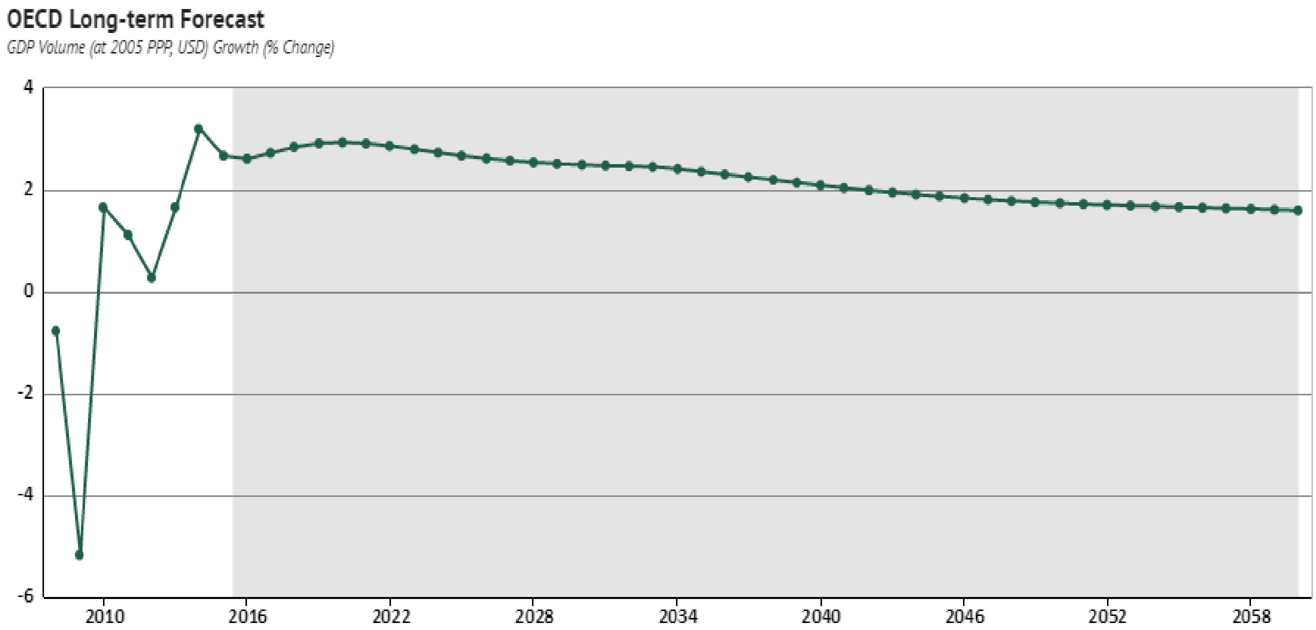
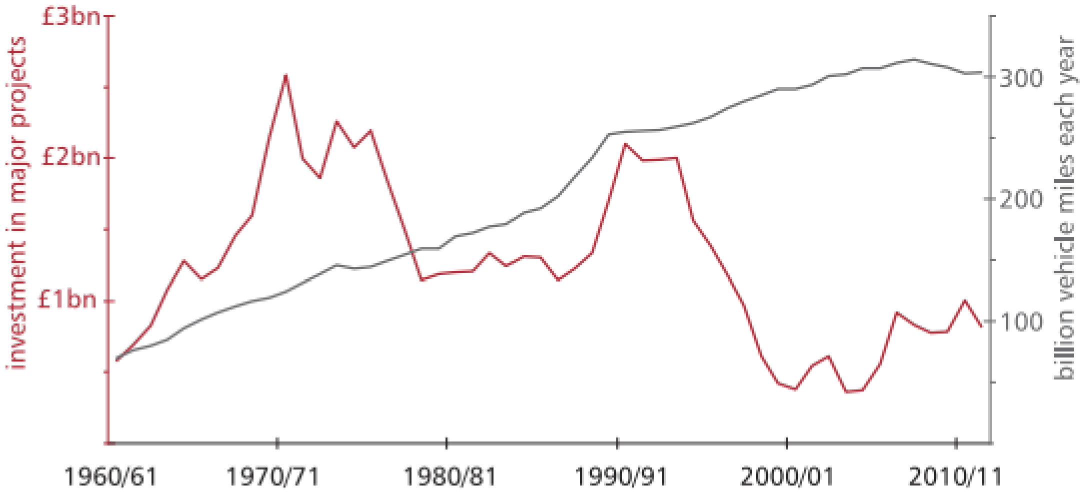


Figure 8.6: OECD long-term forecast (Knoema, 2016)

Road infrastructure and vehicles

Investment

DFT (2013) report on 'A network for the 21st century' indicated that continued demographic and economic growth as well as advancements in fuel efficiency means that traffic in many areas in the UK will rise in the coming decades. It estimated that even in the worst economic case and low population growth, strategic roads will experience 24% rise in traffic by 2040 and the central case traffic will increase by 46% compared to their current states. It also mentioned that according to business figures surveyed by the World Economic Forum UK roads were rated worse than many of its European competitors. However, the UK government has planned to treble its investment in major new road enhancements from their current levels by 2020-2021 with focus on the Strategic Road Network (SRN) which is made up of approximately 4,300 miles of motorways and major 'trunk' A-roads in England alone (HM Treasury, 2013**;** Butcher, 2015). "*We would be investing £15.1 billion in our strategic roads by 2021 to counter the effects of past underinvestment*" DFT (2013). This investment excludes the £12 billion proposed for the network maintenance and £6 billion to resurface over 3,000 miles of the SRN (more on information at DFT, 2013). Figure 8.7 shows the UK government investment in strategic road network from 1960-2011. The investment in strategic road network has not been consistent with the rise in vehicles' annual mileage.



[a] This covers the strategic road network only. England and Wales until 1964, and England only 1965 onwards.

Figure 8.7: The UK government investment in strategic road network 1960-2011 (HM Treasury, 2013)

Technological advancement

Technological advancements have changed the way cars are driven today. The microchip was first featured in car design 30 years ago. Currently various features such as safety features (e.g. anti-lock braking system and stability control system), fuel economy and pollution control equipment, and driver information system (e.g. satellite navigation) are utilised today (DFT, 2013). The fall in the cost of data processors and the rise in their computation power will facilitate the rise in more advanced vehicles features. In a paper by KPMG (2015) on 'Connected and Autonomous Vehicles – The UK Economic Opportunity' projections on semi-autonomous and autonomous vehicles UK market penetration indicated that these classes of vehicles would be trending by 2030 (further discussed in a later section). Their report indicated that vehicles connectivity would be more common within the coming decades as vehicle to vehicle (V2V) and vehicle to infrastructure (V2I) communication will increase, facilitating vehicles cooperation through advanced features such as 'platooning'. Both V2I and other ways in which drivers gather information about their journey (e.g. internet, smart phone applications and a dedicated customer information line) are currently enabling drivers to plan ahead keeping them informed about alterations in the network status on the go. Advancements in information technology will result in the availability of more sophisticated information for drivers allowing better travelling flexibility. Advancements in vehicle technology are resulting in reduced CO_2 emission levels for newer vehicles. Vehicles utilising alternative forms of energy are currently on the rise while newer internal combustion engines are now being designed to be more energy efficient. Proper investment in these technologies could result in a very significant reduction of GHG emission from car travel. The UK government has already shown its support by investing

£400 million to assist the uptake of new vehicles and aims to provide over £500 million additional capital investment by the end of the decade (DFT, 2013).

2. The Traffic flow model

Fundamentals of traffic flow

Road traffic is characterised by the traffic flux (flow rate), the density and the mean speed. Immers and Logghe (2002) described the fundamental road traffic flow characteristics using figure 8.8.

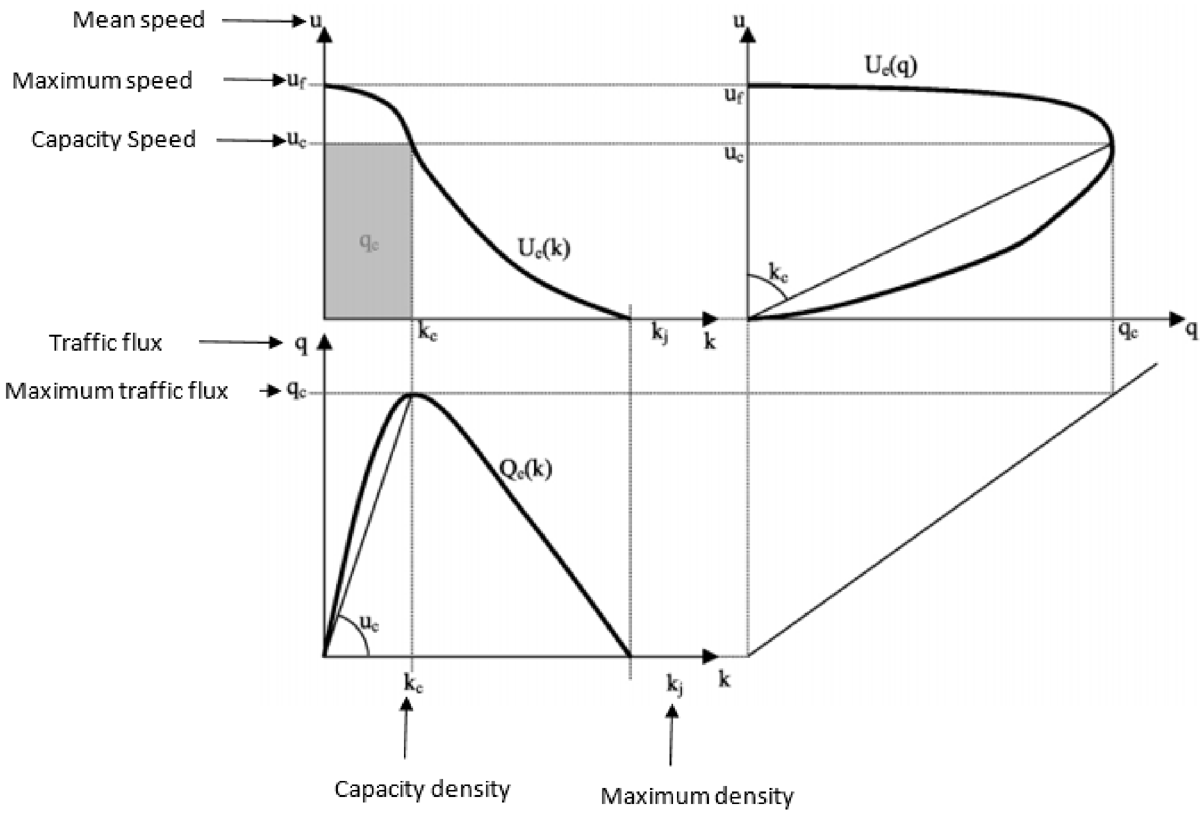


Figure 8.8: The three related road traffic flow fundamental diagrams (Immers and Logghe, 2002)

Figure 8.8 relates the mean speed (u) along a given link to its density (k). The traffic flux (q) along the link is the product of the mean speed and the density. It was plotted on the k-q figure as an angle while an area was used to represent it on the k-u figure. Immers and Logghe (2002) pointed out that a stationary and homogeneous traffic state can always be located along the curves of the fundamental diagrams. The states of a given traffic which are usually of major concern are:

Free flowing traffic

At this state vehicles travel freely at a maximum speed of u_f and are not impeded by other traffic. The maximum speed (free speed) depends on the speed limit of the link, speed restrictions during operation at any given time and weather conditions. The density of the link and its traffic flux would be close to zero during free speed (Immers and Logghe, 2002).

Saturated traffic

When a link is in this state its traffic flux and mean speed would be close to zero as a result of the vehicles queuing and as a result of the maximum density k_j (jam density) of the link reached (Immers and Logghe, 2002).

Capacity traffic

The capacity of a link is defined as its maximum traffic flux q_c. The maximum traffic flux (q_c) has a corresponding capacity speed (u_c) which is located below the maximum speed (u_f) and a capacity density (k_c) (Immers and Logghe, 2002).

Designing the Traffic Flow Model

The traffic flow model was designed and simulated using a *patch-wise* method. This method involved splitting the link into equal patches with patch 1 P1 being at the end of the link and the maximum patch Pn being at the start of the link. Each patch contained registers, generally the number of registers would depend on the size of each patch but for this case each patch was designed to be 8 meters long meaning in a 1000m link there was a total of 125 patches with P1 located at 992 to 1000m and Pn at 0.1 to 8m (note every vehicle generated at 0.1m). The average passenger vehicle is 4.7m long (World Heritage Encyclopaedia, 2016) while the average city bus is 14m long (Ryczkowski, 2016) meaning there could be up to 2 front bumpers and 1 rear bumper or 1 front bumper and 2 rear bumpers in a patch (as illustrated in figure 8.9) as a result each patch was designed to possess two front bumper registers and 2 rear bumper registers. A vehicle may be located in up to two patches and must register each bumper on the corresponding patch where they are located (for example, the location of V1 may be P4(F2), P5(R1), this simply means vehicle 1 front bumper is located in patch 4, front bumper register 2 (i.e. within 966-958m) while its rear bumper is located at patch 5 rear bumper register 1(i.e. within 957-949m)). The patch-wise model ensured patches were simulated sequentially hence vehicles contained in P1 were always simulated before the vehicles in P2 etc.

When considering multiple lanes, each lane in a way was considered as a separate link, meaning each lane was split into patches (P1 to Pn) and vehicles were free to switch lanes provided *the lane changing rules* were met. For each patch each lane was simulated hence a loop which ran from 1 to maximum patch (i.e. 125) contained a loop which ran from 1 to maximum lane (user defined) and this loop contained a loop which ran from 1 to maximum front bumper register (i.e. 2). The rear bumper's position was calculated based on the position of the front bumper and the vehicle's length.

Figure 8.9 shows a four lanes link segment containing two patches (patches 2 and 3) with their border-lines signified by the red lines. From the figure lanes 1 and 2 contain only average size passenger vehicles with lane 1 patch 2 (L1, P2) containing two front bumpers and one rear bumper while lane 1 patch 3 (L1, P3) contain two rear bumpers and one front bumper. Lanes 3 and 4 both contain average size buses (it should be noted that the position of the vehicles on the link is only for illustrative purpose as buses only occupy the first two lanes in the actual design). Due to the size of the bus, lane 3 patch 2 (L3, P2) contains a single front bumper while ‘L3, P3’ contains a rear bumper and a front bumper. The location of a vehicle on the multiple-lane model could be defined by its lane, the registers where its bumpers are registered in the corresponding patches where they are contained. For example, the location of the green vehicle on lane one could be defined as L1, P2(F2), P3(R1) meaning the vehicle is located on lane one and its front and rear bumpers are located on patch 2 front bumper register 2 and patch 3 rear bumper 1 respectively.

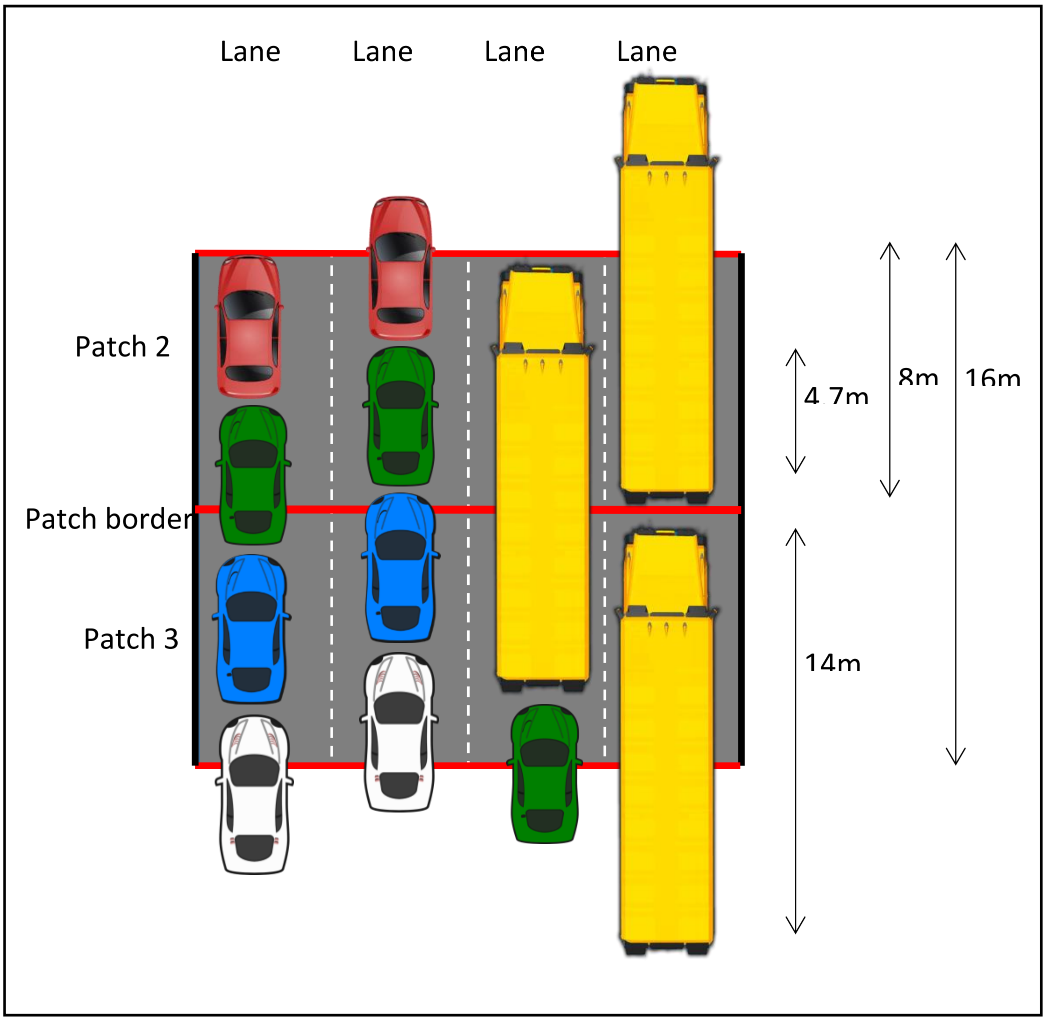


Figure 8.9: The Patch-wise model

Key Functions

The multiple lane model had 7 main user options which were:

- Traffic mode

- Signal mode
- Stop sign status
- Vehicle composition
- Vehicle Type
- Weather condition
- Number of lanes

Traffic control modes

This option had three different modes which were:

- roundabout controlled traffic,
- free flowing traffic
- signal controlled traffic modes

Free flowing and roundabout traffic-controlled modes

When free flowing traffic was activated, lead vehicles exited the link without any special speed requirement (except the speed limit of the link) while when roundabout controlled traffic was activated lead vehicle drivers were required to either come to a complete stop at the end of the link if the stop sign status was on there by simulating the worst case scenario of a traffic jam or in cases were the stop sign status was off drivers were required to reduce their speed to a special speed requirement (5m/s) there by simulating a general traffic jam. The code is shown in appendix 6.

There was a point on the link (i.e. speed_line) beyond which a special speed limit was required for lead vehicles approaching the end of the link. From the code with free-flowing traffic selected lead vehicles accelerated beyond this point there by attempting to maintain a free flow while with congested traffic selected vehicles reduced their speed to the special speed limit (i.e. jam_spd) there by inducing traffic congestion.

The function *'stopline_overshoot_detector'* was a function which operated like the collision detector function (explained later) for the stop sign. It was used when the stop sign status (i.e. *stop_line_status*) was on and basically determined if the observed vehicle would potentially overshoot the stop sign position minus a tolerance distance at the speed it was travelling. The code is shown in appendix 6.

The *'stopline_overshoot_detector'* function operation like the collision detector except the speed of the observed vehicle was compared to the position of the stop sign situated at the end of the link and a tolerance rather than the speed and position of a lead vehicle. The function outputted 1 if the vehicle would potentially overshoot the stop sign or 0 if not.

Signal controlled traffic mode

When the signal-controlled traffic mode was activated, the signal state alternated between two states after a given number of time steps. These were the red and green states, whenever there was a state change a timer commenced. The timer ran from zero to the maximum allowed time of the active state. The red state had a maximum time of 300-time steps (i.e. 30 seconds) while the green light had a maximum time of 600 time steps (i.e. 60 seconds). This is shown in appendix 6.

Basically, the signal automatically controlled the stop sign explained under the previous heading. Whenever the signal was red the stop sign was switched on and lead vehicles of each lane were required to stop behind the stop line while whenever the signal was green the stop sign was switched off and vehicles were required to drive pass the stop sign. The signal somewhat operated alongside congested traffic mode meaning vehicles were required to slow down to a given speed limit at a point on the link (i.e. *speed_line*) when approaching the end on the link. The code used to automatically control the stop sign (i.e. *stop_line_status*) is shown in appendix 6.

The Traffic Stream Vehicle Composition

The traffic composition could be set to either uniform length where all vehicles have the same length and attributes such as mass, frontal area, power etc. or heterogeneous length where vehicles may differ in length and other attributes. When the uniform vehicles option was selected the user was then required to choose between large or small vehicle lengths. During vehicle generation, type 4 vehicle design was automatically chosen for uniform large vehicles while type 1 was chosen for uniform small vehicles. This is shown in the code in appendix 6. Vehicle design is explained in a later section.

Small vehicles had a length of 4.7m which was the value of the variable *'small_L'* while larger vehicles had a length of 14m which was the value of the variable *'big_L'* (Larsson, 2009). Uniform small vehicles were given vehicle design type 1 while uniform large vehicles were given type 4. The design type of each vehicle was saved in cells of an array *'veh_type'* while their lengths were saved in cells of the array *'veh_len'*. The arrays were 1 dimensional and the cells were selected based on the registration of the vehicle being generated *'v_reg'*.

When heterogeneous vehicles option was selected the user was then required to select the desired combination ratio. The model was designed in a way that smaller vehicles were always more or equal to larger vehicles in a traffic stream. This is shown in appendix 6.

With uniform vehicles option off vehicle ratio was used. A counter was used along with the ratio to determine when to select small or large vehicles. When the counter was less than the ratio value selections were made sequentially between the 3 small vehicle design types. The counter *'L_veh_type_cnt'* was used to ensure the design types were selected sequentially and in a loop. Whenever the selection got to the 3rd design type the next selection became the 1st design type and the cycle continued until the counter value equalled the ratio value.

When the counter equalled the *ratio* value a large vehicle design type was then selected and then the counter was reset so smaller vehicle design types were selected afterwards. Just like the small vehicle selection procedure a different counter *'H_veh_type_cnt'* was used to ensure the large vehicle design type selection was done sequentially and once the 3rd vehicle type was selected the counter was reset so that the next selection was the 1st large vehicle design type keeping the selection process in a cycle. This is shown in appendix 6.

The Weather Conditions

The classification of weather conditions based on their precipitation intensities and temperature was shown in chapter 4. Basically, the weather conditions were classified into 5 categories which were:

- Dry/Normal
- Light Rain
- Light Snow
- Heavy Rain
- Heavy Snow

These conditions affected the behaviour of the drivers which was mainly the top speed they were willing to achieve as well as the parameters of the vehicle which were the maximum acceleration and deceleration of the vehicle. The relationship between the weather conditions the vehicles maximum acceleration and deceleration would be later explained under the maximum acceleration and deceleration section. The relationship between weather and the top speed of drivers was derived from Agarwal et al (2005) where estimated drops in speed for various weather conditions were indicated. To be aligned with the UK motorway and Trunk Road driving rules where 70mph has been indicated as the speed limit, only the speed differences between the dry condition and the various weather conditions found in Agarwal et al (2005) were used. The speed differences between Agarwal et al (2005) dry condition and the other conditions were then used to obtain the maximum speed for the other weather conditions for this thesis. This was done by subtracting the corresponding difference of a given weather condition from 70mph to obtain the maximum speed under the weather condition for this thesis. The derived maximum speed for the various weather conditions is shown in the Table 8.4.

Weather condition	Speed (mph)
Dry/Normal	70
Light Rain	63.79
Light Snow	63.79
Heavy Rain	57.57
Heavy Snow	38.93

Table 8.4: The Maximum Speeds for various weather conditions

The implementation in code is shown in appendix 6. In the code the variable *'speed_line'* indicated where lead vehicles had to start considering the special speed limit to avoid overshooting the stop sign since their maximum deceleration rate was influenced by the weather conditions. The variable *'control_vel'* is equivalent to the maximum speed under dry condition. The maximum speeds of the other conditions were obtained by deducting specific values from this value. The variable *'vel_init'* was the initial speed of the vehicles entering the link; this was set to the maximum speed under the specific weather conditions as it was assumed that the link was part of a continuous Trunk Road stretch except in cases were a signal was included or were congestion was induced at the end of the link but in all cases vehicles were initialised to the maximum speed. The variable *'vel_init'* may be regulated to reflect the impact of the various weather conditions on vehicles entering the link although this was not considered in this research. This is shown in appendix 6.

Under dry condition the maximum speed was the same as the speed limit of the link (i.e. 70mph or 31.293m/s) and the speed line was at the highest position on the link compared to other weather conditions (i.e. 700m). Under light rain and light snow conditions the maximum speed was 2.778m/s (or 6.214mph) less than the speed limit. The speed line remained the same because the maximum deceleration rate was not affected significantly enough to have a considerable impact on their stopping distances. Under light rain and light snow conditions the maximum speed was 2.778m/s (or 6.214mph) less than the speed limit. The speed line remained the same as the maximum deceleration rate was not impacted significantly enough to have a significant impact on their stopping distances. Under heavy snow condition the maximum speed was 13.889m/s (or 31.0686mph) less than the speed limit while the speed line was reduced to 500m to compensate for the impact of the weather condition on the maximum deceleration rate. This was implemented in the code under appendix 6.

The Lane Changing model

Lane changing refers to the movement of a vehicle from its current lane to an adjacent lane. It is an integral aspect of multiple lane microscopic traffic simulation and it involves complex decision making by the model drivers which often rely on several objectives that sometimes conflict (Mathew, 2014). Ramanujam (2007) indicated that lane changes are often expressed in terms of *gap acceptance* and *target lane* where a driver intending to switch lanes chooses a target lane then determines if there is an acceptable gap in the selected target lane. An acceptable gap which may be time gap or free space gap must be greater than or equal to the critical gap (minimum acceptable gap required for a lane change execution) for the lane change to be executed.

Lane change durations for various models often range between 4-6 seconds which seems practical except vehicles may take longer than realistic timing when attempting to change lane in various situations. This includes a situation where a driver becomes desperate after failing to switch lanes following multiple attempts, a situation where the driving conditions of the current lane becomes favourable while attempting to switch lanes (depending on the reason for switching lane i.e. mandatory or discrete discussed later). It could also take longer when drivers simultaneously observe multiple lanes for preferred driving conditions (left, current and right lanes) which is often the case in the real world. This report introduces a new timing method which is an extension of the conventional lane change timing method (expressed in seconds) used in previous works. In this method time expressed in seconds was replaced with interest levels where the interest level of a driver may increment or reduce by one level or remain unchanged during each time-step. The levels ranged from 0 to 50, the maximum level 50 was adopted from the average lane change duration utilised by other works. This model was designed based on the UK Highway Code (DFT, 2016) and drivers looking to switch lanes for better driving conditions take this into account when deciding.

Mandatory and discretionary lane change

Mandatory lane changes (MLC) are compulsory lane changes such as changes a driver must make to complete his journey (e.g. if driver is required to turn left or take a left exit in an intersection he may choose to switch to an inner lane) or drivers attempting to adhere to the UK highway codes (e.g. bigger vehicles such as buses sticking to the inner lanes and vehicles generally required to prefer the inner lanes to the outside lanes if the inner lanes meet their preferred driving conditions). Drivers attempting to make a turn in an intersection may respond earlier to the MLC if it is required to make multiple lane changes.

Discretionary lane changes (DLC) are executed when a driver intends to seek better driving conditions from an adjacent lane, avoid merging traffic, avoid following bigger vehicles etc. (Mathew**,** 2014).

Traffic-flow models often combine the MLC and DLC and during selection clashes the MLC always precede over the DLC. An example is a scenario where a driver behind a slow moving vehicle refuses to overtake the vehicle because he intends to take the off-ramp but the distance to the off-ramp is below a threshold. This work has not observed drivers making left or right turns on the Trunk Road.

The Point Based Lane Changing Process

It has been split into three stages:

Decision to change lane: This stage involved the driver observing the driving conditions on its current lane. When it is close enough to the lead vehicle on its current lane it decides if the mean speed of the lane is favourable and if the vehicle ahead is moving at a favourable speed, if these conditions are not met it makes a *decision to change lane*. To meet the UK Highway code specification, if these conditions are met it then compares the mean speed with that of the inner lane, if the mean speed of the inner lane is less than the mean speed of the current lane but the difference falls within a certain threshold then a *decision to change lane* is also made.

Mathew (2014) discussed various equations by Gipps (1986) which may be used to determine *a driver's desire to change lane, feasibility of changing lane and gap acceptance*. While the method seems rather complex, this thesis introduced a simplified method for carrying out the above lane changing processing. Thorough tests of the model proposed in this thesis revealed that the model performed the required tasks without errors.

In this work, to determine a driver's desire to change lane the driver was designed to observe its driving condition until 20 *interest levels* had been gained. An interest to change lane gained a point at each time step when the driving conditions were not favourable and lost a point when it was favourable. After 20 interest driving levels had been gained the driver became unsatisfied and a *decision to change lane* was then made.

The driver was then unable to change his mind from switching to a different lane until 10 *interest levels against* switching lanes had been made. This was done to prevent drivers from changing their decisions rapidly. A point was gained *against switching lanes* if the driving condition of the current lane suddenly became favourable during a time-step while all points were completely lost if the conditions became unfavourable during a time-step to reduce the delay when attempting to switch lanes. This entire stage was only featured when the driver intended to switch to an outer lane. This was because he was required to switch to an inner lane whenever the driving conditions were favourable regardless of whether its current lane driving conditions were favourable or not.

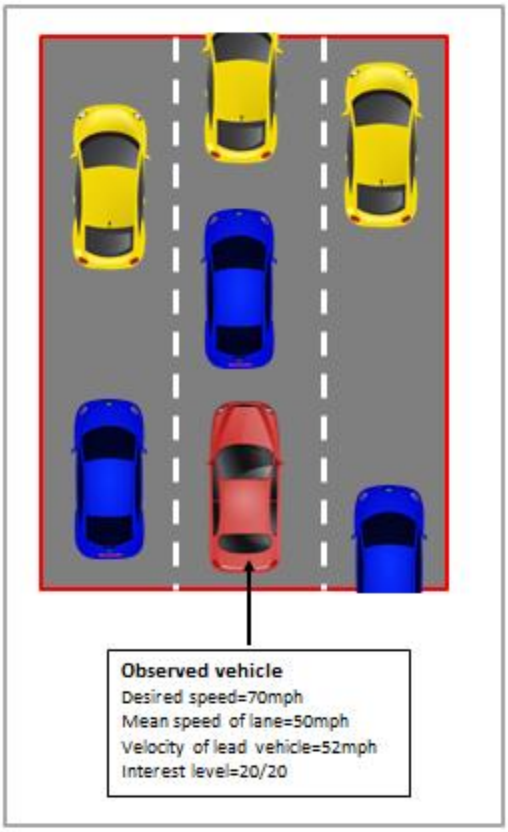


Figure 8.10: Decision to change lane illustration

Figure 8.10 above illustrates how a driver who has decided to change lanes perceives their environment. The driver interest in changing lane is on level 20 meaning he has been observing his current lane for a while (not necessarily 20 time steps as the interest level may gain or lose a point at each clock cycle depending on the driving condition of the current lane), has decided it is not favourable and has made a decision to change lane. His *mind change level* remained at level 0 because the driving condition has either not improved in the current time step or improved and gained a point in a previous time step but became unfavourable in a different time step where all points were immediately lost.

The code in appendix 6 was used by each driver when observing the condition of its current lane. The variable *time_overtake_array* was an array which held the interest level of each driver on their current lane, the variable *veh_reg* held the identifier of the observed vehicle, the variable *timer_change_array* is an array for the which holds interest levels for each vehicle that determined whether the driver regained an interest in its current lane after being interested in changing lane. Most of the variables were explained in later sections, important to understand here is that the driver of the observed vehicle considered its acceleration mode and its speed in the previous time step as well as its interest level when making a decision on whether to increase or reduce its interest in changing lane.

Driving condition on adjacent lanes (feasibility of changing lane): After a decision to change lane had been made the next step was to determine the driver's feasibility of changing lane. The driver commenced observing the driving conditions of the adjacent lanes as well as its current lane (points against switching lanes as explained above). He observed both the outer and inner lane simultaneously, both lanes had interest levels which ranged from 0-40, a point was gained in favour of the inner lane if the driving conditions were favourable and lost if they were not favourable in a given time-step regardless of if a *decision to change lane* had been made by the driver or not. The outer lane started gaining or losing points after a *decision to change lane* had been made. To prevent the vehicle from deciding to switch to the inner lane (possibly slower lane since favourable conditions for the inner lane were designed to be lower than the current lane) a counter was used to determine when the right lane driving conditions were not favourable for 20 consecutive time-steps. A decision to switch to the left lane was only possible if the interest to switch to the right lane was zero or the interest in the right lane lost points for 20 consecutive time steps. The driver stopped observing the right lane (i.e. interest level of the right lane returned to 0) if his *mind change level* was at maximum (i.e. if he felt his current lane driving conditions were better than the right lane or favourable).

The driver also observed the speed of the lead vehicle on the adjacent lane with interest points being gained or lost depending on the speed of the lead vehicle with respect to its current speed.

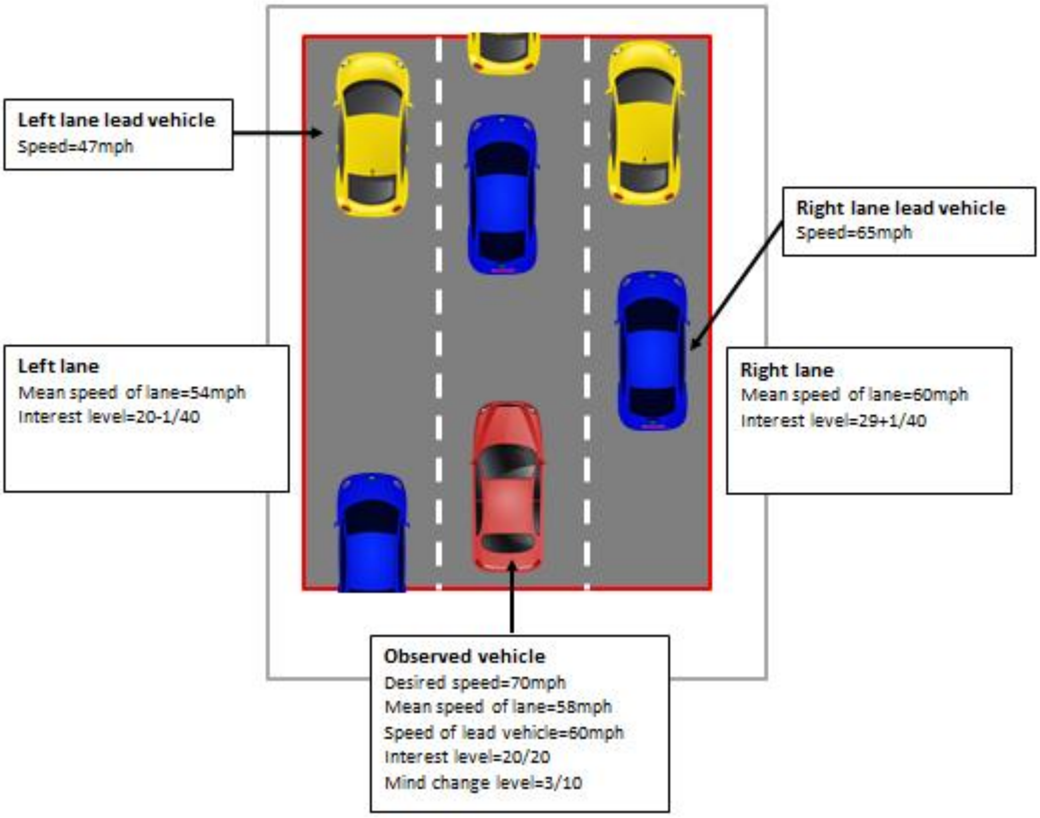


Figure 8.11: Illustration of the driver's perception of the neighbouring lanes

Figure 8.11 above illustrates an observed driver's perception of his neighbouring lanes at a given time step after he had made up his mind to change lane. The mean speed of the right lane was 60mph and the lead vehicle (i.e. the vehicle on the neighbouring lane in front of the observed vehicle) speed was 65mph which was a more favourable condition than the current lane which had a mean speed of 58mph and lead vehicle speed of 60mph hence the interest level for the right lane gained a point on this time step. On the left lane the mean speed was 54mph which was less than the current lane's mean speed, but the difference was within an acceptable threshold, but the lead vehicle's speed was 47mph which was below the threshold and deemed unfavourable hence the interest level for the left lane lost a point during that time step.

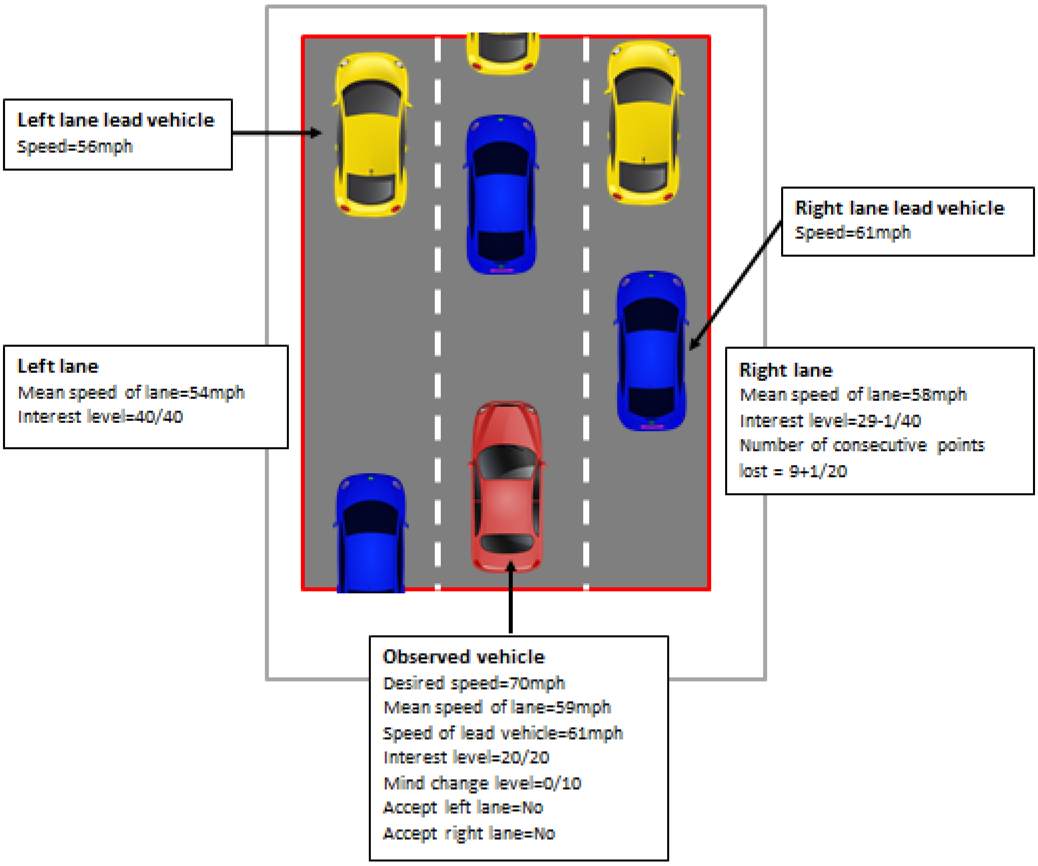


Figure 8.12: Decision when selecting a lane

Figure 8.12 above although the interest level on the left lane was at maximum, the interest level on the right lane was neither at the minimum value nor had it lost points for 20 consecutive levels hence the driver decided to continue his observation until either these conditions were met before switching to the left lane or until the driving conditions on its current lane or the right lane became favourable.

The code shown in appendix 6 was used to calculate the total speed of vehicles on each lane within the driver's range. To determine the mean speed of a given lane the total number of vehicles on the lane as well as their total speed were first determined using the code above. In the code a loop essentially ran from 1 to the maximum value permitted for a vehicle register. During each run an array *Lanes_array* which held the current lane of each vehicle was scanned using the current time step and the value of the loop, its length was the value of the maximum value permitted for a vehicle registration while its width value was the value of the maximum time step. For the first logic, whenever the scanned cell of *Lanes_array* returned the value (identifier) of the observed vehicle current lane it meant a vehicle on that lane had been detected with a vehicle registration the same as the current value of the loop. A variable delegated to keep track of the total number of vehicles in the current lane was then incremented while a variable delegated to keep track of the total speed of vehicles on the lane was increased by the speed of the vehicle detected. The other sections of the code followed similar suit except vehicles were scanned on the neighbouring lanes of the current lane hence instead of scanning for the value of the current lane, the value of neighbouring lanes was for on *Lanes_array*. The first and the last lane both had one neighbour each hence the variables for their right and left neighbours respectively were set to 0.

The code in appendix 6 was used to calculate the mean speed for each lane. The mean speed for each lane (the current, left and right lanes) was then calculated by dividing their total speed by their total number of vehicles. This entire code is located inside a function called *overtake*.

The lead vehicles of the observed vehicle on the current lane and each adjacent lane were determined using a function called reference vehicle detector explained in a later section.

When the current lane of the observed vehicle was not the first lane the code shown in appendix 6 was used to determine whether the driver gained an interest level or lost an interest level on the inner lane. The driver continued observing the inner lane regardless of its satisfaction with its current lane. As mentioned earlier the driver was always willing to accept a lower speed on the inner lane provided the speed was within an acceptable threshold from its desired speed or its current lane mean speed, it was also happy if there was no lead vehicle on the inner lane.

When the current lane of the observed vehicle was not the maximum lane specified, the code shown in appendix 6 was used to determine whether the driver gained or lost an interest in the outer lane. The driver completely lost interest in the outer lane when it had no lead vehicle on its current lane while its interest in its current lane gained a point, it gained or lost an interest point in its outer lane and current lane depending on the condition of the outer lane. An interest point was gained for the outer lane only when the driving condition of that lane met certain threshold values which were set to be better than its current lane conditions. The variable non_interest_counter_array was incremented each time an interest point for the outer lane was lost and reset to 0 each time a point was gained, this was used by the driver of the observed vehicle to determine whether to continue observing the outer lane in which case the value was less than or equals 20 points or switch to the inner lane if the value was greater than 20 points and all other conditions required to switch to the inner lane were met.

Gap acceptance and execution: After a desired lane had been selected the driver then determined if switching lanes would potentially result in a collision between the driver's vehicle and its lead or following vehicle. This was done by determining if there was enough gap between the lead vehicle and the following vehicle on the adjacent lane as well as if a collision would occur if the lead vehicle suddenly started braking and if a collision would occur with the following vehicle if the driver of the observed car suddenly started braking. A function called collision detector explained in a later section was used to determine if there was a risk of collision. If the conditions were positive lane change was then executed else the vehicle waited until the conditions were satisfied while observing the driving conditions of all three lanes and making changes to its decision when required.

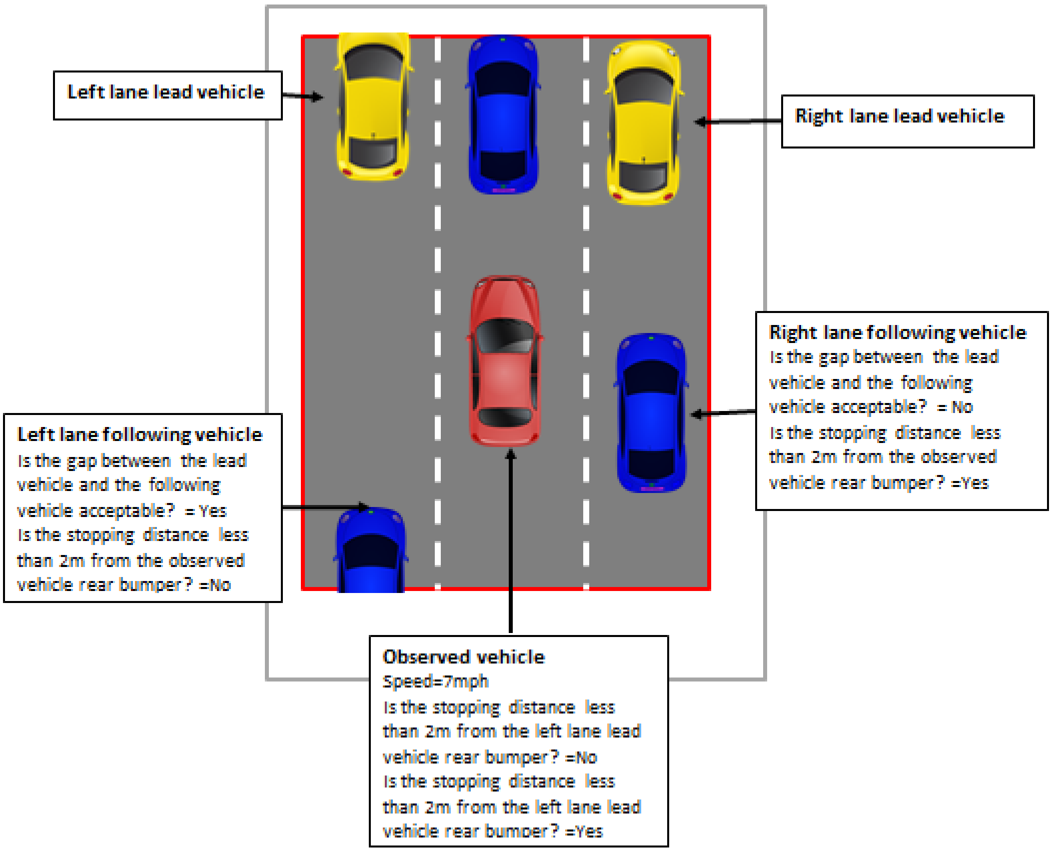


Figure 8.13: Decision on gap

Figure 8.13 above the gap between the lead and following vehicles on the right lane is not acceptable, although switching lanes would not result in a collision with the lead vehicle it would potentially result in a collision with the following vehicle as the stopping distance of the following vehicle would be less than 2 meters from the observed vehicle's rear bumper hence if even if the right lane driving condition was favourable lane change would not be executed until a suitable gap is observed. On the left lane the gap between the lead and following vehicles on the right lane is acceptable, switching lanes would not result in a collision with neither the lead vehicle nor the following vehicle as the stopping distance of the observed vehicle would be less than 2 meters from the lead vehicle's rear bumper and the stopping distance of the following vehicle would be less than 2 meters from the observed vehicle's rear bumper hence if the left lane driving conditions were favourable, lane change would be executed.

After a lane change had been executed all interest variables of the driver were reset to 0. It should be noted that in cases were the driver was in the first or last lane on the outside only a single neighbour was considered.

The code shown in appendix 6 was used by the driver of the observed vehicle when deciding on whether to change its lane or remain in its current lane during the current time step. The variables *N2_avail* and *N1_avail* are variables that held the result of a fail proof test on the target patches for the front and rear bumper of the observed vehicle on the target lane. The variables *change1* and *change2* are also fail proof variables used to determine if the positions of the front bumper of the following vehicles on both adjacent lanes would clash with the position of the observed vehicle during the next time step if a lane change was to be executed.

The first filter basically checked for a possible collision with the lead and following vehicles on the outer lane, checked future positions of the rear and front bumper of the observed and following vehicle on the outer lane respectively, determined if the target patches on the outer lanes were available, determined if the interest on the outer lane of the driver of the observed vehicle was maximum, determined if the current lane was less than the maximum possible lane specified, if all these conditions were met the current lane of the observed vehicle was incremented while other variables related to its interest and observations were reset to 0.

The second filter is like the first filter except the variables for the inner lane were considered, the value of the current lane had to be greater than 1 and either the driver had no interest in the outer lane or its interest on the outer lane had lost 20 points consecutively. If these conditions were met the current lane of the observed vehicle was reduced by 1 while other variables related to its interest and observations were reset to 0.

In cases where the conditions for the first or second filters were not met the vehicle remained in its current lane.

The UK Highway Code

The UK Highway code prohibits drivers from using the right-hand lane when the road is clear, and it restricts heavier vehicles such as buses from using the right-hand lane. It also prohibits drivers from overtaking using the left lane except during congestion where traffic in the left-hand lane may be moving faster than traffic in the right-hand lane. Vehicles are also prohibited from weaving in and out of lanes to overtake (DFT, 2018).

Lane changing model test result

Test of the lane changing algorithm showed drivers exhibiting a realistic decision-making attribute as drivers were able to simultaneously evaluate the driving conditions of all three lanes during the decision-making process. Test results showed that drivers spent an average of 4.9 seconds between deciding to change lanes and executing the lane change under low traffic density with drivers generally completing this process within 4 seconds (40 time-steps) without any disruptions to the decision-making process.

Driving conditions definitions

The Current lane Good driving conditions

This condition was true when the speed of the observed vehicle was less than its maximum speed and its acceleration was greater than or equals its acceleration whenever the lead vehicle was pulling away or its current acceleration was its maximum acceleration. It was also true whenever the observed vehicle was travelling at its maximum speed. This is shown in the logic equation 8.1:

velo<max_velo & (accel>=aB OR accel=max_accel) OR velo=max_velo [8.1]

The Current lane Bad driving conditions

This condition was true when the observed vehicle's speed was less than its maximum speed and its acceleration was less than or equalled any of its possible accelerations when in its cruise mode. It was also true when the observed vehicle's speed was less than its maximum speed and the speed of its lead vehicle on its current lane was less than the mean speed of the current lane. This is shown in the logic equation 8.2:

velo<max_velo & (accel<=aA OR accel<aB OR accel<=aC OR velo_refC<mean_velo_cur) [8.2]

The Left lane Good driving conditions

This condition was true when the mean speed of the left lane was greater than the maximum speed of the observed vehicle minus 10m/s or the mean speed of the left lane was greater than or equals the mean speed of the current lane minus 2m/s or no lead vehicle on the left lane. It was also true when no lead vehicle on the left lane and the observed vehicle's speed was less than the mean speed of the left lane minus 2m/s. This is shown in the logic equation 8.3:

mean_velo_left>max_velo-10 OR mean_velo_left>=mean_velo_cur-2 OR refL=0 OR (refL=0 & velo<mean_velo_left-2) [8.3]

refL=0 means no lead vehicle on the left lane

The left lane Bad driving conditions

This condition was true when the mean speed of the left lane was less than the maximum speed of the observed vehicle minus 10m/s and the mean speed of the left lane was less than or equals the mean speed of the current lane minus 2m/s. It was also true when the speed of the lead vehicle on the left lane was less than the mean speed of the left lane. This is shown in the logic equation 8.4:

(mean_velo_left<max_velo-10 & mean_velo_left<=mean_velo_cur-2) OR velo_refL<mean_velo_left [8.4]

The Right lane Good driving conditions

This condition was true when the mean speed of the right lane was greater than the mean speed of the current lane plus 2m/s, it was also true when there was no lead vehicle on the right lane, it was also true when the speed of the lead vehicle on the current lane was less than the mean speed of the right lane minus 2m/s. This is shown in the logic equation 8.5:

mean_velo_right>mean_velo_cur+2 OR refR=0 OR velo_refC<mean_velo_right-2   [8.5]

refR=0 means no lead vehicle on the right lane

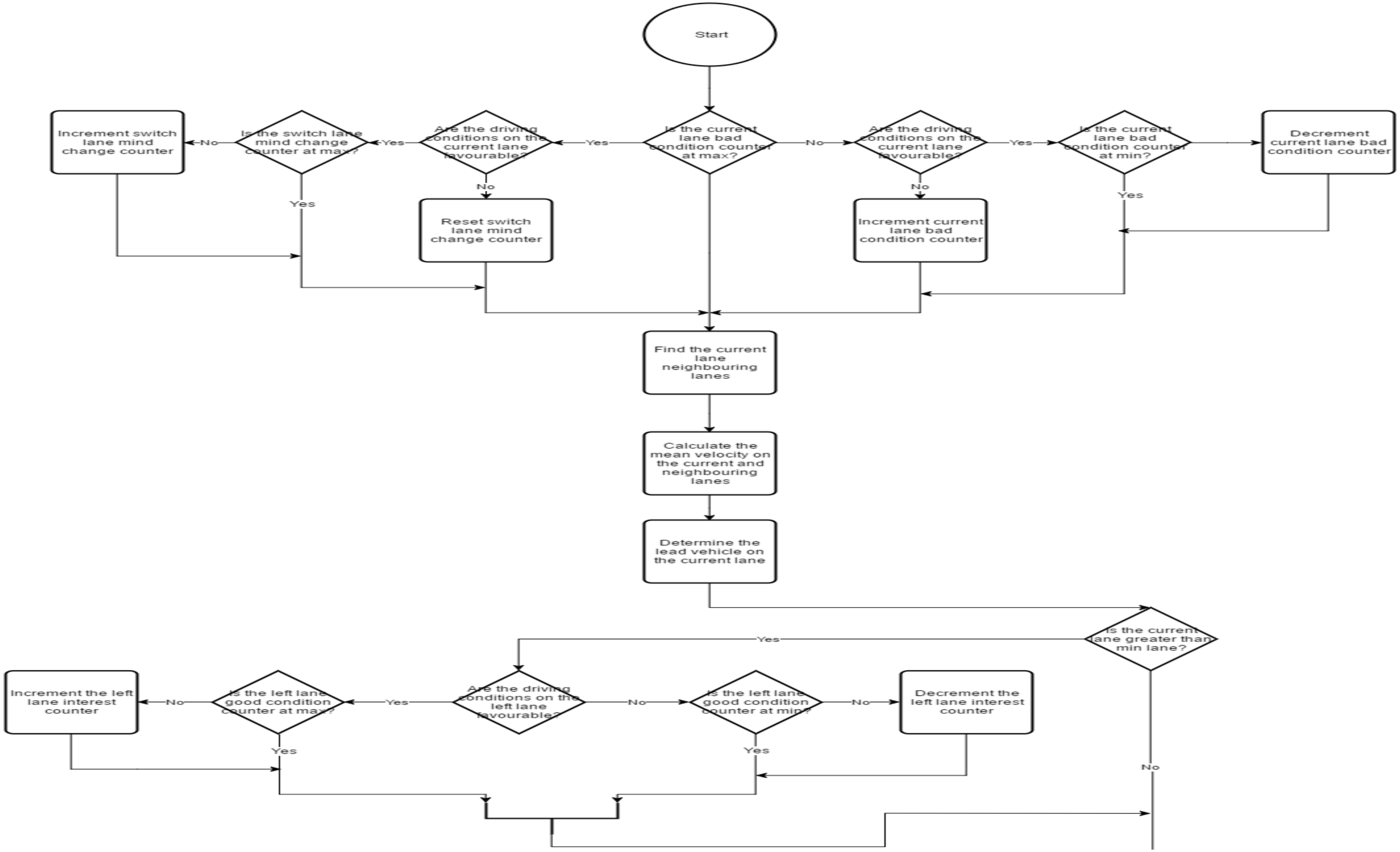
The Right lane Bad driving conditions

This condition was true when there was no lead vehicle on the current lane, it was also true when there was a lead vehicle on the current lane and the mean speed of the right lane was less than the mean speed of the left lane plus 2m/s or the speed of the lead vehicle on the right lane was less than the mean speed of the current lane plus 2m/s. This is shown in the logic equation 8.6:

refC=0 OR refC>0 & (mean_velo_right<mean_velo_left+2 OR velo_refR<mean_velo_cur+2   [8.6]

The Lane changing model flow chart

The flow chart for the lane changing model is shown in figure 8.14


Start
Is the current lane bad condition counter at max?
Yes
No
Are the driving conditions on the current lane favourable?
Yes
No
Is the switch lane mind change counter at max?
No
Yes
Increment switch lane mind change counter
Reset switch lane mind change counter
Are the driving conditions on the current lane favourable?
Yes
No
Is the current lane bad condition counter at min?
Yes
Decrement current lane bad condition counter
Increment current lane bad condition counter
Find the current lane neighbouring lanes
Calculate the mean velocity on the current and neighbouring lanes
Determine the lead vehicle on the current lane
Is the current lane greater than min lane?
Yes
No
Are the driving conditions on the left lane favourable?
Yes
No
Is the left lane good condition counter at max?
No
Yes
Increment the left lane interest counter
Is the left lane good condition counter at min?
No
Yes
Decrement the left lane interest counter

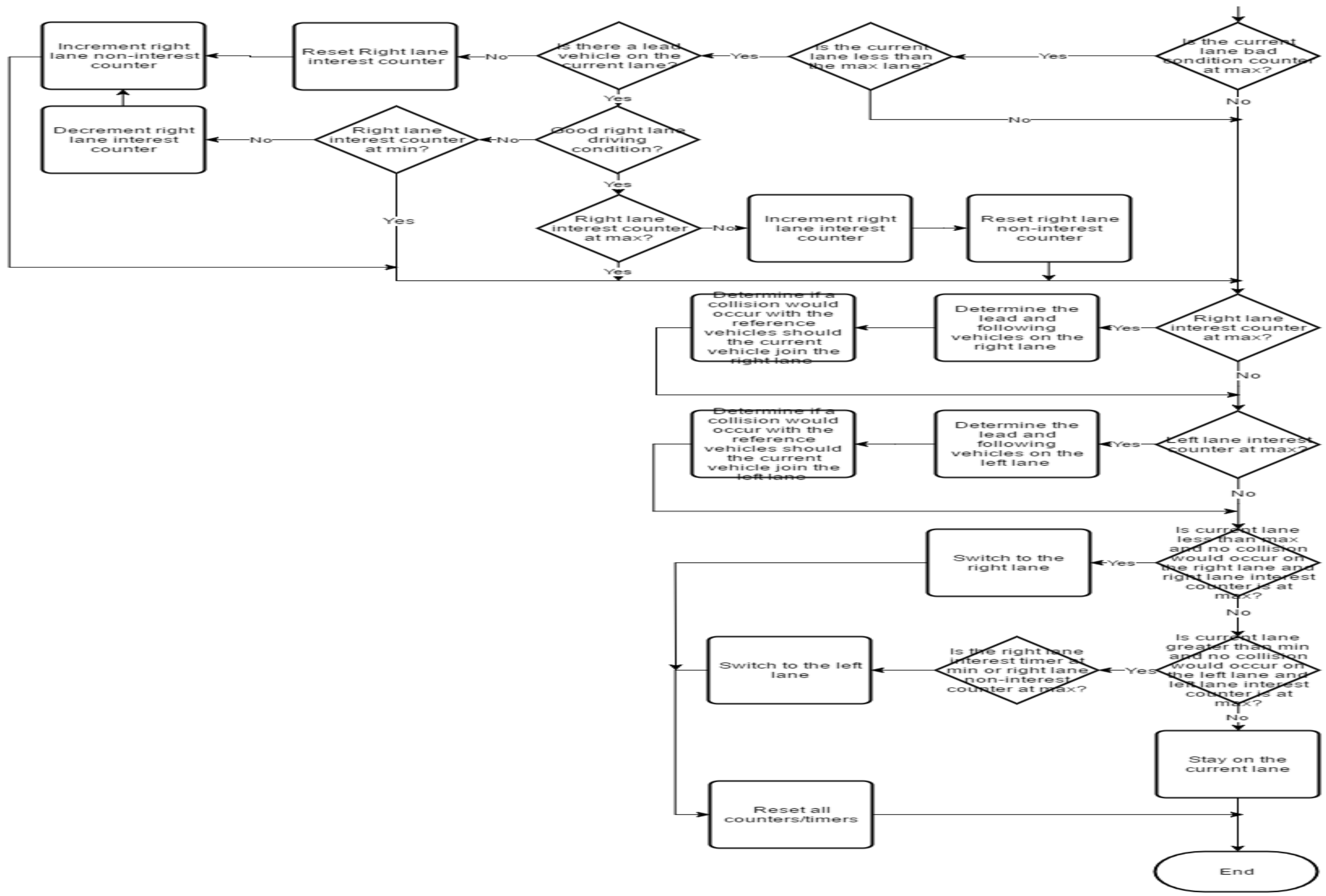


Figure 8.14: Flow chart for the lane changing model

Figure 8.14 above shows the flow chat of the lane changing algorithm, the full code can be seen in appendix 6.

Other key functions

Reference vehicle detection

This function was used to detect the lead and following vehicles of the observed vehicle where necessary. On the current lane of the observed vehicle it was used to detect the vehicle immediately ahead (the lead vehicle) while during lane change operation it was used to detect the lead and following vehicles on the neighbouring lanes with respect to the observed vehicle.

The function operated by initially scanning through the registers of the patch containing the observed vehicle for front bumpers and rear bumpers. When a bumper was detected it then compared the position of the bumper to the bumper of the vehicle being observed. When a lead vehicle was being scanned for, it compared detected rear bumper positions to the position of the observed vehicle's front bumper. The vehicle with the rear bumper ahead of the observed vehicle's front bumper became the lead vehicle of the observed vehicle. In a situation where a rear bumper was not detected within the registers of the patch containing the observed vehicle the scan was expanded to other patches ahead of the vehicle's containing patch starting from the patch ahead.

When a vehicle registration was detected in a patch register it meant the patch register contained the bumper of the vehicle.

Initialising patch registers of the observed lane

A variable L held the observed lane's value (lane number). Each lane had four registers, registers a and b were for the front bumpers while registers c and d were for the rear bumpers. Whenever a vehicle registration was detected in a patch register it meant the patch register contained the vehicle's bumper. Whenever a lane was being scanned its registers were selected as shown in the code in appendix 6. *Table* 8.5 below shows each lane patch registers.

Lane	Front bumper registers (a, b)	Rear bumper registers (c, d)
1	1,2	3,4
2	5,6	7,8
3	9,10	11,12
4	13,14	15,16

Table 8.5: Lane patch registers

Scanning for the Lead vehicle

This operation was used when scanning for both the lead vehicle on the observed vehicle's (OV) current lane and the lead vehicles on the adjacent lanes but the lane to be scanned was indicated before each scan to enable the required patch registered to be scanned. This operation was split into two segments. The first segment scanned the OV current patch for a lead vehicle and had two stages while the second segment also had two stages but scanned subsequent patches for a lead vehicle. Note that the OV current patch here could also mean the equivalent patch on its neighbouring lane depending on the lane where the lead vehicle was being detected.

Scan Segment 1: Scanning the Current Patch registers

The first segment searched the current patch of the observed vehicle for a lead vehicle. The search was split into two stages:

- Scanning the current patch front bumper patch registers
- Scanning the current patch rear bumper patch registers

Scan Stage 1a: Scanning the current patch front bumper patch registers

The first stage scanned the front bumper patch registers of the OV current patch for a potential lead vehicle front bumper as shown in the code below. The OV current patch was scanned for front bumpers and any detected front bumper was compared with the position of the OV front bumper. Whenever two front bumpers were detected such as in cases where the operation was used on neighbouring lanes their positions were compared and the one with the lower position value was used as the reference vehicle if its position was higher than that of the OV else the one with the higher position was used. Patch registers a and b were for the front bumpers, vehicle with a detected front bumper ahead of the OV front bumper became the lead vehicle of the OV. The code is shown in appendix 6.

To prevent the scan from proceeding to the next stage after a lead vehicle had been detected which may result in the detected lead vehicle being overwritten a flag (e.g. *ref_found2*) was used to indicate when a lead vehicle had been detected. Note that various flags were used at different sections for this purpose and this was for convenience. For example, the flag *found_ref* was featured in stages 3 and 4 to break the loop when a lead vehicle was found to avoid overwriting the lead vehicle during further scans.

Scan Stage 2a: Scanning the current patch rear bumper patch registers

In situations where no front bumper at the first stage was detected rear bumpers were then scanned for. The patch registers for rear bumpers were c and d. The OV current patch was scanned for rear bumpers and when rear bumper was detected, its front bumper was compared with the position of the OV front bumper. A vehicle with a detected rear bumper on the scanned patch which had its front bumper ahead of the OV front bumper became the lead vehicle of the OV. This is shown in the code under appendix 6.

Scan Segment 2: Scanning the Current Patch registers

In a situation where no lead vehicle was found at the current patch of the OV, the scan proceeded to scan subsequent patches for a lead vehicle. This segment was enclosed in a loop which ran from the OV current patch number down to patch 1 (the top of patch of the link). During iterations the registers of the patch with the same value as the loop were scanned and the same steps as stages 1a and 2a were followed i.e. the front and rear registers were scanned and the front bumper position of any vehicle detected was compared with the front bumper position of the OV. A flag *found_ref* was used to break the loop when a lead vehicle was found to prevent the found vehicle from possibly being overwritten during subsequent iteration. The search was split into two stages:

- Scanning the subsequent patches front bumper patch registers
- Scanning the subsequent patches rear bumper patch registers

Scan Stage 1b: Scanning the subsequent patches front bumper registers

In this stage the front bumper patch registers of the patch being searched was scanned for a potential lead vehicle front bumper as shown in the code below. The Patch in focus was scanned for front bumpers and any detected front bumper was compared with the position of the OV front bumper. Patch registers a and b remained the patch registers for the front bumpers. The vehicle registration of the first front bumper to be detected during this scan was regarded as the registration number of the lead vehicle. This stage is shown in the code under appendix 6.

Scan Stage 2b: Scanning the subsequent patches rear bumper registers

Like scan stage 2a, in situations where no front bumper at scan stage 1b was detected rear bumpers were then scanned for. The patch registers for rear bumpers were c and d. The patch in focus was scanned for rear bumpers and when a rear bumper was detected, its front bumper was compared with the position of the OV front bumper. A vehicle with a detected rear bumper on the scanned patch which had its front bumper ahead of the OV front bumper became the lead vehicle of the OV. This is shown in the code under appendix 6.

Scanning for the following vehicle

The *following vehicle detector* operated similarly the *lead vehicle detector* except patches were scanned backwards from the current patch of the OV rather than forward as seen in the lead vehicle detector. Note than OV current patch here meant the equivalent patch on its neighbouring lane. The operation was only used when detecting following vehicles on the adjacent (neighbouring) lane as drivers do not often analyse the driving condition of the following vehicles on their lane but may concentrate on the neighbouring lanes when analysing driving conditions or interested in switching lanes. This differed from the lead vehicle detector where following drivers had to always analyse the lead vehicle at all times as well as the lead vehicles on the adjacent lanes when comparing driving condition or interested in switching lanes. A variable *lane_checker_mode* had to be set high to indicate this operation was to be used to avoid unnecessary scans which would have potentially slowed down the simulations.

In this operation the front bumper registers were scanned, and their positions compared to that of the OV's rear bumper position and the front bumper at the closest proximity to the rear bumper of the observed was detected as the following vehicle. Cases found when this operation was used for detecting on the neighbouring lanes where the front bumper of a potential following vehicle may be ahead of the rear bumper of the OV but behind the front bumper of the OV were also considered. When this operation was being used the lane to be scanned was predefined before the scan. This operation was split into two segments each comprising of single stages only because the front bumpers were mainly considered. There were some cases were the rear bumpers were considered but this was only done to capture exceptions where the rear bumper of the OV and/or potential following vehicles may be located outside the link.

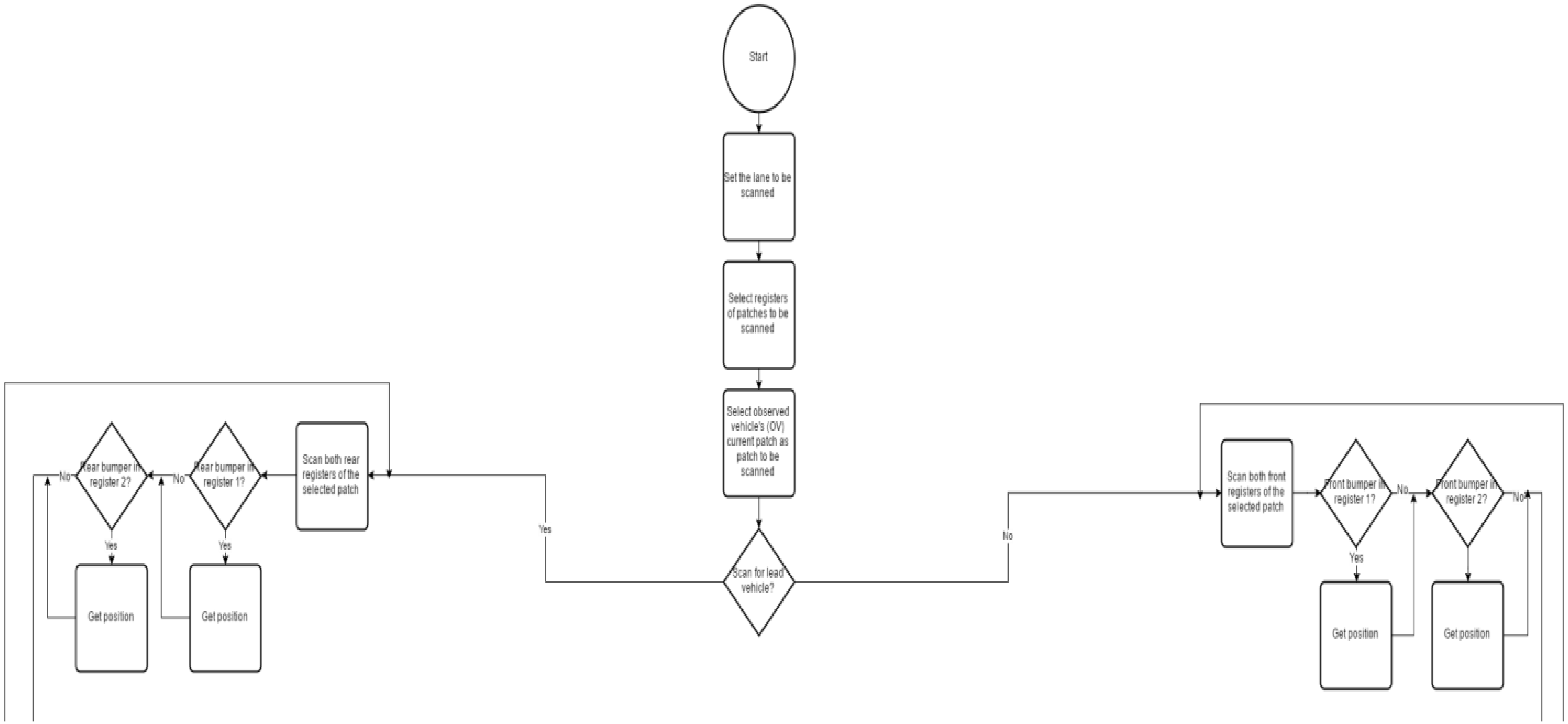
Segment1: Scanning the OV's current patch for a following vehicle

The front bumper registers of the OV patch was scanned in this stage and whenever a vehicle registration number was detected it was compared with the registration of the OV and was accepted as a potential following vehicle pending further evaluations if it differed in value. In cases where two vehicles were present on the patch and none was the OV, the positions of their front bumpers were compared and the one with the higher value was deemed the following vehicle of the OV if its front bumper position was less than that of the OV front bumper. If it was higher and the second vehicle's bumper was lower than the OV front bumper the second vehicle was then regarded as the following vehicle. This is shown in the code under appendix 6.

Segment2: Scanning the predecessor patches for a following vehicle

Whenever no following vehicle was found on the first scan segment the search was then extended to the second segment patches behind the OV's current patch like segment 1. Only the front bumper registers were considered and the position of detected front bumpers was compared to the OV's front bumper. When two front bumpers were detected behind the OV's front bumper the closest to the OV's front bumper was chosen as the following vehicle. A flag was used to break out of the search loop whenever a reference vehicle was found to prevent it from being overwritten and to increase simulation speed. The code is shown under appendix 6.

An overview of the algorithm is shown in figure 8.15 below:



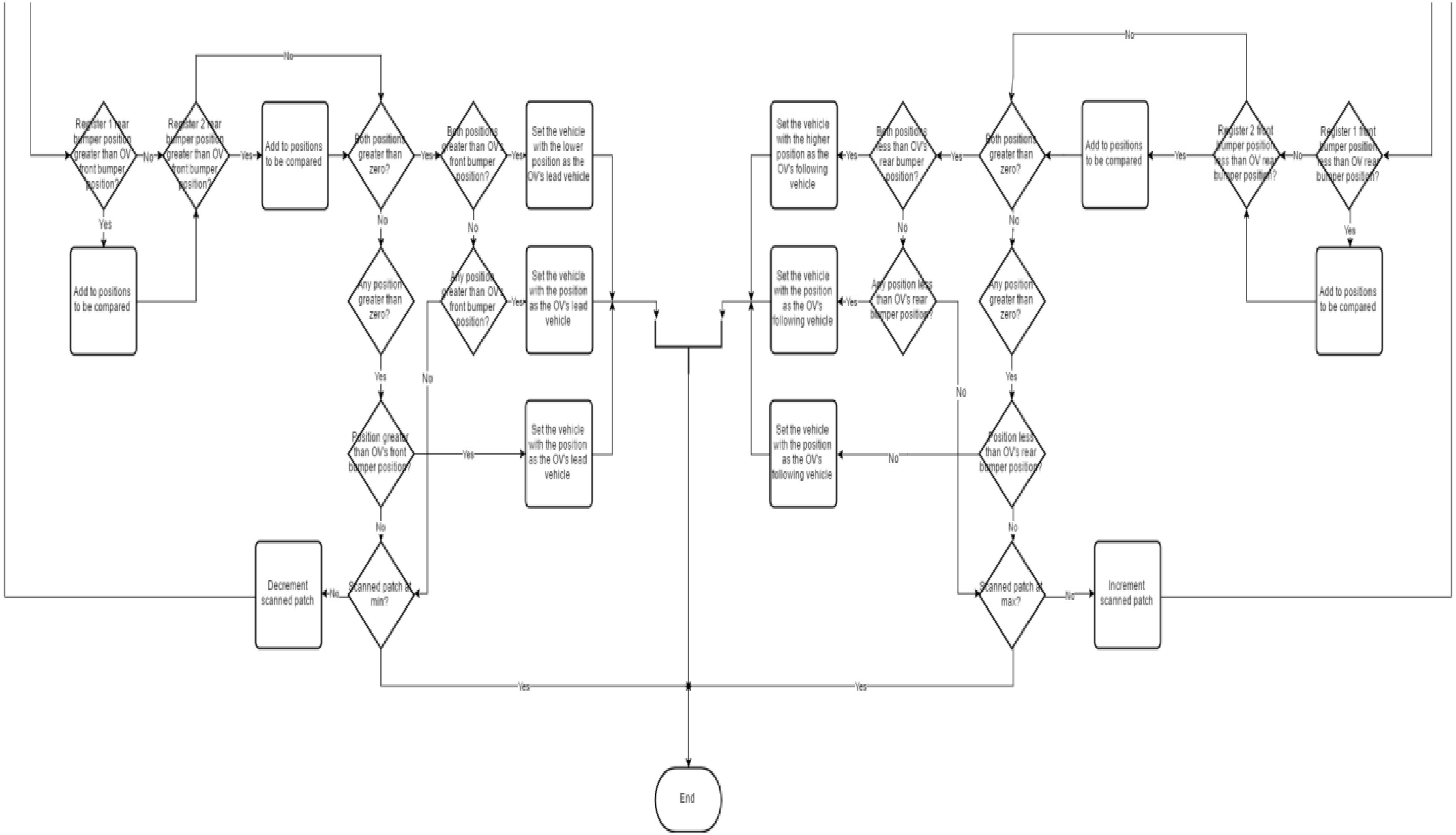


Figure 8.15: Flow Chart of the reference vehicle detection algorithm

Distance to patch convertor

The Patch Generator

This function was used to convert the distance covered by each vehicle to patch variables. The length of the link to be featured was first divided into patches, each patch was 8 meters long and the total number of patches for any given link with a length being a multiple of 8 could be deduced using equation 8.7:

$$totalpatch = linklength/8 \qquad [8.7]$$

A look up table containing a range of distances from 1 to the link length (meters) split into groups (patches) was generated and fed into the patch generator function. For this research the link length was 1000 meters long hence there was a total of 125 patches. The distances were assigned to patches in descending order meaning 1m was assigned to patch 125 and 1000m assigned to patch 1.

Decimal positions were rounded up to higher integers, for example 8.1m was rounded up to 9m even though this would normally be rounded to 8m this was because 8.1m would be located on the 124th patch rather than the 125th patch which contained values from 1-8m also this way values less than 1m but greater than 0m were rounded up to 1m rather than assuming they were out of range.

After the positions to be searched were rounded to integers (i.e. the front bumper and the rear bumper positions of a vehicle) they were searched for on the look up table and the corresponding column value of where they were located was assigned to their patch value. The patch generator code is shown in appendix 6.

The first step when converting distances to patches was to obtain the generated patch table. The next step was to deduce the position of the rear bumper of the vehicle based on the position of its front bumper and the total length of the vehicle. Afterwards, the positions of the bumpers were rounded to whole numbers.

The second step was to find the patch associated with the rounded position. A MATLAB function 'find' was used to search the generated patch look up table for the rounded value. The output of the function was indices of the value on the look up table if the value was found. Only the column index was of interest as it indicated the patch of the rounded number on the look up table. Filters were used to ensure only values within the range of 1 to 1000 were searched for and other values were assumed to be 0 (i.e. out of range) which could only occur when a vehicle was exiting the link or when a vehicle was entering the link and its rear bumper was still situated outside the link.

The patch look up table

The look up table was generated at the start of the main program. It contained a primary *for loop* which contained a secondary *for loop*. The primary for loop ran from 1000 down to 1 in steps of 8 while the secondary for loop ran from 2 to 8 in steps of 1. Values were extracted from the primary and secondary for loops which were used to create an array. The primary loop was used to assign values to the top row while the secondary loop was used to assign values to each column except for values located at the top row. A screen shot of a section of the patch look up table is shown in Table 8.6. The row on the patch look up table labelled 1-10 signified the patches assigned to each distance below it. As mentioned earlier each patch was made up of 8m as shown on the column labelled 1-8.

	1	2	3	4	5	6	7	8	9	10
1	1000	992	984	976	968	960	952	944	936	928
2	999	991	983	975	967	959	951	943	935	927
3	998	990	982	974	966	958	950	942	934	926
4	997	989	981	973	965	957	949	941	933	925
5	996	988	980	972	964	956	948	940	932	924
6	995	987	979	971	963	955	947	939	931	923
7	994	986	978	970	962	954	946	938	930	922
8	993	985	977	969	961	953	945	937	929	921

Table 8.6: The patch look-up table

The code used to generate the patch look up table is shown under appendix 6.

The array 'patches' where the designated distances were saved was 8 cells long and 125 cells wide. The first *for* loop counted down from 1000 to 1 in steps of 8 and the value a variable 'a' was assigned as the value of the loop during the iterations, a variable 'patch' was also incremented during the iterations. The second loop ran from 2 to 8 and the value of the loop was used to select the rows of the array 'patches'. The loop started from 2 because the value of the first loop was assigned to the first row of the corresponding column. In the second loop during the iterations the cell with coordinates corresponding to the values of the first and second loop was filled with the value of the variable 'a' less the value of the second loop minus 1 since the first cell of each column was assigned the value of the first loop during iterations and the second loop started with the second cell.

Figure 8.16 shows the flow chat of the distance to patch convertor algorithm

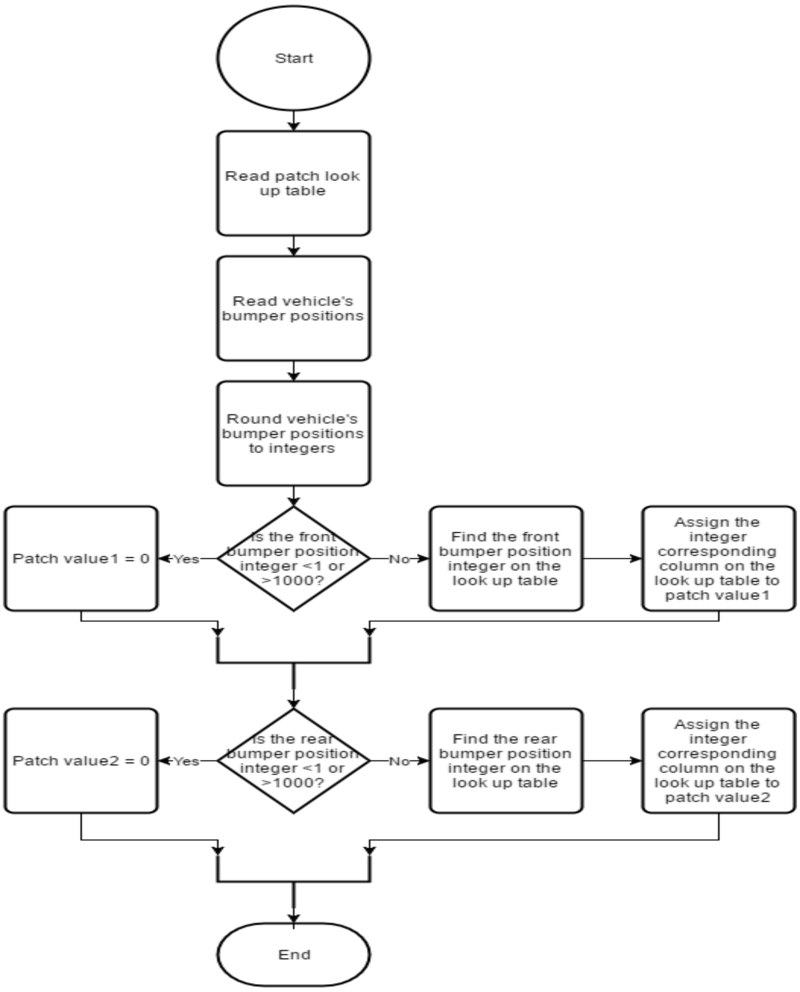


Figure 8.16: The flow chat of the distance to patch convertor algorithm

Collision detector

A collision detection function was used as a fail proof to avoid collisions in situations (if any) were Paramics vehicle following function failed and during vehicle lane changing operation.

In the Paramics Technical report there are three modes of car following which are *braking*, *cruising* and *acceleration* modes. Detailed explanation of the braking and acceleration mode were not given except that a following driver would over compensate if it sensed its lead vehicle was braking and would accelerate at a maximum rate if the lead vehicle was perceived to be accelerating and was in a position greater than the following vehicle's *safe stopping distance* away plus 2m which is the minimum gap as defined by Paramics (Duncan, 1998).

Mathew (2014) suggested a vehicle looking to switch from its current lane to a different lane should determine if a collision would occur with the reference vehicles (lead and following vehicles) on the target lane before making the switch. This involved comparing the speeds of the individual vehicles to its current speed as well as determining if there would be enough time to respond by either itself or the reference vehicles to avoid a collision should any of the three vehicles suddenly start braking.

The collision detection function was used to calculate the stopping distances of both the lead and following vehicles and to determine if the following vehicle's front bumper would be greater than the minimum gap based on its current speed. The formula used are shown in equations 8.8 and 8.9:

$$t = \Delta v / \Delta a \qquad [8.8]$$

$$db = 0.5 * v * t \qquad [8.9]$$

Where: t= stop time; Δv=change in speed; Δa=deceleration rate (maximum deceleration); db=distance covered while braking (Monster, 2003)

Equations 8.8 & 8.9 were used to calculate the distance covered while braking of the reference vehicles and the lead vehicle. After the calculation was made it was then determined if the following vehicle's front bumper was greater than the lead vehicle's rear bumper minus a tolerance (average gap between vehicles during congestion) by adding their current bumper positions to their corresponding distance covered while braking and making a comparison between both resulting positions. The collision detector code is shown in appendix 6.

The stopping time and stopping distance

The first step was to calculate the stopping of the reference vehicle which was calculated by dividing the speed of the vehicle by its maximum deceleration rate. Similarly, the stopping time of the observed vehicle was calculated by dividing the speed of the vehicle by its maximum deceleration rate. The stopping distance of the reference vehicle (lead or following) vehicle was calculated by multiplying the product of its speed and its stopping time by 0.5. Similarly, the stopping distance of the observed vehicle was calculated by multiplying the product of its speed and its stopping time by 0.5.

The collision detector modes

The collision detector function was split into two modes. They were collision detector function:

- Used with the Lane changing function
- Used with Paramics car following function

Used with the lane changing function

A variable 'used_for_lane' was set to high when the function was being used along with the lane change function and set to low when it was used as a fail proof for the Paramics car following function. When it was used along with the lane change function, the displacement of the observed vehicle was first calculated. This was done because the observed vehicle driver had to assume that its vehicle was in its target position instead of its current position when it was determining if a collision would potentially occur. Although the response time of the driver was considered under Paramics car following function it was not considered under the collision detector function to reduce the complexity of the program. Ideally to take the driver's response time/awareness level into account, the driver of the current vehicle should have some time delay when observing the parameters of the reference vehicle hence it should observe the parameters at a few time steps behind the current time step. Since 1 time step equals 100 milliseconds (ms) a response time of 2 seconds would be equivalent to 20 time steps.

To determine if there would potentially be a collision the sum of the position of the observed vehicle front bumper, its displacement for the current time as well as its stopping distance was compared to the sum of the reference vehicle rear and its stopping distance minus the minimum traffic gap. A potential collision was flagged whenever the first equation was greater than or equals the second or if a collision had already occured, it was not flagged when the first equation was less than the second equation or when there was no collision.

It should be noted that the reference vehicle here referred to the lead vehicle while the observed vehicle referred to the following vehicle hence the reference vehicle may be the observed vehicle if it was observing the following vehicle on the neighbouring lane.

Used with Paramics car following function

When the function was used alongside Paramics function, the variable 'used_for_lane' was set to low. The next step was then to determine if the gap (the gap plus the minimum gap between vehicles) between the lead and the observed vehicle was wide enough for the observed vehicle to accelerate at maximum rate (desired acceleration). The term desired acceleration was used because the maximum acceleration rate depended on the maximum rate the driver was comfortable with which was a percentage of the actual maximum acceleration rate of the vehicle. This was further explained in a different function.

To determine if the gap was wide enough a threshold gap of 200m was chosen because it was at least 2 times wider than the stopping distance at maximum speed of the different vehicles featured. The gap between both vehicles was compared to this threshold and if the gap was wider it was assumed that the observed vehicle could safely accelerate at maximum rate.

To determine if there would potentially be a collision the sum of the position of the observed vehicle front bumper and its stopping distance was compared to the sum of the reference vehicle rear and its stopping distance minus the minimum traffic gap. A potential collision was flagged whenever the first equation was greater than or equals the second or if a collision had already occurred, it was not flagged when the first equation was less than the second equation or when there was no collision.

It should be noted that the reference vehicle here was always the lead vehicle on the current lane while the observed vehicle was always the actual observed vehicle.

Paramics Car following function

Drivers controlled their speed under two main modes, the first mode was used when the driver was either the lead vehicle or there was enough gap between itself and the lead vehicle where it accelerated at a desired maximum rate until it was at a distance from the intersection. The second mode was used when the driver was following a lead vehicle and had to control its speed based on its perception of the lead vehicle.

The second mode operated using the Paramics car following function. When this function was operational drivers controlled their speed based on their perception of the speed of their corresponding lead vehicle. Their speed variations were normally smooth but there were abrupt speed changes in cases where the lead vehicle braked or started accelerating at a high rate. This function had three modes which were:

- Braking mode
- Acceleration mode
- Cruising mode

Braking mode

This mode was triggered when the stopping distance was greater than the safe stopping distance plus the minimum traffic gap plus a tolerance gap (note that as suggested by Duncan (1998) the following vehicle always over compensated due to its reaction time). It was also triggered when the lead vehicle rapidly lost speed within a time threshold. This situation had to occur at 5 consecutive time steps for the following vehicle brake to be triggered. The driver of the following vehicle also considered parameters of its lead vehicle based on its awareness level. Braking mode triggers the maximum deceleration of the vehicle. The condition that triggered the braking mode is shown in equation 8.10 while equation 8.11 is the equation for the maximum deceleration (braking).

$$SD > (SSD + minTG + TolG) OR (Lv_t - Lv_{t-1} = aD AND Lv_{t-1} - Lv_{t-2} = aD ... Lv_{t-4} - Lv_{t-5} = aD)$$

[8.10]

$$aD = md$$ [8.11]

where: SD is the stopping distance, SSD is the safe stopping distance, TolG is the tolerance gap of the vehicle, minTG is the minimum traffic gap, md is the maximum deceleration rate of the vehicle, Lv is the lead vehicle's speed.

A function was designed to determine when the lead vehicle was rapidly losing speed. This is shown in the code under appendix 6. The function was called in the main code also shown under appendix 6.

In the codes the following vehicle observed the lead vehicle speed for 5 consecutive time steps to determine if the lead vehicle was constantly reducing its speed or if it was stationary. Each time step value considered was the difference of the current time step and the sum of the time step value being considered plus the driver's reaction time (i.e. the variable *'Aw_lev'*). The speeds corresponding to the resulting time step were fed into the test function shown in the first code as variables. For example, *'vellead_fiveago'* corresponded to the speed of the lead vehicle for the earliest time step considered. The variable *'braking_verification_Leadcar'* held the result of the test and was saved into the array *'z'* for each time step. The array *'z'* will be further discussed in a later section. The variable *'Ign'* was used when the function was being debugged.

Acceleration mode

This mode was triggered when the lead vehicle was at a position much greater than the following vehicle's safe stopping distance including all tolerances or in a situation where the lead vehicle was accelerating with its speed being higher than the following vehicle's speed and, in a position, greater than the following vehicle's safe stopping distance including all tolerances. The condition that triggered the acceleration mode is shown in equation 8.12 while equation 8.13 is the equation for the maximum acceleration.

$$Lp > (p + SSD + minTG + TolG + 10) OR (Lp > (p + SSD + minTG + TolG) AND (Lv > v) AND (a = ma)) \quad [8.12]$$

aE=ma [8.13]

Where: Lp is the lead vehicle's rear bumper position, v is the following vehicle's speed and p is the position of the following vehicle's front bumper

The maximum acceleration the driver is willing to utilise

The maximum acceleration of vehicles under various weather conditions was modelled using Rakha et al. (1999)'s vehicle dynamics model for estimating maximum vehicle acceleration levels based on vehicle's tractive effort and aerodynamic, rolling and grade resistance forces. Although Rakha et al. (1999) designed their model for trucks; Snare (2002) study showed that the model could also be effectively applied to lighter vehicles.

The Tractive Effort

The model constrained the maximum tractive force computed in Equation 8.14 using Equation 8.15 as demonstrated in Equation 8.16. The friction between the tyres of the vehicle's tractive axle and the road surface accounted for in Equation 8.15 while Equation 8.16 ensured that the tractive effort did not approach infinity while travelling at low speeds.

$$F_t = 3600\eta\frac{P}{V}$$ [8.14]

$$F_{max} = 9.8066 M_{ta} \upsilon$$ [8.15]

$$F = min(F_t, F_{max})$$ [8.16]

Where F_t : tractive effort (N); P:engine power (kW);V: truck speed (km/h);
n: transmission efficiency Typical transmission efficiencies range from 0.89 to 0.94; F_{max}: maximum tractive force (N); M_{ta}: vehicle mass on tractive axle (kg) such that M_{ta}=M.$perc_{ta}$; $perc_{ta}$: percent mass acting on tractive axle;μ: coefficient of friction between t ires and pavement; and F: tractive effort effectively acting on vehicle (N).

Rakha et al (2012) included a gear reduction factor to account for the impact of gear shift when trucks accelerate from a low speed. The factor is a linear function of vehicle speed with an intercept of 1/u_0 and a maximum value of 1.0 at u_0 (optimum speed or the speed at which the vehicle attains its full power). The tractive effort for trucks was calculated using equation 8.17:

$$F_T = 3600\beta\eta\frac{P}{\upsilon}$$ [8.17]

Where β is a gear reduction factor calculated using equation 8.18:

$$\beta = \frac{1}{\mu_0}[1 + min(\mu, \mu_0)(1 - \frac{1}{\mu_0})]$$ [8.18]

The intercept was used to guarantee that the vehicle had enough power to accelerate from a stop. The vehicle's optimum speed was then calculated as a function of its weight to power ratio (ω) for ranges between 30 to 170 kg/kW. This is shown in equation 8.19:

$$\mu_0 = 1164\omega^{-0.75}$$ [8.19]

Where u_0 is the optimum speed

Rakha et al (2012) indicated that the gear shift parameter β is not required for the modelling of light-duty vehicle acceleration behaviour (weight-to-power is less than 30 kg/kW) hence equation 8.14 was used for smaller vehicles while equation 8.17 was used for the heavier vehicles. In code the tractive force was obtained as shown in appendix 6.

The Resistance Forces

Rakha et al. (1999)'s model took three major types of resistance forces into account, which were aerodynamic, rolling, and grade resistance. The total resistance force was the determined as the summation of the three resistance components as shown in Equation 8.20.

$$R = R_a + R_r + R_g \quad [8.20]$$

Where R: total resistance (N); Ra: air drag or aerodynamic resistance (N); R_r: rolling resistance (N); and R_g: grade resistance (N).

Aerodynamic Resistance

The aerodynamic resistance was a function of the vehicle frontal area, the altitude, the vehicle drag coefficient, and the square of speed of the vehicle, as shown in Equations 8.21 and 8.22 (Rakha et al., 1999).

$$Ra = c_1 C_d C_h A V^2 \quad [8.21]$$

$$C_h = 1 - 1.85 \times 10^{-5} H \quad [8.22]$$

Where A: truck frontal area (m^2); V: truck speed (km/h); C_d: truck drag coefficient; C_h: altitude coefficient; c_1: constant equals to 0.047285; and H: altitude (m).

Rolling Resistance

The rolling resistance was a function of the vehicle mass and speed, as shown in Equation 8.23. Rolling coefficients (C_r) typical values as a function of the road surface type and condition can be found in Rakha et al. (1999). The rolling resistance coefficients (c_2 and c_3) as shown in Rakha et al. (1999) which vary based on the vehicle's tyre type were also considered.

$$R_r = 9.8066 C_r (C_2 V + C_3) \frac{M}{1000} \quad [8.23]$$

Where M: vehicle total mass (kg); Cr: rolling coefficient; and c2, c3: rolling resistance coefficients.

Grade Resistance

The grade resistance which was a constant depended on the vehicle's total mass and the percentage grade on which the vehicle travelled along, shown in Equation 24. The proportion of the vehicle's weight that resisted the vehicle's movement was accounted for by the grade resistance.

$$R_g = 9.8066 M i \quad [8.24]$$

Where i: percent grade (m/100 m)

In code the resistance forces were computed as shown in appendix 6.

The maximum vehicle acceleration

The maximum acceleration of the vehicle was then computed as the forces acting on the vehicle as shown in Equation 8.25.

$$a = \frac{F - R}{M} \qquad [8.25]$$

Where a: maximum truck acceleration (m/s^2); F: tractive effort (N); R: total resistance force (N); and M: vehicle total mass (kg).

An average driver would normally only utilise a fraction of the maximum acceleration of their vehicle. Rakha et al indicated that field studies have shown this fraction to be around 0.65 (Snare (2002) and Rakha et al (2012)) and was accounted for in Equation 8.26.

$$a^0_{max} = f_p \frac{F - R}{M} \qquad [8.26]$$

Where a^0_{max} is the maximum acceleration the driver is willing to utilise.

Equation 8.27 was then used to calibrate vehicle acceleration behaviour under *inclement weather condition*.

$$a_{max} = a^0_{max} - f_p g i \qquad [8.27]$$

Where i is a rain adjustment factor

In code the maximum acceleration was computed as shown under appendix 6.

The maximum vehicle deceleration

Rakha et al (2012) indicated that that the maximum braking force acting on each axle of a vehicle can be derived as the product of the coefficient of roadway adhesion and the vehicle weight normal to the roadway surface. Actual optimal brake force is not often achieved in non-antilock braking systems hence a braking efficiency term is also accounted for when computing the maximum braking force as shown in equation 8.28.

$$d_{max} = \eta_b \upsilon_g \qquad [8.28]$$

Where η_b is the braking efficiency, υ is the coefficient of roadway adhesion also known as the coefficient of friction, and g is the gravitational acceleration (9.8066 m/s^2).

For this research all vehicles were assumed to be equipped with antilock brake systems. With antilock braking system the braking efficiency approaches 100%.

Equation 8.28 was modified by Rakha et al (2012) to account for the effect of precipitation on driver/vehicle behaviour. The modified equation for computing the maximum vehicle deceleration shown in Equation 8.29 was adjusted using a rain adjustment factor which accounted for the impact of rain intensity on the deceleration behaviour.

$$d_{max} = \eta_b v_g (1.0 - 0.07759i) \qquad [8.29]$$

Where i is a rain adjustment factor

In code the maximum vehicle deceleration of was computed as shown under appendix 6.

Where n= μ, all vehicles where assumed to be fitted with anti-lock braking systems for this research therefore braking efficiency was assumed to be 100% hence E= ηb=1

Conditions and vehicles specifications

Both light and heavy vehicles were featured during this research, the specifications for the various light and heavy vehicles as well as pavement and tyre conditions were obtained from both Rakha et al. (1999) and Snare (2002). The featured heavy vehicles are abstract. This is summarised in Table 8.7 below:

Vehicle	1995 Acura Integra	Mazda 2001 Protégé	1995 BMW 740I	Semi-trailer and low mass	Semi-trailer with No aerodynamic aids and medium	Semi-trailer with Full aerodynamic aids and high mass
Power (hp)	142	130	282	349.71	349.71	349.71
% Mass Tractive Axle	0.515	0.525	0.515	0.40	0.40	0.40
Altitude (m)	599	599	599	599	599	599
Grade	0	0	0	0	0	0
Engine Efficiency	0.68	0.7	0.7	0.62	0.65	0.7
Coefficient friction	0.6	0.6	0.6	0.6	0.6	0.6
Cd	0.32	0.34	0.32	0.70	0.78	0.58
Ch	0.95	0.95	0.95	0.95	0.95	0.95
C1	0.047285	0.047285	0.047285	0.047285	0.047285	0.047285
C2	0.0328	0.0328	0.0328	0.0328	0.0328	0.0328
C3	4.575	4.575	4.575	4.575	4.575	4.575
Cr	1.25	1.25	1.25	1.25	1.25	1.25
Frontal Area (m^2)	1.94	2.04	2.27	6.8	7.0	10.0
Power (kW)	105.932	96.98	210.372	260.78	260.78	260.78
Mass (kg)	1670	1610	2370	22208	34263	43910

Table 8.7: Conditions and vehicles specifications

- Vehicle Engine Power: This is the maximum power that a given vehicle's engine can put out.
- Engine Efficiency: Internal friction and other factors result in power losses in the engine and they usually account for between 20-35% of the total engine losses for light duty vehicles hence typical efficiency values range between 0.65-0.80.

- Vehicle Mass: The total mass of the vehicle
- Percentage of Vehicle Mass on the Tractive Axle: Four-wheel drive vehicles often have 100% for this value while typical values for two-wheel drive vehicles often range between 50-65% for front wheel drives and 35-50% for rear wheel drives. Although not included in this thesis for simplicity, it should be noted that many modern 4-wheel drive light vehicles (such as the newer Honda CR-V models (Honda, 2019)) have 'intelligent' systems whereby they normally operate as 2-wheel drive (or nearly 2 wheel drive) but can vector torque to all wheels as condition vary.
- Pavement: Several constants are obtained using the pavement type and condition
- Coefficient of Friction: This value depended on the pavement type and condition.
- Altitude: The region of interest's altitude above sea.
- Air Drag Coefficient: Depending on the aerodynamic features of the vehicle, the values for light duty vehicles usually range from 0.30 to 0.35.
- Frontal Area: The frontal area of the vehicle which could be approximated as 85% of the height times the width of the vehicle if unknown
- Rolling Resistance Constants: The rolling resistance constants used in the model.
- Grade: The grade of the roadway is given as a decimal (m/100 m). The grade is often considered a constant for a given section of roadway. However, the gradient of the links featured were assumed to be 0.

In the code pavement conditions were defined as shown in appendix 6 while the vehicle types were defined as shown in appendix 6. Other parameters were defined in the code as shown in appendix 6.

Cruising mode

This mode was triggered when the conditions satisfying the braking and acceleration conditions were not met. This meant the lead and following vehicles were travelling without abrupt changes to their speeds (i.e. cruising). Paramics gave three secondary modes (or acceleration components) for the cruising mode. The modes are:

Target point overshot: This mode was triggered when the separation of the vehicles was less than the target point of the following vehicle. The target point was calculated using the equation 8.30:

$$t = \frac{s^2}{g}$$

[8.30]

While the acceleration for this secondary mode was calculated using Equation 8.31:

$$a_A = k_2 \Delta V$$

[8.31]

Where: t is the target separation, s is the separation and g is the gap, aA is the *target point overshot* acceleration, k_2 is a constant which equals 0.1 and Δv is the speed difference between both vehicles.

In code the target point was calculated as shown in appendix 6.

The Matlab functions *'isnan'* and *'isinf'* were both used to determine if the value of the variable *'Output_Target'* was either not a number or an infinite number respectively and the variable was set to 0 whenever either case was true.

In the main code the code for calculating the target point was called as shown in appendix 6. The variable *'v_reg'* held the observed vehicle's registration value. The separation and gap (i.e. arrays *'s'* and *'g'*) of the vehicle for the current time were fed into the function *'Target_p2'* and the output was saved to the array *'T'* for each time step.

In code the *target point overshot* acceleration component (aA) was written as shown in appendix 6. The variable *'constant_b'* held the value of the constant k_2 while the variables '*Leadvehicle_speed'* and *'speed'* held the values of the lead and following vehicle respectively for the current time step. The acceleration component *'aA'* was first calculated using the code above, it was then limited to the maximum acceleration and deceleration using the code shown in appendix 6.

In the code above the value obtained for the variable *'buffer_overshot_accel'* was compared to the maximum acceleration and deceleration. Whenever it was greater than the maximum acceleration value it was assigned the value of the maximum acceleration, it was assigned the value of the maximum deceleration (i.e. which was a negative value) whenever it was less than the maximum deceleration value while whenever it was within the threshold it retained its value.

The acceleration component functions *'aA' were* called in the main code as shown in appendix 6. In the code above the variable *'kb'* held the value of the constant k_2. The speeds of both the lead and observed vehicles were fed into the function '*buffer_accel_overshot'* which is the original code. The variable *'ref_veh'* held the registration number of the lead vehicle while the variable *'v_reg'* held the registration number of the observed vehicle. The array '*kaA'* held the output from the function for each time step and was fed into the function *'accel_overshot'* for limiting. This function was also fed the values of the maximum acceleration and deceleration of the observed vehicle for the current time step and its output was saved in the array *'aA'* for each time step.

Lead vehicle pulling away: This mode was triggered when the separation of the vehicles increased with time. The separation was calculated using the Equation 8.32 and the condition is shown on 8.33:

$$s = h\Delta V \qquad [8.32]$$

$$s_n > s_{n-a}$$ [8.33]

While the acceleration for this secondary mode was calculated using Equation 8.34:

$$a_B = k_2 \Delta V + k_1 \frac{g-t}{t}$$ [8.34]

Where: s is the separation, h is the desired headway, again Δv is the speed difference between both vehicles, n is the reaction time of the driver, a is the time used to contrast by the driver, aB was the acceleration when the lead vehicle was pulling away, and k_1 is a constant.

In code the separation was calculated as shown in appendix 6 while the *Lead vehicle pulling away* acceleration component (*aB*) was written as shown in appendix 6. Again, the Matlab functions *'isnan'* and *'isinf'* were both used to determine if the value of the variable *'bufferpullingaway_accel'* was either not a number or an infinite number respectively and the variable was set to 0 whenever either case was true. The variable *'constant_B'* held the value of the constant k_2 while the variable *'constant_A'* held the value of k_2. The acceleration component *'aB'* was first calculated using the code above, it was then limited to the maximum acceleration and deceleration using the code shown in appendix 6.

The acceleration component function *'aB'* was called in the main code as shown in appendix 6. In the code above the variables *'ka'* and *'kb'* held the values of the constants k_1 and k_2 respectively. The gap and target as well as the speeds of both the lead and observed vehicles were fed into the function '*bufferaccel_pullingaway'* which is the original code. The variable *'ref_veh'* held the registration number of the lead vehicle while the variable *'v_reg'* held the registration number of the observed vehicle. The array '*kaB'* held the output from the function for each time step and was fed into the function *'accel_pullingaway'* for limiting. This function was also fed the values of the maximum acceleration and deceleration of the observed vehicle for the current time step and its output was saved in the array *'aB'* for each time step.

Constant separation or coming together: This mode was triggered when the separation of the vehicles was constant or reduced with time. The condition is shown on Equation 8.35.

$$s_n < s_{n-a}$$ [8.35]

The acceleration for this secondary mode was calculated using Equation 8.36:

$$a_C = c - \frac{(\Delta V)^2}{g-t}$$ [8.36]

Where: aC was the acceleration when the difference between the lead and following vehicle's speed was constant or gradually reducing with time, again Δv is the speed difference between both vehicles, while c is a variable used to bring vehicles together rapidly. Its value reduces as vehicles approach the minimum gap of 2 meters. It is given as shown in Equation 8.37:

$$c = k_1 \frac{g - 2.0}{g} \quad [8.37]$$

In code the bunching acceleration was written shown in appendix 6. In the code above the variable *'traffic_gap'* held the value of the minimum gap between vehicles.

In code the *Constant separation or coming together* acceleration component (*aC*) was written as shown in appendix 6. Again, the Matlab functions *'isnan'* and *'isinf'* were both used to determine if the value of the variable *'buffercruise_accel'* was either not a number or an infinite number respectively and the variable was set to 0 whenever either case was true. The acceleration component *'aC'* was first calculated using the code above, it was then limited to the maximum acceleration and deceleration using the code in appendix 6.

The acceleration component function *'aC'* was called in the main code as shown in appendix 6. The bunching acceleration, gap and target as well as the speeds of both the lead and observed vehicles were fed into the function '*bufferaccel_cruise2'* which is the original code. The variable *'ref_veh'* held the registration number of the lead vehicle while the variable *'v_reg'* held the registration number of the observed vehicle. The array '*kaC'* held the output from the function for each time step and was fed into the function *'accel_cruise'* for limiting. This function was also fed the values of the maximum acceleration and deceleration of the observed vehicle for the current time step and its output was saved in the array *'aC'* for each time step.

The flow diagram used for Paramics car following model is shown in figure 8.17 below. It should be noted that the separation and target point are as observed by the following driver sometime in the past. This time depends on the driver's awareness level (*AW*). The following driver occasionally used a contrast time (*ct*) when attempting to reach a decision.

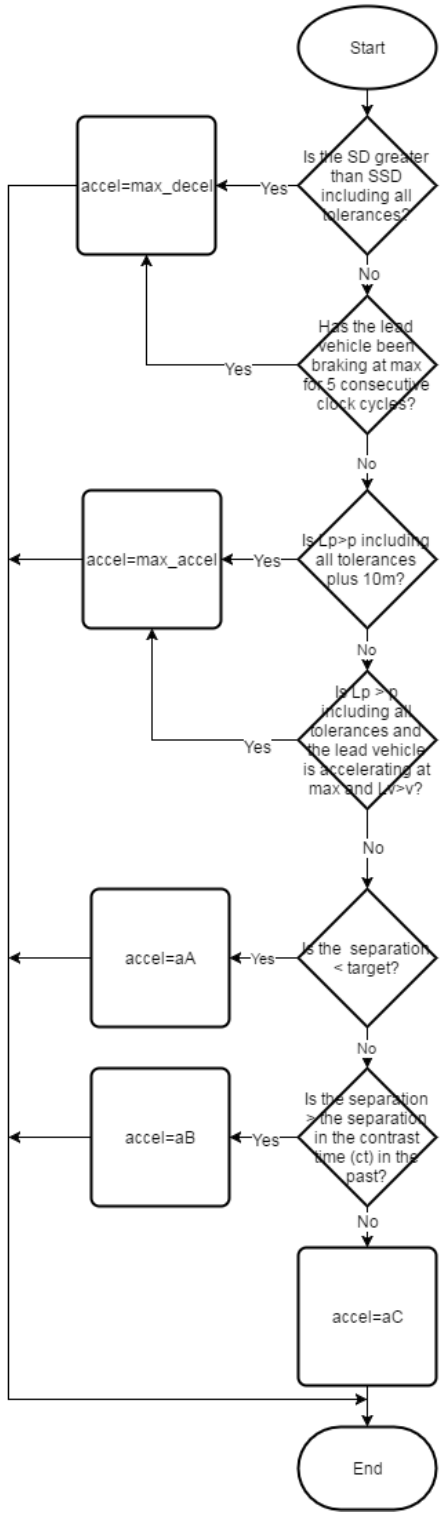


Figure 8.17: Paramics car following algorithm flow diagram

Simulating the Traffic Flow Model

The Primary code

This section of the program was responsible for simulating the entire program by calling functions and calculating various parameters of the driver-vehicle unit (DVU).

Weather conditions affect the DVU abilities such as the maximum acceleration/deceleration, top speed (the driver's maximum speed tolerance) and the headway. These parameters are exacerbated as the weather condition worsens with the headway increasing while top speed and maximum acceleration/deceleration decrease.

Due to the increased drag and the decrease in the coefficient of friction (roll resistance) between the road surface and the vehicle tyres as the vehicle speed increases the maximum acceleration of the vehicle reduces. At low speed the roll resistance is the main resistance force while at higher speeds the drag takes over in magnitude.

The *simulation main loop* was initiated immediately after the initialisation of the various parameters including various arrays whose sizes depended on the maximum allowed vehicle density on the link and the maximum simulation time both specified by the user. Every other aspect of the simulation occurred within this loop including function calls and calculations of DVUs parameters.

Initialisation

The model had a main menu with 7 user settings which the user was required to initialise before running the program. These options were:

- Traffic mode
- Signal mode
- Stop sign status
- Vehicle composition
- Vehicle Type
- Weather condition
- Number of lanes

This was written in the code as shown in appendix 6. After the user initialisation the initialisation of the various parameters including various arrays some of whose sizes depended on the maximum allowed vehicle density on the link and the maximum simulation time were carried out at the start of the simulation.

The first time step

The main simulation loop (the time loop) encapsulated every other loop within the simulation program. This loop ran from 1 to the maximum simulation time (time step) specified by the user. Within this loop was a second loop (the patch loop) which cycled from patch 1 to the maximum patch (patch 125) during each time step.

During the first time step, the first vehicle entered the link and it was immediately given a vehicle registration number. Vehicle registration numbers ranged from 1 to the link maximum density and were allocated based on availability with the lower values being favoured over the higher values. In this case the first vehicle was allocated registration number 1. The registration numbers were used by DVUs to identify other DVUs in the traffic stream. From this point a vehicle would be referred to by its registration number except otherwise stated.

Vehicle 1 lane was then initialised to lane 1 while its front bumper position was initialised to the minimum position of the link (0.1m) and its rear bumper's position was calculated by subtracting the vehicle's length from its front bumper's position. This is shown in Equation 8.38.

$$p_r = p_f - VL \qquad [8.38]$$

Where p_r is the vehicle's rear bumper position, p_f is the vehicle's front bumper position and VL is the vehicle's length.

The vehicle's position (distance covered) was then converted into a patch value which was done by calling a distance to patch conversion function explained in section 3.2.6.2. The vehicle was then registered to the vehicle patch register. As mentioned earlier, this register showed the position of vehicles on patches. Its size was determined by the number of lanes and the length of the link. A patch was 8m long and the model's link length was 1000m long hence the vehicle patch register had a total of 125 patches. Depending on the number of lanes (up to 4 lanes) each patch had between 4 and 16 slots with 4 slots allocated to each lane. The first two slots of each lane were the front bumper registers while the last two were the rear bumper registers. The lead vehicle in a patch always occupied the first bumper register while the following vehicle occupied the second. The vehicle patch register was explained extensively in an earlier section.

The vehicle was given a vehicle type depending on the user's specified vehicle combination. A function which calculated the maximum acceleration and deceleration of the vehicle was then called and the acceleration of vehicle 1 was initialised based on its output.

Other variables were also taken into account such as the time step vehicle 1 entered the link (start time) which was later used to calculate the vehicle's journey time by subtracting its start time from its finish time and also used to calculate the interval between vehicles entering the link and the density of the link was incremented. Figure 8.18 illustrates vehicle 1 entering the link at time step 1.

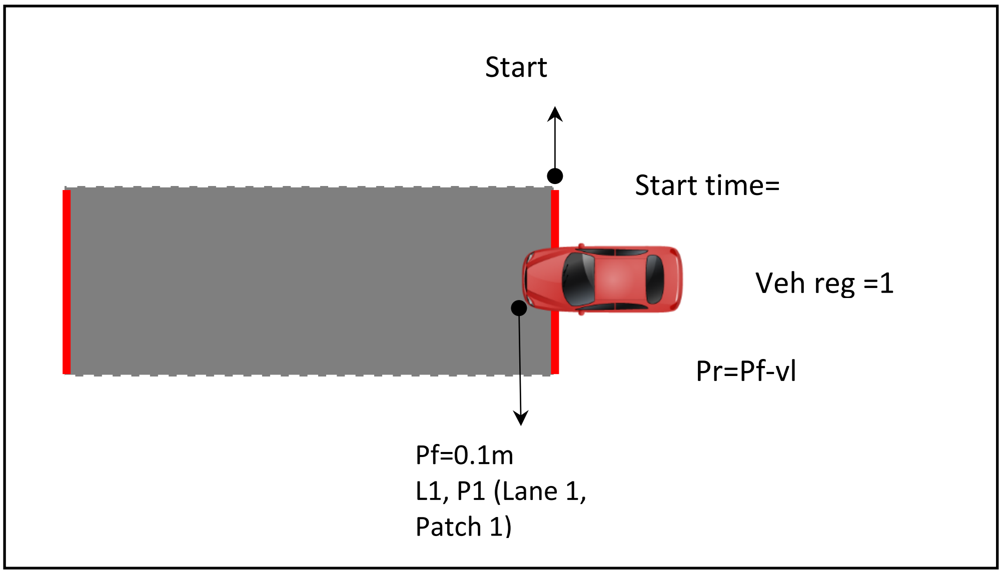


Figure 8.18: An illustration of vehicle 1 entering the link at time step 1

This was written in code as shown in appendix 6.

The other time steps

A second loop (i.e the patch loop) cycled through the patches; it encapsulated a third loop (i.e the lane loop) which cycled through each lane hence for each patch selected the lane loop made a complete cycle.

When the time step was greater than 1, the patch loop was incremented, and the lane loop was initiated. Vehicle patch register slots were allocated to each lane based on the lane number with lane 1 allocated slots 1 and 2 for front bumpers while 3 and 4 were allocated to rear bumpers, lane 2 was allocated slots 5 and 6 for front bumpers while 7 and 8 were reserved for rear bumpers etc. Table 8.8 shows an illustration of the vehicle patch register.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	1	5	1	0	2	6	2	0	3	19	3	0	4	0	4	0
2	7	0	5	0	8	0	6	0	22	0	19	0	26	30	26	0
3	9	0	7	0	10	0	8	0	21	0	22	0	34	0	30	0
4	11	0	9	0	25	0	10	0	29	0	21	29	38	0	34	0
5	12	0	11	12	18	0	25	18	33	37	33	0	42	0	38	42
6	13	14	13	0	20	17	20	0	41	0	37	0	46	49	46	0
7	15	0	14	0	23	0	17	0	50	0	41	0	27	0	49	0
8	16	0	15	0	28	0	23	0	24	0	50	0	47	0	27	0
9	31	0	16	31	44	0	28	44	35	0	24	35	45	0	47	45
10	32	36	32	0	48	43	48	0	40	0	40	0	0	0	0	0
11	39	0	36	0	0	0	43	0	0	0	0	0	0	0	0	0
12	0	0	39	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 8.8: The vehicle patch register

This register was generated when the simulation ran for 2000 time steps with a maximum density of 50 vehicles. For illustrative purpose the signal at the end of the link was set to constant red causing vehicles to stop at the end of the link. From the table vehicles had their bumpers registered on corresponding slots based on their positions.

A fourth loop (slot loop) located within the lane loop cycled through the front bumper slots of each lane. Each slot selected was tested to verify if a vehicle registration number was present, whenever there was a vehicle registration number this number was stored in a variable (veh_reg). The lane of the observed vehicle (the vehicle registration number stored in veh_reg) was then updated. This was done by calling the *lane change* function explained earlier depending on the output of the function the vehicle then either stayed on its current lane or switched to a neighbouring target lane. The lane of each vehicle for each time step was stored in an array, a portion of this array is shown Table 8.9.

	1	2	3	4	5	6	7	8	9
617	1	2	3	4	1	1	1	1	1
618	1	2	3	4	1	1	1	1	1
619	1	2	3	4	1	1	1	1	1
620	1	2	3	4	1	2	1	1	1
621	1	2	3	4	1	2	1	1	1
622	1	2	3	4	1	2	1	1	1
623	1	2	3	4	1	2	1	1	1
624	1	2	3	4	1	2	1	1	1
625	1	2	3	4	1	2	1	1	1
626	1	2	3	4	1	2	1	1	1
627	1	2	3	4	1	2	1	1	1
628	1	2	3	4	1	2	1	1	1

Table 8.9: A portion of the vehicles' lanes for each time step

Whenever a vehicle switched lanes its bumpers registration on the previous vehicle patch registration slots were cancelled then its bumpers were registered on their corresponding slots on the vehicle's new lane. The portion in Table 8.9 shows a period when the vehicle stored in *vehicle handle* 6 changed its lane from lane 1 to lane 2 shown in time step 620. It should be noted that the vehicle was referred to as the vehicle stored in vehicle handle 6 rather than vehicle 6 because each vehicle is given a registration number upon entering the link and are referred to by their registration number rather than their handle number. The vehicle stored in each handle changed as the vehicle stored exited the link. This was written in code as shown in appendix 6. The switch_board function is shown in the code in appendix 6.

The next step was to detect the lead vehicle of the observed vehicle (if any), this was done by calling the *reference vehicle detector* function explained earlier and setting it to lead vehicle detection mode. The output of the function was 0 when there was no lead vehicle detected or the lead vehicle registration number when a lead vehicle was detected. The reference vehicle detector called in the main code is shown in appendix 6.

The displacement of the DVU for the current time (D_i) step was first calculated to calculate the position of the vehicle for the time step. The displacement was calculated using Equation 8.39:

$$D_i = v_o * t + 1/2 * a_o * t^2 \quad [8.39]$$

Each time step was equivalent to 0.1 second hence time (t) in the equation was equivalent to 0.1 second. The speed and the acceleration in the equation represent the initial speed (v_o) and acceleration (a_o) respectively of the DVU at the previous time step. A filter was used to ground displacements less than 0m to 0 m to prevent negative displacements (i.e. vehicles moving in reverse). This was written in code as shown in appendix 6.

The current position of the observed DVU front bumper (Pf_i) was then calculated by adding the initial position (Pf_o) (I.e. at the previous time step) to the current displacement (D_i) shown in Equation 8.40.

$$p_{fi} = p_{fo} + D_i \qquad [40]$$

The position of the rear bumper was then calculated using equation 8.40. The position, displacement, speed, acceleration and various other parameters of each registered vehicle was logged at every time step. Table 8.10 shows a portion of the positions of various vehicles at various time steps. Again, it should be noted that the top horizontal numbers represent the vehicle handles not the actual vehicles registration numbers.

	24	25	26	27	28	29	30	31	32	33	34
610	240.5082	323.5470	320.4078	192.3712	229.6257	223.5876	220.5983	158.2022	127.9609	137.7529	135.3983
611	242.5096	326.6862	323.5470	194.3381	232.6745	226.5968	223.5876	160.0599	129.7384	140.1275	137.7529
612	244.5309	329.8253	326.6862	196.3249	235.7430	229.6257	226.5968	161.9150	131.5131	142.5220	140.1275
613	246.5495	332.9645	329.8253	198.3317	238.8314	232.6745	229.6257	163.7900	133.2852	144.9365	142.5220
614	248.5653	336.1037	332.9645	200.3358	241.9395	235.7430	232.6745	165.6849	135.0771	147.3709	144.9365
615	250.6012	339.2429	336.1037	202.3372	245.0675	238.8314	235.7430	167.5998	136.8664	149.8253	147.3709
616	252.6570	342.3821	339.2429	204.3585	248.2067	241.9395	238.8314	169.5346	138.6530	152.2996	149.8253
617	254.7327	345.5212	342.3821	206.3998	251.3458	245.0675	241.9395	171.4894	140.4595	154.7939	152.2996
618	256.8284	348.6604	345.5212	208.4610	254.4850	248.2067	245.0675	173.4641	142.2860	157.3080	154.7939
619	258.9440	351.7996	348.6604	210.5422	257.6242	251.3458	248.2067	175.4588	144.1324	159.8420	157.3080
620	261.0796	354.9388	351.7996	212.6433	260.7634	254.4850	251.3458	177.4735	145.9987	162.3957	159.8420
621	263.2351	358.0780	354.9388	214.7644	263.9026	257.6242	254.4850	179.5080	147.8851	164.9693	162.3957

Table 8.10: A portion of the positions of various vehicles at various time steps

It can be observed from Table 8.10 that the position values are not in a descending order from left to right as would be expected of *the vehicle label-wise model* since every vehicle maintained a single lane in that mode. Instead the positions are in an undefined order from left to right the reason being because the vehicles contained in the vehicle handles are not all in the same lane.

The position of the observed DVU's front bumper can also be calculated by integrating the speed of the observed DVU over time using Euler method for mathematical integration. This is shown in equation 8.41.

$$p_{fi} = p_{fo} + \Delta t * v \qquad [8.41]$$

The new position of the DVU was then updated to the vehicle patch register using a method like the method used when the vehicle's lane was changed except the registration was done on the same lane but depending on the new position of the DVU a different slot was selected if the vehicle's new position was in a different patch.

When the DVU's position was greater than the link length its registration number was cancelled from the rear bumper vehicle patch registration slot and its finish time was updated. The vehicle's registration number was automatically released and free for use by a new DVU since no bumper of the vehicle was registered to any patch slot. This step was written in code as shown in appendix 6.

Other parameters such as the gap (g) and the bunching acceleration (c) which was used to bring vehicles together faster were calculated after the position of the vehicle was calculated. The gap between the lead and following vehicle was calculated using Equation 8.42.

$$g = p_{rl} - p_{ff} \qquad [8.42]$$

The gap (g) was calculated by subtracting the position of the following vehicle front bumper (Pff) from the positon of the lead vehicle rear bumper (Prl). The bunching acceleration '*c*' was calculated right after the gap was calculated and it was explained earlier.

The observed vehicle's speed 'v_i' was then calculated by integrating acceleration overtime. Equation 8.43 was used to calculate the current speed. Again time *'t'* in the equation was equivalent to 0.1s.

$$v_i = v_o + a_o * t \qquad [8.43]$$

In Paramics drivers are given memories which hold their speed at some point in the past as well as their position, since their speed is based around the speed of the lead vehicle they can decide what their current speed would be based on their memory of previous speed and position. Each driver is also given a *headway* which they try to attain by varying their speed. More aggressive drivers accept smaller headways while drivers with more awareness accept longer headways.

Headway parameters for various situations were identified on Paramics technical report (Duncan, 1998). The report identified 1.5 seconds as the average headway observed on a single-lane highway while 0.5 seconds was identified as the average headway during traffic jams (note: traffic jam was defined as a period where both the lead and following vehicles travelled at low speeds) and 2 metres was selected as the average gap between vehicles during congestion.

Paramics technical report didn't give a clear relationship between headway and weather conditions but rather a range of 1.1 to 3.0 seconds was given for various weather conditions.

Using 1.5 seconds for vehicles travelling under dry conditions as specified in the Paramics report, the headways for the other weather conditions were projected by relating the headway given in the report to the headway observed by Agbolosu-Amison and Sadek (2004). The headways used for the various weather conditions are summarised in Table 8.11.

The headways for the various weather conditions were then selected within this range as shown in Table 3.8. Agbolosu-Amison and Sadek (2004) observed the headways of vehicles travelling on a road in Vermont and indicated that there was a negligible difference in the headways of light snowy and light rainy conditions hence the same headway was assigned to both.

Weather condition	Headway (s)
Normal (Dry)	1.5
Light Rain	2
Light Snow	2
Heavy Rain	2.5
Heavy Snow	3

Table 8.11: Headways used for the various weather conditions

The separation, target and acceleration and braking components were then calculated for the observed vehicle.

This process iterated until the time loop got to its maximum value after which the program was terminated.

In code the observed vehicle's gap and speed were calculated using the codes in appendix 6.

In the code used for calculating the OV gap the variables Leadvehicle_rearbumperposit and vehicle_frontbumperposit were used in the gap function which held the positions of the lead vehicle rear bumper and observed vehicle front bumper. In the code used for calculating the OV speed the speed was first calculated then limited to the speed limit of the link as an upper limit and 0 as a lower limit to avoid negative speed. In the code used for calculating the headway the estimated headway between the lead and observed vehicle was calculated only when a lead vehicle was present. The OV average speed was calculated by dividing its current position by its journey time which was determined as the current simulation time minus its journey start time.

The acceleration control

Paramics car following logics along with various other logics such as the logic that was used to attempt to depict the interaction between the drivers and their environment (e.g. drivers and the stop line) as well as assumptions that were made to control the acceleration of vehicles in traffic streams under certain conditions.

The code used for vehicles acceleration control is shown in appendix 6 while the various logical steps of the code are explained below.

The Logical steps of the acceleration control

The Lead Vehicles acceleration control

1. The first step was to determine if the observed vehicle (OV) was at a risk of overshooting the stop line at its current speed. A function known as the *'stop_line_overshoot_detector'* was designed for this purpose. The function operated like the collision detector function except the OV's speed and position was compared to the position of the stop line rather than the position and speed of its lead vehicle.
2. When the OV had no lead vehicle ('*ref_veh==0*') and no congestion was to be induced at the end of the link it was designed to accelerate at its maximum rate.
3. In cases where congestion was to be induced and the OV had no lead vehicle
   - 3.1. In a case where the stop line was ON and the OV would potentially overshoot the stop sign *('i.e.stop==1'*) the OV was made to decelerate at its maximum rate (brake).
   - 3.2. In a case where the OV front bumper position was greater than or equal to the *'speed_line'* position and its speed was greater than the *'jam_spd'* the OV was required to brake. The *'speed_line'* was a point on the link beyond which a special speed limit was required as vehicles approached the end of the link. The *'jam_spd'* was a special speed limit that was required when the *'speed_line'* had been crossed. It was used to induce congestion towards the end of the link.
   - 3.3. In a case were the OV's front bumper position was greater or equals the *'speed_line'* and its speed less than the *'jam_sp'* it was required to accelerate at its maximum rate.
   - 3.4. In a case where its front bumper was greater than or equal to the *'speed_line'* and its speed was equal to the *'jam_spd'*, it was required to neither accelerate nor decelerate.
   - 3.5. In a case where the position of its front bumper was less than the *'speed_line'* it was required to accelerate at its maximum rate.

The following Vehicles acceleration control

4. In cases where the OV had a lead vehicle
   - 4.1. In a case where the OV was at risk of colliding with its lead vehicle it was required to decelerate at its maximum rate. Steps 4.1 and 4.2 were used to safely bring the OV closer to its lead vehicle during congestion.
   - 4.2. In a case where the OV was not at a risk of colliding with its lead vehicle and it was within a given safe threshold distance from its lead vehicle it was required to accelerate at its maximum rate

4.3. The subsequent steps were called in a case where the OV had been on the link for a period less than the addition of their response time and the time they require to observe the speed of their lead vehicle to determine if it is braking and their vehicle was not at a risk of colliding with it. Note that when this condition was true the response time of the driver was not included since the driver did not have any memory before its journey started.

4.3.1. In cases where the speed of the lead vehicle speed was zero.

4.3.1.1. In a case where the gap between the OV and its lead vehicle was greater than the *'stop_gap'* and the speed of the OV was less than the gap between both vehicles minus the *'stop_gap'* then the preliminary acceleration was assumed using Equation 8.44:

$$Pa = 0.1 \times g \qquad [8.44]$$

Where Pa is the preliminary acceleration, a time step was equivalent to 0.1s.

With this assumption the driver applied just enough acceleration to close the gap between its vehicle and its lead vehicle. The acceleration was then limited to the maximum acceleration and deceleration. The *'stop_gap'* was the required minimum gap between vehicles in a traffic jam.

4.3.1.2. In a case where the gap was less than the 'stop_gap' or the OV was at a risk of colliding with its lead vehicle the OV was required to decelerate at its maximum rate.

4.3.2. In cases where the speed of the OV lead vehicle was greater than zero

4.3.2.1. In a case where the OV was within the given safe threshold distance from its lead vehicle and was not at a risk of colliding with it then it was required to accelerate at its maximum rate.

4.3.2.2. In a case where the OV was at a risk of colliding with its lead vehicle it was required to brake at max

4.3.2.3. In cases where the OV was not within the given safe threshold distance from its lead vehicle and was not at a risk of colliding with it

4.3.2.3.1. In cases where its separation from its lead vehicle was less than or equals its target separation

4.3.2.3.1.1. In a case where its lead vehicle was not braking ('*i.e. z==0*') then the OV was expected to accelerate at *'aA'* acceleration component

4.3.2.3.1.2. In a case where its lead vehicle was braking (*'i.e. z==1'*) then the OV was expected to brake at its maximum rate

4.3.2.3.2. In cases where the separation of the OV from its lead vehicle was greater than the its target separation

4.3.2.3.2.1. In a case where the speed of the OV at the current time step was greater than its speed at the previous time step then the OV was expected to accelerate at *'aB'* acceleration component

4.3.2.3.2.2. In a case where its lead vehicle was not braking it was expected to accelerate at acceleration component *'aC'*

4.3.2.3.2.3. In a case where its lead vehicle was braking, or it was at a risk of colliding with its lead vehicle it was expected to brake its maximum rate

4.4. This step was like step 4.3 except the response time of the OV was considered. It was called in a case where the OV had been on the link for a longer or the similar period as the addition of their response time and the time they require to observe the speed of their lead vehicle to determine if it is braking and they were not at a risk of colliding with it. The response time of the driver *('Aw_lev'*) was included since the driver's memory started during its *journey start time* and its memory covered its response time which was slower than the actual time (*t*) hence its memory was focused on a period in the past (i.e. *t-Aw_lev*). The OV driver essentially observed the driving parameters of its lead vehicle from a time equal to *t-Aw_lev* instead of its instantaneous driving parameters.

New vehicle generation

New DVUs were generated on patch 125 of any lane depending on the conditions of the lane entry with the inner lane having higher priorities than the outer lanes. New DVUs were generated when the patch loop was at its maximum value and the link entry conditions were satisfied. The conditions were:

- The availability of a vehicle registration number: When the link was at the maximum vehicle density specified by the user no vehicle registration was available. The registration numbers of vehicles exiting the link became available for newer DVUs. And
- The density of the link was greater than 15 vehicles and the position of the rear bumper of the lead DVU of the potential DVU to be generated was greater than the minimum traffic gap. Basically, there had to be enough room at the beginning of the lane where the new vehicle was to be generated. For the room to be acceptable, the rear bumper of the last vehicle in the lane had to be at a minimum distance from the start of the link which was equivalent to *the minimum traffic gap* or greater. Or

- The entry time interval had been met and the position of the rear bumper of the lead DVU of the DVU to be generated was greater than the minimum traffic gap. Or
- There was no lead vehicle in the lane to be entered

New DVUs were given vehicle registrations, generated at the minimum position (0.1m), their start time was logged, the position of their rear bumper was calculated, and their current lane was set to the lane they were generated on. The link total density was then incremented. The code used for generating new vehicles is shown on appendix 6.

The Traffic Simulator Output Data

Various data such as the traffic flux, traffic density, the maximum traffic density, average traffic speed and average journey time were collected during the simulation. The data collected were saved in an array called *'data'*. The maximum density was updated each time the density of the link was greater than its current value. The average speed was calculated after each time step. It was calculated as the sum of the average speeds of all vehicles that had exited the link between the start of the simulation and the current time step divided by the total number of vehicles that exited the link during the same period. This is shown in the Equation 8.45:

$$b_{tn} = \frac{\sum b_o}{r_{tn}} \qquad [8.45]$$

Where b_{tn} is the average speed from the start of the simulation up to the current time step, b_o is the average speed of each vehicle that exited the link and r_{tn} is the total number of vehicles that had exited the link both during the same period.

The average speed of each vehicle that exited the link (b_o) was calculated as the length of the link divided by the vehicle's total journey time. The equation is shown in Equation 8.46.

$$b_o = \frac{L}{t_v} \qquad [8.46]$$

The traffic mean speed during the traffic stable state (i.e. the period when vehicles entered and exited the link during the same time step) at the current time step was calculated as the sum of the average speed of all vehicles that exited the link during this period divided by the total vehicles that exited the link during the same period. This is shown in the equation 8.47.

$$b_{stn} = \frac{\sum b_{so}}{r_{tsn}} \qquad [8.47]$$

Where b_{stn} is the average speed from the start of the stable state up to the current time step, b_{so} is the average speed of each vehicle that exited the link and r_{stn} is the total number of vehicles that had exited the link both during the same period.

The traffic flux was computed from the start of the stable state and was calculated as the product of the average speed of the vehicles that had exited the link from the start of the stable state to the current time step and the density during the current time. This is shown in the equation 8.48.

$$FX_{tn} = b_o \times Q_{tn} \qquad [8.48]$$

Where FX_{tn} is the traffic flux from the start of the stable state to the current time and Q_{tn} is the current density.

The array 'data' was then saved as an excel file to enable the simulation data to be exported to a different program.

The code used to compute and collect the simulation data is shown in appendix 6 while the entire main code is shown in appendix 6.

The flow diagram for the overview of the program is shown in figure 8.19 below:

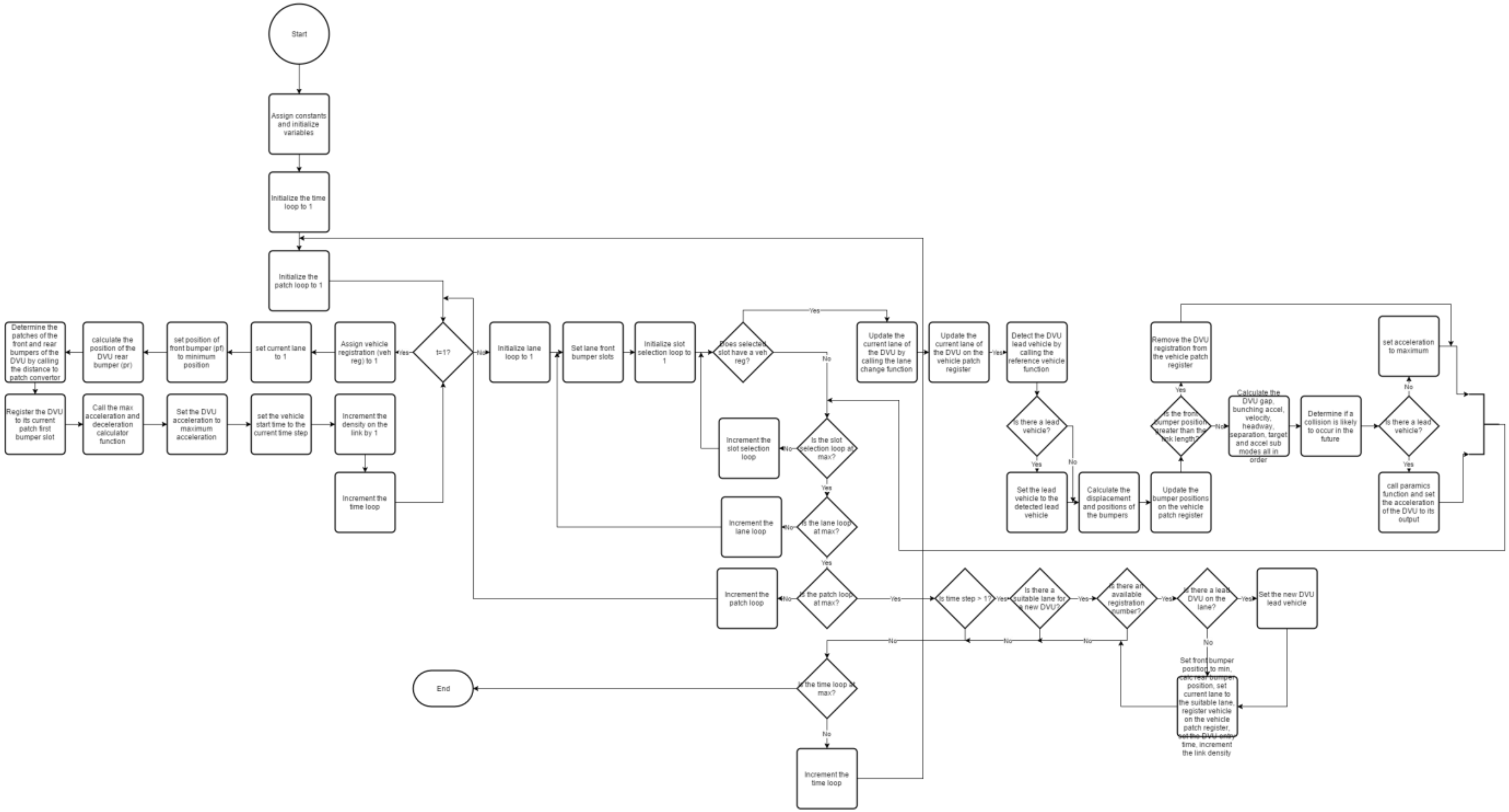


Figure 8.19: The Primary code overview

Testing the Traffic Simulator

The Car Following and Lane Changing Algorithm tests

To test the car following algorithm vehicles were made to queue up at the end of the link behind the stop line. This test was carried out using single lane and multiple lanes. Figure 8.20 shows a 2D position/time curve of a single lane 1000m link model. Vehicle 1 entered the link at 1ms and accelerated at maximum acceleration until it got to the end of the link where it decelerated until it came to an indefinite halt at approximately 2m from the stop line. Other vehicles entered the link at 3s intervals from their corresponding lead vehicles then utilised Paramics car following algorithm combined with a fail proof algorithm to *follow* their lead vehicles until they eventually came to a complete and indefinite halt at approximately 2m from their lead vehicles. Table 8.12 shows a portion of the spread sheet of the vehicles positions against time during a period where the vehicles were close to the end of the link while Table 8.13 shows the spread sheet of the gap between each vehicle within the same time frame.

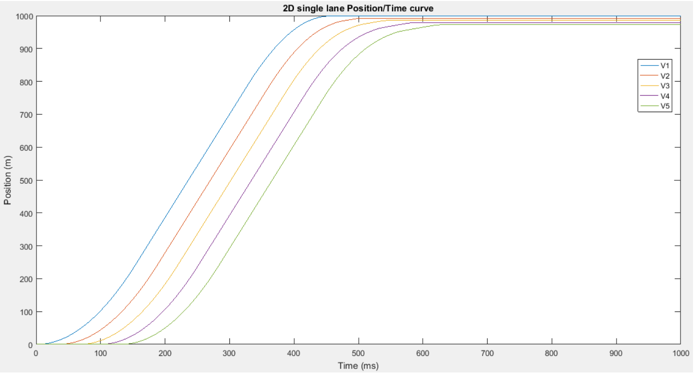


Figure 8.20: 2D single lane position/time curve

	1	2	3	4	5
623	998.5663	991.9546	985.4083	978.8812	971.8765
624	998.5663	991.9546	985.4083	978.8812	971.9941
625	998.5663	991.9546	985.4083	978.8812	972.0849
626	998.5663	991.9546	985.4083	978.8812	972.1490
627	998.5663	991.9546	985.4083	978.8812	972.1864
628	998.5663	991.9546	985.4083	978.8812	972.1971
629	998.5663	991.9546	985.4083	978.8812	972.1971
630	998.5663	991.9546	985.4083	978.8812	972.1971
631	998.5663	991.9546	985.4083	978.8812	972.1971
632	998.5663	991.9546	985.4083	978.8812	972.1971
633	998.5663	991.9546	985.4083	978.8812	972.1971
634	998.5663	991.9546	985.4083	978.8812	972.1971
635	998.5663	991.9546	985.4083	978.8812	972.1971
636	998.5663	991.9546	985.4083	978.8812	972.1971
637	998.5663	991.9546	985.4083	978.8812	972.1971
638	998.5663	991.9546	985.4083	978.8812	972.1971
639	998.5663	991.9546	985.4083	978.8812	972.1971
640	998.5663	991.9546	985.4083	978.8812	972.1971
641	998.5663	991.9546	985.4083	978.8812	972.1971
642	998.5663	991.9546	985.4083	978.8812	972.1971

Table 8.12: Table showing the vehicles positions against time

	1	2	3	4	5
623	0	1.9117	1.8463	1.8271	2.3047
624	0	1.9117	1.8463	1.8271	2.1872
625	0	1.9117	1.8463	1.8271	2.0964
626	0	1.9117	1.8463	1.8271	2.0322
627	0	1.9117	1.8463	1.8271	1.9948
628	0	1.9117	1.8463	1.8271	1.9841
629	0	1.9117	1.8463	1.8271	1.9841
630	0	1.9117	1.8463	1.8271	1.9841
631	0	1.9117	1.8463	1.8271	1.9841
632	0	1.9117	1.8463	1.8271	1.9841
633	0	1.9117	1.8463	1.8271	1.9841
634	0	1.9117	1.8463	1.8271	1.9841
635	0	1.9117	1.8463	1.8271	1.9841
636	0	1.9117	1.8463	1.8271	1.9841
637	0	1.9117	1.8463	1.8271	1.9841
638	0	1.9117	1.8463	1.8271	1.9841
639	0	1.9117	1.8463	1.8271	1.9841
640	0	1.9117	1.8463	1.8271	1.9841
641	0	1.9117	1.8463	1.8271	1.9841
642	0	1.9117	1.8463	1.8271	1.9841

Table 8.13: Table showing the vehicles gaps against time

Figure 8.21 shows the time/position/lane 3D curve of 10 vehicles in a 2 lane 1000m link. While most of the vehicles started their journeys using lane 1 because of lane 1 meeting the entry conditions during their attempted entry times, vehicles 2, 5 and 9 started their journeys on lane 2 because of lane 1 not meeting the lane entry conditions during their attempted entry times. Vehicle 2 maintained lane 2 throughout its journey because lane one did not show a more suitable driving condition than lane 2 throughout its journey while vehicle 5 and 9 switched to lane 1 shortly after entering the link due to more suitable driving conditions detected on lane 1. Vehicle 5 switched its lane after just 3.9s into its journey covering just 15.26m deduced from figure 8.22. A portion of the vehicles lanes against time is shown on the spreadsheet in Table 8.14**.** The portion captures the period where vehicle 5 switched lanes from lane 2 to lane 1. Various vehicles switched lanes during their journey as can be seen from the phase shift (referring to lanes) of some of the curves.

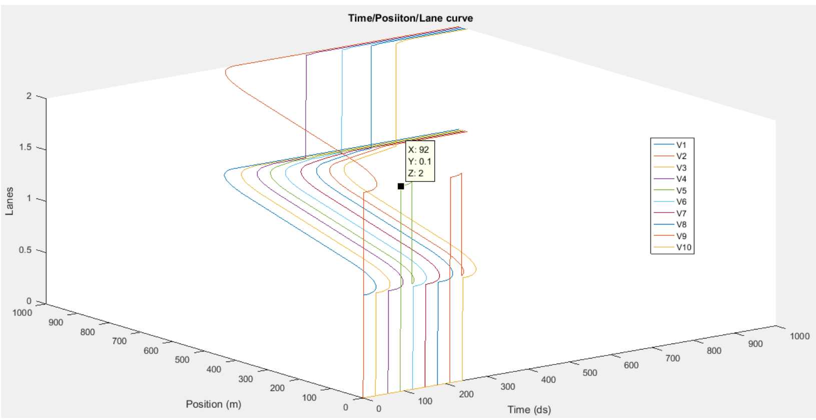


Figure 8.21: Time/position/lane 3D curve

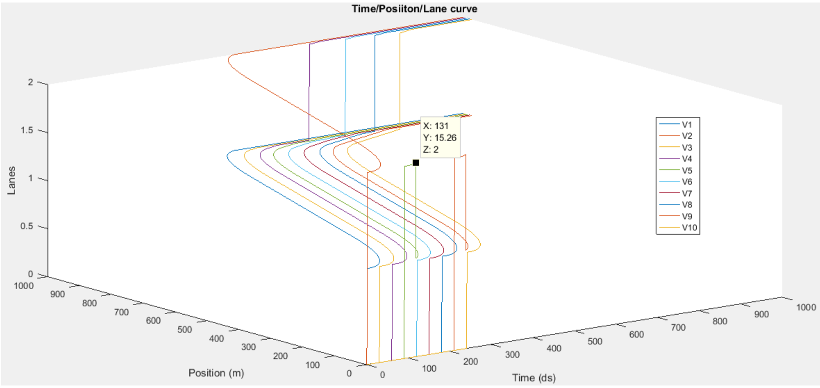


Figure 8.22: Lanes switch on a 2 lanes 3D curve

	1	2	3	4	5	6	7	8	9	10
126	1	2	1	1	2	1	0	0	0	0
127	1	2	1	1	2	1	0	0	0	0
128	1	2	1	1	2	1	0	0	0	0
129	1	2	1	1	2	1	0	0	0	0
130	1	2	1	1	2	1	0	0	0	0
131	1	2	1	1	2	1	0	0	0	0
132	1	2	1	1	1	1	0	0	0	0
133	1	2	1	1	1	1	0	0	0	0
134	1	2	1	1	1	1	0	0	0	0
135	1	2	1	1	1	1	0	0	0	0
136	1	2	1	1	1	1	0	0	0	0
137	1	2	1	1	1	1	0	0	0	0
138	1	2	1	1	1	1	0	0	0	0
139	1	2	1	1	1	1	0	0	0	0
140	1	2	1	1	1	1	0	0	0	0
141	1	2	1	1	1	1	0	0	0	0
142	1	2	1	1	1	1	0	0	0	0
143	1	2	1	1	1	1	0	0	0	0
144	1	2	1	1	1	1	0	0	0	0
145	1	2	1	1	1	1	0	0	0	0

Table 8.14: A portion of the vehicles' lanes with time

Figure 8.23 shows the time/position/lane curves of 10 vehicles on a 4 lane 1000m long link. From the figure it can be seen the first four vehicles utilised the four lanes due to the entry conditions and driving conditions of neighbouring lanes. It should be noted that since all four vehicles entered the link at approximately the same time and travelled at a similar speed they travelled side by side to each other hence the driving conditions of neighbouring lanes were unfavourable throughout their journeys. Other vehicles followed these vehicles with more vehicles being on the first lane due to a section of the UK Highway Code being embedded into the program. The section of the Highway Code suggests drivers stick to the inner lanes for as long as the driving conditions remain favourable. Drivers were also programmed to always attempt starting their journeys on the inner lane if the entry conditions were met.

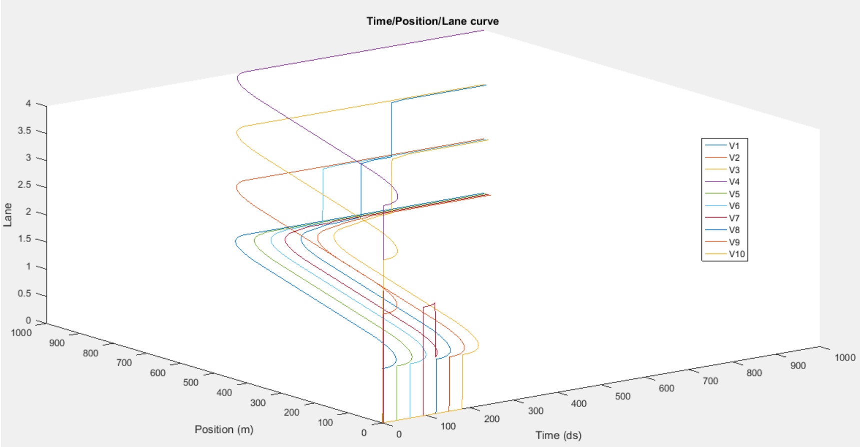


Figure 8.23: Four lanes time/position/lane curve

The impact of driving parameters on the journey times of the DVUs

To validate the impact of the main driving parameters featured in the model (acceleration, headway and speed), the observed variable was varied during a simulation while the other variables were left constant. The effect of the observed variable on the mean journey times of DVUs was then recorded.

Figure 8.24 represents the impact of acceleration on the journey times of DVUs when the maximum density on the link was set to 50, the number of lanes set to 4 and the maximum simulation period set to 3,000 time steps (i.e. 5 minutes) and other driving variables left constant. From figure 8.24 as the maximum acceleration of the DVUs increased the journey time reduced because of DVUs being able to attain higher speeds at progressively faster rates resulting in higher average speeds.

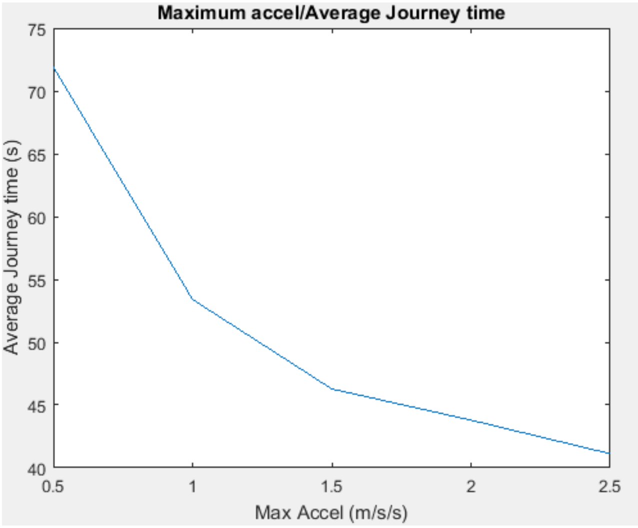


Figure 8.24: The impact of acceleration on the journey times of DVUs

Figure 8.25 represents the impact of the maximum speed of the DVUs on their journey times when the maximum density on the link was set to 50, the number of lanes set to 4 and the maximum simulation period set to 3,000 time steps (i.e. 5 minutes) and other driving variables left constant. From figure 8.25 as the maximum speed of the DVUs was increased the journey time reduced because of DVUs being able to attain higher maximum speeds also resulting in higher average speeds.

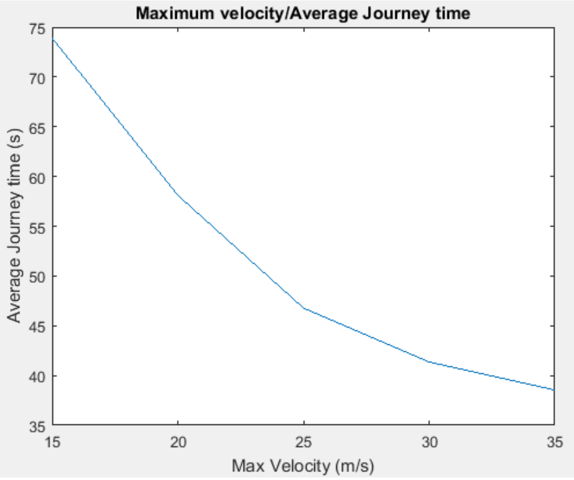


Figure 8.25: The impact of speed on the journey times of DVUs

The driving parameters where then selected into groups which were very good, good, moderate, poor, very poor conditions with the highest acceleration and highest maximum speed belonging to the very good condition while the lowest acceleration and lowest maximum speed belonging to the very poor condition. At later stages of the research these parameters were then referred to as dry, light rain, light snow, heavy rain and heavy snow conditions. It should be noted that the values used for the various parameters are not empirical values. Empirical values were later collected and used for the actual simulations. Figure 8.26 represents the impact of the various driving conditions on the journey time of the DVUs. From the figure better driving conditions (lower headway, higher acceleration and maximum speed) resulted in lower journey times.

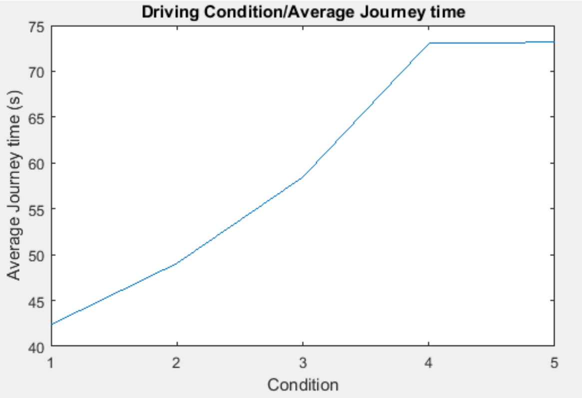


Figure 8.26: The impact of the various driving conditions on journey times

Congestion was then induced on the link by forcing the lead vehicles on each lane (leaders of the traffic stream on each lane) to brake down to 7m/s after covering 700m and maintain that speed until the end of their journey. This was done for all 5 conditions and the curve in figure 8.27 below shows the average journey time for all 5 conditions.

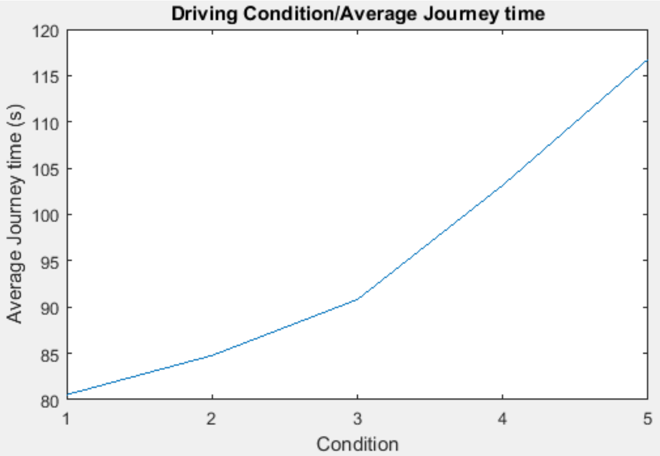


Figure 8.27: The impact of congestion on the journey times of the DVUs under various conditions

3. The UKCP09 Weather Generator

Using the UKCP09 weather generator

Various steps were followed when attempting to use the *UKCP09 weather generator* to generate weather variables at hourly temporal resolution.

Step 1: Selecting a starting point

The first step was to start a new request where three starting options were presented. They were starting by:

- *Data source* were all possible outputs were accessible
- *Climate variable* were only the section of a single variable was accessible
- *UK location* were only a single variable at a single land location was accessible

Data source was selected for this step which gave access to all possible outputs, the screenshot shown in figure 8.28 shows the available options for the first step.

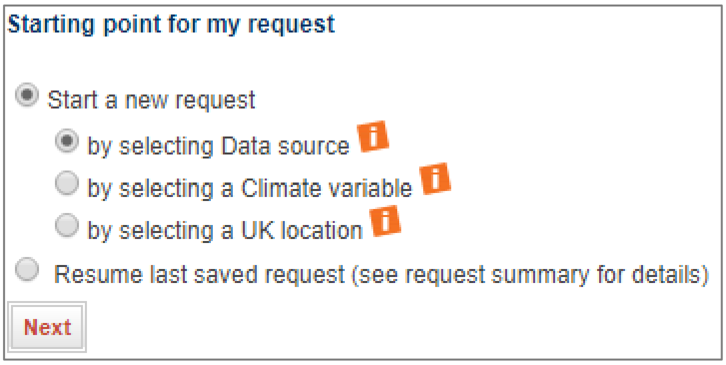


Figure 8.28: Selecting a starting point when using the UKCP09 (Met Office, 2010)

Step 2: Selecting a data source

The second step was to select the *data source* to be used for the generation according to the climate information type in focus. The various options given were:

- *UK Probabilistic Projection of Climate Change over Land*: A modelling method which examines the uncertainty in the MOHC climate model HadCM3 by running a perturbed physical experiment was used to generate the results under this data source (for more info see Met Office, 2010).
- *UK probabilistic Projections of Climate over Marine Regions*: The result for this option are produced the same way as *Probabilistic Projection of Climate Change over Land*,
- *Weather Generator Simulations*: This downscaling approach is used when producing daily and hourly time series of variables which may be used when impact, vulnerability and adaptation assessment are being considered where higher spatial and temporal resolutions than is available from *the probabilistic projections* is regarded necessary (Met Office, 2010).
- *Past and Future Multi-level Ocean Model Simulations for UK Waters*: This option is used to generate results of projections of future changes in sub-surface marine variables around the UK.
- *Projection of Trend in Storm surge for UK Waters*: This option is used to generate results of projections of future changes in sew storm surge around the UK.
- *Projection of Sea level rise for UK Waters*: This option is used to generate results of projections of future changes in sea level around the UK

The screenshot in figure 8.29 shows the available options when selecting a data source when using the UKCP09. Since generating an hourly time series of variables was the focus *Weather Generator Simulations* was selected.

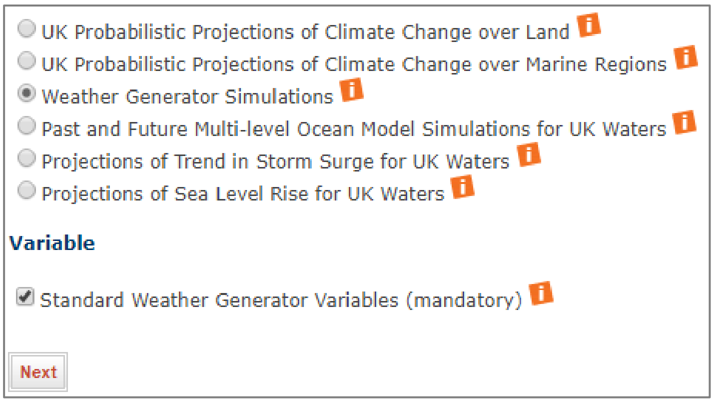


Figure 8.29: Selecting a data source and output variables when using the UKCP09 (Met Office, 2010)

Unlike the other data source options which had multiple variable set options, the *Weather Generator Simulations* data source had a single variable set. The variables were produced at the daily and hourly temporal resolution, daily mode featured nine variables as the outputs, and the hourly mode featured seven variables as the outputs (Met Office, 2010).

- *The Weather Generator daily variables are:*
  - Mean total daily precipitation rate (mm)
  - Minimum daily temperature (°C)
  - Maximum daily temperature (°C)
  - Vapour pressure (hPa)
  - Relative humidity (%)
  - Sunshine hours (hr)
  - Potential evapotranspiration (PET) (mm/day)
  - Direct irradiation (W/m^2)
  - Downward diffuse irradiation (W/m^2)
- *The Weather Generator hourly variables are:*
  - Mean total hourly precipitation rate (mm)
  - Mean hourly temperature (°C)
  - Vapour pressure (hPa)
  - Relative humidity (%)
  - Sunshine hours (hr)
  - Direct radiation (W/m^2)
  - Downward diffuse radiation (W/m^2)

Step 3: Selecting an emission level

The third step when using *the UKCP09 Weather Generator Simulations* was to select the emission scenario in focus which ranged from low to high emission scenario. The emission scenarios on the UKCP09 weather generator represented the future development of greenhouse gas emissions and were based on a coherent and internally consistent set of assumptions about driving forces (such as demographic and socio-economic development and technological change) (Met Office, 2010). The screenshot shown in figure 8.30 shows the emission level options presented when using *the UKCP09 Weather Generator Simulations* tool.

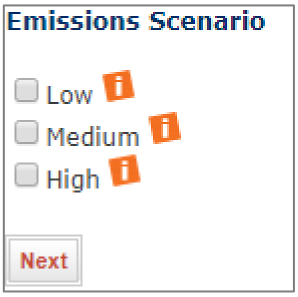


Figure 8.30: Selecting an emission scenario when using the UKCP09 weather generator (Met Office, 2010)

Step 4: Selecting a Period

The fourth step was to select a *period* (i.e. a 30-year period over which climate averages are calculated) in focus, it was specified that the research would focus on 2050s hence 2050s was selected. Depending on the data source selected and the output type the tool may allow the user to select *temporal averages* (i.e. time unit such as month, season or annual), multiple temporal averages were available for Weather Generator simulations but were set as all 12 months only.

The screenshot shown in figure 8.31 shows the *period* being selected; from the figure all 12 months were automatically selected as the *temporal averages*. Due to the research primary focus being on summer and winter period it was therefore important to come up with an algorithm that would separate the summer and winter months from the entire 12 months.

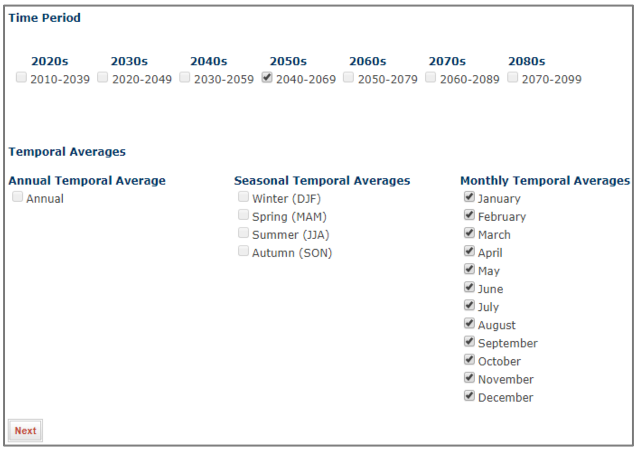


Figure 8.31: Selecting a Time Period when using the UKCP09 weather generator (Met Office, 2010)

Step 5: Selecting a UK location

The fifth step was to select a UK location on the tool, it was specified that the research would focus on two hypothetical trunk roads based in an area between Winwick and Croft, Greater Manchester hence that was the location to be specified on the tool. Since the location was less than 5km long, a single 5km grid square was enough to highlight the location. The screenshot shown in the figure 8.32 shows the highlighted location on the UKCP09 weather generator tool.

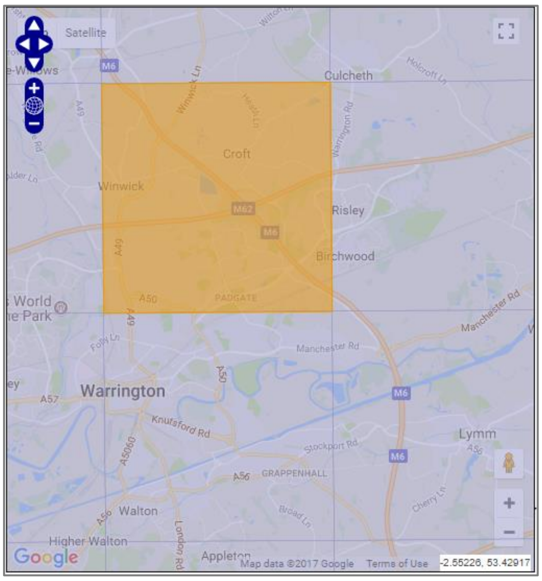


Figure 8.32: Selected location on the UKCP09 weather generator tool (Met Office, 2010)

Step 6: Selecting the type and scope of probabilistic projection data used to drive the weather generator

In the sixth step a sub-set of the available probabilistic projections used to define the future climate driving the weather generator runs was selected. Various methods were available for selecting a sample of the available model variants. Each variant can produce a different climate projection within reasonable limits. Four different sampling methods were available (Met Office, 2010):

- *Select all*: To access all 10,000 available variants but this was limited to 1000 model variants for the weather generator due to limitations on processing power.
- *Random sampling of model variants*: To select the number of random samples which was set to a minimum of 100 and limited to 1000 when using the weather generator.
- *Selecting a specific set of model variants*: Allowed tagging of model variants in the data with specific sampling IDs
- *Sampling a particular sub-set of the probabilities*: To work with one or two variables at given percentiles and for selecting temporal averages to define the type of conditions being sampled from.

For this research random sampling of model variants was selected, it was important to have the number of samples between 100 and 1000 inclusive when using this method. The tool regards the minimum value 100 as the smallest possible number of samples that could be used to maintain the probabilistic nature of the data. The maximum value is smaller when using the weather generator compared to when using the selected sampled data to limit the size of the outputs. Each selection is regarded as an independent event by the tool's random selection algorithm hence it was possible to produce multiple samples that may be the same in the output data.

The screenshot in figure 8.33 shows the sampling method being selected from the given options when using the UKCP09 weather generator as a data source.

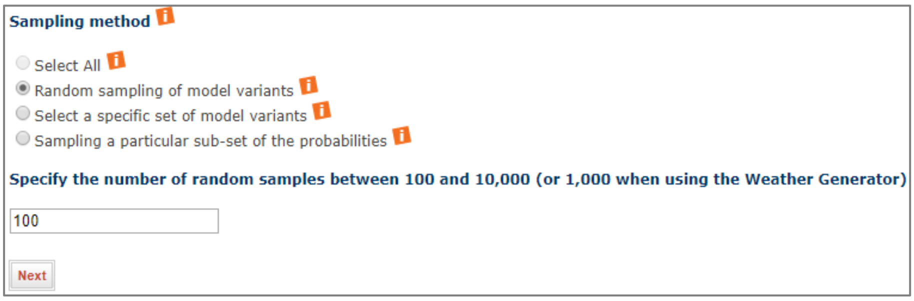


Figure 8.33: Selecting a Sampling method when using the UKCP09 weather generator (Met Office, 2010)

Step 7: Configuring the weather generator to produce the required output

The weather generator could be setup to produce daily or hourly simulations, the length of the simulations and the required output. Daily frequency is the standard mode of the weather generator and permits the maximum length of simulation (100years) while with hourly frequency which was used for this research, the weather generator was limited to 100 runs and 30-year duration because hourly data was 24 times the volume of daily data hence would produce much larger files. Hourly data were generated by disaggregating daily data and were perturbed by the same temporal resolution used in the future climate change projections featured in the daily data.

The random seed was the initial number used as the starting point in the random number generation algorithm and it had a range of 1-29999 which could be set automatically or manually, it was set to 100 for this research (Met Office, 2010). The screenshot shown in figure 8.34 shows the configuration used for the weather generator output.

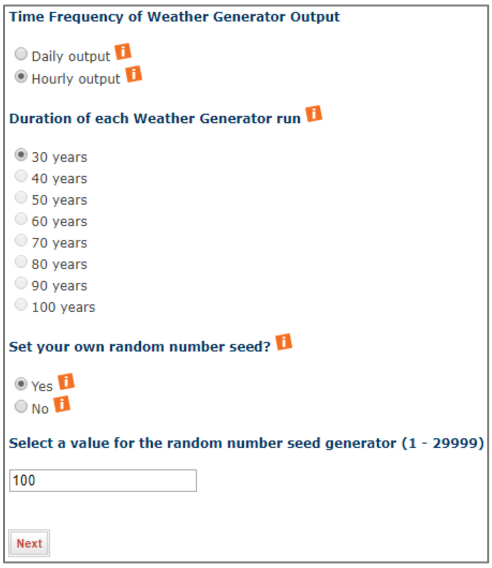


Figure 8.34: Configuring the weather generator to produce the required output (Met Office, 2010)

Step 8: Selecting the output data format

In this step the output data format was selected when using the weather generator, it was possible to select only raw data which could be used in other models or programs. The raw data outputs were available in CF-netCDF and CSV (comma-separated variable) files. CF-netCDF is a binary format while CSV could be read in a text editor or spreadsheet package, the CSV format was selected for this research because it could be imported into MATLAB and processed.

The other output data formats which were not available when using the weather generator produced images and information which could be used in reports and presentations. It was possible to set a unique reference automatically or manually, this was set manually so that each job was easily identified (Met Office, 2010). The screen shot shown in figure 8.35 shows the output data format selected and a request identification manually entered.

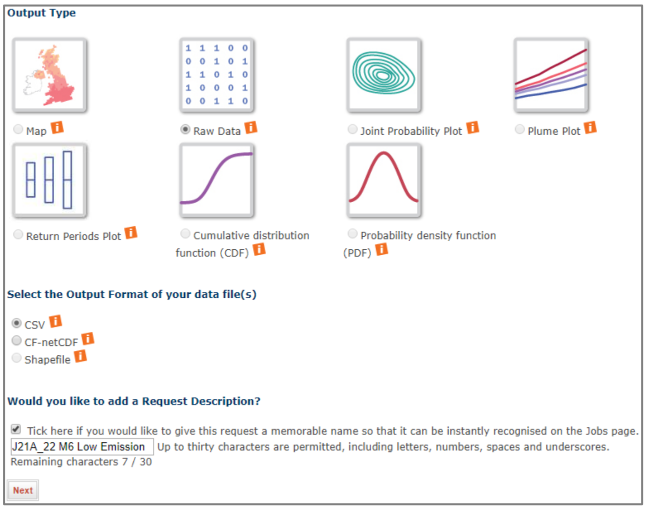


Figure 8.35: Selecting the output data format when using the UKCP09 Weather Generator (Met Office, 2010)

Step 9: Request Submission

The final step was to submit the request, jobs requiring small volumes of data could be serviced within minutes but jobs requiring larger volumes of data such as weather generator could run for much longer periods (usually minutes or hours). These were referred to within the UKCP09 system as offline jobs (Met Office, 2010).

Before submitting the job an estimate of how long it would take for the job to run and the total volume of the output files was shown, and this is shown in the screenshot in figure 8.36.

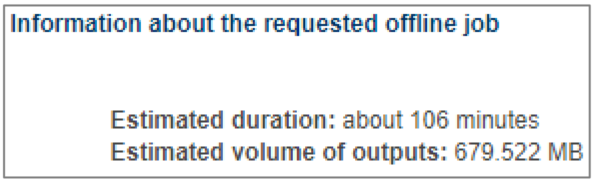


Figure 8.36: Run duration and volume of the requested job (Met Office, 2010)

Figure 8.37 illustrates the steps taken when using the UKCP09 weather generator.

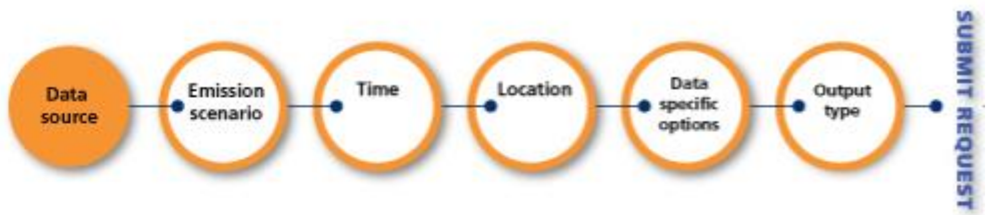


Figure 8.37: Steps taken when using the UKCP09 weather generator (Met Office, 2010)

The UKCP09 Weather Generator Hourly Output Data

The hourly data output of the UKCP09 Weather Generator (WG) was downloaded as large zip files containing CSV files. Each control and *future climate* run had a single CSV file and due to the number of *random sampling variants* specified there were a total of 100 files each. One of the zip files contained the header information which held the variable names for each column in the CSV files as it was not included on the first column of each file. The variables included in the hourly WG data are shown below (Met Office, 2014):

- *Year*: On each file the year started at 3001 which indicated the first year and ran through the entire 30-year period at an hourly time step until the maximum year elapsed which was 3030
- *Month*: This showed the month of the *current* time step and it ran from 1 to 12 signifying January to December
- *Day*: This showed the day of the month of the *current* time step
- *Hour:* This showed the hour of the day and ran from 0 to 2300 in steps of 100.
- *Mean total hourly precipitation rate* (units: mm/day)
- *Mean hourly temperature, units*: degrees C.
- *Vapour pressure*, units: hPa
- *Relative humidity*, units: %, expressed as decimal values in the file, the percentages could be gotten by multiplying by 100
- *Sunshine hours*, units: hours (0-24).
- *Downward diffuse radiation*, units: W/m2
- *Direct radiation*, units: W/m2

Tables 8.15a & b below shows a sample variant for high emission future climate data, although there are only 20 rows on the table it should be noted that the file contained a total of 262969 hours equivalent to the total hours in a 30-year period.

Each row represented an hour of the 30-year period and the relevant columns to this research were:

- *Column A*: used to determine the start and end of each year for analysis. Deducting 3000 from each cell value in column A showed the year of each row, for example cell A1 showed year 1.
- *Column B*: used to filter the summer and winter months.
- *Column C*: used to determine the start and end of each day.
- *Column D*: used to filter the peak hours of each day.
- *Column E*: used to determine the total precipitation of each hour.
- *Column F*: used to determine the temperature of each hour.

	A	B	C	D	E	F	G	H	I	J	K	L
1	year	month	day	hour	precip_ht	temp_hm	vapourpr	relhum_h	sunshine_	diffradt_I	dirradt_htotal	
2	-	-	-	-	mm/hour	degC	hPa	%	hours	Wh/m2	Wh/m2	

Table 8.15a: Headers of the weather data

	A	B	C	D	E	F	G	H	I	J	K
1	3001	1	1	0	0	1.1	6.6	1	0	0	0
2	3001	1	1	100	0	-0.1	6.1	1	0	0	0
3	3001	1	1	200	0	1.9	7	1	0	0	0
4	3001	1	1	300	0	1.1	6	0.92	0	0	0
5	3001	1	1	400	0	2	6.3	0.9	0	0	0
6	3001	1	1	500	0	1.1	6.5	1	0	0	0
7	3001	1	1	600	0	2.5	7.2	0.99	0	0	0
8	3001	1	1	700	0	1.3	6.4	0.97	0	0	0
9	3001	1	1	800	0	1	6.4	0.98	0	1.6	0
10	3001	1	1	900	0	0.8	6.4	1	0.3	50.7	14.3
11	3001	1	1	1000	0	3.5	7.4	0.95	0.2	81.6	15.4
12	3001	1	1	1100	0	4	5.8	0.72	0.5	97.6	53.9
13	3001	1	1	1200	0	5	6.2	0.72	0.9	98.4	109.7
14	3001	1	1	1300	0	5.7	7.1	0.79	0.7	84.5	70.1
15	3001	1	1	1400	0	5.6	7.3	0.81	0.5	56.2	28.6
16	3001	1	1	1500	0	5.6	6.7	0.75	0.2	11.8	0
17	3001	1	1	1600	0	4.7	6.9	0.82	0	0	0
18	3001	1	1	1700	0	3.1	6.9	0.92	0	0	0
19	3001	1	1	1800	0	4	6.4	0.8	0	0	0
20	3001	1	1	1900	0	3.2	6.3	0.83	0	0	0

Table 8.15b: A section of a sample variant for high emission future climate data

The impact of the emission scenarios on the general weather conditions frequency

It has been projected that *there will be hotter dryer summers and warmer wetter winters with more extreme conditions under future weather conditions* (Baker, 2013) but the degree of this impact would depend on the emission scenario between the control (control period) and the future climate in focus (2050s) with *high emission scenario* projected to have more impact than *medium* and *low emissions scenarios*.

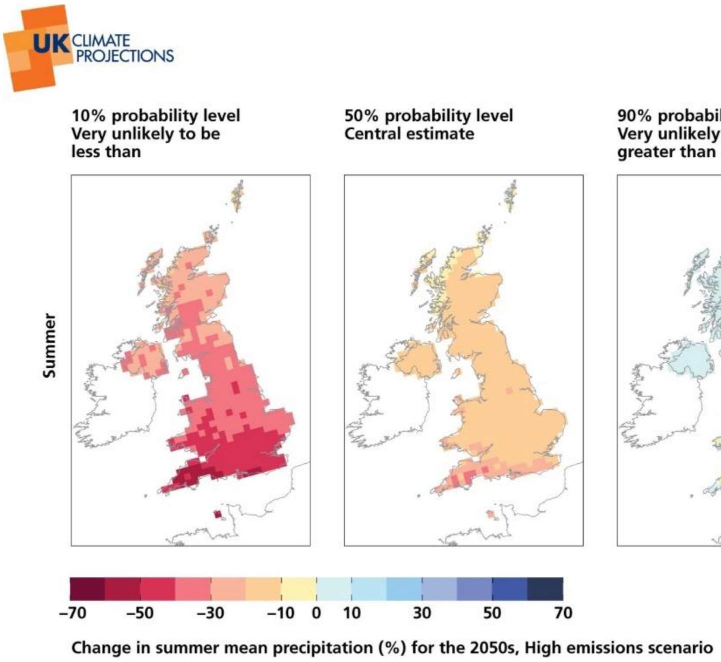
Weather projections from the UKCP09 did not differentiate between rainfall and snowfall hence thresholds were used to make the differentiations for the traffic flow model. To make such differentiation the precipitation level for each hour as well as their temperature level were used to estimate the weather condition for a given hour. It was assumed that temperatures below 0°C would result in snowfall if the hour experienced precipitation whiles those greater than 0°C would result in rainfall. The justification for this assumption was discussed in section 4.3.2.1.

Projections of regional changes across the UK were presented using maps by the MET Office (UK Climate Projections, 2009). It was indicated that a warmer atmosphere can hold more moisture, and globally water vapour increases by 7% for every degree centigrade of warming. It is likely that in a warmer climate heavy rainfall will increase and be produced by fewer more intense events. This could lead to longer dry spells and a higher risk of floods

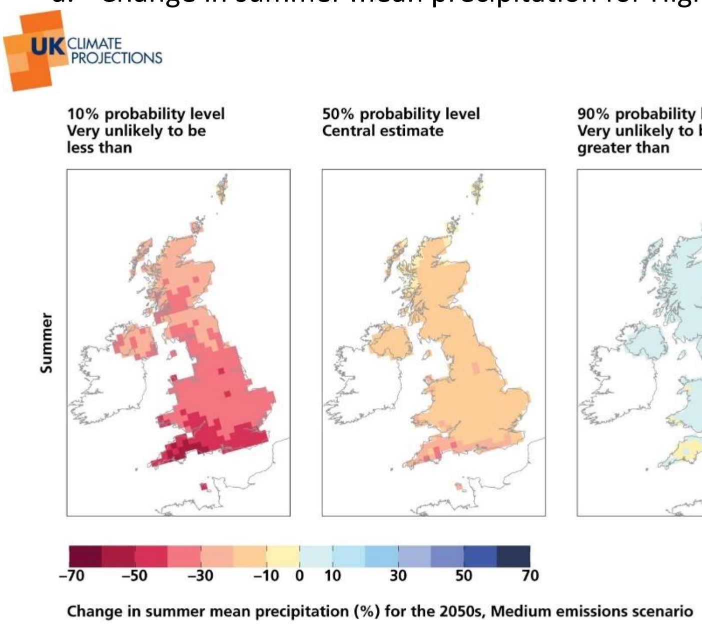
(Met Office & The Guardian, 2011). Basically, increase in the global temperature would result in hotter, drier summers and warmer, wetter winters with higher extremes. Figure 8.38 was extracted from © UK Climate Projections 2009 and they present maps showing the UKCP09 projected change in both seasons mean precipitation for all the emission scenarios.

Precipitation

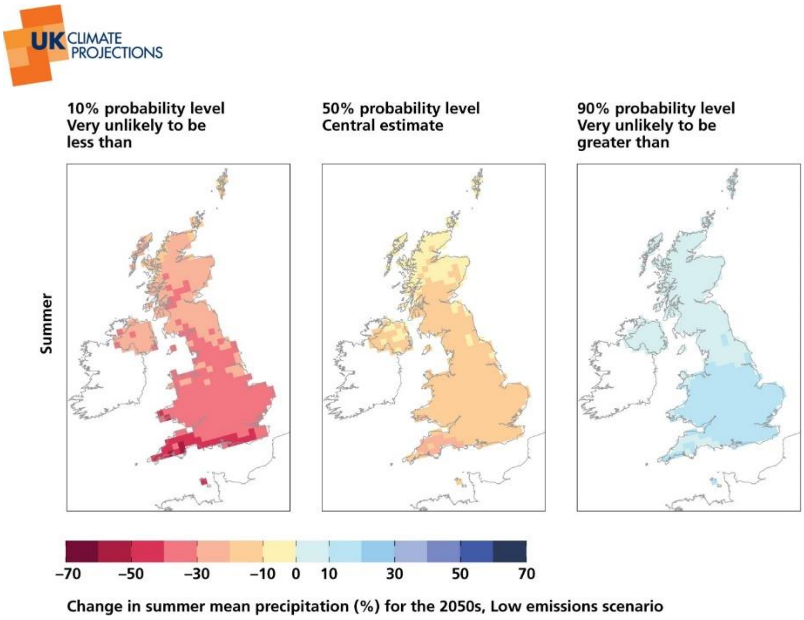
Change in summer mean precipitation



a. Change in summer mean precipitation for High Emissions Scenario



b. Change in summer mean precipitation for Medium Emissions Scenario



c. Change in summer mean precipitation for low Emissions Scenario

Figure 8.38: Change in summer mean precipitation for all the Emissions Scenario (© UK Climate Projections, 2009)

Figure 8.38 shows the change in summer mean precipitation for all the emission scenarios on various maps. From the figure the further south you go the more prone the region is to precipitation loss with the extreme south showing the highest loss in all emissions scenario. Generally, the dry areas are projected to become drier during the summer period as can be seen in the southern regions and the higher the emission level the drier the regions become.

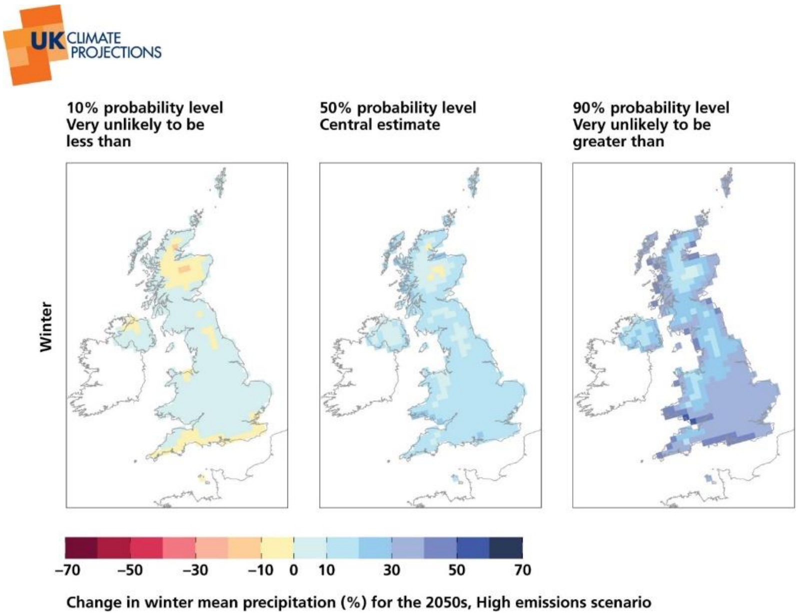
Table 8.16 summarises the outputs from the map for the Region of Interest (ROI) which is on the northwest of England.

	Emissions Scenario		
Percentile (%)	Low	Medium	High
10	-40	-50	-60
50	-20	-20	-20
90	30	20	20

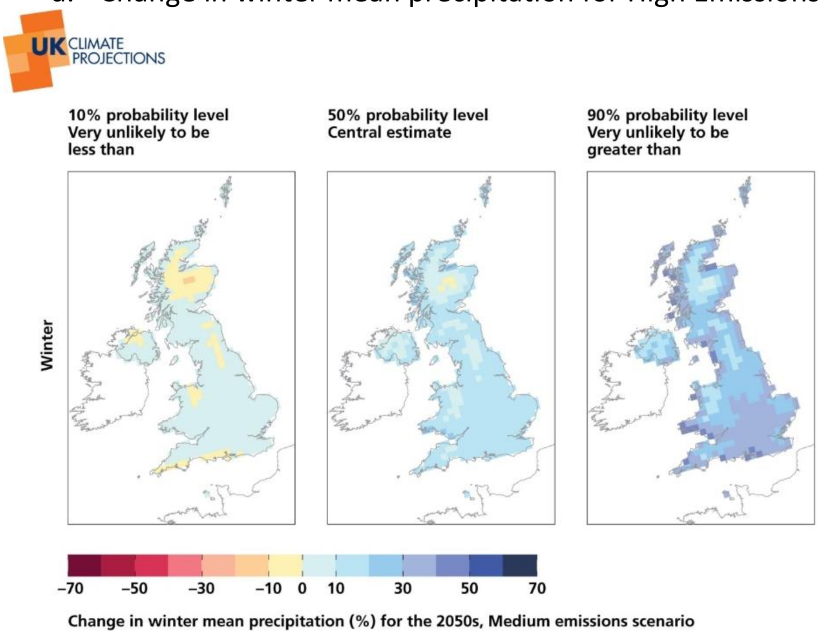
Table 8.16: Change in summer mean precipitation for all the Emissions Scenario for the ROI

By observing the emissions scenario on the maps, it can be seen from table 8.16 that the changes in the precipitation levels of the ROI are not as significant as the southern regions. The 10th percentile for the low, medium and high emissions scenarios showed -40%, -50% and -60%, the 50th percentile appears to be pretty much the same across each scenario while the 90th percentile showed 30 for low and 20 for the other emissions scenarios. Beyond the 2050s the ROI will most likely show more significant changes in precipitation levels.

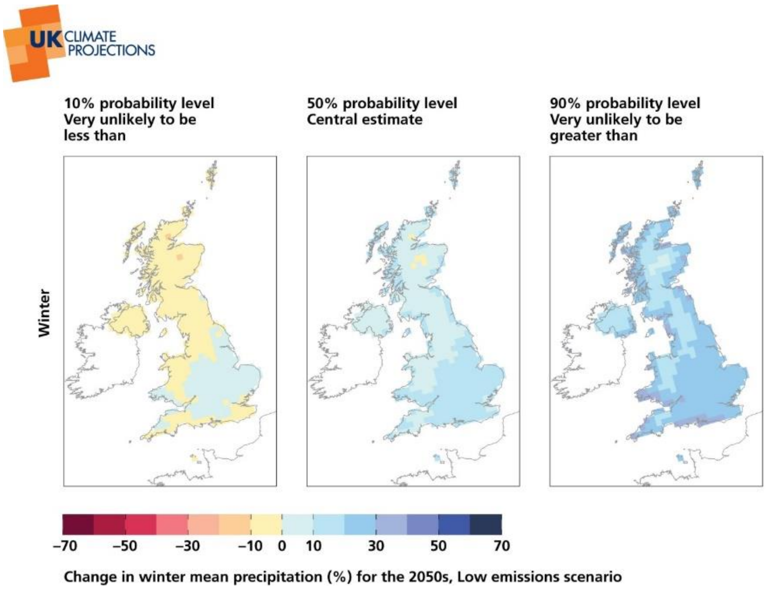
Change in winter mean precipitation



a. Change in winter mean precipitation for High Emissions Scenario



b. Change in winter mean precipitation for Medium Emissions Scenario



c. Change in winter mean precipitation for low Emissions Scenario

Figure 8.39: Change in winter mean precipitation for all the Emissions Scenario (© UK Climate Projections, 2009)

For the winter period figure 8.39 shows the change in mean precipitation for the entire emissions scenario. From the figure higher emission levels resulted in wetter winter conditions.

Table 8.17 summarises the outputs from the map for the ROI which is on the northwest of England.

	Emissions Scenario		
Percentile (%)	Low	Medium	High
10	-10	10	10
50	10	20	20
90	20	30	30

Table 8.17: Change in summer mean precipitation for all the Emissions Scenario for the ROI

Although from the table above it may seem like there was no significant changes with increasing emission level, but a broader view shows that the low emission scenario experienced much drier winter compared to medium and high scenarios especially when the bottom 10% is considered.

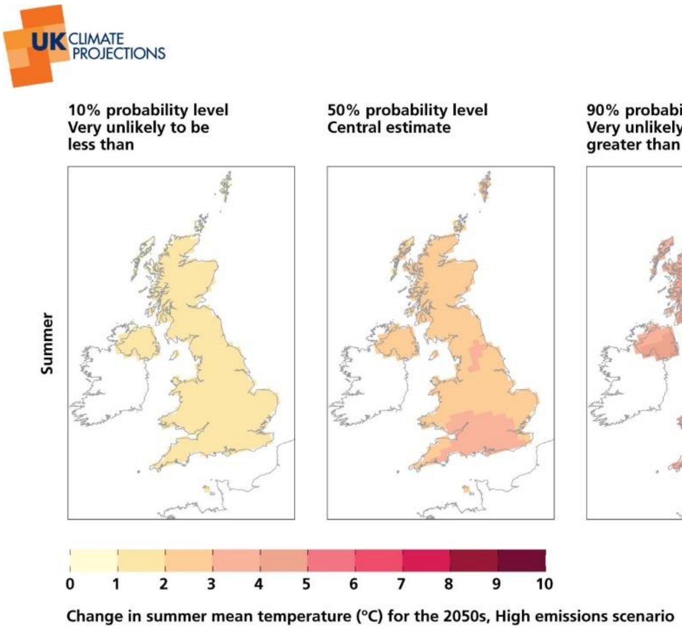
Table 8.18 shows the changes in mean precipitation for North West England for each emission scenario, it was extracted from © UK Climate Projections 2009. The wider range is defined as the range from the lowest to highest value of change for all Emissions scenario and all three (10, 50, and 90%) probability levels for each 30-year period.

	Probability Level				
	10%	50%	90%	Wider range	
	Summer				
High	–37	–18	+2	–37	+8
Medium	–36	–18	+1	–37	+8
Low	–34	–14	+8	–37	+8
	Winter				
High	+3	+13	+27	–1	+27
Medium	+3	+13	+26	–1	+27
Low	–4	+4	+14	–4	+14

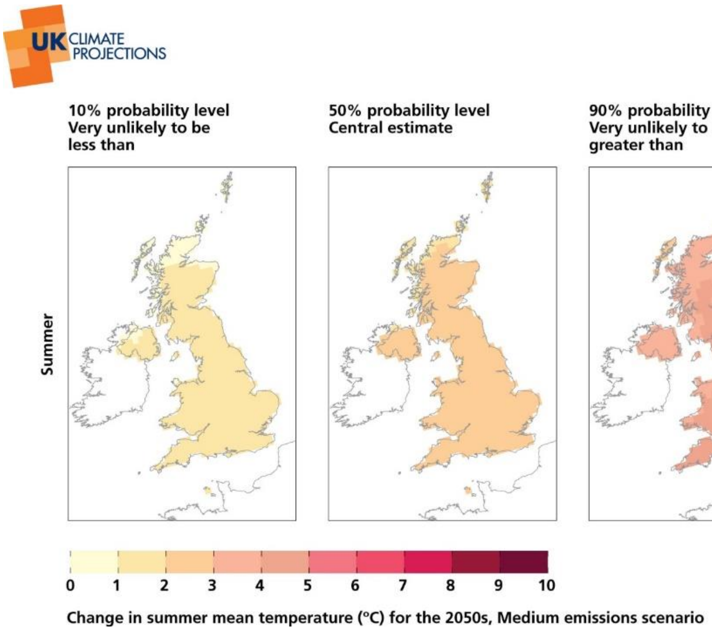
Table 8.18: Change in mean precipitation (© UK Climate Projections, 2009)

Temperature

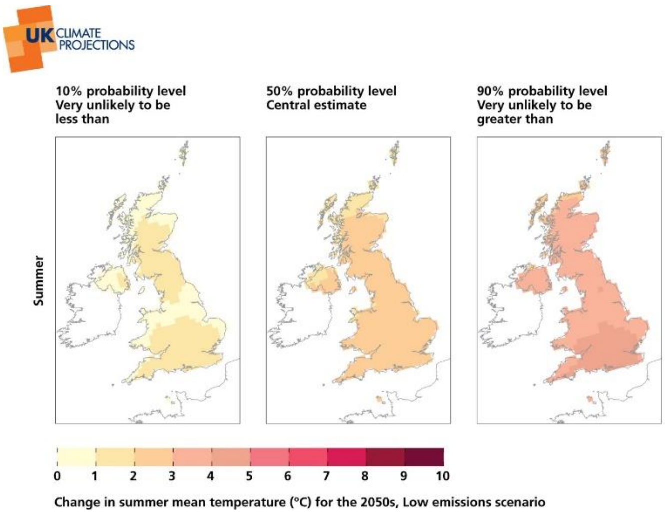
Change in summer mean temperature



a. Change in summer mean temperature for High Emissions Scenario



b. Change in summer mean temperature for Medium Emissions Scenario



c. Change in summer mean temperature for low Emissions Scenario

Figure 8.40: Change in summer mean temperature for all the Emissions Scenario (© UK Climate Projections, 2009)

Figure 8.40 shows the change in summer mean temperature for all the emission scenarios on maps. From the figure the further south you go the more prone the region is to higher temperature rises with the extreme south showing the highest rise in all emissions scenario. It can also be seen that higher emission levels resulted in higher temperature rises.

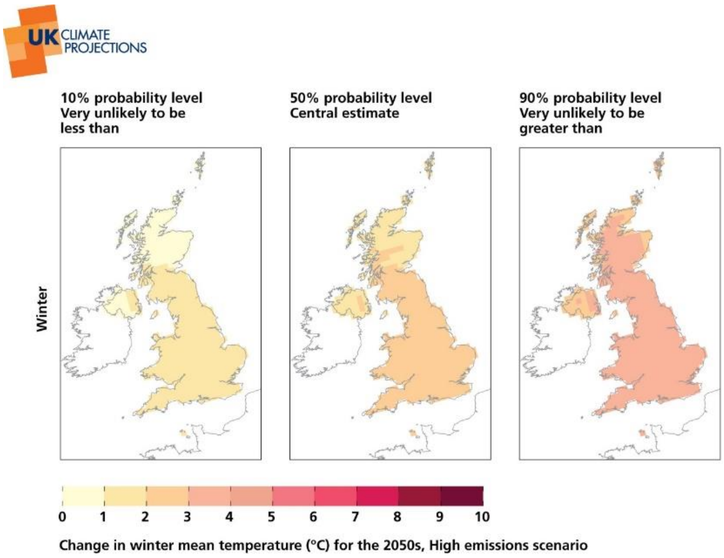
Table 8.19 summarises the outputs from the map for the ROI which is on the northwest of England.

	Emissions Scenario		
Percentile (%)	Low	Medium	High
10	0	1	1
50	2	2	2
90	3	3	4

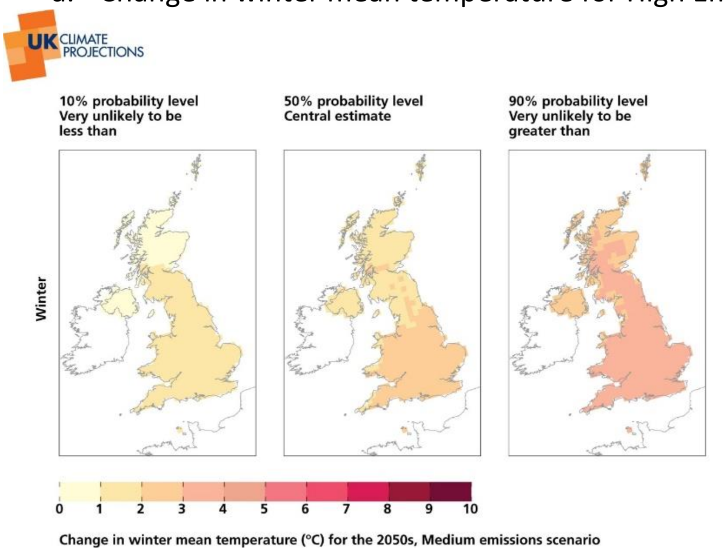
Table 8.19: Change in summer mean precipitation for all the Emissions Scenario for the ROI

Table 8.19 shows that for the summer periods the level of change for the region did increase as the emission level was increased. All the emissions scenario appeared to have the same mid-level probability, but the differences can be observed at the extremes. Just like the precipitation projections, beyond the 2050s there would most likely be more significant changes as from the map although the impact was not high enough to make significant impacts on the region but over time the impact would become more severe.

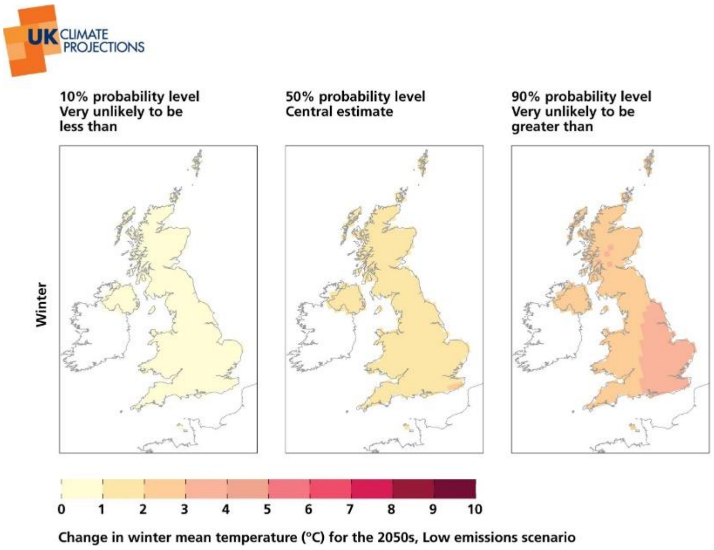
Change in winter mean precipitation



a. Change in winter mean temperature for High Emissions Scenario



b. Change in winter mean temperature for Medium Emissions Scenario



c. Change in winter mean temperature for low Emissions Scenario

Figure 8.41: Change in winter mean temperature for all the Emissions Scenario (© UK Climate Projections, 2009)

For the winter period figure 8.41 shows the change in mean temperature for the entire emissions scenario. From the figure higher emission levels resulted in warmer winter conditions.

Table 8.20 summarises the outputs from the map for the ROI which is on the northwest of England.

	Emissions Scenario		
Percentile (%)	Low	Medium	High
10	0	1	1
50	1	2	2
90	2	3	3

Table 8.20: Change in summer mean precipitation for all the Emissions Scenario for the ROI

Similar to the precipitation projections, although from the table above it mays seem like there was no significant changes with increasing emission level but a broader view shows that the high emission scenario experienced much warmer winter temperatures compared to medium and low emission scenarios especially higher up north where the region becomes wetter as a result of rises in temperature.

Table 8.21 shows the changes in the mean precipitation for North West England for each emission scenario, it was extracted from © UK Climate Projections 2009.

Probability Level					
	10%	50%	90%	Wider range	
	Summer				
High	1.5	3.0	4.7	1.1	4.7
Medium	1.2	2.6	4.1	1.1	4.7
Low	0.8	1.6	2.5	0.6	2.5
Winter					
High	1.2	2.1	3.3	0.8	3.3
Medium	1.1	1.9	3.0	0.8	3.3
Low	0.8	1.8	2.8	0.8	3.3

Table 8.21: Change in mean temperature (© UK Climate Projections, 2009)

4. The Integrated weather Impact simulator

The Inputs

Initialising variables

```
%Define arrays
peak_hours_flux_S_scen=zeros(length(D_1),30);
peak_hours_flux_S_cnt=zeros(length(D_1),30);
peak_hours_flux_W_scen=zeros(length(D_1),30);
peak_hours_flux_W_cnt=zeros(length(D_1),30);
```

The code above is an example of some arrays being initialised. Basically, the code initialised the length (rows) of each array to the length of an array called D_1 and their width (columns) to 30.

The User's input (options)

```
%User Options
lane_type=single;
traffic_type=congested;
vehicle_type=small;
traffic_condition=optimum;
emission=high;
```

The code above shows the user selected a uniform congested single lane traffic flow featuring small vehicles, an optimal traffic flux and a high emission scenario.

Importing the traffic data

```
%Import traffic flow data
WE_Con_US_S=csvread('WE_Conj_Uni_Small_Single.csv');
WE_Con_UL_S=csvread('WE_Conj_Uni_Large_Single.csv');
WE_Con_Mix_S=csvread('WE_Conj_Mixed_Single.csv');
WE_Tra_US_S=csvread('WE_Traffic_Uni_Small_Single.csv');
```

A portion of the traffic flow data selector

```
%Traffic flow data selection
if traffic_type==congested && vehicle_type==small && lane_type==single
    use_data=WE_Con_US_S;
elseif traffic_type==congested && vehicle_type==large && lane_type==single
    use_data=WE_Con_UL_S;
elseif traffic_type==congested && vehicle_type==mixed && lane_type==single
    use_data=WE_Con_Mix_S;
```

Importing and selecting weather data

```
%automatic file import future Scenerio
% Select folder containing data interactively
if emission==high
    Location_1 = 'C:\Users\Isi\Documents\MATLAB\Paramics functions\M6_J14_15\Scenario_M6_J14_15_High_Emission';
elseif emission==medium
    Location_1 ='C:\Users\Isi\Documents\MATLAB\Paramics functions\M6_J14_15\Scenario_M6_J14_15_Medium_Emission';
elseif emission==low
    Location_1 ='C:\Users\Isi\Documents\MATLAB\Paramics functions\M6_J14_15\Scenario_M6_J14_15_Low_Emission';
end
% Identify where to search for files
% Store the name of all .csv files as a vector D
D_1 = dir([Location_1, '\*.csv']);
% Extract the file names
filenames_1 = {D_1(:).name}.';
data_1 = cell(length(D_1),1);
```

Located inside the first loop

```
% Create the full file name and partial filename
fullname = [Location_1 filesep D_1(file).name];
% Read in the data
data_1{file} = csvread(fullname);

weather_data=data_1{file};
```

Weather condition definition and grading

```
%weather condition definition
condition_scen=0;
if brap(all,1)==0
    condition_scen=1;
elseif brap(all,1)>0 && brap(all,1)<=6.35 && brap(all,7)>0
    condition_scen=2;
elseif  brap(all,1)>0 && brap(all,1)<=12.7 && brap(all,7)<=0
    condition_scen=3;
elseif brap(all,1)>6.35 && brap(all,7)>0
    condition_scen=4;
elseif brap(all,1)>12.7 && brap(all,7)<=0
    condition_scen=5;
end
```

```
 condition_cnt=0;
if brap(all,2)==0
    condition_cnt=1;
elseif brap(all,2)>0 && brap(all,2)<=6.35 && brap(all,8)>0
    condition_cnt=2;
elseif   brap(all,2)>0 && brap(all,2)<=12.7 && brap(all,8)<=0
    condition_cnt=3;
elseif brap(all,2)>6.35 && brap(all,8)>0
    condition_cnt=4;
elseif brap(all,2)>12.7 && brap(all,8)<=0
    condition_cnt=5;
end
```

The precipitation column of the file being processed was copied into the 1st column of array brap while the temperature column of the same file was copied into the 7th column of array brap. The second loop variable '*all'* held the current state of the loop corresponding to the current hour of the file being processed. Numbers sequence 1 to 5 copied into the weather variable '*condition_scen*' represented the various weather conditions (i.e. dry, light rain, light snow, heavy rain and heavy snow). This step was repeated for the control and future scenario files.

Traffic condition selection

```
%traffic condition selection
if traffic_condition==capacity
    traff_cond=max(use_data,[],2); %determine the max value along all rows of the array use_data
elseif traffic_condition==saturated
    traff_cond=min(use_data(:,2:length(use_data)),[],2); %determine the min value along rows while ignoring the first column
end
```

The functions *'max'* and *'min'* were both used to determine the maximum and minimum values of the array and saved to a vector *'traff_cond'*. The direction of operation had to be specified (i.e 1 for column and 2 for row), with 2 selected the max or min value for each row was determined.

When determining the minimum flux, to avoid free flowing traffic, the range of data to be operated on was selected. Each column of the traffic data shown in table 5.1 represented a given density level, hence the range selected was from density level 2 to the maximum density i.e. the length of the array obtained using the function *'length(array)'*.

The vector *'traff_cond'* was then called each time the required flux for a given weather condition was to be determined.

The Processes

Initialising the first loop

```
 file_amount=length(D_1);
```

```
for file=1:file_amount
```

The current value of the loop was saved to the variable *'file'*, the variable *'file_amount'* held the value of the total number of file names held in the vector '*D_1*' which held the names of the CSV files in the selected address as shown under the heading '*Selecting weather data files location'*.

Initialising the second loop

```
for all=1:length(brap)
```

The vector *'brap'* which contained the precipitation and temperature data of the files being processed had the same length as each file hence its length was used when initialising the second loop.

Summer and winter months selection

The month column on the *weather data* sheet was copied to column 4 of *brap* array as part of the initialisation stage. The codes used to filter out the summer and winter months are shown below.

```
%winter months filter
if brap(all,4)==1||brap(all,4)==2||brap(all,4)==12

%summer months filter
if brap(all,4)==6||brap(all,4)==7||brap(all,4)==8
```

Peak hours selection

The hour column on the *weather data* sheet was copied to the 6th column of *brap* array as part of the initialisation process. The code used to filter the peak hours is shown below.

```
%peak period filter
if brap(all,6)==700||brap(all,6)==800||brap(all,6)==900||brap(all,6)==1000||brap(all,6)==1500||brap(all,6)==1600||brap(all,6)==1700||brap(all,6)==1800
```

The weather transition and flux assignment

It should be noted that this was also repeated for the control scenario and *scen* in the code represents future scenario (e.g. scen_HS). The control scenario code was not included here for easy readability.

```
%For Heavy snow the timers of other conditions are reset to
%zero while heavy snow condition is set to 13 (i.e 12hrs)
if condition_scen==5
    scen_HS=13;
    scen_HR=0;
    scen_LS=0;
    scen_LR=0;
    as=35;
    scen_flux=traff_cond(as,1);
end
%HS counter was reduced by 1 and if the counter is greater
%than 2hrs the current flux was set to HS flux else it is
%set to light rain flux
if scen_HS>0
    as=35;
    scen_HS=scen_HS-1;
    scen_flux=traff_cond(as,1);
    if scen_HS<=2
        as=14;
       scen_flux=traff_cond(as,1);
    end
end
```

```
%This condition was true when the condition was heavy rain
%and the HS counter was 0 or less than 2
if condition_scen==4 &&(scen_HS==0||scen_HS<=2)
    scen_HS=0;
    scen_HR=9;
    scen_LS=0;
    scen_LR=0;
    as=21;
    scen_flux=traff_cond(as,1);
end
%HR counter was reduced by 1 and if the counter was greater
%than 2hrs the current flux was set to HR flux else it was
%set to LR flux
if scen_HR>0
    as=21;
    scen_HR=scen_HR-1;
    scen_flux=traff_cond(as,1);
    if scen_HR<=2
        as=14;
       scen_flux=traff_cond(as,1);
    end
end
```

```
%This condition was true when the condition was light snow
%and the HS counter was 0 or less than 2 and HR counter was
%0 or less than 2
if condition_scen==3 &&((scen_HS==0||scen_HS<=2)&&(scen_HR==0||scen_HR<=2))
    scen_HS=0;
    scen_HR=0;
    scen_LS=7;
    scen_LR=0;
    as=9;
    scen_flux=traff_cond(as,1);
end
%LS counter was reduced by 1 and if the counter was greater
%than 2hrs the current flux was set to LS flux else it was
%set to LR flux
if scen_LS>0
    as=9;
    scen_LS=scen_LS-1;
    scen_flux=traff_cond(as,1);
    if scen_LS<=2
        as=9;
       scen_flux=traff_cond(as,1);
    end
end
```

```
%This condition was true when the condition was light rain
%and the HS counter was 0 or less than 2 and HR counter was
%0 or less than 2 and LS counter was 0 or less than 2
if condition_scen==2 &&((scen_HS==0||scen_HS<=2)&&(scen_HR==0||scen_HR<=2)&&(scen_LS==0||scen_LS<=2))
    scen_HS=0;
    scen_HR=0;
    scen_LS=0;
    scen_LR=5;
    as=9;
    scen_flux=traff_cond(as,1);
end
%LR counter was reduced by 1 and the current flux was set
%to LR flux
if scen_LR>0
    as=9;
    scen_LR=scen_LR-1;
    scen_flux=traff_cond(as,1);
end
```

```
%This condition was true when the condition was dry and all
%other conditions counters were 0. The current flux was set
%to dry flux
if condition_scen==1 &&(scen_HS==0 &&scen_HR==0 &&scen_LS==0 &&scen_LR==0)
    as=9;
    scen_flux=traff_cond(as,1);
end
```

The Outputs

Data collection and analysis

The Total precipitated hours

The total precipitated hours for the summer and winter periods of each year were considered within the second loop. In the code the first filter as used to keep an account of the total hours that experienced heavy rain during the given period, the second was for heavy snow, the third was for light rain while the fourth was for light snow. The first array within each filter kept an account of the total hours that experienced that precipitation level (i.e. heavy or light precipitation). Each time a filter condition pertaining to a given weather condition was true the cell of the given array corresponding to the year in focus was then incremented. Notice that both heavy snow and heavy rain share the same array. This entire process was repeated for both the control and future scenarios summer and winter months but for simplicity only the code for the future scenario summer month has been included in this appendix section. The entire code can be seen in appendix 6.

```
%Future scenario summer precipitation levels
if brap(all,1)>6.35 && brap(all,7)>0
    peak_hours_precH_S_scen(file,year)=peak_hours_precH_S_scen(file,year)+1;
    tot_rainH_S_S(file,year)=tot_rainH_S_S(file,year)+1;
elseif brap(all,1)>12.7 && brap(all,7)<=0
    peak_hours_precH_S_scen(file,year)=peak_hours_precH_S_scen(file,year)+1;
    tot_snowH_S_S(file,year)=tot_snowH_S_S(file,year)+1;
elseif brap(all,1)>0 && brap(all,1)<6.35 && brap(all,7)>0
    peak_hours_precL_S_scen(file,year)=peak_hours_precL_S_scen(file,year)+1;
    tot_rainL_S_S(file,year)=tot_rainL_S_S(file,year)+1;
elseif brap(all,1)>0 && brap(all,1)<12.7 && brap(all,7)<=0
    peak_hours_precL_S_scen(file,year)=peak_hours_precL_S_scen(file,year)+1;
    tot_snowL_S_S(file,year)=tot_snowL_S_S(file,year)+1;
end
```

Calculating the average fluxes

```
%Integrating the determined flux for each hour of the given season of the given year being processed for each scenario
peak_hours_flux_W_scen(file,year)=peak_hours_flux_W_scen(file,year)+scen_flux;
```

From the code above, each row of the array holding the total fluxes represented each file while the columns represented the year of each file. The first loop controlled the *rows* (*the file* variable) while the columns (the *year* variable) were controlled by the second loop. During the iteration of the second loop, the variable *scen_flux* was added to the cell of the given array corresponding to the current file and year.

At the end of each year within the second loop, the peak hours average flux of the ending year was calculated for the summer and winter periods of the control and future scenarios of the given file, this was done by dividing the total flux of each season of the given year of the scenario being processed by the corresponding total hour for the given season. The code below shows how this process was carried out:

```
%The peak hours average flux of the ending year
if previous_year~=year
    AV_peak_hours_flux_S_scen(file,previous_year)=peak_hours_flux_S_scen(file,previous_year)/sh(file,previous_year);
    AV_peak_hours_flux_S_cnt(file,previous_year)=peak_hours_flux_S_cnt(file,previous_year)/sh(file,previous_year);
    AV_peak_hours_flux_W_scen(file,previous_year)=peak_hours_flux_W_scen(file,previous_year)/wh(file,previous_year);
    AV_peak_hours_flux_W_cnt(file,previous_year)=peak_hours_flux_W_cnt(file,previous_year)/wh(file,previous_year);
end
```

Each array on the left of the equation represented the average flux of the peak hours of their corresponding season and scenario (Please note the abbreviations *S summer, W winter, scen future, cnt control*).

The Total peak hours of each season

The total peak hours of the ending year were counted during the second loop iteration for the summer and winter periods of the given file and saved to corresponding arrays. The total peak hour was incremented only when the condition for peak hours was met and this was done under the *Peak hours filter* section of the code. The code below shows how the total peak hour array was incremented and how the required cell of the array was selected:

```
%Summer Hour counter
sh(file,year)=sh(file,year)+1;
```

The code below shows the peak hours filter

```
%peak period filter
if brap(all,6)==700||brap(all,6)==800||brap(all,6)==900||brap(all,6)==1000||brap(all,6)==1500||brap(all,6)==1600||brap(all,6)==1700||brap(all,6)==1800
```

The simulation results

The impact of weather condition on traffic flux

```
ss=AV_peak_hours_flux_S_scen;
sc=AV_peak_hours_flux_S_cnt;
ws=AV_peak_hours_flux_W_scen;
wc=AV_peak_hours_flux_W_cnt;

%Sort the fluxes of each year in ascending order along the column.
%Wihin the sort function 1 is for column wise while 2 is for row wise
sorted_peak_hours_flux_S_scen=sort(ss,2);
sorted_peak_hours_flux_S_cnt=sort(sc,2);
sorted_peak_hours_flux_W_scen=sort(ws,2);
sorted_peak_hours_flux_W_cnt=sort(wc,2);

%finding the top 4 lowest flux years for the current file
sal=1;
for year=1:4
    lowest_flux_S_scen(file,sal)=sorted_peak_hours_flux_S_scen(file,year);
    lowest_flux_S_cnt(file,sal)=sorted_peak_hours_flux_S_cnt(file,year);
    lowest_flux_W_scen(file,sal)=sorted_peak_hours_flux_W_scen(file,year);
    lowest_flux_W_cnt(file,sal)=sorted_peak_hours_flux_W_cnt(file,year);
    sal=sal+1;
end
```

```
%sorting the files
% 1 in the sort function indicated columnwise ascending order mode
sort_lowest_flux_S_cnt=sort(lowest_flux_S_cnt,1);
sort_lowest_flux_S_scen=sort(lowest_flux_S_scen,1);
sort_lowest_flux_W_cnt=sort(lowest_flux_W_cnt,1);
sort_lowest_flux_W_scen=sort(lowest_flux_W_scen,1);

%Selecting the top 4 years with the most fluxes
for file=1:file_amount
    for year=1:4
        diff_S_scen(file,year)=traff_cond(13,1)-sort_lowest_flux_S_scen(file,year);
        diff_S_cnt(file,year)=traff_cond(13,1)-sort_lowest_flux_S_cnt(file,year);
        diff_W_scen(file,year)=traff_cond(13,1)-sort_lowest_flux_W_scen(file,year);
        diff_W_cnt(file,year)=traff_cond(13,1)-sort_lowest_flux_W_cnt(file,year);
    end
end
```

The PDF and CDF curves

```
%CDF and PDF curves
%The Actual Frequency
%There are 100 points. Each point is 1/100 of the entire collection. The
%proportion of each value in the collecion was added to the next value.
for sea=1:100
    if sea==1
        ca(sea,1)=(1/100);
    else
        ca(sea,1)=(1/100) + ca(sea-1,1);
    end
end

%Normal standard distribution
c1=std(sorted_diff_S_cnt,0,1);
c2=mean(sorted_diff_S_cnt,1);

for pea=1:100
    %The normal frequency
    c3(pea,1)=sorted_diff_S_cnt(pea,1)-c2(1,1);
    c4(pea,1)=c3(pea,1)/c1(1,1);
    c5(pea,1)=normcdf(c4(pea,1));                                        %cdf
    c6(pea,1)=normpdf(sorted_diff_S_cnt(pea,1),c2(1,1),c1(1,1));         %pdf
end

%Plot
figure; plot(sorted_diff_S_cnt(:,1),ca(:,1),'ko', sorted_diff_S_cnt(:,1),c5(:,1),'r');

figure; plot(sorted_diff_S_cnt(:,1),c6(:,1));
```

5. Factors affecting the future of road transport

The Impact of the Socio-economic scenarios on the traffic stream

As explained in the previous sections the socio-economic values may have an impact on the nature of vehicles featured in the traffic stream of a link with a more consumeristic nature featuring more privately-owned vehicles (i.e. small vehicles) while a more community driven nature featuring more public vehicles (i.e. large vehicles). The government nature may affect the emission level with a more interdependent government featuring a lower emission level than an autonomous government which may feature a high emission level.

For illustrative purposes figure 2.3 has been edited to feature scales on the axis as shown in figures 8.42 and 8.43, the lower the value towards consumerism the on the x axis the more the smaller vehicles on the traffic stream. On the y axis, the more the values towards either extremes of the axis the more the government bias towards that extreme. Figure 8.42 illustrates the CDSU while Figure 8.43 shows illustrations of various government natures and socio-economic values. The scales on the figures are arbitrary.

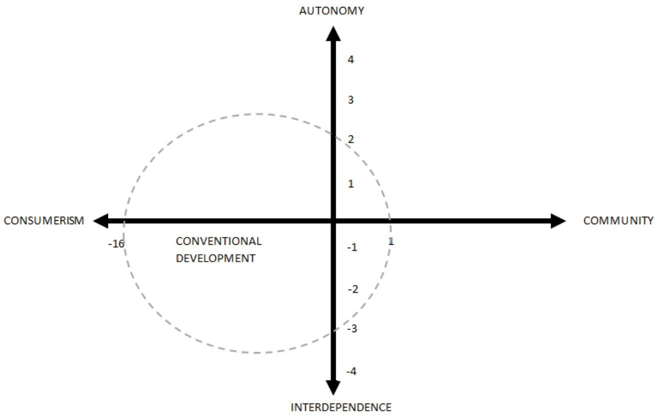
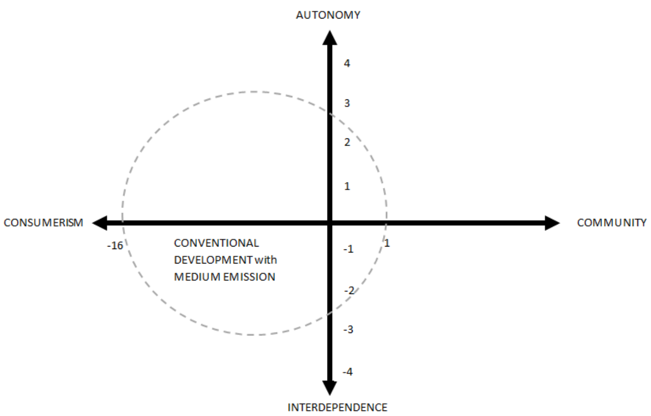
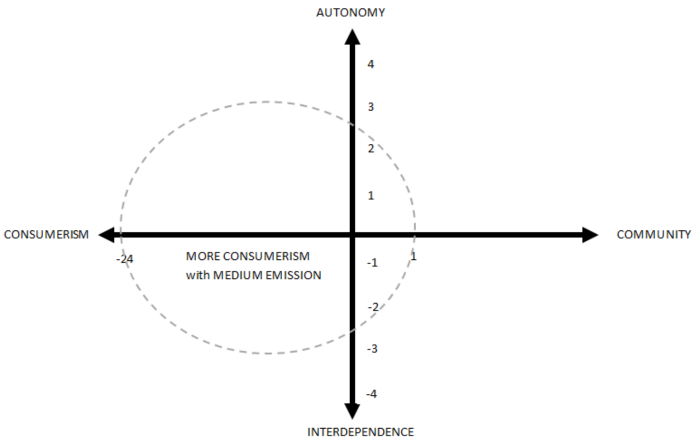


Figure 8.42: The conventional development system for the UK (CDSU)

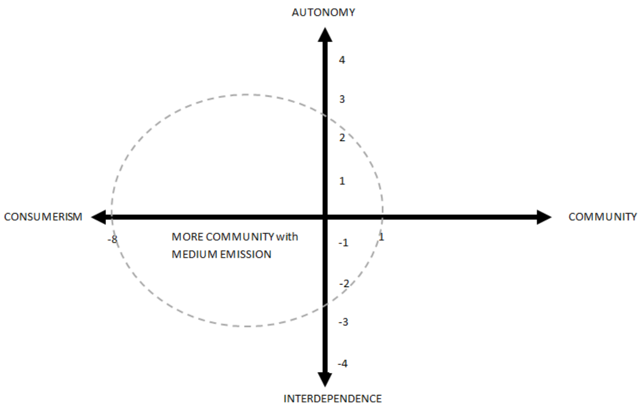
The conventional development system for the UK



A more consumeristic oriented economy

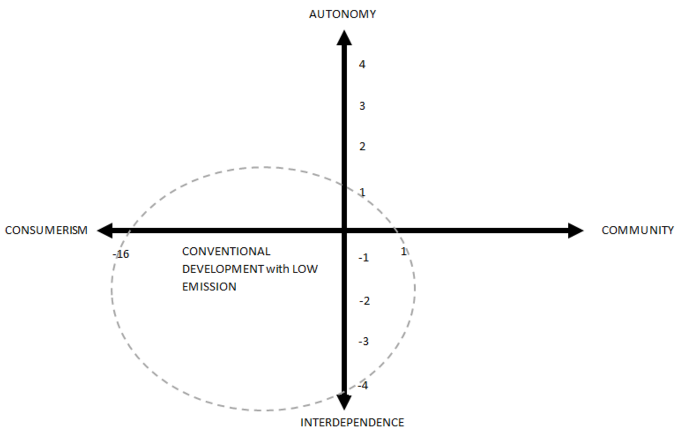


A more community-oriented economy

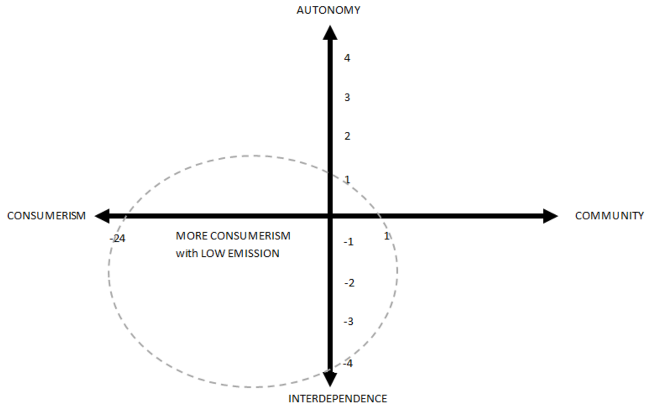


a. *A balanced government (medium emission scenario) and various social-economic values*

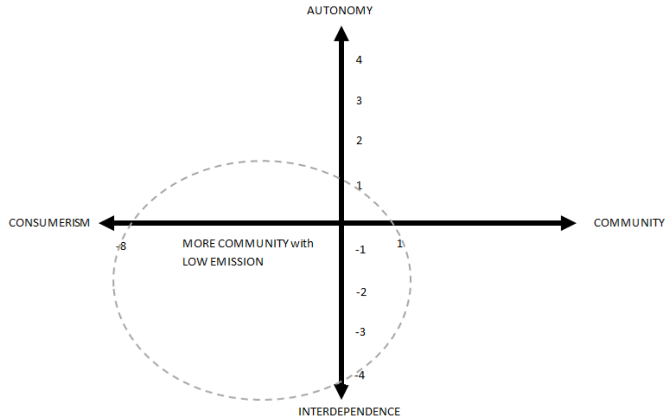
The conventional development system for the UK



A more consumeristic Oriented economy

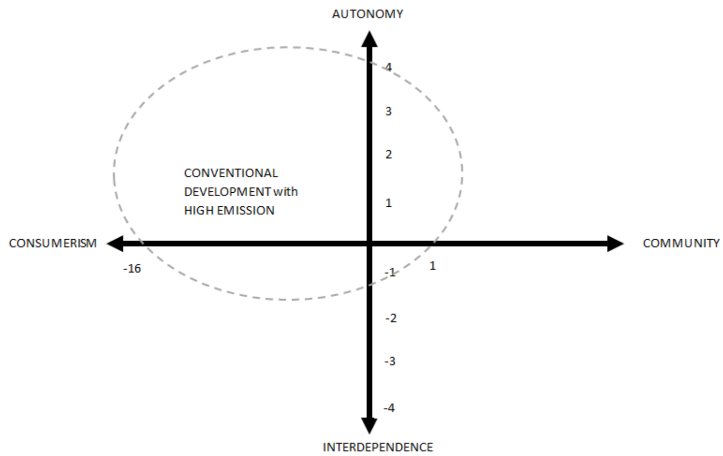


A more community-oriented economy

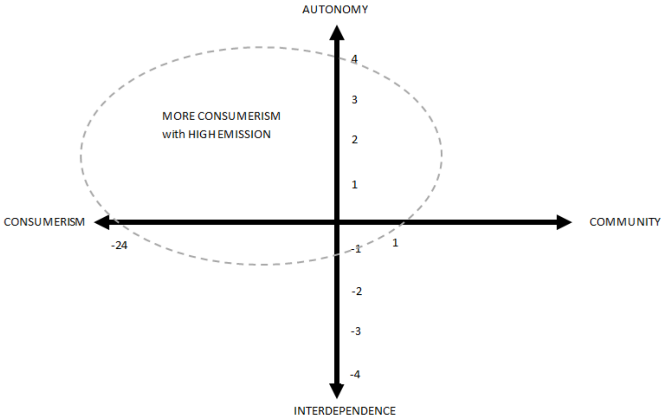


b. An interdependent government (low emission scenario) and various socio-economic values

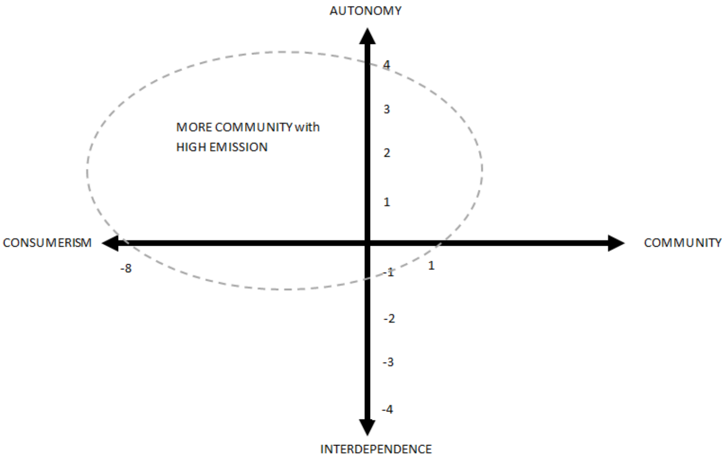
The conventional development system for the UK



A more consumeristic oriented economy



A more community-oriented economy



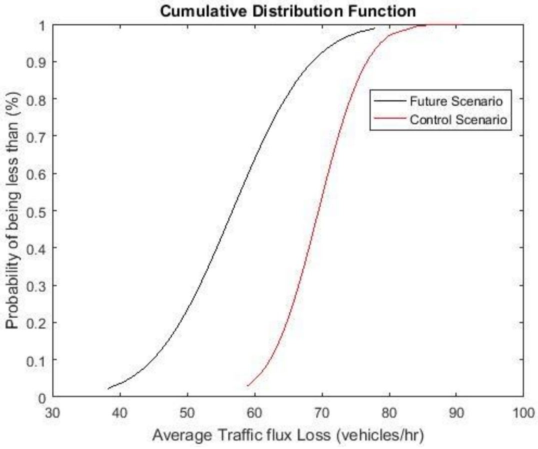
c. *An autonomous government (high emission scenario) and various socio-economic values*

Figure 8.43: Illustration of various government natures and socio-economic values

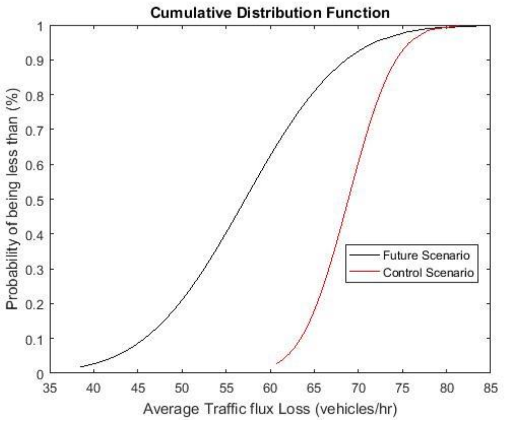
In figures 8.42 & 8.43 the values on the x axis represents the ratio of small to large vehicles. Towards the left which is consumerism values smaller vehicles are featured while towards the right which is community values larger vehicles are featured. The y axis represents the nature of government, at the top is autonomy while at the bottom is interdependence. Moving the ellipse so that its top lies on 4 represents an almost completely autonomous government which is assumed to induce a high emissions scenario, moving the ellipse so it lies on +2 and -2 represents a neutral government/medium emissions scenario while moving the ellipse to 1 and -4 represents an almost completely interdependent government/low emissions scenario.

The CDF curves for the average traffic flux loss under the various emissions scenarios for the various link types during the various seasons under the consumeristic and community socio-economic values

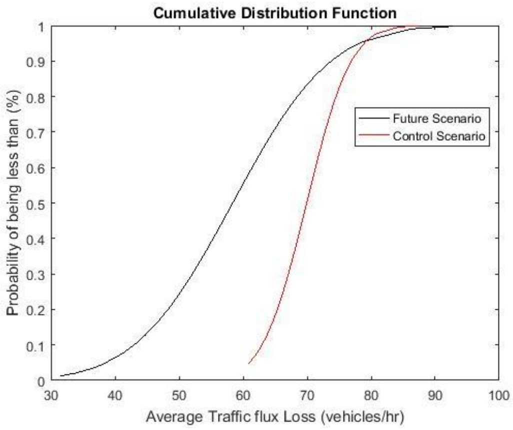
Consumeristic socio-economic values: Roundabout Controlled link



a. The CDF curve for the average traffic flux loss under the high emission scenarios

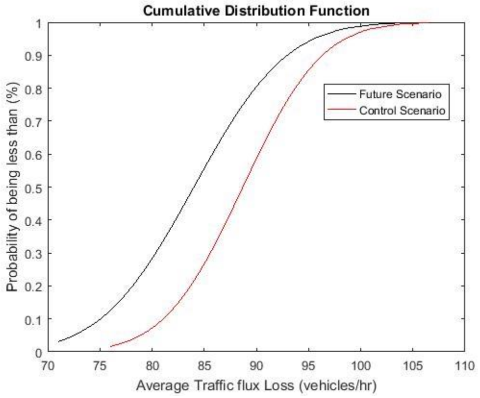


b. The CDF curve for the average traffic flux loss under the medium emission scenarios

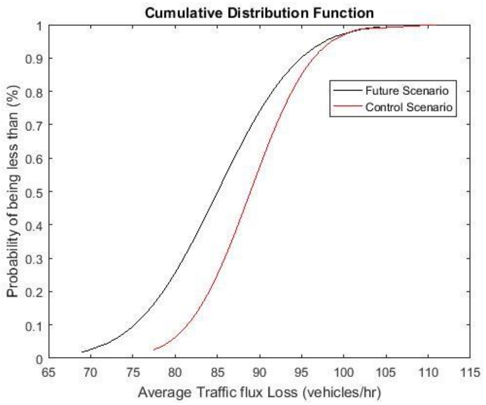


c. The CDF curve for the average traffic flux loss under the low emission scenarios

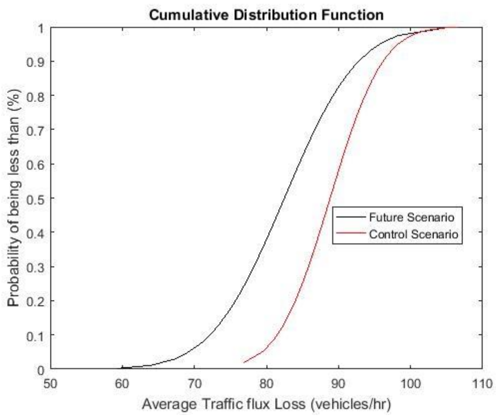
Figure 8.44: CDF curves showing the average traffic loss under the various emission scenarios for a roundabout controlled 3 lanes link during summer periods under the consumeristic socio-economic value scenario



a. The CDF curve for the average traffic flux loss under the high emission scenarios



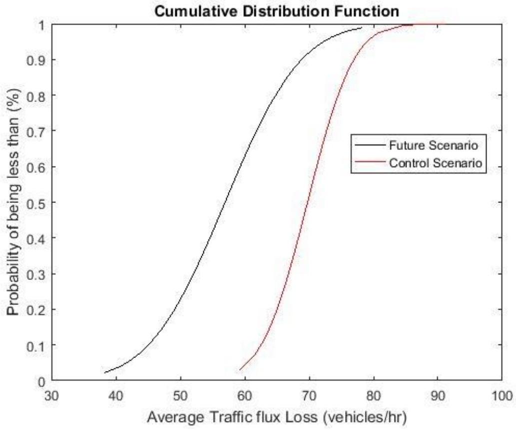
b. The CDF curve for the average traffic flux loss under the medium emission scenarios



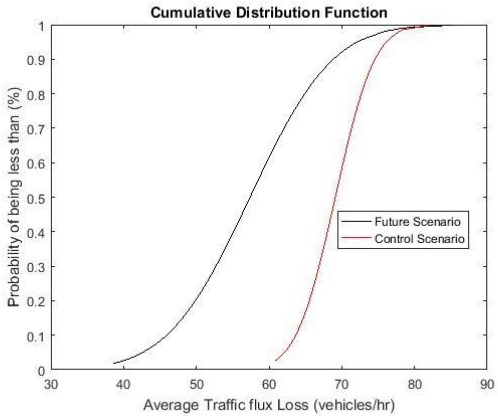
c. The CDF curve for the average traffic flux loss under the low emission scenarios

Figure 8.45: CDF curves showing the average traffic loss under the various emission scenarios for a roundabout controlled 3 lanes link during winter periods under the consumeristic socio-economic value scenario

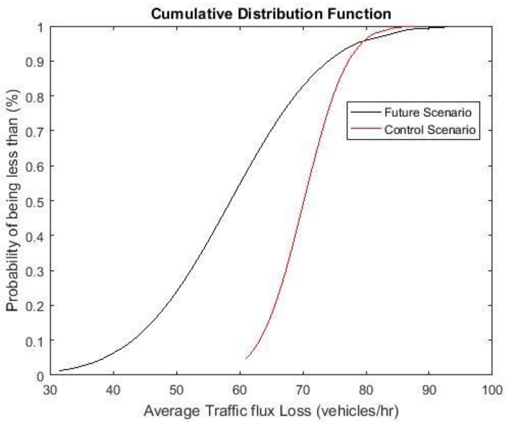
Consumeristic Signalized link



a. The CDF curve for the average traffic flux loss under the high emission scenarios

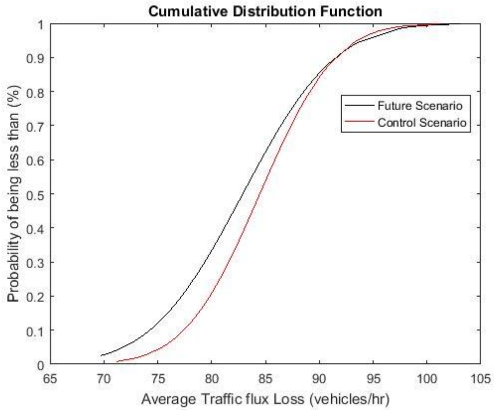


b. The CDF curve for the average traffic flux loss under the medium emission scenarios

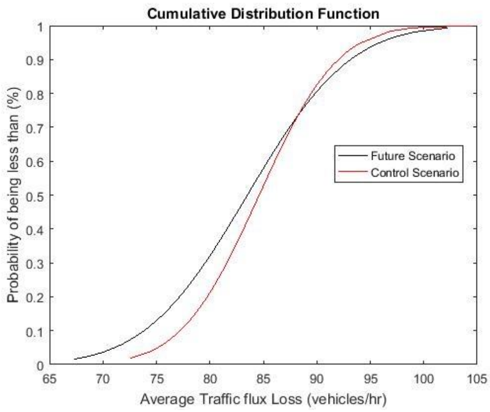


c. The CDF curve for the average traffic flux loss under the low emission scenarios

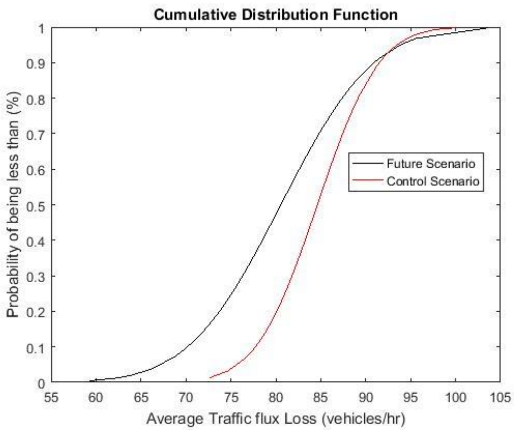
Figure 8.46: CDF curves showing the average traffic loss under the various emission scenarios for a roundabout controlled 3 lanes link during summer periods under the consumeristic socio-economic value scenario



a. The CDF curve for the average traffic flux loss under the high emission scenarios

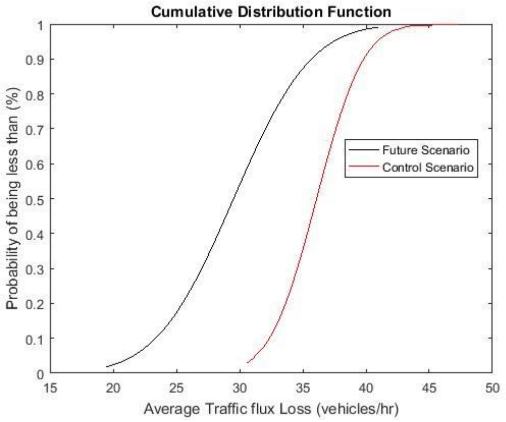


b. The CDF curve for the average traffic flux loss under the medium emission scenarios

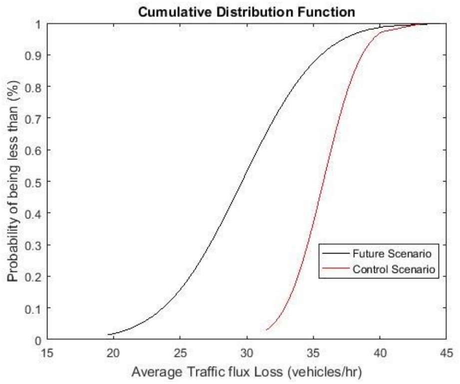


c. The CDF curve for the average traffic flux loss under the low emission scenarios

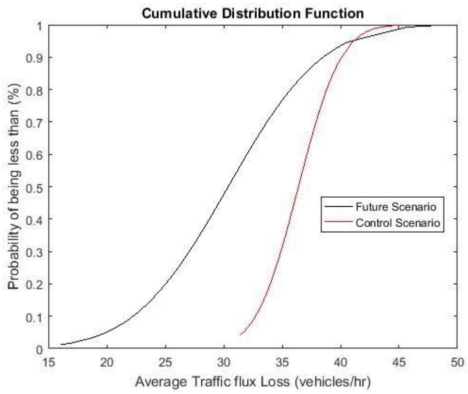
Figure 8.47: CDF curves showing the average traffic loss under the various emission scenarios for a roundabout controlled 3 lanes link during winter periods under the consumeristic socio-economic value scenario



a. The CDF curve for the average traffic flux loss under the high emission scenarios

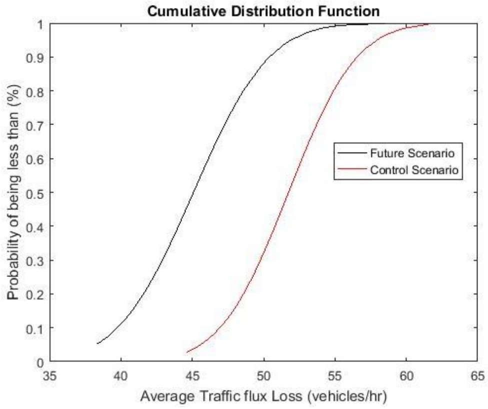


b. The CDF curve for the average traffic flux loss under the medium emission scenarios

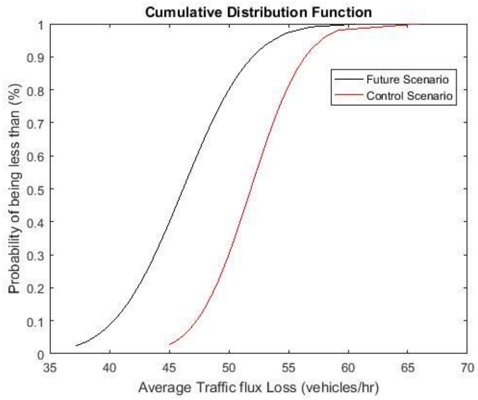


c. The CDF curve for the average traffic flux loss under the low emission scenarios

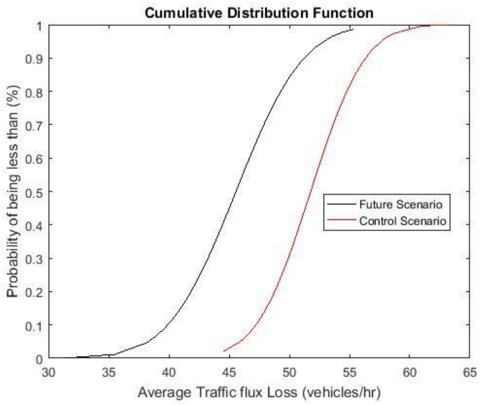
Figure 8.48: CDF curves showing the average traffic loss under the various emission scenarios for a roundabout controlled 3 lanes link during summer periods under the community socio-economic value scenario



a. The CDF curve for the average traffic flux loss under the high emission scenarios



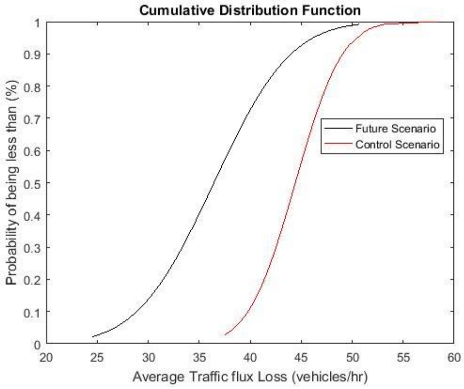
b. The CDF curve for the average traffic flux loss under the medium emission scenarios



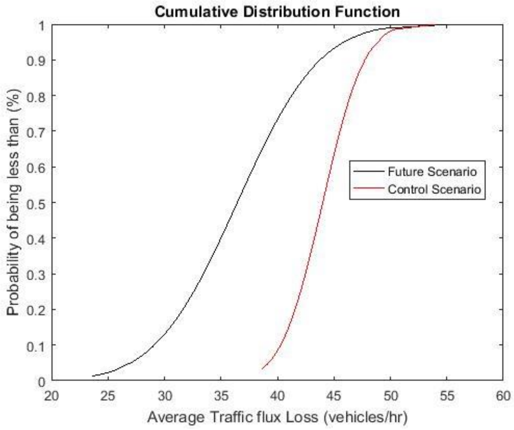
c. The CDF curve for the average traffic flux loss under the low emission scenarios

Figure 8.49: CDF curves showing the average traffic loss under the various emission scenarios for a roundabout controlled 3 lanes link during winter periods under the community socio-economic value scenario

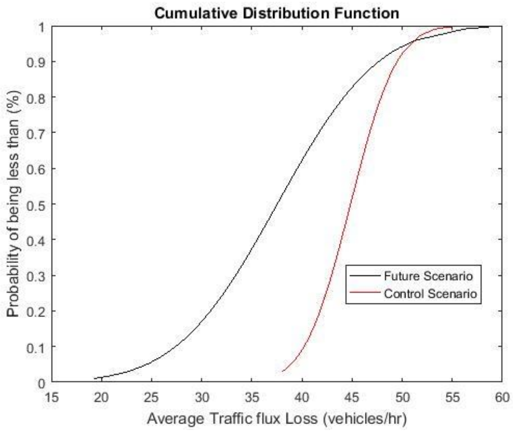
Community values Signalized link



a. The CDF curve for the average traffic flux loss under the high emission scenarios

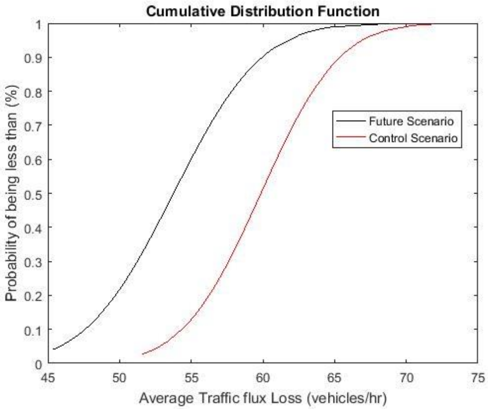


b. The CDF curve for the average traffic flux loss under the medium emission scenarios

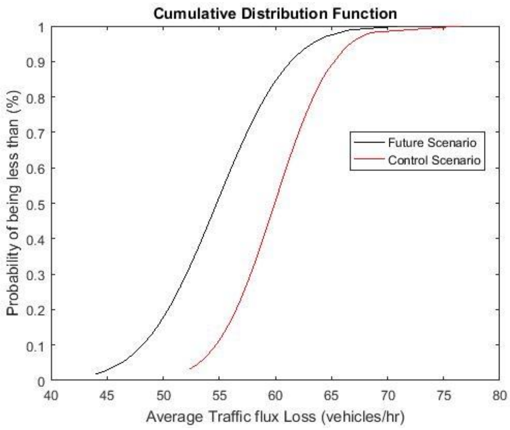


c. The CDF curve for the average traffic flux loss under the low emission scenarios

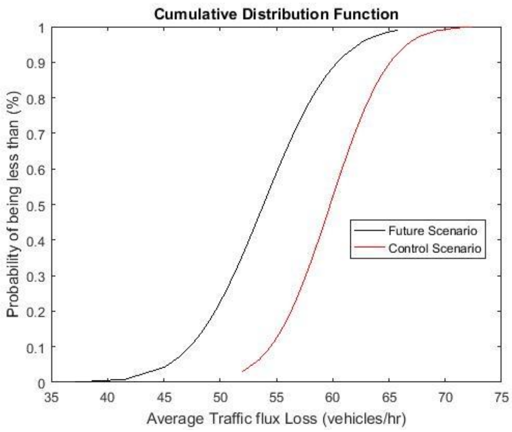
Figure 8.50: CDF curves showing the average traffic loss under the various emission scenarios for a roundabout controlled 3 lanes link during summer periods under the community socio-economic value scenario



a. The CDF curve for the average traffic flux loss under the high emission scenarios



b. The CDF curve for the average traffic flux loss under the medium emission scenarios



c. The CDF curve for the average traffic flux loss under the low emission scenarios

Figure 8.51: CDF curves showing the average traffic loss under the various emission scenarios for a roundabout controlled 3 lanes link during winter periods under the community socio-economic value scenario

The sections of the traffic flow code edited to accommodate autonomous vehicles

The 1st edit made shown in the main code and it was to include an array register which held autonomy capabilities of each vehicle (i.e. either automatic or manual). The second line in the code below was a variable that was included to specify the percentage of autonomous vehicles on the link. The percentages included were 33%, 67% and 100% (i.e. 1/3, 2/3 and 3/3 as shown in the code).

```
auto=zeros(time,veh);                    %register for the type of vehicles (i.e. autonomous or not autonomous
auto_level=1;                            %The fraction of autonomous vehicles on the link. 1=1/3, 2=2/3, 3=3/3.
```

The 2nd edit was also made in the main code. It was to make the first vehicle on the link autonomous. The first vehicle on the link at the start of the simulation was always generated in lane 1. This meant that when autonomous vehicles were featured in the traffic stream the first vehicle on the link was always an autonomous vehicle. The inner lanes were used as the designated platooning lanes for cases were manually driven vehicles were also featured in the traffic stream. That is, the platooning lanes started from lane 1 to lane 3.

An alternative method may designate the outer lanes as the platooning lanes. This way in the real world fewer manually driven vehicles will attempt to merge with platooning fleets especially from junctions situated on the left-hand side.

```
auto(t,v_reg)=1;                  %The first vehicle is made autonomous because it apawns on lane 1
```

The 3rd edit was also made in the main code and it was firstly to update the assigned cell of the observed vehicle in the array register which held the autonomy capabilities of each vehicle, this had to be updated at every time step; and secondly to set the current lane of the observed vehicle to its previous lane if it was an autonomous vehicle or to go through the lane change algorithm if it was a manual vehicle. This edit is shown in the code below.

```
%autonomous edit*****************************************************************************
%Each vehicle on the link were assigned cells in an array register which held the autonomy
%capabilities of each vehicle and was updated at every time step
%If the vehicle is autonomous then its lane at the previous time step
%(which was the designated autonomous vehicles lane i.e. lane 1) remains its current lane
%while the manual vehicles go through the lane change algorithm where they may select any
%lane except the designated autonomous vehicles lanes
auto(t,v_reg)=auto(t-1,v_reg);
if auto(t,v_reg)==0
    [timer_N1(:,:),timer_N2(:,:),lanes(:,:),non_interest_counter(:,:),timer_overtake(:,:),
elseif auto(t,v_reg)==1
    lanes(t,v_reg)=lanes(t-1,v_reg);
end
```

Continuation of the lane change call function: Note this is the same as the original code except for the section highlighted with red. The variable holding the autonomous vehicle percentage on the link (i.e. '*auto_level*') was fed into the lane change function (i.e. overtake7_auto).

```
timer_change(:,:)]=overtake7_auto(lanes(:,:),v_reg,veh,vel(:,:),max_vel,g(:,:),t,timer_N1(:,:),timer_N2(:,:),non_interest_counter(:,:),

patch_veh_reg(:,:),pa,posit_f(:,:),posit_r(:,:),max_dec(:,:),stop_gap, aA(:,:),aB(:,:),aC(:,:), accel(:,:), max_accel(:,:),timer_overtake(:,:),

timer_change(:,:),reset_lane_timers(:,:),veh_len(:,:),patch_table,no_lane,auto_level);
```

The 4th edit was made within the lane change function and it was done to prevent manual vehicles from switching to the autonomous designated lanes. Depending on the autonomous percentage used the edited code would prevent manual vehicles from switching to certain inner lanes since the designated autonomous vehicles lanes were always situated on the inside. 33% or 1/3 prevented manual vehicles from switching to the 1st lane, 2/3 prevented manual vehicles from switching to the 1st and second lanes. 3/3 was not included in the edit function because that meant 100% autonomous vehicles on the link hence the lane change function was always skipped. The edited code worked by forcing manual vehicles to remain on their current lane if their target lane was designated for autonomous vehicles otherwise they could switch lanes. Manual vehicles were never generated on autonomous vehicles designated lanes; this would be explained further subsequently.

```
    %Change to the Inner lane
    %autonomous edit*****************************************************************************************
elseif collision_N1==0 && change1==1 && N1_avail==1 && timer_N1_array(1,veh_reg)>=40 && (timer_N2_array(1,veh_reg)==0 ||
    %Vehicles remain on their current lane if their target lane is a designated autonomous lane.
    if auton_level==1 && current_lane==2
        Lanes_array(time,veh_reg)=Lanes_array(time,veh_reg);
    elseif auton_level==2 && current_lane==3
        Lanes_array(time,veh_reg)=Lanes_array(time,veh_reg);
    else
        Lanes_array(time,veh_reg)=Lanes_array(time,veh_reg)-1;
        timer_N2_array(1,veh_reg)=0;
        timer_N1_array(1,veh_reg)=0;
        non_interest_counter_array(1,veh_reg)=0;
        timer_overtake_array(1,veh_reg)=0;
        timer_change_array(1,veh_reg)=0;
    end
```

Continuation of the *'change to the inner lane'* filter

```
non_interest_counter_array(1,veh_reg)>20)&& current_lane>1
```

Each vehicle on the link was assigned cells in an array register which held the autonomy capabilities of each vehicle and was updated at every time step. The 5th step was to reset the cell of a given time step assigned to a given vehicle if the vehicle exited the link at the given time step. This was done to reset autonomous vehicles settings from 1 to 0. This is shown in the code below.

```
auto(t,v_reg)=0;            %Resets the vehicle from autonomous to the default
```

The 5th edit was done in the main code within the car following section. It was done to trigger the platooning feature when the observed vehicle was within a 100m range from its lead vehicle and within an acceptable speed range from its lead vehicle's speed. It was also done to control the acceleration of the following vehicle based on the acceleration and speed of its lead vehicle. In their paper, Hee et al. (2015) illustrated the relationship between autonomous vehicles in platoons speed and their distances from their lead vehicles. This was compared to the distances human drivers attempt to maintain from their lead vehicles at the same speed range. The graph presented was used in this thesis to derive a relationship between the speed of autonomous platooning vehicles and their target distances from their lead vehicle and was featured in the code below. Hee et al. (2015) graph was presented using the metric system hence there is a conversion in the code for simplicity. The target distance calculated in the code was referred to as *'Hee_gap'* in the code. When the platooning feature of an autonomous vehicle was switched ON, whenever the distance between it and its lead vehicle was higher than the *'Hee_gap'* its acceleration was increased by 0.2m/s^2 provided its maximum acceleration would not exceeded. Where its maximum acceleration would be exceeded its maximum acceleration was used instead. In cases where the distance between both vehicles was higher than the *'Hee_gap'*, the acceleration of the following vehicle was reduced by 0.2m/s^2. While in cases where the gap was equivalent to the *'Hee_gap'* the acceleration of the lead vehicle was used for both vehicles. This was done only if its acceleration did not exceed the maximum acceleration of the following vehicle otherwise the maximum acceleration of the following vehicle was used for both vehicles.

```
    %autonomous edit**************************************************************************************
    %This is used to override the acceleration of the vehicle if the vehicle is autonomous
    %The autonomous system kicks in when the following vehicle is at most 6m away from its lead vehicle
    %Note that the response system does not use the response of the driver but rather the response of
    %the autonomous and the autonomous system was assumed to be as fast as possible hence the
    %minimum response time was used which is 0.1sec which appears to be instantaneous hence no
    %need for a response time lapse
elseif auto(t,v_reg)==1 && g(t,v_reg)<=100 && vel(t,v_reg)<=vel(t,ref_veh)
    %converting velo from m/s to kph so that Hee et al.(2015) gap can be used
    vel_mph=vel(t,v_reg)*2.23694;
    vel_kph=vel_mph*1.60934;
    Hee_gap=(5/112)*vel_kph;
    %If the speed of the vehicle is less than or equals the speed of the lead vehicle and the gap is greater
    %than the gap suggested by Hee et al.(2015) then the acceleration of the velicle is increased by 0.2m/s(2)
    %if the increase wont be greater than its maximum acceleration else the maximum acceleration is used.
    %Iif the autonomous system kicks in and the gap is less than the Hee_gap then the acceleration is
    %reduced by 0.2m/s(2). Elseif the gap equalse the Hee_gap then the following vehicle uses the
    %acceleration of its lead vehicle.

        if vel(t,v_reg)<=vel(t,ref_veh) && g(t,v_reg)>Hee_gap
            if (accel(t,ref_veh)+0.2)< max_accel(t,v_reg)
                accel(t,v_reg)=accel(t,ref_veh)+0.2;
            elseif (accel(t,ref_veh)+0.2)>= max_accel(t,v_reg)
                accel(t,v_reg)=max_accel(t,v_reg);
            end
        elseif vel(t,v_reg)<=vel(t,ref_veh) && g(t,v_reg)<Hee_gap
            accel(t,v_reg)=accel(t,ref_veh)-0.2;
        elseif accel(t,ref_veh)<=max_accel(t,v_reg)
            accel(t,v_reg)=accel(t,ref_veh);
        else
            accel(t,v_reg)=max_accel(t,v_reg);
        end
        accel_found=1;
```

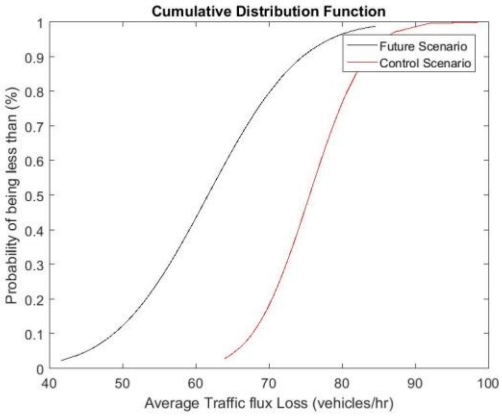
The 6th edit was done within the new vehicle generation in the main code and was done after a new vehicle was successfully generated. The code basically assigned new vehicles generated on the designated autonomous vehicles lane as new vehicles. Vehicles were made autonomous depending on whether they were generated on a designated autonomous vehicles lane or not. If the percentage of autonomous vehicles was 33% or 1/3 then only vehicles generated on the first lane were made autonomous. If it was 2/3 only vehicles generated on the 1st and second lanes were made autonomous while if it was 3/3 or 100% all new vehicles were made autonomous. The code is shown below.

```
%Autonomous edit*****************************************************************
%Vehicles were made autonomous depending on whether they were generated
%on a designated autonomous vehicles lane or not. If the percentage of
%autonomous vehicles was 33% or 1/3 then only vehicles generated on the
%first lane were made autonomous. If it was 2/3 only vehicles generated
%on the 1st and second lanes were made autonomous while if it was 3/3 or
%100% all new vehicles were made autonomous.
if auto_level==1
    if lanes(t,v_reg)==1
        auto(t,v_reg)=1;
    end
elseif auto_level==2
    if lanes(t,v_reg)==1 || lanes(t,v_reg)==2
        auto(t,v_reg)=1;
    end
elseif auto_level==3
    if lanes(t,v_reg)==1 || lanes(t,v_reg)==2 || lanes(t,v_reg)==3
        auto(t,v_reg)=1;
    end
end
```

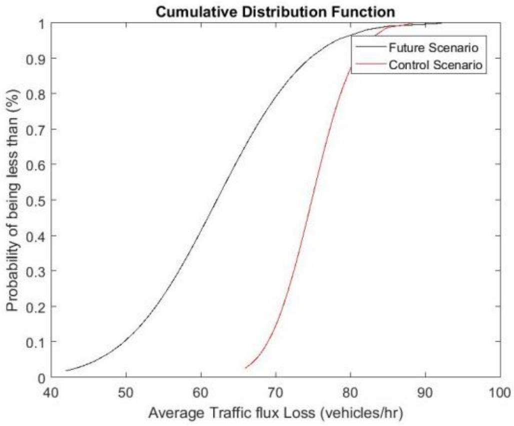
The entire edited code is shown in appendix 6.

The CDF curves for the average traffic flux loss under the various emissions scenarios for the various link types during the various seasons containing the various percentages of autonomous vehicles in the flow is shown in figure 8.45

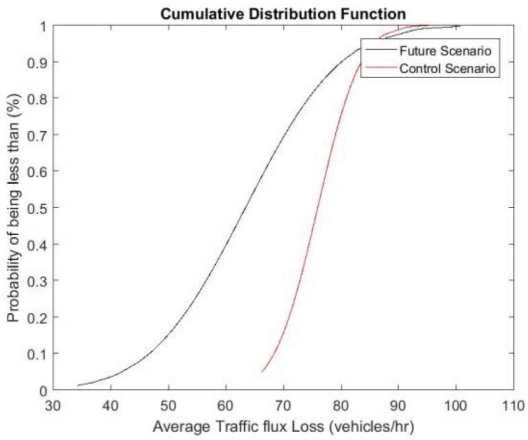
Signalised Link: 33% Autonomous Vehicles



a. The CDF curve for the average traffic flux loss under the high emission scenarios

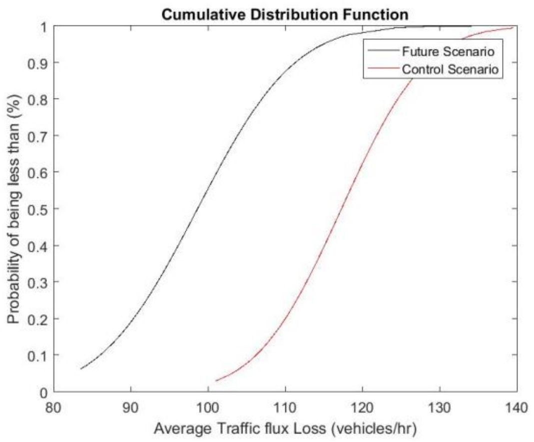


b. The CDF curve for the average traffic flux loss under the medium emission scenarios

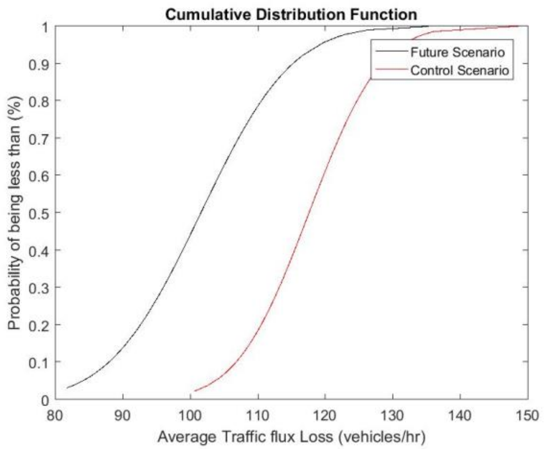


c. The CDF curve for the average traffic flux loss under the low emission scenarios

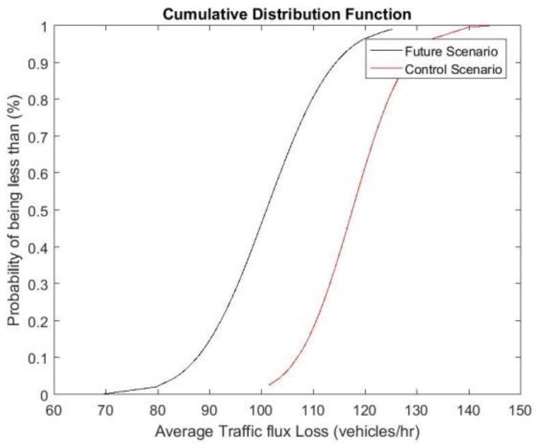
Figure 8.52: CDF curves showing the average traffic loss under the various emission scenarios for a signal controlled 3 lanes link during summer periods containing 33% autonomous vehicles in the traffic streams



a. The CDF curve for the average traffic flux loss under the high emission scenarios



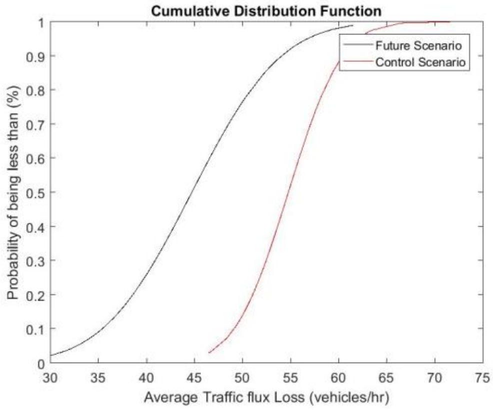
b. The CDF curve for the average traffic flux loss under the medium emission scenarios



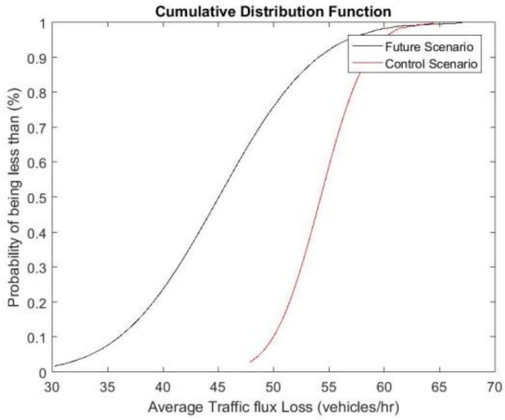
c. The CDF curve for the average traffic flux loss under the low emission scenarios

Figure 8.53: CDF curves showing the average traffic loss under the various emission scenarios for a signal controlled 3 lanes link during winter periods containing 33% autonomous vehicles in the traffic streams

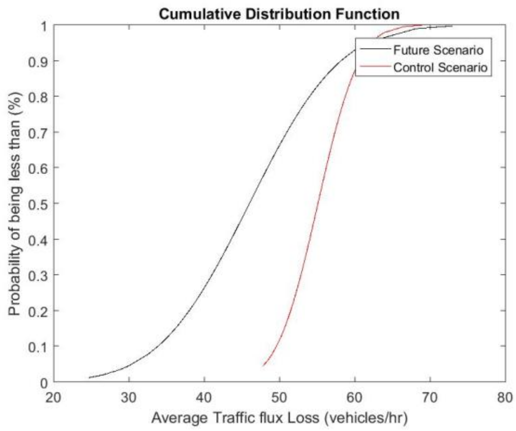
Signalised Link: 67% Autonomous Vehicles



a. The CDF curve for the average traffic flux loss under the high emission scenarios

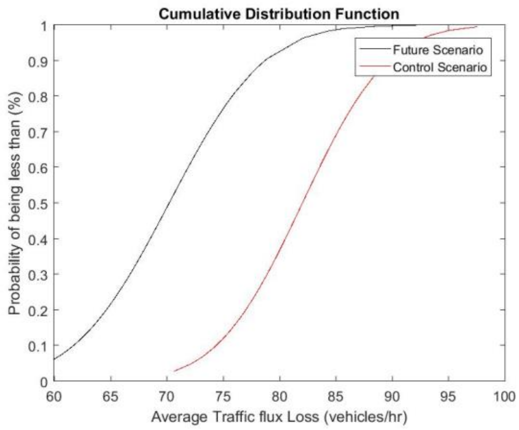


b. The CDF curve for the average traffic flux loss under the medium emission scenarios

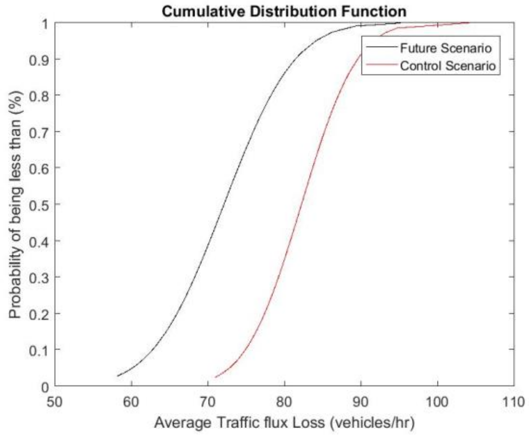


c. The CDF curve for the average traffic flux loss under the low emission scenarios

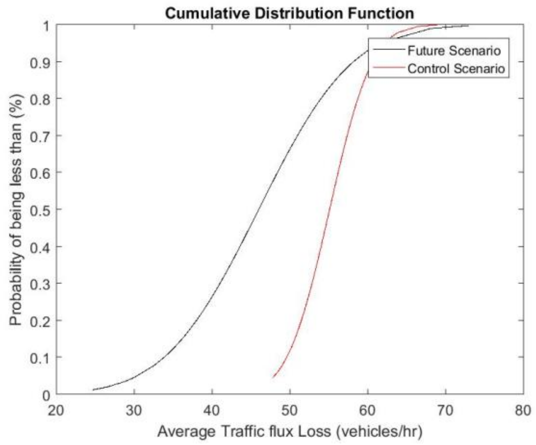
Figure 8.54: CDF curves showing the average traffic loss under the various emission scenarios for a signal controlled 3 lanes link during summer periods containing 67% autonomous vehicles in the traffic streams



a. The CDF curve for the average traffic flux loss under the high emission scenarios



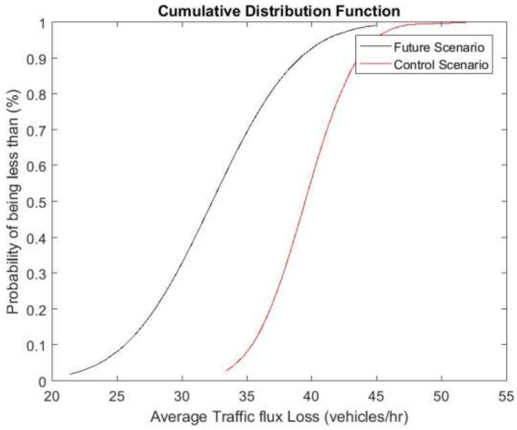
b. The CDF curve for the average traffic flux loss under the medium emission scenarios



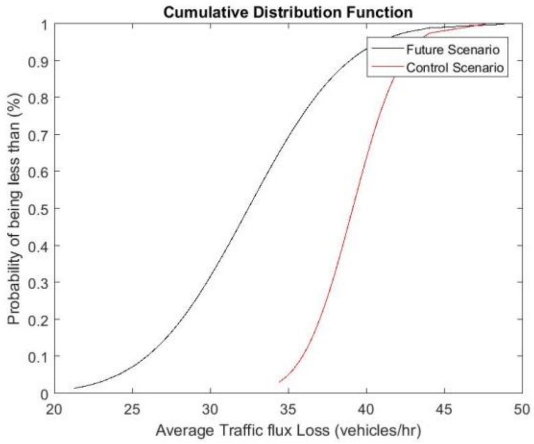
c. The CDF curve for the average traffic flux loss under the low emission scenarios

Figure 8.55: CDF curves showing the average traffic loss under the various emission scenarios for a signal controlled 3 lanes link during winter periods containing 67% autonomous vehicles in the traffic streams

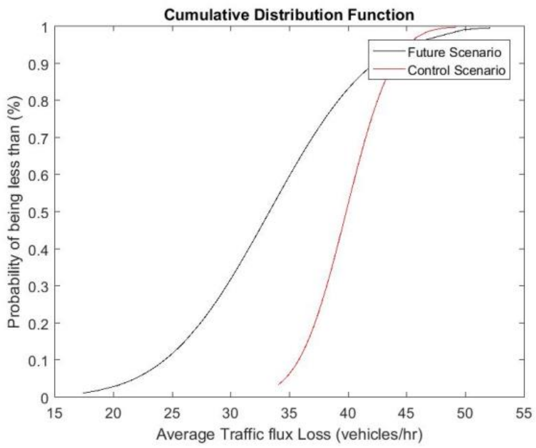
Signalised Link: 100% Autonomous Vehicles



a. The CDF curve for the average traffic flux loss under the high emission scenarios

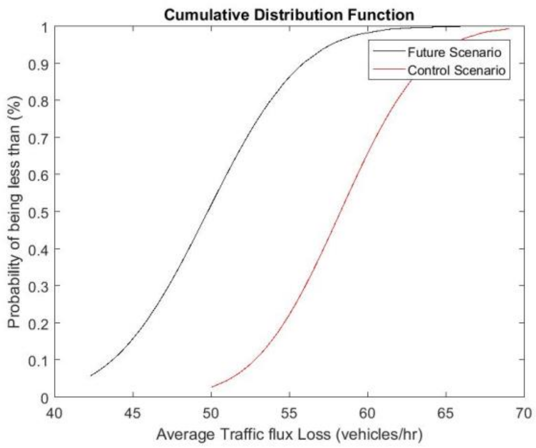


b. The CDF curve for the average traffic flux loss under the medium emission scenarios

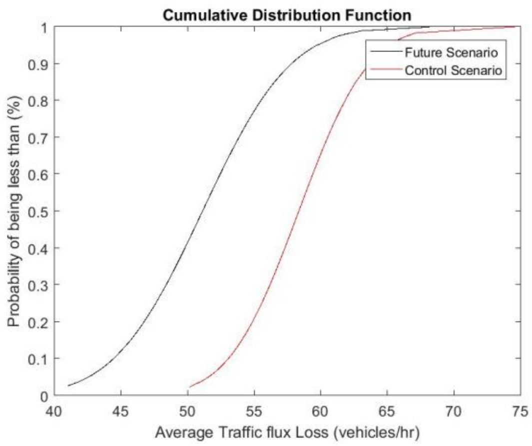


c. The CDF curve for the average traffic flux loss under the low emission scenarios

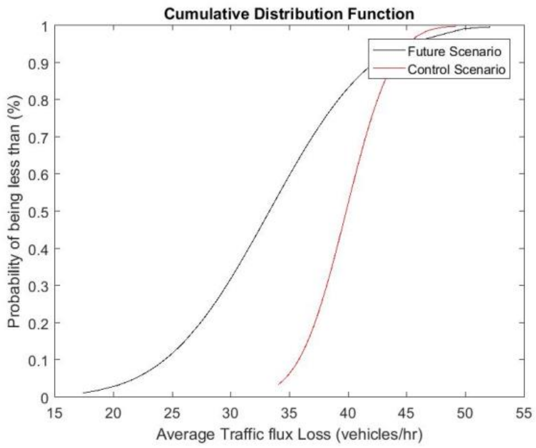
Figure 8.56: CDF curves showing the average traffic loss under the various emission scenarios for a signal controlled 3 lanes link during summer periods containing 100% autonomous vehicles in the traffic streams



a. The CDF curve for the average traffic flux loss under the high emission scenarios



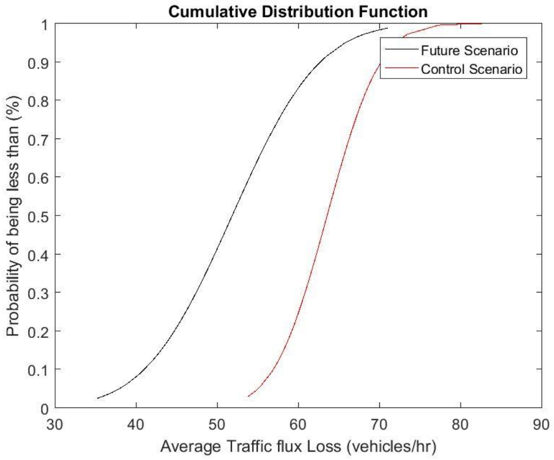
b. The CDF curve for the average traffic flux loss under the medium emission scenarios



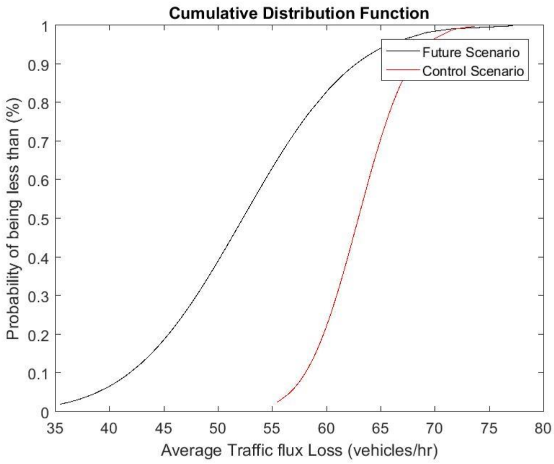
c. The CDF curve for the average traffic flux loss under the low emission scenarios

Figure 8.57: CDF curves showing the average traffic loss under the various emission scenarios for a signal controlled 3 lanes link during winter periods containing 100% autonomous vehicles in the traffic streams

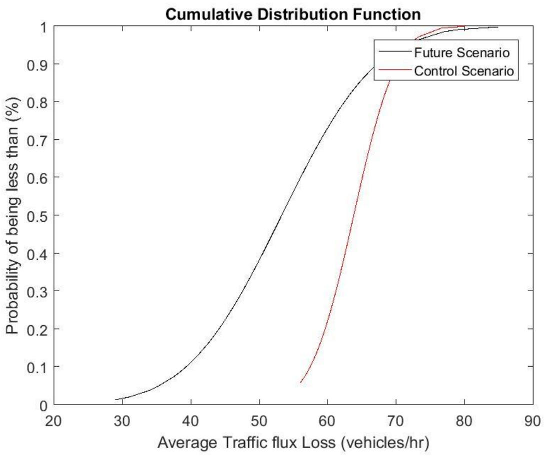
Roundabout controlled Link: 33% Autonomous Vehicles



a. The CDF curve for the average traffic flux loss under the high emission scenarios

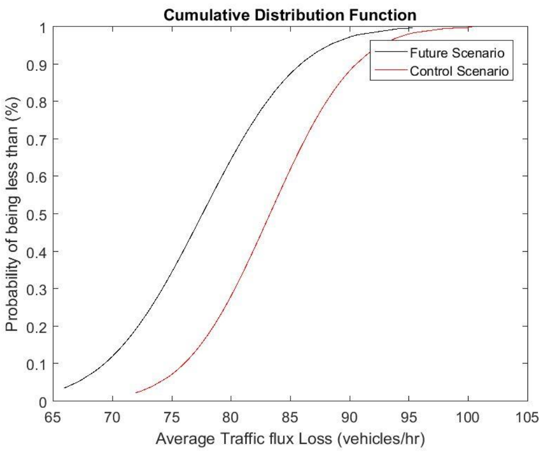


b. The CDF curve for the average traffic flux loss under the medium emission scenarios

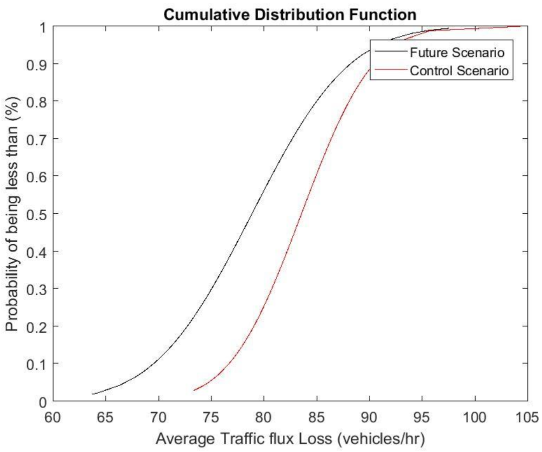


c. The CDF curve for the average traffic flux loss under the low emission scenarios

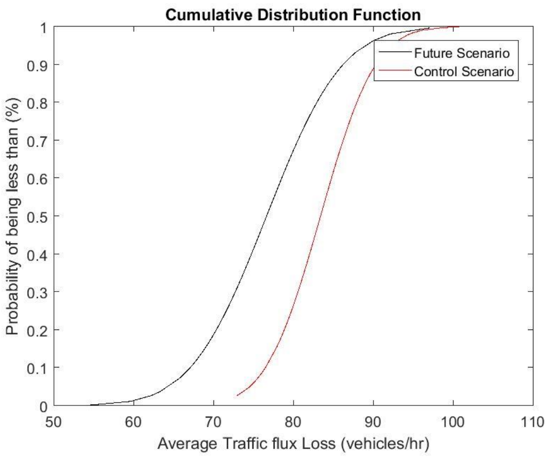
Figure 8.58: CDF curves showing the average traffic loss under the various emission scenarios for a roundabout controlled 3 lanes link during summer periods containing 33% autonomous vehicles in the traffic streams



a. The CDF curve for the average traffic flux loss under the high emission scenarios



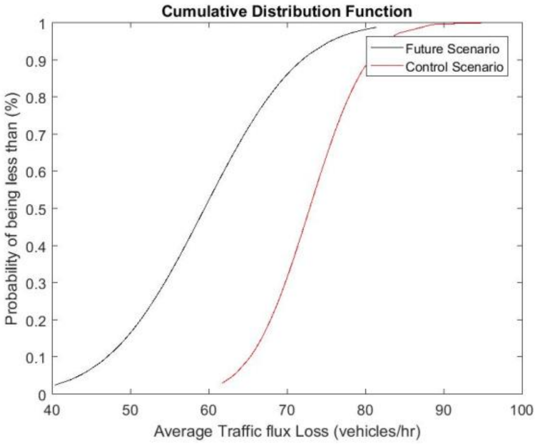
b. The CDF curve for the average traffic flux loss under the medium emission scenarios



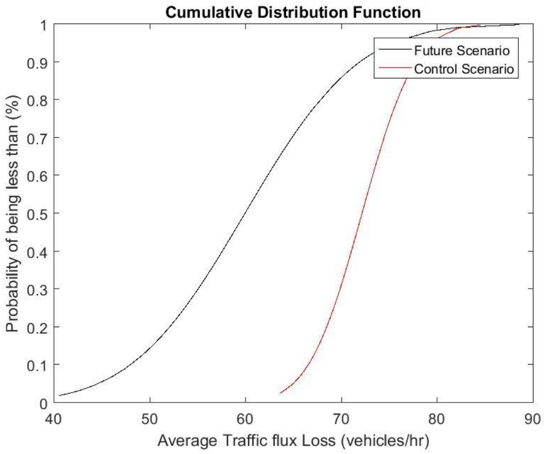
c. The CDF curve for the average traffic flux loss under the low emission scenarios

Figure 8.59: CDF curves showing the average traffic loss under the various emission scenarios for a roundabout controlled 3 lanes link during winter periods containing 33% autonomous vehicles in the traffic streams

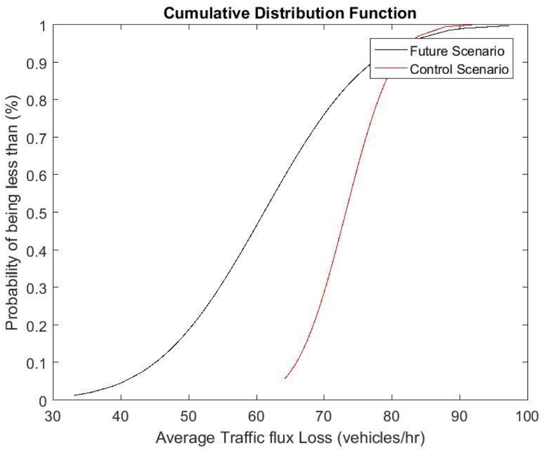
Roundabout Controlled Link: 67% Autonomous Vehicles



a. The CDF curve for the average traffic flux loss under the high emission scenarios

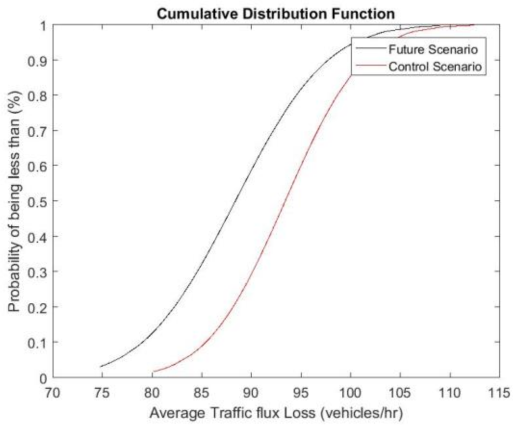


b. The CDF curve for the average traffic flux loss under the medium emission scenarios

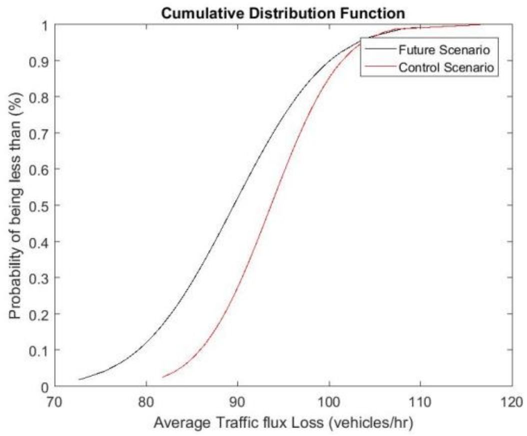


c. The CDF curve for the average traffic flux loss under the low emission scenarios

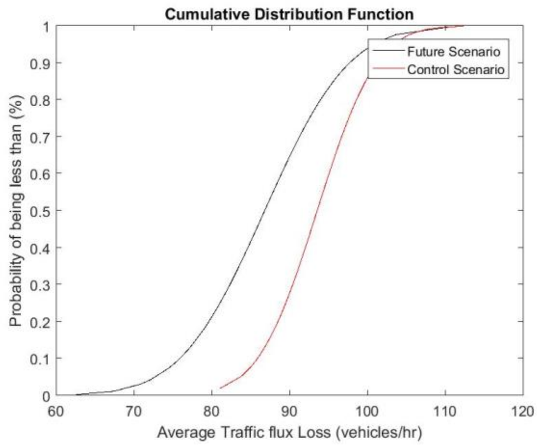
Figure 8.60: CDF curves showing the average traffic loss under the various emission scenarios for a roundabout controlled 3 lanes link during summer periods containing 67% autonomous vehicles in the traffic streams



a. The CDF curve for the average traffic flux loss under the high emission scenarios



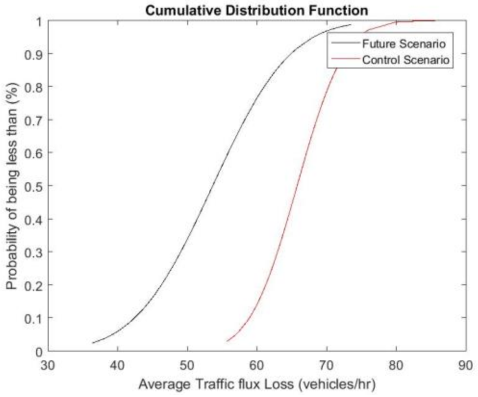
b. The CDF curve for the average traffic flux loss under the medium emission scenarios



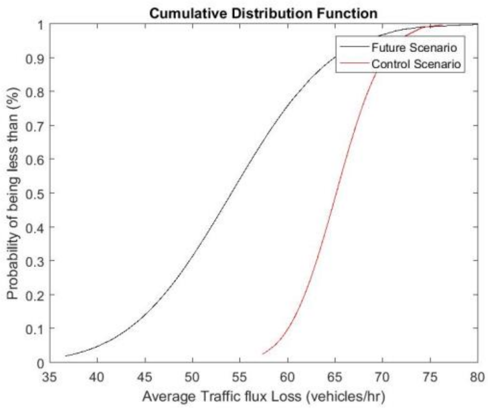
c. The CDF curve for the average traffic flux loss under the low emission scenarios

Figure 8.61: CDF curves showing the average traffic loss under the various emission scenarios for a roundabout controlled 3 lanes link during winter periods containing 67% autonomous vehicles in the traffic streams

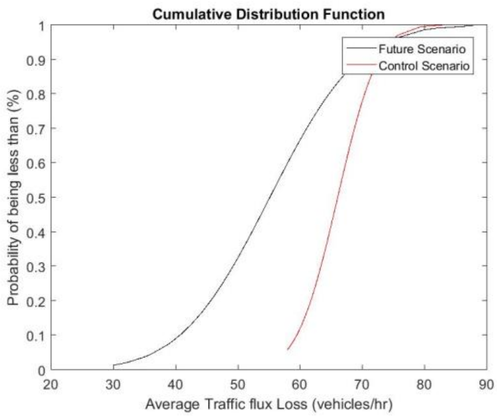
Roundabout Controlled Link: 100% Autonomous Vehicles



a. The CDF curve for the average traffic flux loss under the high emission scenarios

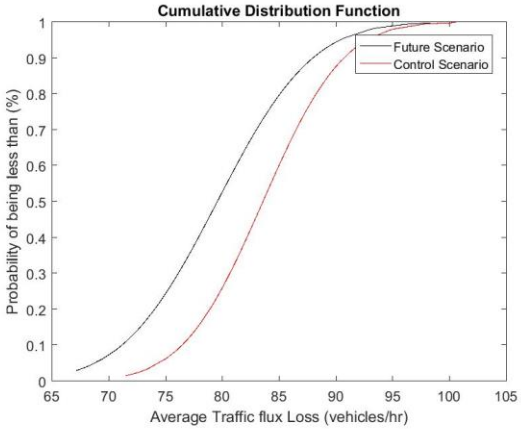


b. The CDF curve for the average traffic flux loss under the medium emission scenarios

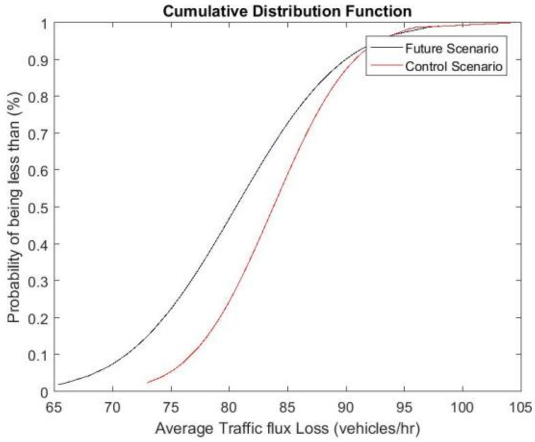


c. The CDF curve for the average traffic flux loss under the low emission scenarios

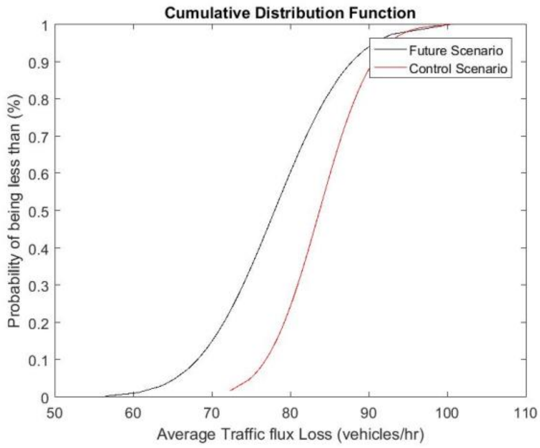
Figure 8.62: CDF curves showing the average traffic loss under the various emission scenarios for a roundabout controlled 3 lanes link during summer periods containing 100% autonomous vehicles in the traffic streams



a. The CDF curve for the average traffic flux loss under the high emission scenarios



b. The CDF curve for the average traffic flux loss under the medium emission scenarios

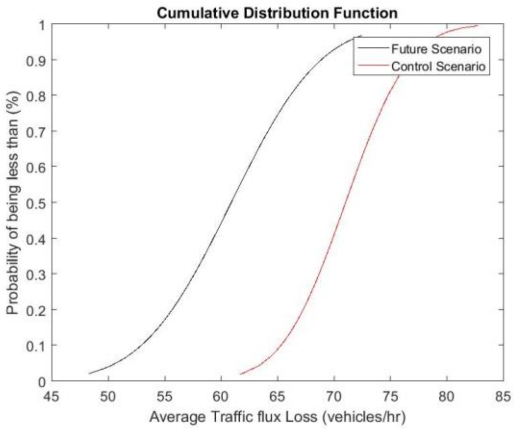


c. The CDF curve for the average traffic flux loss under the low emission scenarios

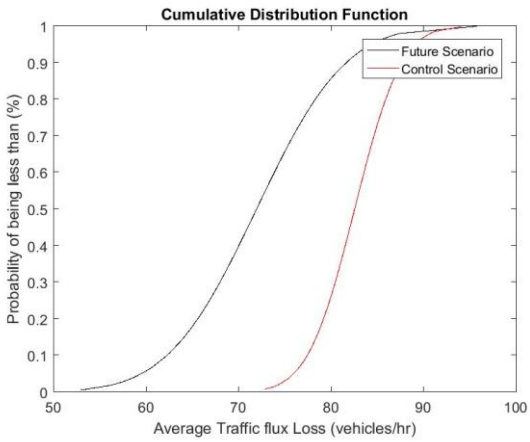
Figure 8.63: CDF curves showing the average traffic loss under the various emission scenarios for a roundabout controlled 3 lanes link during winter periods containing 100% autonomous vehicles in the traffic streams

The CDF curves for the average traffic flux loss under each emissions scenario for both link types located in the North and South of the UK during the summer and winter seasons

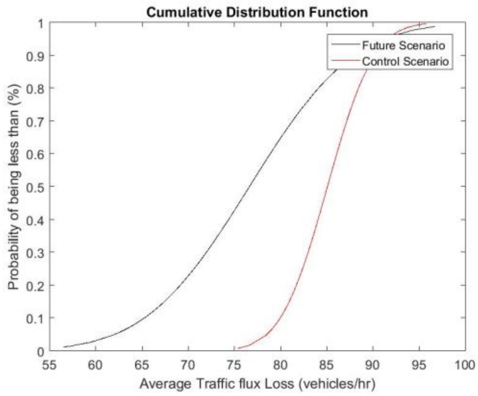
Signalised Link: Northern UK



a. The CDF curve for the average traffic flux loss under the high emission scenarios

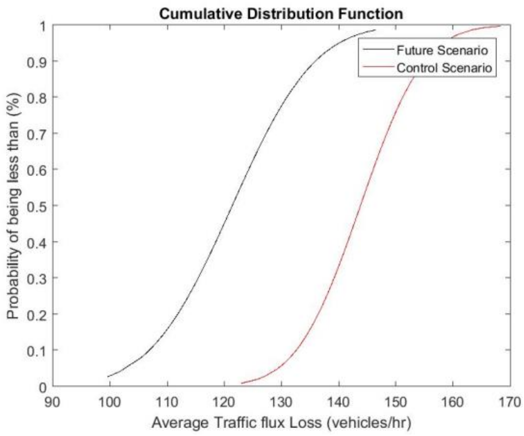


b. The CDF curve for the average traffic flux loss under the medium emission scenarios

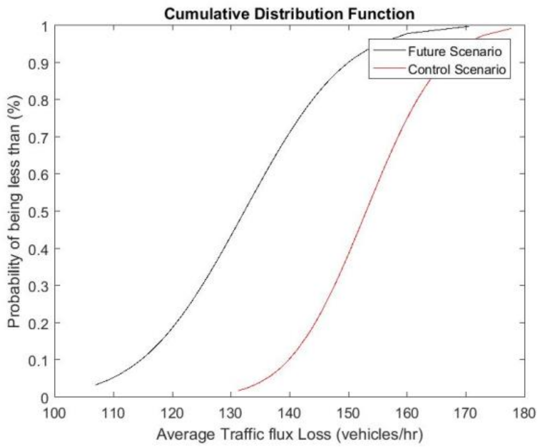


c. The CDF curve for the average traffic flux loss under the low emission scenarios

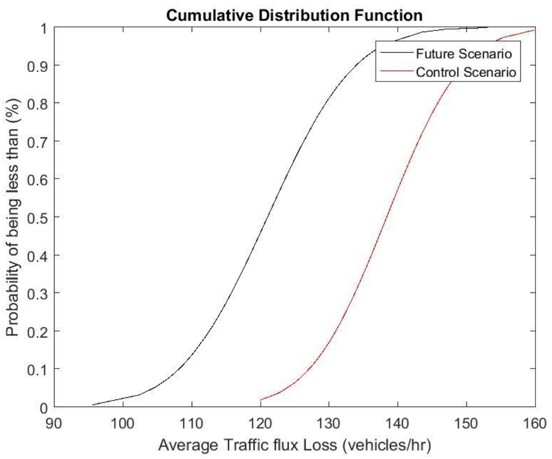
Figure 8.64: CDF curves showing the average traffic flux loss under each emissions scenario for a signal controlled 3 lanes link located in the North of the UK during the summer season



a. The CDF curve for the average traffic flux loss under the high emission scenarios



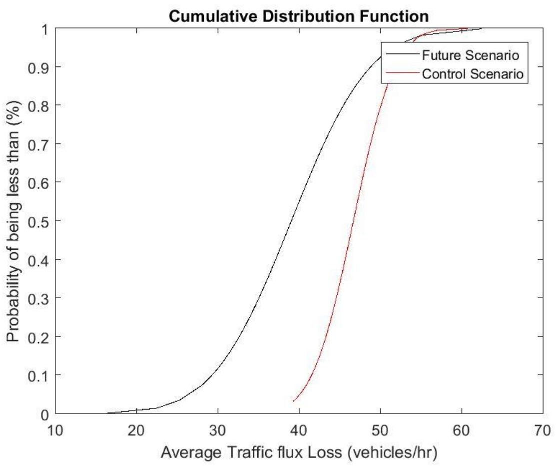
b. The CDF curve for the average traffic flux loss under the medium emission scenarios



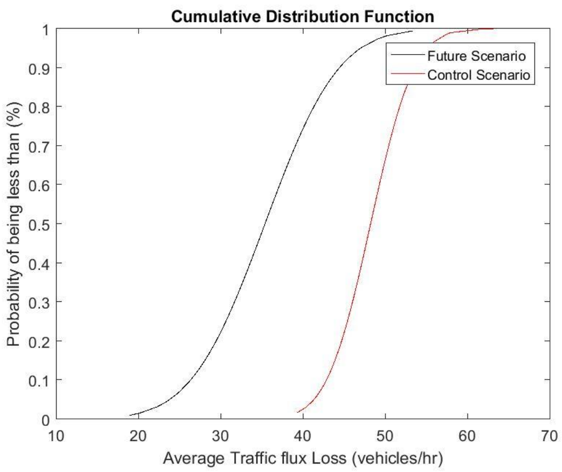
c. The CDF curve for the average traffic flux loss under the low emission scenarios

Figure 8.65: CDF curves showing the average traffic flux loss under each emissions scenario for a signal controlled 3 lanes link located in the North of the UK during the winter season

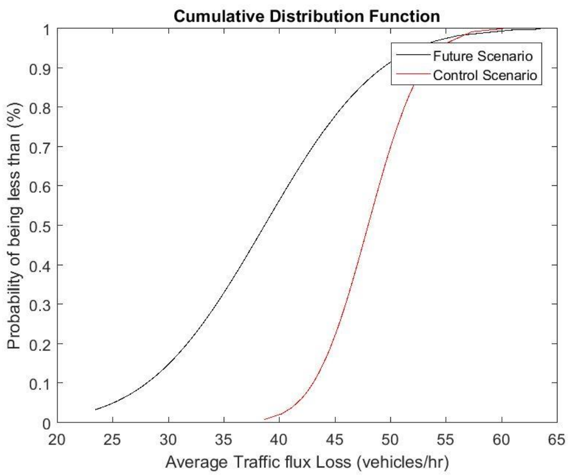
Signalised Link: Southern UK



a. The CDF curve for the average traffic flux loss under the high emission scenarios

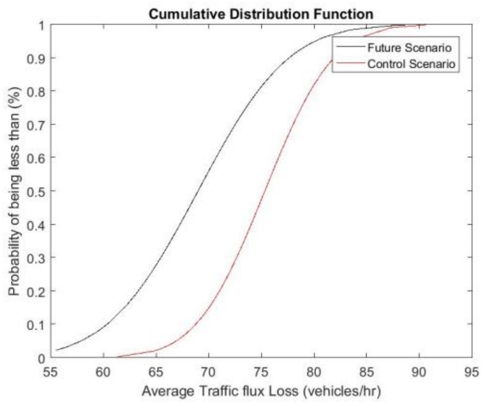


b. The CDF curve for the average traffic flux loss under the medium emission scenarios

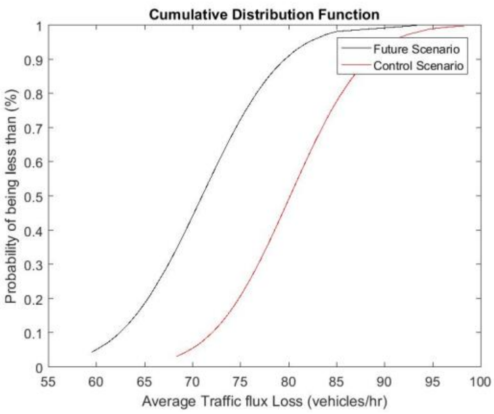


c. The CDF curve for the average traffic flux loss under the low emission scenarios

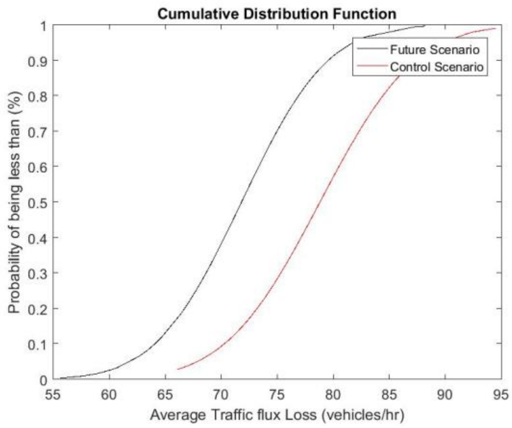
Figure 8.66: CDF curves showing the average traffic flux loss under each emissions scenario for a signal controlled 3 lanes link located in the South of the UK during the summer season



a. The CDF curve for the average traffic flux loss under the high emission scenarios



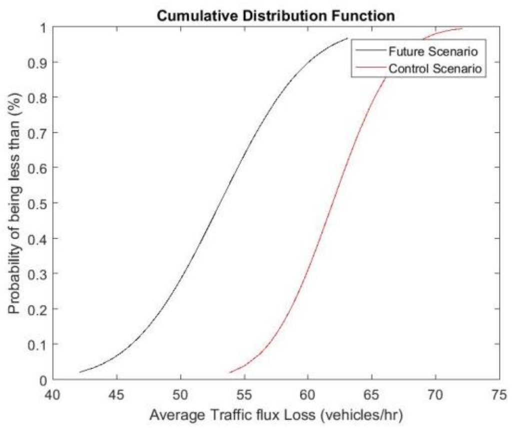
b. The CDF curve for the average traffic flux loss under the medium emission scenarios



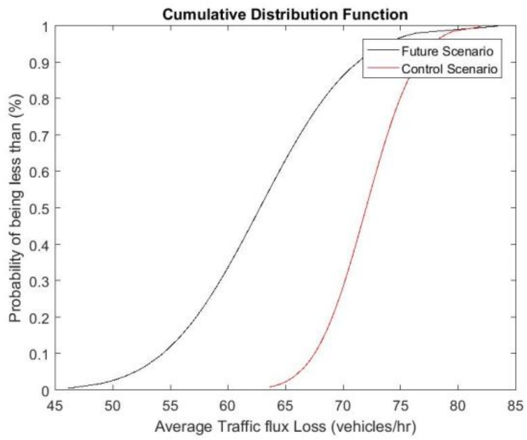
c. The CDF curve for the average traffic flux loss under the low emission scenarios

Figure 8.67: CDF curves showing the average traffic flux loss under each emissions scenario for a signal controlled 3 lanes link located in the South of the UK during the winter season

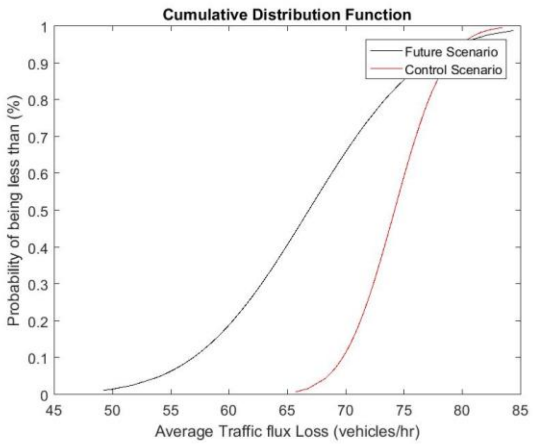
Roundabout controlled Link: Northern UK



a. The CDF curve for the average traffic flux loss under the high emission scenarios

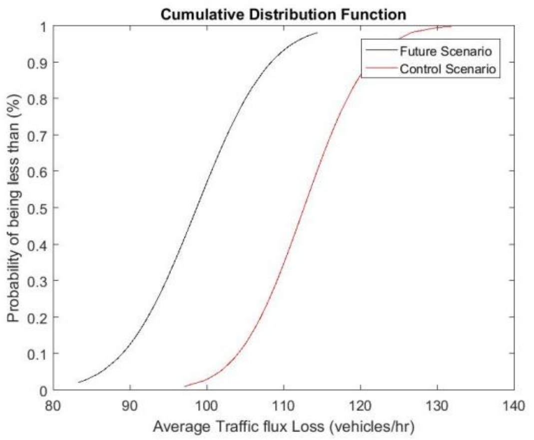


b. The CDF curve for the average traffic flux loss under the medium emission scenarios

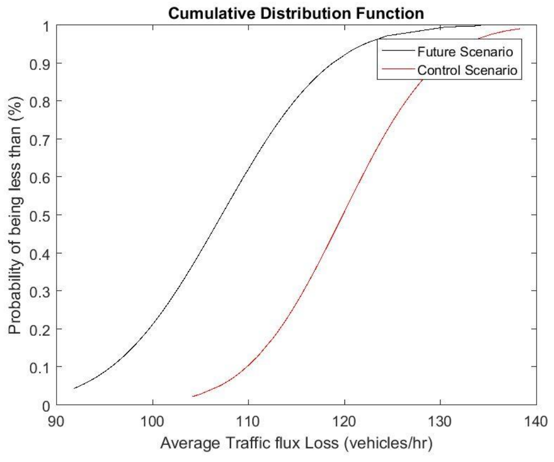


c. The CDF curve for the average traffic flux loss under the low emission scenarios

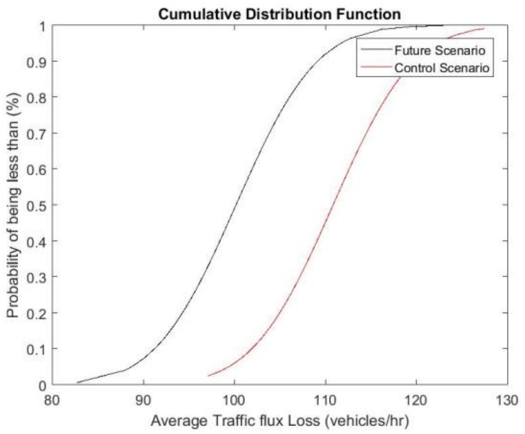
Figure 8.68: CDF curves showing the average traffic flux loss under each emissions scenario for a roundabout controlled 3 lanes link located in the North of the UK during the summer season



a. The CDF curve for the average traffic flux loss under the high emission scenarios



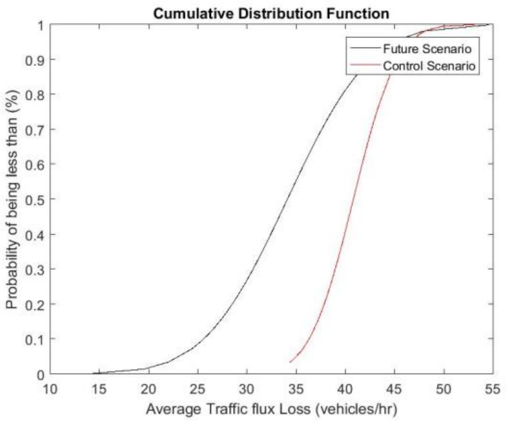
b. The CDF curve for the average traffic flux loss under the medium emission scenarios



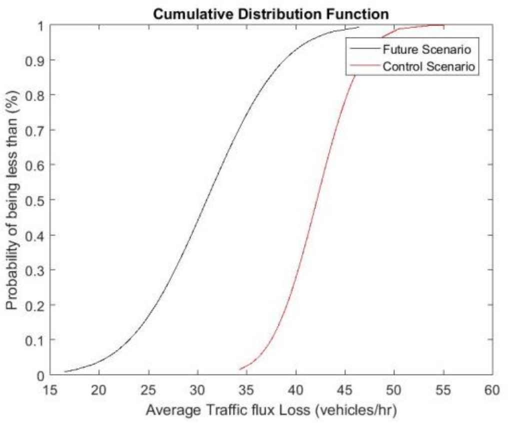
c. The CDF curve for the average traffic flux loss under the low emission scenarios

Figure 8.69: CDF curves showing the average traffic flux loss under each emissions scenario for a roundabout controlled 3 lanes link located in the North of the UK during the winter season

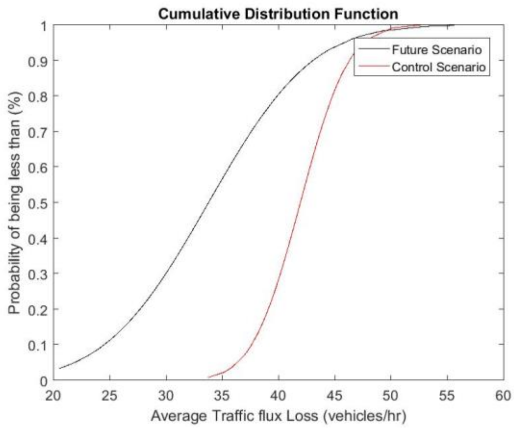
Roundabout Controlled Link: Southern UK



a. The CDF curve for the average traffic flux loss under the high emission scenarios

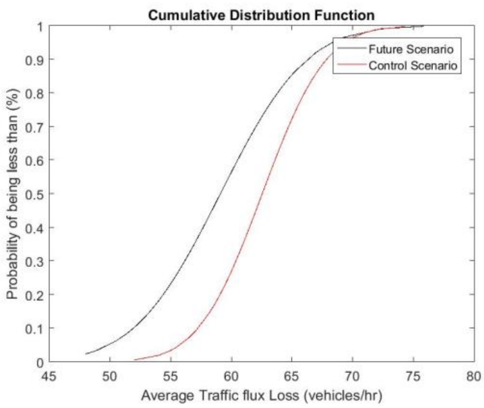


b. The CDF curve for the average traffic flux loss under the medium emission scenarios

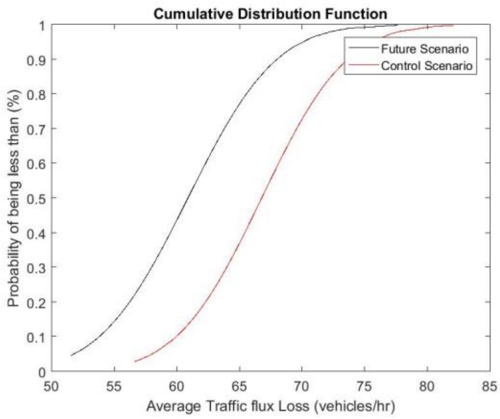


c. The CDF curve for the average traffic flux loss under the low emission scenarios

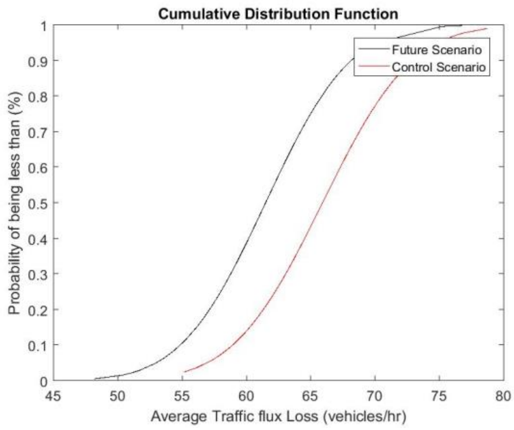
Figure 8.70: CDF curves showing the average traffic flux loss under each emissions scenario for a roundabout controlled 3 lanes link located in the South of the UK during the summer season



a. The CDF curve for the average traffic flux loss under the high emission scenarios



b. The CDF curve for the average traffic flux loss under the medium emission scenarios

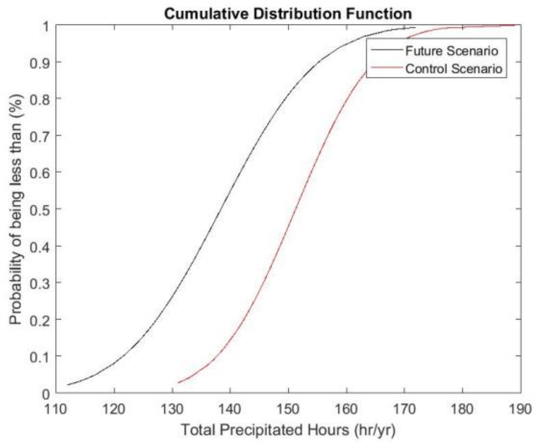


c. The CDF curve for the average traffic flux loss under the low emission scenarios

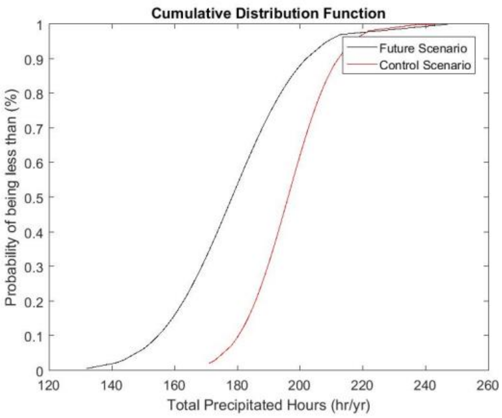
Figure 8.71: CDF curves showing the average traffic flux loss under each emissions scenario for a roundabout controlled 3 lanes link located in the South of the UK during the winter season

The probability of experiencing precipitated conditions for each season of the entire emissions scenario.

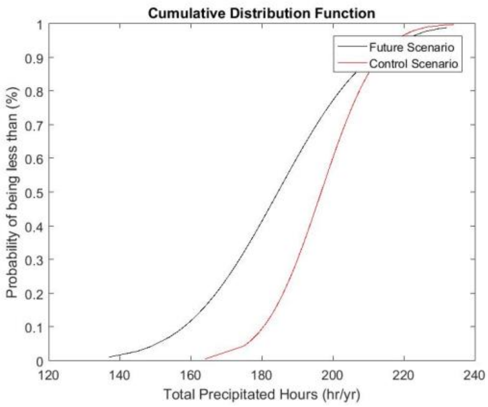
Total Precipitation: Northern UK



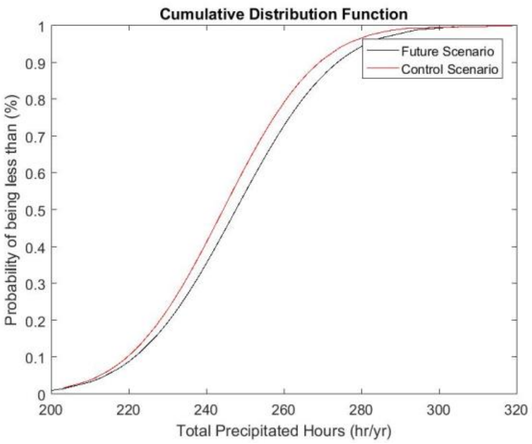
a. The probability of experiencing precipitated hours for the summer period under high emissions scenario



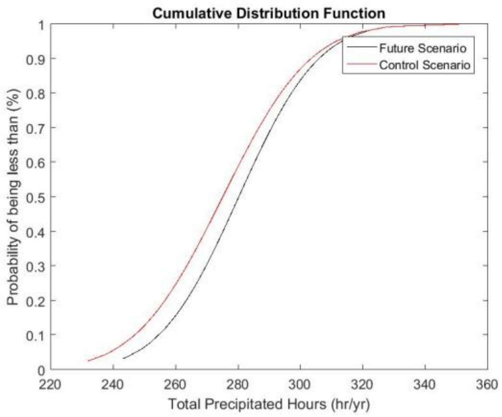
b. The probability of experiencing precipitated hours for the summer period under medium emissions scenario



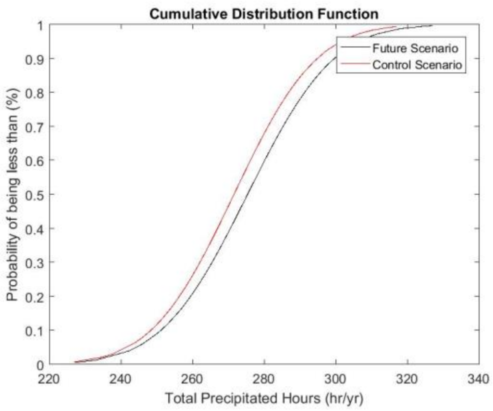
c. The probability of experiencing precipitated hours for the summer period under low emissions scenario



d. The probability of experiencing precipitated hours for the winter period under high emissions scenario



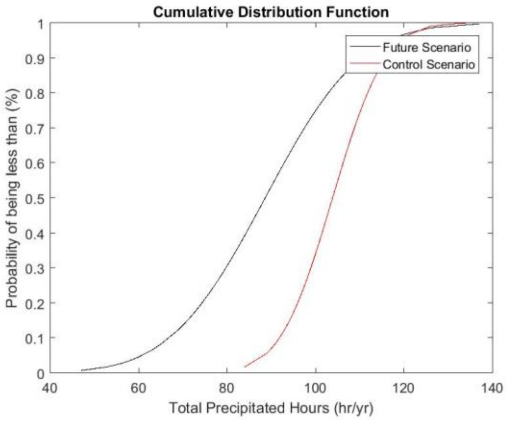
e. The probability of experiencing precipitated hours for the winter period under medium emissions scenario



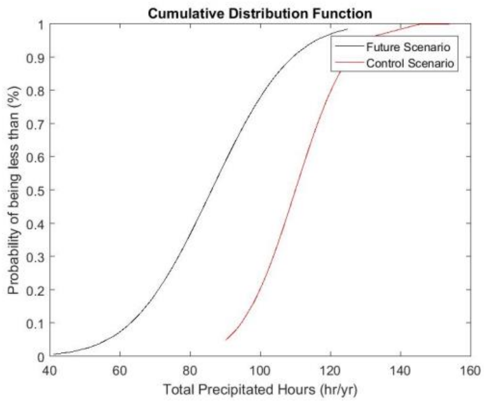
f. The probability of experiencing precipitated hours for the winter period under low emissions scenario

Figure 8.72: The probability of experiencing precipitated hours for both seasons under each emissions scenario for the northern UK

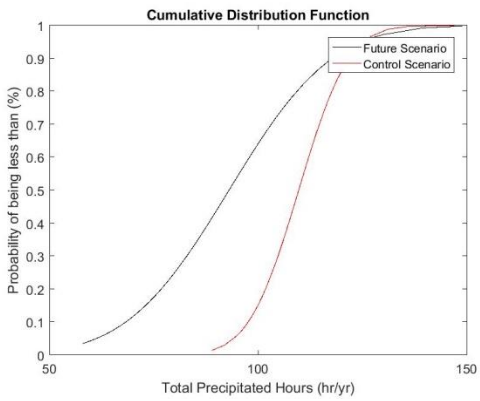
Total Precipitation: Southern UK



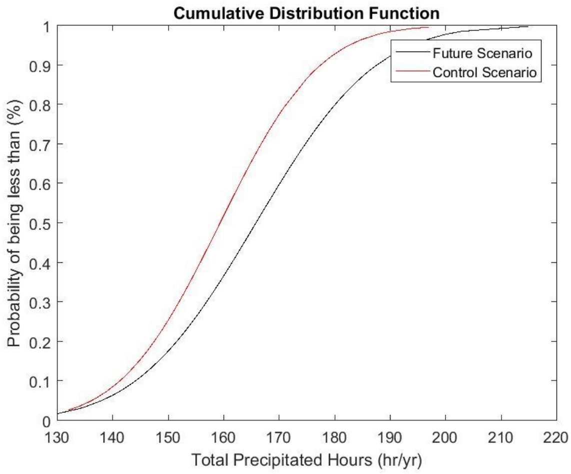
a. The probability of experiencing precipitated hours for the summer period under high emissions scenario



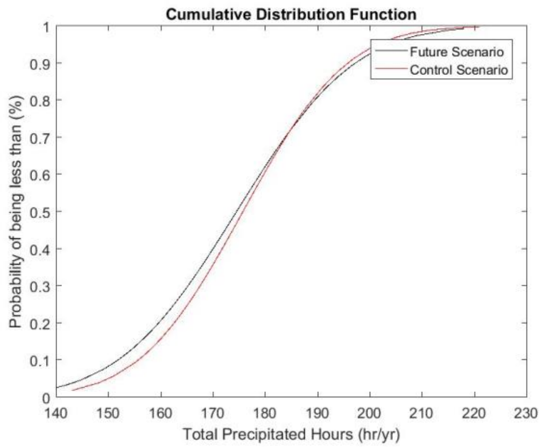
b. The probability of experiencing precipitated hours for the summer period under medium emissions scenario



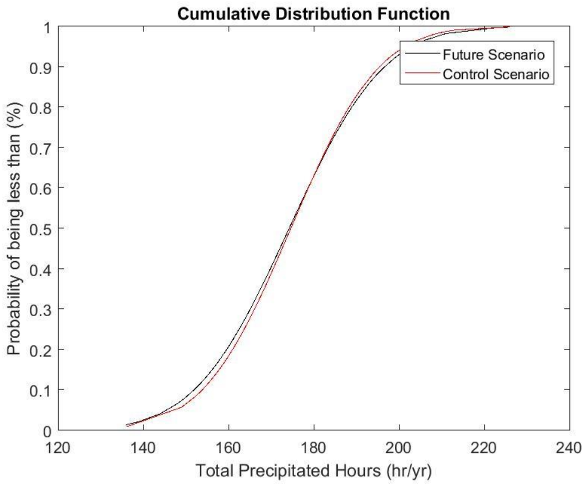
c. The probability of experiencing precipitated hours for the summer period under low emissions scenario



d. The probability of experiencing precipitated hours for the winter period under high emissions scenario



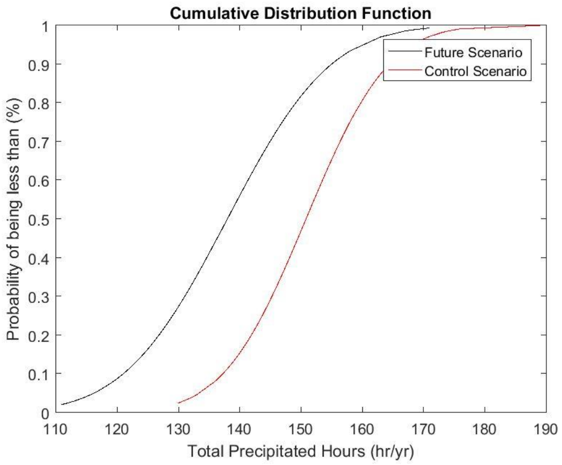
e. The probability of experiencing precipitated hours for the winter period under medium emissions scenario



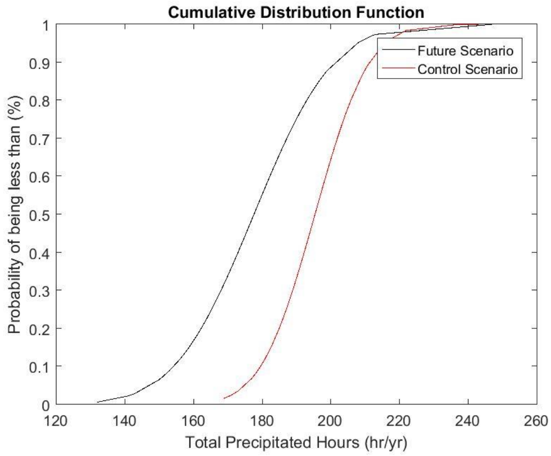
f. The probability of experiencing precipitated hours for the winter period under low emissions scenario

Figure 8.73: The probability of experiencing precipitated hours for both seasons under each emissions scenario for the southern UK

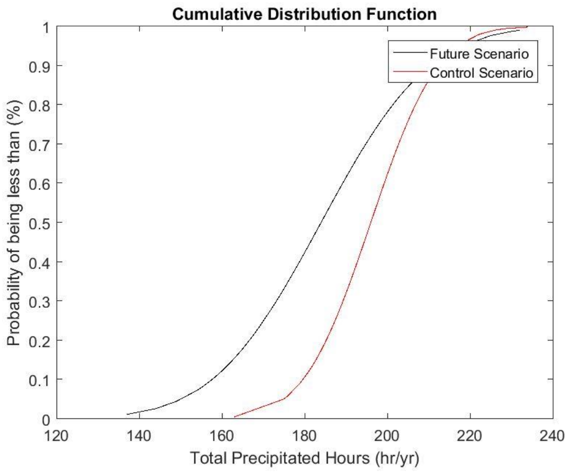
Light Rain: Northern UK



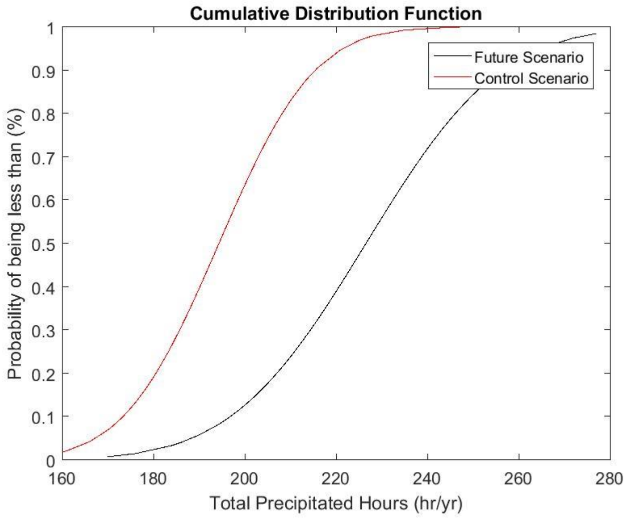
a. The probability of experiencing light rain hours for the summer period under high emissions scenario



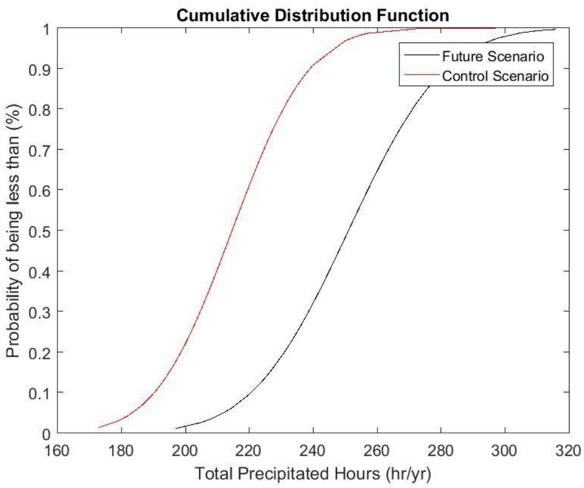
b. The probability of experiencing light rain hours for the summer period under medium emissions scenario



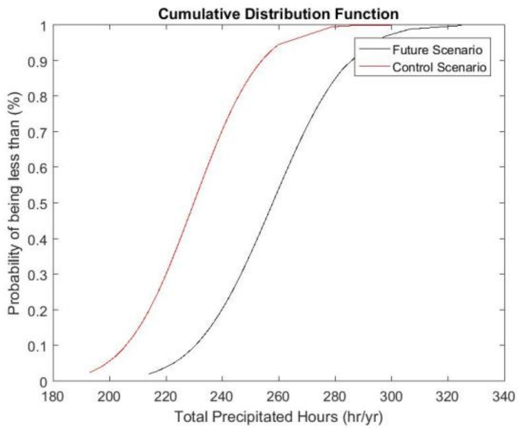
c. The probability of experiencing light rain hours for the summer period under low emissions scenario



d. The probability of experiencing light rain hours for the winter period under high emissions scenario



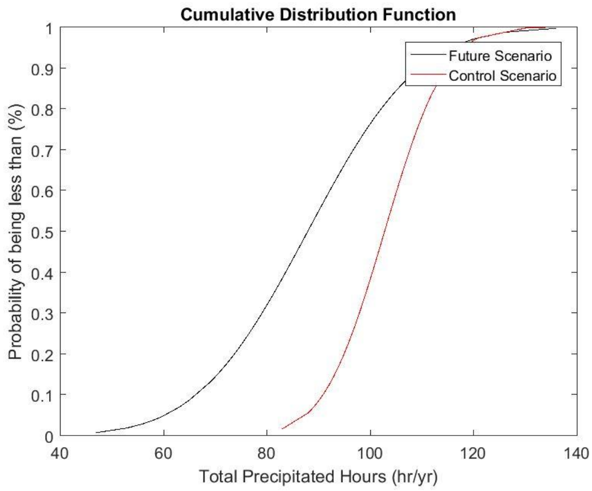
e. The probability of experiencing light rain hours for the winter period under medium emissions scenario



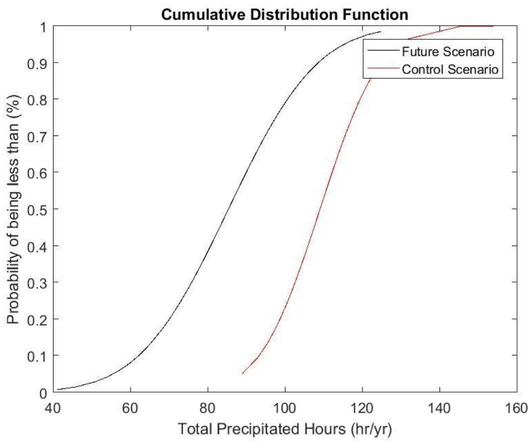
f. The probability of experiencing light rain hours for the winter period under low emissions scenario

Figure 8.74: The probability of experiencing light rain hours for both seasons under each emissions scenario for the northern UK

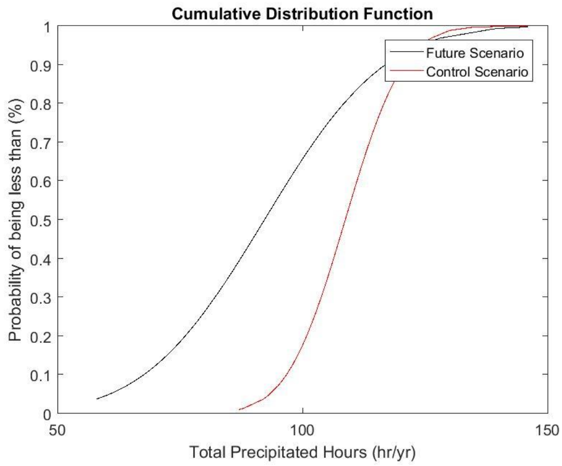
Light Rain: Southern UK



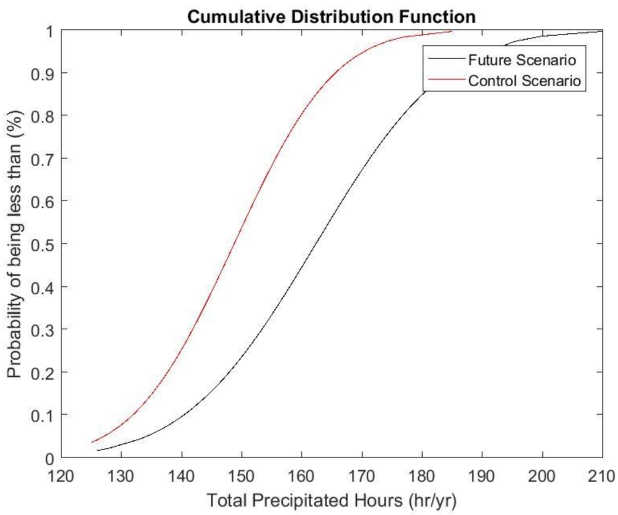
a. The probability of experiencing light rain hours for the summer period under high emissions scenario



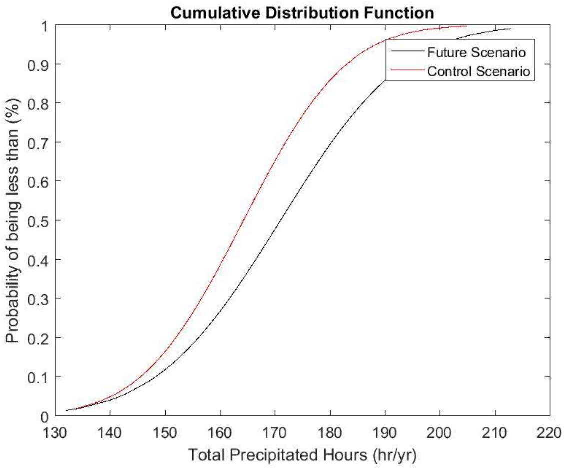
b. The probability of experiencing light rain hours for the summer period under medium emissions scenario



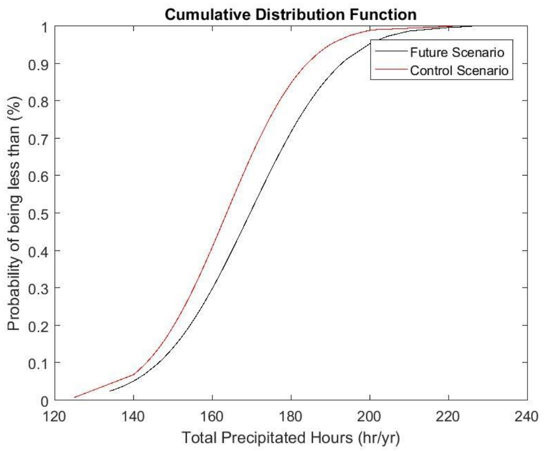
c. The probability of experiencing light rain hours for the summer period under low emissions scenario



d. The probability of experiencing light rain hours for the winter period under high emissions scenario



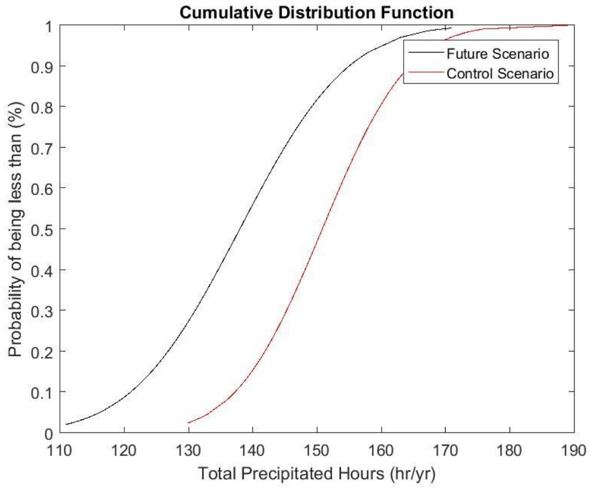
e. The probability of experiencing light rain hours for the winter period under medium emissions scenario



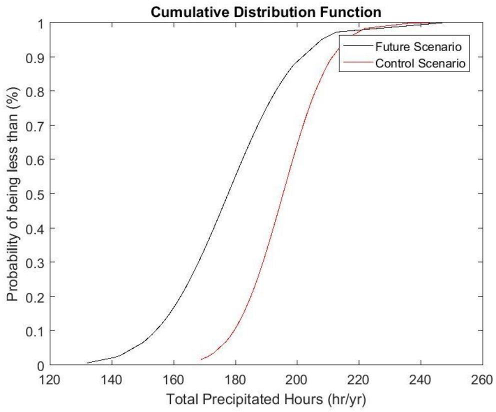
f. The probability of experiencing light rain hours for the winter period under low emissions scenario

Figure 8.75: The probability of experiencing light rain hours for both seasons under each emissions scenario for the southern UK

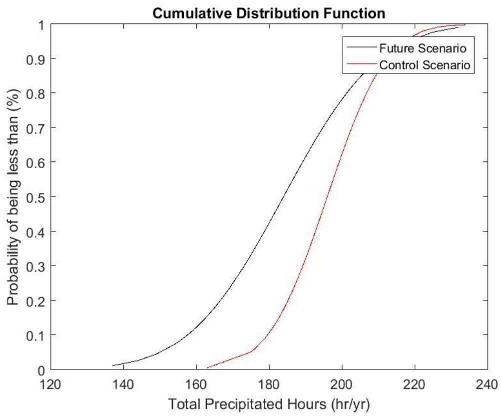
Light Snow: Northern UK



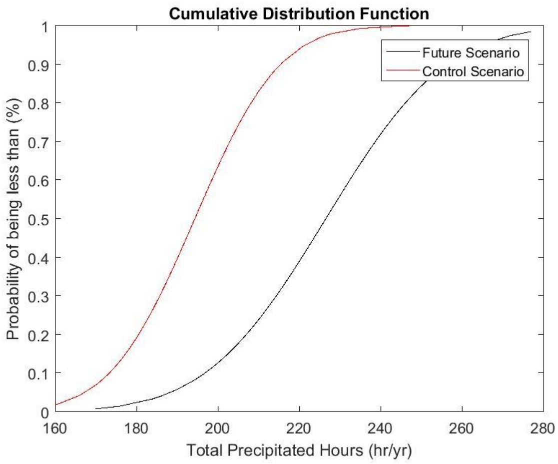
a. The probability of experiencing light snow hours for the summer period under high emissions scenario



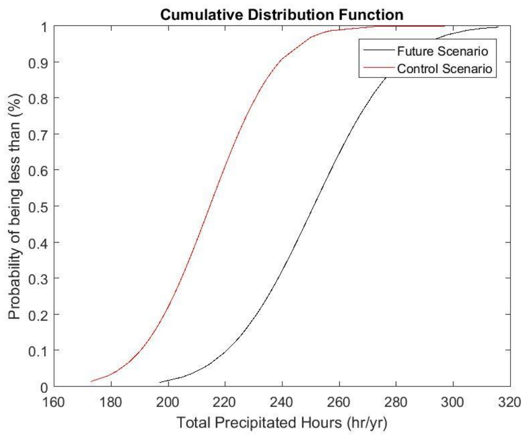
b. The probability of experiencing light snow hours for the summer period under medium emissions scenario



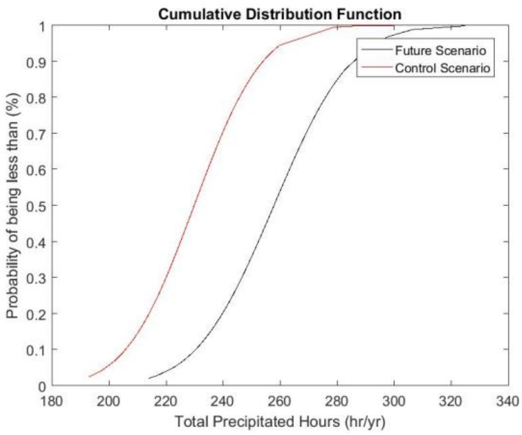
c. The probability of experiencing light snow hours for the summer period under low emissions scenario



d. The probability of experiencing light snow hours for the winter period under high emissions scenario



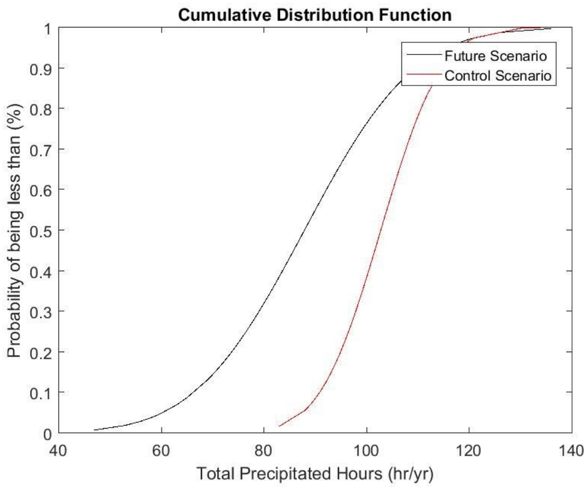
e. The probability of experiencing light snow hours for the winter period under medium emissions scenario



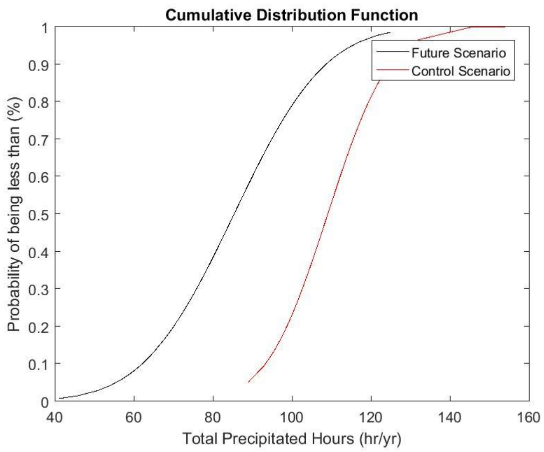
f. The probability of experiencing light snow hours for the winter period under low emissions scenario

Figure 8.76: The probability of experiencing light snow hours for both seasons under each emissions scenario for the northern UK

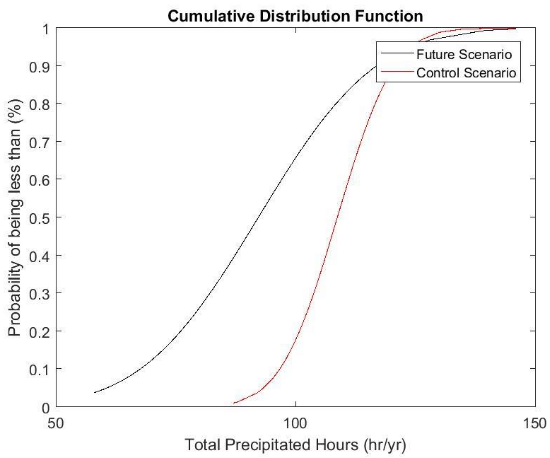
Light Snow: Southern UK



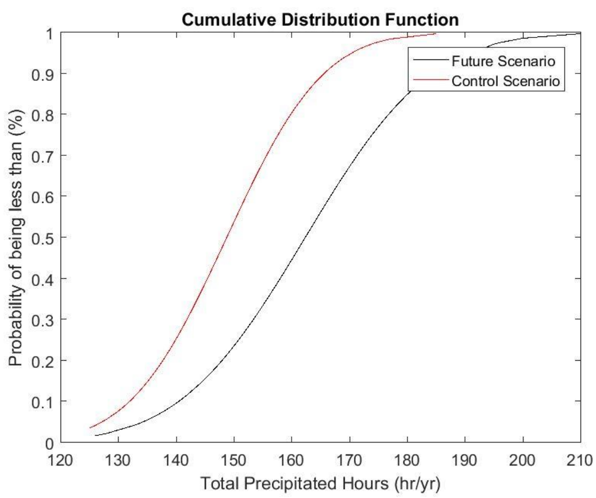
a. The probability of experiencing light snow hours for the summer period under high emissions scenario



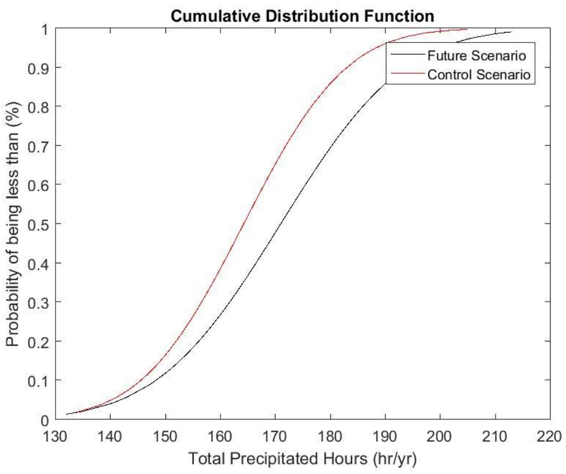
b. The probability of experiencing light snow hours for the summer period under medium emissions scenario



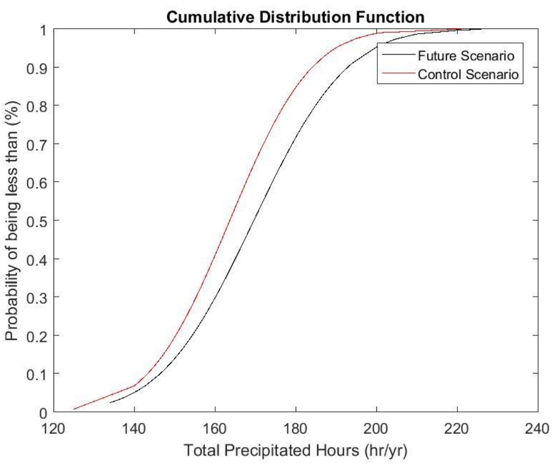
c. The probability of experiencing light snow hours for the summer period under low emissions scenario



d. The probability of experiencing light snow hours for the winter period under high emissions scenario



e. The probability of experiencing light snow hours for the winter period under medium emissions scenario



f. The probability of experiencing light snow hours for the winter period under low emissions scenario

Figure 8.77: The probability of experiencing light rain hours for both seasons under each emissions scenario for the southern UK

6. The Traffic flow Code

Code section

```
[ stop ] = stopline_overshoot_detector( vel(:,:),max_dec(:,:),link,t,v_reg,posit_f(:,:));
%accel_found1==0 meant acceleration mode not found

%ref_veh==0 meaning no lead vehicle and traffic congestion is OFF
if ref_veh==0 && accel_found1==0 && congestion==off
        accel(t,v_reg)=max_accel(t,v_reg);
        accel_found1=1;
%congestion is ON and no lead vehicle
elseif congestion==on && ref_veh==0
%The stop line is ON and the vehicle would potentially overshoot the stop sign (i.e.stop==1)
    if stop==1 && stop_line_status==on && accel_found1==0
        accel(t,v_reg)=max_dec(t,v_reg);
        accel_found1=1;
%speed_line is a point on the link beyond which a special speed limit was required as vehicles approach
%the end of the link. jam_spd is special speed limit for the end of the link
    elseif posit_f(t,v_reg)>=speed_line && vel(t,v_reg)>=jam_spd && accel_found1==0
        accel(t,v_reg)=max_dec(t,v_reg);
        accel_found1=1;
    elseif posit_f(t,v_reg)>=speed_line && vel(t,v_reg)<=jam_spd-1 && accel_found1==0
        accel(t,v_reg)=max_accel(t,v_reg);
        accel_found1=1;
    elseif posit_f(t,v_reg)>=speed_line && vel(t,v_reg)>jam_spd-1 && vel(t,v_reg)<jam_spd && accel_found1==0
        accel(t,v_reg)=0;
        accel_found1=1;
    end
```

Code section

```
%stopping time; brake times -1 to remove the brake negative sign
braking_time=velocity_array(time,veh_reg)/(max_brake_array(time,veh_reg)*(-1));

%vehicle distance covered while braking
dist_covered=0.5*velocity_array(time,veh_reg)*braking_time;

%determine whether the vehicle would overshoot the end of the link tolerance (2m)
if (dist_covered+posit_frnt_array(time,veh_reg))>Link_length-2
     overshot_stopline=1;
else
     overshot_stopline=0;
end

end
```

Code section

```
%traffic light
%The light array kept track of the state of the traffic light for
%each time step. Both states had counter variables which were
%red_cnt and green_cnt. Whenever a state was active its counter was
%incremented during each time step. After its maximum active time
%had elapsed its counter was reset and the traffic light state was
%switched to the next state.
if light(t,1)==1 || red_cnt>0
    red_cnt=red_cnt+1;
    light(t,1)=1;
    if red_cnt>=300
        red_cnt=0;
        light(t,1)=2;
        if t<time
            light(t+1,1)=2;
        end
    end
end
if light(t,1)==2 || green_cnt>0
    green_cnt=green_cnt+1;
    light(t,1)=2;
    if green_cnt>=600
        green_cnt=0;
        light(t,1)=1;
        if t<time
            light(t+1,1)=1;
        end
    end
end
```

Code section

```
%Stop_line response
%The stop sign (i.e. stop_line_status)
%was on when the light was red (1)
%during the current time step and
%was off when the light was green
%(2) during the current time step
if traffic_light==on
    if light(t,1)==1
        stop_line_status=on;
        stopline_check(t,1)=on;
    elseif light(t,1)==2
        stop_line_status=off;
        stopline_check(t,1)=off;
    end
end
```

Code section

```
%Small vehicles have a length of 4.7m while
%large vehicles have a length of 14m (reference)
%Uniform small vehicles were given type 1
%vehicle design while unifrom large vehicles
%were given type 4.
if uniform_veh==on
    if choose_veh==small
        veh_len(1,v_reg)=small_L;
        veh_type(1,v_reg)=1;
    elseif choose_veh==large
        veh_len(1,v_reg)=big_L;
        veh_type(1,v_reg)=4;
    end
```

Code section

```
%With uniform vehicles option off vehicle ratio
%was used. A counter was used along side the
%ratio to determine when to select small or
%large vehicles. When the counter was less than
%the ratio value selections were made
%sequentially between the 3 small vehicle
%design types. The selection got to the 3rd
%type the next selection became the first one
%and the cycle continued until the counter
%value equaled the ratio value.
elseif uniform_veh==off
    if veh_len_cnt<ratio
        veh_len(1,v_reg)=small_L;
        switch L_veh_type_cnt
            case 0
                veh_type(1,v_reg)=1;
                L_veh_type_cnt=L_veh_type_cnt+1;
            case 1
                veh_type(1,v_reg)=2;
                L_veh_type_cnt=L_veh_type_cnt+1;
            case 2
                veh_type(1,v_reg)=3;
                L_veh_type_cnt=0;
        end
        veh_len_cnt=veh_len_cnt+1;
```

Code section

```
  %When the counter equalled the ratio value
  %a large vehicle was then selected and then
  %the counter was reset so smaller vehicle
  %lengths were selected afterwards. Just like
  %the small vehicle selection procedure a
  %different counter was used to ensure the selection was
  %done sequentially and once the 3rd vehicle
  %type was selected the counter was reset so
  %that the next selection was the first
  %selection keeping the selection process in a
  %cycle.
    elseif veh_len_cnt>=ratio
        veh_len(1,v_reg)=big_L;
        switch H_veh_type_cnt
            case 0
                veh_type(1,v_reg)=4;
                H_veh_type_cnt=H_veh_type_cnt+1;
            case 1
                veh_type(1,v_reg)=5;
                H_veh_type_cnt=H_veh_type_cnt+1;
            case 2
                veh_type(1,v_reg)=6;
                H_veh_type_cnt=0;
        end
        veh_len_cnt=0;
    end
end
```

Code section

```
%The variable speed_line indicated where vehicle had to start considering the
%special speed limit in order to avoid overshooting the stop sign since
%their maximum deceleration rate was infuenced by the weather conditions. The
%variable control_vel is equivalent to the maximum speed under dry condition
%and the max speed of other conditions were gotten by deduction
%specific values from this value. The variable vel_init was the initial
%speed of vehicles entering the link, this was set to the maximum
%speed under the specific weather condition as it was assumed that
%the link was part of a continous motorway stretch except in cases were
%a traffic light was included or were congestion was induced at the end
%of the link but in all cases vehicles were initialised to maximum
%speed.
speed_line=0;                           %controls the speed limit line
control_vel=31.2928;                    %free flow vel or speed limit
vel_init=0;                             %initial velocity
```

Code section

```
%Under dry condition the maximum velocity was the same as the speed
%limit of the link (i.e. 70mph or 31.293m/s) and the speed line is at the
%highest position on the link compared to other weather conditions(i.e.
%700m)
if condition==1
    max_vel = control_vel;
    speed_line=700;
    vel_init=max_vel;
%Under light rain and light snow conditions the maximum speed was
%2.778m/s (or 6.214mph) less than the speed limit. The speed line
%remained the same as the maximum deceleration rate was not impacted much enough to
%have a significant impact on their stopping distances.
elseif condition==2
    max_vel = control_vel-2.778;
    speed_line=700;
    vel_init=max_vel*1;
elseif condition==3
    max_vel = control_vel-2.778;
    speed_line=700;
    vel_init=max_vel;

%Under heavy rain condition the maximum speed was 5.556m/s (or 12.427mph)
%less than the speed limit while the speed line was reduced to 650m to
%compensate for the impact of the weather conditon on the maximum deceleration rate.
elseif condition==4
    max_vel = control_vel-5.556;
    speed_line=650;
    vel_init=max_vel;
%Under heavy snow condition the maximum speed was 13.889m/s (or 31.0686mph)
%less than the speed limit while the speed line was reduced to 500m to
%compensate for the impact of the weather conditon on the maximum deceleration rate.
elseif condition==5
    max_vel = control_vel-13.889;
    speed_line=500;
    vel_init=max_vel;
end
```

Code section

```
%Decision to change lane (interest levels)
if (timer_overtake_array(1,veh_reg)==20 &&
timer_change_array(1,veh_reg)==10)||(timer_overtake_array(1,veh_reg)<20)
    if timer_overtake_array(1,veh_reg)<20 && velo_array(time-
1,veh_reg)<max_velo && ((accel_array(time-1,veh_reg)<=aA_array(time-
1,veh_reg)&&aA_array(time-1,veh_reg)<max_accel_array(time-
1,veh_reg))||(accel_array(time-1,veh_reg)<=aC_array(time-
1,veh_reg)&&aC_array(time-1,veh_reg)<max_accel_array(time-
1,veh_reg))||accel_array(time-1,veh_reg)<aB_array(time-1,veh_reg))
        timer_overtake_array(1,veh_reg)=timer_overtake_array(1,veh_reg)+1;
    elseif timer_overtake_array(1,veh_reg)>0 && (accel_array(time-
1,veh_reg)>=aB_array(time-1,veh_reg)||accel_array(time-
1,veh_reg)==max_accel_array(time-1,veh_reg))||velo_array(time-
1,veh_reg)==max_velo
        timer_overtake_array(1,veh_reg)=timer_overtake_array(1,veh_reg)-1;
    end
end
```

Code section

```
%calculating total velocity for vehicles on the same lane
for ch=1:veh
    %calculating the velocity for current lane
    if Lanes_array(time-1,ch)==current_lane
        no_of_veh=no_of_veh+1;
        total_vel=total_vel+velo_array(time-1,ch);
    end
    %calculating the velocity for the neighbouring lanes
    switch neigh_state
        %if current lane is 1
        case 1.1
            if Lanes_array(time-1,ch)==2
                no_of_veh_N2=no_of_veh_N2+1;
                total_vel_N2=total_vel_N2+velo_array(time-1,ch);
            end
            no_of_veh_N1=0;
            total_vel_N1=0;
            %if current lane is 2
        case 1.2
            no_of_veh_N2=0;
            total_vel_N2=0;

            no_of_veh_N1=0;
            total_vel_N1=0;

        case 2.1
            if Lanes_array(time-1,ch)==1
                no_of_veh_N1=no_of_veh_N1+1;
                total_vel_N1=total_vel_N1+velo_array(time-1,ch);
            end
            if Lanes_array(time-1,ch)==3
                no_of_veh_N2=no_of_veh_N2+1;
                total_vel_N2=total_vel_N2+velo_array(time-1,ch);
            end
        case 2.2
            if Lanes_array(time-1,ch)==1
                no_of_veh_N1=no_of_veh_N1+1;
                total_vel_N1=total_vel_N1+velo_array(time-1,ch);
            end
            no_of_veh_N2=0;
            total_vel_N2=0;
```

```
            %if current lane is 3
        case 3.1
            if Lanes_array(time-1,ch)==2
                no_of_veh_N1=no_of_veh_N1+1;
                total_vel_N1=total_vel_N1+velo_array(time-1,ch);
            end
            if Lanes_array(time-1,ch)==4
                no_of_veh_N2=no_of_veh_N2+1;
                total_vel_N2=total_vel_N2+velo_array(time-1,ch);
            end
        case 3.2
            if Lanes_array(time-1,ch)==2
                no_of_veh_N1=no_of_veh_N1+1;
                total_vel_N1=total_vel_N1+velo_array(time-1,ch);
            end
            no_of_veh_N2=0;
            total_vel_N2=0;
            %if current lane is 4
        case 4
            if Lanes_array(time-1,ch)==3
                no_of_veh_N1=no_of_veh_N1+1;
                total_vel_N1=total_vel_N1+velo_array(time-1,ch);
            end
            no_of_veh_N2=0;
            total_vel_N2=0;
    end
end
```

Code section

```
%average velocity of vehicles on the current lane
if total_vel>0 && no_of_veh>0
    mean_velo_cur=total_vel/no_of_veh;
end

%average velocity of vehicles on the Neighbouring lane 1 (N1) lane
if total_vel_N1>0 && no_of_veh_N1>0
    mean_velo_N1=total_vel_N1/no_of_veh_N1;
end

%average velocity of vehicles on the Neighbouring lane 2 (N2) lane
if total_vel_N2>0 && no_of_veh_N2>0
    mean_velo_N2=total_vel_N2/no_of_veh_N2;
end
```

Code section

```
%Interest on neighbouring lanes
if current_lane>1&& timer_N1_array(1,veh_reg)<40 &&
((mean_velo_N1>=max_velo-10||mean_velo_N1>=mean_velo_cur-2||
RN1a==0)||(Rcur==0 && velo_array(time-1,veh_reg)<mean_velo_N1-2))
    timer_N1_array(1,veh_reg)=timer_N1_array(1,veh_reg)+1;
    ch3=1;
elseif current_lane>1 && timer_N1_array(1,veh_reg)>0 &&
(mean_velo_N1<max_velo-10&&mean_velo_N1<=mean_velo_cur-2) && ch3==0
    timer_N1_array(1,veh_reg)=timer_N1_array(1,veh_reg)-1;
    set2=1;
end
```

Code section

```
%Before observing the outer lane lane the driver needs to be unsatisfied with its current lane
%No Interest in the Outer lane
if timer_overtake_array(1,veh_reg)==20
    if current_lane<max_lane && Rcur==0
        timer_N2_array(1,veh_reg)=0;
        if non_interest_counter_array(1,veh_reg)>=0
            non_interest_counter_array(1,veh_reg)=non_interest_counter_array(1,veh_reg)+1;
        end
        ch2=1;
        %Increased Interest in the Outer lane
    elseif current_lane<max_lane && timer_N2_array(1,veh_reg)<40 && ch2==0 && gap_array(time-1,veh_reg)<70 &&Rcur~=0
        if (mean_velo_N2>mean_velo_cur+2 ) || RN1a==0 || velo_array(time-1,Rcur)<mean_velo_N2-2
            timer_N2_array(1,veh_reg)=timer_N2_array(1,veh_reg)+1;
            non_interest_counter_array(1,veh_reg)=0;
            ch2=1;
        end
        %Reduced Interest in the Outer lane
    elseif current_lane<max_lane && ch2==0 && Rcur~=0
        if (mean_velo_N2<mean_velo_cur+2 || gap_array(time-1,veh_reg)>70) && timer_N2_array(1,veh_reg)>0
            timer_N2_array(1,veh_reg)=timer_N2_array(1,veh_reg)-1;
            non_interest_counter_array(1,veh_reg)=non_interest_counter_array(1,veh_reg)+1;
            set1=1;
        end
    end
end
```

Code section

```
%Change to the Outer lane
if collision_N2==0 && change2==1 && N2_avail==1 &&
timer_N2_array(1,veh_reg)>=40 && current_lane<max_lane
    Lanes_array(time,veh_reg)=Lanes_array(time,veh_reg)+1;
    timer_N2_array(1,veh_reg)=0;
    timer_N1_array(1,veh_reg)=0;
    non_interest_counter_array(1,veh_reg)=0;
    timer_overtake_array(1,veh_reg)=0;
    timer_change_array(1,veh_reg)=0;
    %Change to the Inner lane
elseif collision_N1==0 && change1==1 && N1_avail==1 &&
timer_N1_array(1,veh_reg)>=40 && (timer_N2_array(1,veh_reg)==0 ||
non_interest_counter_array(1,veh_reg)>20) && current_lane>1
    Lanes_array(time,veh_reg)=Lanes_array(time,veh_reg)-1;
    timer_N2_array(1,veh_reg)=0;
    timer_N1_array(1,veh_reg)=0;
    non_interest_counter_array(1,veh_reg)=0;
    timer_overtake_array(1,veh_reg)=0;
    timer_change_array(1,veh_reg)=0;
    %Stay in the current lane
else
    Lanes_array(time,veh_reg)=Lanes_array(time,veh_reg);
end
```

Code section

```
%%%Initialising patch registers of the observed lane%%%
L=lane_no;

%L held the lane number of the lane to be scanned. Each lane had four
%registers. Registers a and b were for the front bumpers while registers
%c and d were for the rear bumpers. Whenever a lane was being scanned
%its registers were selected
switch L
    case 1
        a=1;b=2;c=3;d=4;
    case 2
        a=5;b=6;c=7;d=8;
    case 3
        a=9;b=10;c=11;d=12;
    case 4
        a=13;b=14;c=15;d=16;
end
```

Code section

```
%%%Scanning for the Observed vehicle's lead vehicle%%%

%When a vehicle registration was detected in a patch register it meant the
patch register
%contained a the vehicle's bumper. Note than OV current patch here could
%also mean the equivalent patch on its neighbouring lane depending on the
%lane the lead vehicle is being detected

%%Segment1: Scanning the observed vehicle's (OV) current patch for a lead
vehicle%%

%%Stage 1: Scanning the front bumper patch registers on the OV current
patch%%

%The OV patch was scanned for front bumpers and any detected front bumper
%was compared with the position of the OV front bumper. Whenever two
%front bumpers were detected such as in cases where the operation was used
%on the neighbouring lanes their positions were compared and the one with
the lower
%position was used as the reference vehicle if its position was higher than
%that of the OV else the one with the higher position was used.
%Patch registers a and b were for front bumpers A vehicle with a detected
%front bumper ahead of the OV front bumper became the lead vehicle of the
OV.
if (register(pt,a)>0 && register(pt,a)~=v_regi) &&(register(pt,b)>0 &&
register(pt,b)~=v_regi) && new_veh_ref==0 &&
((pos_fb(tim,register(pt,a))>pos_fb(tim,register(pt,b))) &&
(pos_fb(tim,register(pt,b))>pos_fb(tim-1,v_regi)))
    ref_v=register(pt,b);
    ref_found2=1;
elseif (register(pt,a)>0 && register(pt,a)~=v_regi) &&(register(pt,b)>0 &&
register(pt,b)~=v_regi) && new_veh_ref==0 &&
((pos_fb(tim,register(pt,a))>pos_fb(tim,register(pt,b))) &&
(pos_fb(tim,register(pt,b))>pos_fb(tim-1,v_regi)))
    ref_v=register(pt,a);
    ref_found2=1;
elseif (register(pt,a)>0 && register(pt,a)~=v_regi) &&(register(pt,b)>0 &&
register(pt,b)~=v_regi) && new_veh_ref==0 &&
((pos_fb(tim,register(pt,a))>pos_fb(tim,register(pt,b))) &&
(pos_fb(tim,register(pt,b))<pos_fb(tim-1,v_regi) &&
(pos_fb(tim,register(pt,a))>pos_fb(tim-1,v_regi))) && ref_found2==0)
    ref_v=register(pt,a);
    ref_found2=1;
elseif (register(pt,a)>0 && register(pt,a)~=v_regi) &&(register(pt,b)>0 &&
register(pt,b)~=v_regi) && new_veh_ref==0 &&
((pos_fb(tim,register(pt,a))<pos_fb(tim,register(pt,b))) &&
(pos_fb(tim,register(pt,a))<pos_fb(tim-1,v_regi) &&
(pos_fb(tim,register(pt,b))>pos_fb(tim-1,v_regi))) && ref_found2==0)
    ref_v=register(pt,b);
    ref_found2=1;
```

```
elseif (register(pt,a)>0 && register(pt,a)~=v_regi) &&(register(pt,b)>0 &&
register(pt,b)~=v_regi) && new_veh_ref==1 &&
((pos_fb(tim,register(pt,a))>pos_fb(tim,register(pt,b))))
    ref_v=register(pt,b);
    ref_found2=1;
elseif (register(pt,a)>0 && register(pt,a)~=v_regi) &&(register(pt,b)>0 &&
register(pt,b)~=v_regi) && new_veh_ref==1 &&
((pos_fb(tim,register(pt,a))<pos_fb(tim,register(pt,b))) && ref_found2==0)
    ref_v=register(pt,a);
    ref_found2=1;

elseif xor(register(pt,a)>0, register(pt,b)>0) && (register(pt,a)~=v_regi
&& register(pt,b)~=v_regi) && ref_found2==0 && new_veh_ref==0 &&
(register(pt,a)>0 && (pos_fb(tim,register(pt,a))>pos_fb(tim-1,v_regi)))
    ref_v=register(pt,a);
    ref_found2=1;
elseif xor(register(pt,a)>0, register(pt,b)>0) && (register(pt,a)~=v_regi
&& register(pt,b)~=v_regi) && ref_found2==0 && new_veh_ref==0 &&
(register(pt,b)>0 && (pos_fb(tim,register(pt,b))>pos_fb(tim-1,v_regi)))
    ref_v=register(pt,b);
    ref_found2=1;
elseif xor(register(pt,a)>0, register(pt,b)>0) && (register(pt,a)~=v_regi
&& register(pt,b)~=v_regi) && ref_found2==0 && new_veh_ref==1 &&
(register(pt,a)>0)
    ref_v=register(pt,a);
    ref_found2=1;
elseif xor(register(pt,a)>0, register(pt,b)>0) && (register(pt,a)~=v_regi
&& register(pt,b)~=v_regi) && ref_found2==0 && new_veh_ref==1 &&
(register(pt,b)>0)
    ref_v=register(pt,b);
    ref_found2=1;
```

Code section

```
%%Stage 2: Scanning the rear bumper patch registers on the OV current
patch%%

%In situations where no front bumper at the first stage was detected rear
%bumpers were then scanned for. The patch registers for rear bumpers
%where c and d. The OV current patch was scanned for rear bumpers and
%when rear bumper was detected, its front bumper was compared with the
%position of the OV front bumper. A vehicle with a detected rear bumper on
%the scanned patch which had its front bumper ahead of the OV front bumper
%became the lead vehicle of the OV.
elseif ((register(pt,c)==0&&register(pt,d)==0) && ((register(pt,a)>0 &&
register(pt,a)~=v_regi) ||(register(pt,b)>0 && register(pt,b)~=v_regi)) &&
ref_found2==0 && new_veh_ref==0 && (register(pt,a)>0 &&
register(pt,a)~=v_regi && (pos_fb(tim,register(pt,a))>pos_fb(tim-
1,v_regi)))
    ref_v=register(pt,a);
    ref_found=1;
elseif ((register(pt,c)==0&&register(pt,d)==0) && ((register(pt,a)>0 &&
register(pt,a)~=v_regi) ||(register(pt,b)>0 && register(pt,b)~=v_regi)) &&
ref_found2==0 && new_veh_ref==0 && (register(pt,b)>0 &&
register(pt,b)~=v_regi && (pos_fb(tim,register(pt,b))>pos_fb(tim-
1,v_regi))&&ref_found==0)
    ref_v=register(pt,b);
    ref_found=1;
elseif ((register(pt,c)==0&&register(pt,d)==0) && ((register(pt,a)>0 &&
register(pt,a)~=v_regi) ||(register(pt,b)>0 && register(pt,b)~=v_regi)) &&
ref_found2==0 && new_veh_ref==1 && (register(pt,a)>0 &&
register(pt,a)~=v_regi)
    ref_v=register(pt,a);
    ref_found=1;
elseif ((register(pt,c)==0&&register(pt,d)==0) && ((register(pt,a)>0 &&
register(pt,a)~=v_regi) ||(register(pt,b)>0 && register(pt,b)~=v_regi)) &&
ref_found2==0 && new_veh_ref==1 && (register(pt,b)>0 &&
register(pt,b)~=v_regi && ref_found==0)
    ref_v=register(pt,b);
    ref_found=1;

elseif register(pt,c)>0&&register(pt,d)>0 && ref_found==0 && new_veh_ref==0
&& ((pos_rb(tim,register(pt,c))>pos_rb(tim,register(pt,d))) &&
register(pt,c)~=v_regi && (pos_fb(tim,register(pt,c))>pos_fb(tim-
1,v_regi)))
    ref_v=register(pt,c);
    ref_found=1;
elseif register(pt,c)>0&&register(pt,d)>0 && ref_found==0 && new_veh_ref==0
&& (pos_rb(tim,register(pt,c))<pos_rb(tim,register(pt,d)) &&
register(pt,d)~=v_regi && (pos_fb(tim,register(pt,d))>pos_fb(tim-1,v_regi))
&& ref_found==0)
    ref_v=register(pt,d);
    ref_found=1;
```

```
elseif register(pt,c)>0&&register(pt,d)>0 && ref_found==0 && new_veh_ref==1
&& ((pos_rb(tim,register(pt,c))>pos_rb(tim,register(pt,d))) &&
register(pt,c)~=v_regi)
     ref_v=register(pt,c);
     ref_found=1;
elseif register(pt,c)>0&&register(pt,d)>0 && ref_found==0 && new_veh_ref==1
&& (pos_rb(tim,register(pt,c))<pos_rb(tim,register(pt,d)) &&
register(pt,d)~=v_regi && ref_found==0)
     ref_v=register(pt,d);
     ref_found=1;

elseif xor(register(pt,c)>0, register(pt,d)>0) && (register(pt,c)~=v_regi
&& register(pt,d)~=v_regi) && ref_found==0 &&  new_veh_ref==0 &&
(register(pt,c)>0 && register(pt,c)~=v_regi &&
(pos_fb(tim,register(pt,c))>pos_fb(tim-1,v_regi)))
     ref_v=register(pt,c);
     ref_found=1;
elseif xor(register(pt,c)>0, register(pt,d)>0) && (register(pt,c)~=v_regi
&& register(pt,d)~=v_regi) && ref_found==0 &&  new_veh_ref==0 &&
(register(pt,d)>0 && register(pt,d)~=v_regi &&
(pos_fb(tim,register(pt,d))>pos_fb(tim-1,v_regi))  && ref_found==0)
     ref_v=register(pt,d);
     ref_found=1;
elseif xor(register(pt,c)>0, register(pt,d)>0) && (register(pt,c)~=v_regi
&& register(pt,d)~=v_regi) && ref_found==0 &&  new_veh_ref==1 &&
(register(pt,c)>0 && register(pt,c)~=v_regi)
     ref_v=register(pt,c);
     ref_found=1;
elseif xor(register(pt,c)>0, register(pt,d)>0) && (register(pt,c)~=v_regi
&& register(pt,d)~=v_regi) && ref_found==0 &&  new_veh_ref==1 &&
(register(pt,d)>0 && register(pt,d)~=v_regi && ref_found==0)
     ref_v=register(pt,d);
     ref_found=1;
```

Code section

```
%%%Segment2: Scanning other patches for a lead vehicle%%%

%In a situation where no lead vehicle was found at the current patch of
%the OV, the scan proceeded to scan other patches for the lead vehicle.
%The next couple of stages were enclosed in a loop which ran from the OV
%current patch number down to patch 1. During each iteration the registers
%of the patch with the same value as the loop were scanned. And the same
%steps similar to stages 1 and 2 were followed i.e. the front and rear
%registers were scanned.

%%Stage 1b: Scanning the front bumper patch registers on the other
patches%%
elseif (register(pt,c)==0&&register(pt,d)==0) && ref_found==0 ||
(register(pt,c)>0 && register(pt,d)==0 && register(pt,c)==v_regi) &&
ref_found==0  || (register(pt,c)==0&&register(pt,d)>0 &&
register(pt,d)==v_regi) && ref_found==0
    for q=pt-1:-1:1
        if (register(q,a)>0 && register(q,a)~=v_regi) &&(register(q,b)>0 &&
register(q,b)~=v_regi) && new_veh_ref==0 &&
((pos_fb(tim,register(q,a))>pos_fb(tim,register(q,b))) &&
(pos_fb(tim,register(q,b))>pos_fb(tim-1,v_regi)))
            ref_v=register(q,b);
            found_ref=1;
        elseif (register(q,a)>0 && register(q,a)~=v_regi)
&&(register(q,b)>0 && register(q,b)~=v_regi) && new_veh_ref==0 &&
((pos_fb(tim,register(q,a))>pos_fb(tim,register(q,b))) &&
(pos_fb(tim,register(q,b))>pos_fb(tim-1,v_regi)))
            ref_v=register(q,a);
            found_ref=1;
        elseif (register(q,a)>0 && register(q,a)~=v_regi)
&&(register(q,b)>0 && register(q,b)~=v_regi) && new_veh_ref==0 &&
((pos_fb(tim,register(q,a))>pos_fb(tim,register(q,b))) &&
(pos_fb(tim,register(q,b))<pos_fb(tim-1,v_regi) &&
(pos_fb(tim,register(q,a))>pos_fb(tim-1,v_regi))) && found_ref==0)
            ref_v=register(q,a);
            found_ref=1;
        elseif (register(q,a)>0 && register(q,a)~=v_regi)
&&(register(q,b)>0 && register(q,b)~=v_regi) && new_veh_ref==0 &&
((pos_fb(tim,register(q,a))<pos_fb(tim,register(q,b))) &&
(pos_fb(tim,register(q,a))<pos_fb(tim-1,v_regi) &&
(pos_fb(tim,register(q,b))>pos_fb(tim-1,v_regi))) && found_ref==0)
            ref_v=register(q,b);
            found_ref=1;
        elseif (register(q,a)>0 && register(q,a)~=v_regi)
&&(register(q,b)>0 && register(q,b)~=v_regi) && new_veh_ref==1 &&
((pos_fb(tim,register(q,a))>pos_fb(tim,register(q,b))))
            ref_v=register(q,b);
            found_ref=1;
```

```
        elseif (register(q,a)>0 && register(q,a)~=v_regi)
&&(register(q,b)>0 && register(q,b)~=v_regi) && new_veh_ref==1 &&
((pos_fb(tim,register(q,a))<pos_fb(tim,register(q,b))) && found_ref==0)
            ref_v=register(q,a);
            found_ref=1;

        elseif xor(register(q,a)>0, register(q,b)>0) &&
(register(q,a)~=v_regi && register(q,b)~=v_regi) && found_ref==0 &&
new_veh_ref==0 && (register(q,a)>0 &&
(pos_fb(tim,register(q,a))>pos_fb(tim-1,v_regi)))
            ref_v=register(q,a);
            found_ref=1;
        elseif xor(register(q,a)>0, register(q,b)>0) &&
(register(q,a)~=v_regi && register(q,b)~=v_regi) && found_ref==0 &&
new_veh_ref==0 && (register(q,b)>0 &&
(pos_fb(tim,register(q,b))>pos_fb(tim-1,v_regi)))
            ref_v=register(q,b);
            found_ref=1;
        elseif xor(register(q,a)>0, register(q,b)>0) &&
(register(q,a)~=v_regi && register(q,b)~=v_regi) && found_ref==0 &&
new_veh_ref==1 && (register(q,a)>0)
            ref_v=register(q,a);
            found_ref=1;
        elseif xor(register(q,a)>0, register(q,b)>0) &&
(register(q,a)~=v_regi && register(q,b)~=v_regi) && found_ref==0 &&
new_veh_ref==1 && (register(q,b)>0)
            ref_v=register(q,b);
            found_ref=1;
```

Code section

```
%Similar to scan stage 2a, in situations where no front bumper at scan
%stage 1b was detected rear bumpers were then scanned for.
%The patch registers for rear bumpers where c and d.
%The patch in focus was scanned for rear bumpers and when a rear bumper was
detected,
%its front bumper was compared with the position of the OV front bumper.
%A vehicle with a detected rear bumper on the scanned patch which had
%its front bumper ahead of the OV front bumper became the lead vehicle of
the OV.
        elseif ((register(q,c)==0&&register(q,d)==0) && ((register(q,a)>0
&& register(q,a)~=v_regi) ||(register(q,b)>0 && register(q,b)~=v_regi)) &&
found_ref==0 && new_veh_ref==0 && (register(q,a)>0 && register(q,a)~=v_regi
&& (pos_fb(tim,register(q,a))>pos_fb(tim-1,v_regi)))
            ref_v=register(q,a);
            ref_found=1;
        elseif ((register(q,c)==0&&register(q,d)==0) && ((register(q,a)>0
&& register(q,a)~=v_regi) ||(register(q,b)>0 && register(q,b)~=v_regi)) &&
found_ref==0 && new_veh_ref==0 && (register(q,b)>0 && register(q,b)~=v_regi
&& (pos_fb(tim,register(q,b))>pos_fb(tim-1,v_regi))&&ref_found==0)
            ref_v=register(q,b);
            ref_found=1;
        elseif ((register(q,c)==0&&register(q,d)==0) && ((register(q,a)>0
&& register(q,a)~=v_regi) ||(register(q,b)>0 && register(q,b)~=v_regi)) &&
found_ref==0 && new_veh_ref==1 && (register(q,a)>0 &&
register(q,a)~=v_regi)
            ref_v=register(q,a);
            ref_found=1;
        elseif ((register(q,c)==0&&register(q,d)==0) && ((register(q,a)>0
&& register(q,a)~=v_regi) ||(register(q,b)>0 && register(q,b)~=v_regi)) &&
found_ref==0 && new_veh_ref==1 && (register(q,b)>0 && register(q,b)~=v_regi
&& ref_found==0)
            ref_v=register(q,b);
            ref_found=1;

        elseif register(q,c)>0 && register(q,d)>0 &&  found_ref==0 &&
new_veh_ref==0 && (pos_rb(tim,register(q,c))>pos_rb(tim,register(q,d)) &&
(pos_fb(tim,register(q,d))>pos_fb(tim-1,v_regi)))
            ref_v=register(q,d);
            found_ref=1;
        elseif register(q,c)>0 && register(q,d)>0 &&  found_ref==0 &&
new_veh_ref==0 && (pos_rb(tim,register(q,c))<pos_rb(tim,register(q,d)) &&
(pos_fb(tim,register(q,c))>pos_fb(tim-1,v_regi)))
            ref_v=register(q,c);
            found_ref=1;
        elseif register(q,c)>0 && register(q,d)>0  && found_ref==0 &&
new_veh_ref==0 && (pos_rb(tim,register(q,c))>pos_rb(tim,register(q,d)) &&
(pos_fb(tim,register(q,d))<pos_fb(tim-1,v_regi))
&&((pos_fb(tim,register(q,c))>pos_fb(tim-1,v_regi))))
            ref_v=register(q,c);
```

```
        elseif register(q,c)>0 && register(q,d)>0 &&  found_ref==0 &&
new_veh_ref==0 && (pos_rb(tim,register(q,c))<pos_rb(tim,register(q,d)) &&
(pos_fb(tim,register(q,c))<pos_fb(tim-1,v_regi))
&&((pos_fb(tim,register(q,d))>pos_fb(tim-1,v_regi))))
            ref_v=register(q,d);
            found_ref=1;
        elseif register(q,c)>0 && register(q,d)>0 &&  found_ref==0 &&
new_veh_ref==1 && (pos_rb(tim,register(q,c))>pos_rb(tim,register(q,d)))
            ref_v=register(q,d);
            found_ref=1;
        elseif register(q,c)>0 && register(q,d)>0 &&  found_ref==0 &&
new_veh_ref==1 && (pos_rb(tim,register(q,c))<pos_rb(tim,register(q,d)))
            ref_v=register(q,c);
            found_ref=1;

        elseif xor(register(q,c)>0, register(q,d)>0)  &&  found_ref==0 &&
new_veh_ref==0 && (register(q,c)>0 && register(q,c)~=v_regi &&
(pos_fb(tim,register(q,c))>pos_fb(tim-1,v_regi)))
            ref_v=register(q,c);
            found_ref=1;
        elseif xor(register(q,c)>0, register(q,d)>0)  &&  found_ref==0 &&
new_veh_ref==0 && (register(q,d)>0 && register(q,d)~=v_regi &&
(pos_fb(tim,register(q,d))>pos_fb(tim-1,v_regi)))
            ref_v=register(q,d);
            found_ref=1;
        elseif xor(register(q,c)>0, register(q,d)>0)  &&  found_ref==0 &&
new_veh_ref==1 && (register(q,c)>0 && register(q,c)~=v_regi)
            ref_v=register(q,c);
            found_ref=1;
        elseif xor(register(q,c)>0, register(q,d)>0)  &&  found_ref==0 &&
new_veh_ref==1 && (register(q,d)>0 && register(q,d)~=v_regi)
            ref_v=register(q,d);
            found_ref=1;
        end
        if found_ref==1   %exits the for loop if the patch containing a
lead vehicle have been found
            break;
        end
    end
end
```

Code section

```
%%%Scanning for the Observed vehicle's following vehicle %%%

%Scanning for the following vehicle had only a single stage in each segment
%because only the front bumpers were really considered. There were special
%cases were the rear bumpers were considered but this was only done to
%capture exceptions where the rear bumper of the OV and/or potential
following vehicles
%may be located outside the link

%%%Segment1: Scanning the OV's current patch for a following vehicle%%%
%Note than OV current patch here means the equivalent patch on its
neighbouring lane

%%Scanning the front bumper patch registers on the OV current patch%%

%The front bumper registers of the OV patch was scanned in this stage.
%Whenever a vehicle registration number was detected it was compared
%with the registration of the OV and was accepted as a different vehicle
%if it differed in value. Whenever two vehicles were present on the
%patch and none of them was the OV the positions of their front bumpers
%were compared and the one with the higher value was deemed the
%following vehicle of the OV if its front bumper position was less than
%that of the OV front bumper. If it was higher and the second vehicle's
%bumper was lower than the OV front bumper the second vehicle was then
%regarded as the following vehicle.
if lane_checker_mode==1
    %reference vehicle behind
    ref_found=0;
    ref_found2=0;
    found_ref=0;
    if (register(pt,a)>0 && register(pt,a)~=v_regi) &&(register(pt,b)>0 &&
register(pt,b)~=v_regi) &&((pos_fb(tim,register(pt,a))<=pos_fb(tim-
1,v_regi))||(pos_fb(tim,register(pt,b))<=pos_fb(tim-1,v_regi))) &&
((pos_fb(tim,register(pt,a))>pos_fb(tim,register(pt,b))) &&
(pos_fb(tim,register(pt,a))<=pos_fb(tim-1,v_regi)))
        ref_v_B=register(pt,a);
        ref_found2=1;
    elseif (register(pt,a)>0 && register(pt,a)~=v_regi) &&(register(pt,b)>0
&& register(pt,b)~=v_regi) &&((pos_fb(tim,register(pt,a))<=pos_fb(tim-
1,v_regi))||(pos_fb(tim,register(pt,b))<=pos_fb(tim-1,v_regi))) &&
((pos_fb(tim,register(pt,a))<pos_fb(tim,register(pt,b))) &&
(pos_fb(tim,register(pt,b))<=pos_fb(tim-1,v_regi)) && ref_found2==0)
        ref_v_B=register(pt,b);
        ref_found2=1;

    elseif ((register(pt,c)==0&&register(pt,d)==0) && ((register(pt,a)>0 &&
register(pt,a)~=v_regi) ||(register(pt,b)>0 && register(pt,b)~=v_regi)) &&
ref_found2==0 && (register(pt,a)>0 && register(pt,a)~=v_regi &&
(pos_fb(tim,register(pt,a))<=pos_fb(tim-1,v_regi)))
        ref_v_B=register(pt,a);
        ref_found=1;
```

```
    elseif ((register(pt,c)==0&&register(pt,d)==0) && ((register(pt,a)>0 &&
register(pt,a)~=v_regi) ||(register(pt,b)>0 && register(pt,b)~=v_regi))) &&
ref_found2==0 && (register(pt,b)>0 && register(pt,b)~=v_regi &&
(pos_fb(tim,register(pt,b))<=pos_fb(tim-1,v_regi)) && ref_found==0)
          ref_v_B=register(pt,b);
          ref_found=1;

    elseif register(pt,a)>0&&register(pt,b)>0 && ref_found==0  &&
((pos_fb(tim,register(pt,a))>pos_fb(tim,register(pt,b))) &&
register(pt,a)~=v_regi && (pos_fb(tim,register(pt,a))<=pos_fb(tim-
1,v_regi)))
          ref_v_B=register(pt,a);
          ref_found=1;
    elseif register(pt,a)>0&&register(pt,b)>0 && ref_found==0 &&
(pos_rb(tim,register(pt,a))<pos_rb(tim,register(pt,b)) &&
register(pt,b)~=v_regi && (pos_fb(tim,register(pt,b))<=pos_fb(tim-
1,v_regi))&&ref_found==0)
          ref_v_B=register(pt,b);
          ref_found=1;


    elseif xor(register(pt,a)>0, register(pt,b)>0) &&
(register(pt,a)~=v_regi && register(pt,b)~=v_regi) && ref_found==0 &&
(register(pt,a)>0 && register(pt,a)~=v_regi &&
(pos_fb(tim,register(pt,a))<=pos_fb(tim-1,v_regi)))
          ref_v_B=register(pt,a);
          ref_found=1;
    elseif xor(register(pt,a)>0, register(pt,b)>0) &&
(register(pt,a)~=v_regi && register(pt,b)~=v_regi) && ref_found==0  &&
(register(pt,b)>0 && register(pt,b)~=v_regi &&
(pos_fb(tim,register(pt,b))<=pos_fb(tim-1,v_regi)) && ref_found==0)
          ref_v_B=register(pt,b);
          ref_found=1;
```

Code section

```
%%%Segment2: Scanning predecessor patches for a following vehicle%%%
%Note than OV current patch here meant the equivalent patch on its
neighbouring lane

%%Scanning the front bumper patch registers on the OV current patch%%
%whenever no following vehicle was found on the first scan segment the
search was
%then extended to the second segment patches below the OV's current patch
%was subsequently scanned similar to segment 1. Only the front bumper
%registers were considered and the position of detected front bumpers were
%compared to the OV's front bumper. When two front bumpers were detected
%behind the OV's front bumper the closest to the OV's front bumper
%was chosen as the following vehicle. A flag was used to break out of the
%search loop whenever a reference vehicle was found to prevent it from
%being overwritten and to increase simulation speed.
    elseif (register(pt,a)==0&&register(pt,b)==0) && ref_found==0 ||
(register(pt,a)>0 && register(pt,b)==0 && register(pt,a)==v_regi) &&
ref_found==0  || (register(pt,a)==0&&register(pt,b)>0 &&
register(pt,b)==v_regi) && ref_found==0
        for q=pt+1:125
%finding the next pt ahead containing vehicles
            if register(q,a)>0 && register(q,b)>0 &&
(pos_fb(tim,register(q,a))>=pos_fb(tim,register(q,b)) &&
(pos_fb(tim,register(q,a))<pos_fb(tim-1,v_regi)))
                ref_v_B=register(q,a);
                found_ref=1;
            elseif register(q,a)>0 && register(q,b)>0 &&
(pos_fb(tim,register(q,a))<pos_fb(tim,register(q,b)) &&
(pos_fb(tim,register(q,b))<pos_fb(tim-1,v_regi)))
                ref_v_B=register(q,b);
                found_ref=1;

            elseif xor(register(q,a)>0, register(q,b)>0) &&
(register(q,a)>0 && (pos_fb(tim,register(q,a))<pos_fb(tim-1,v_regi)))
                ref_v_B=register(q,a);
                found_ref=1;
            elseif xor(register(q,a)>0, register(q,b)>0) &&
(register(q,b)>0 && (pos_fb(tim,register(q,b))<pos_fb(tim-1,v_regi)))
                ref_v_B=register(q,b);
                found_ref=1;
            end
            if found_ref==1
%exits the for loop if the next pt containing rear bumper have been found
                break;
            end
        end
    end
end

end
```

Code section

```
%Step 1

%The first step when converting distances to patches was to obtain the
%generated patch table. The next step was to deduce the position of the
%rear bumper of the vehicle based on the position of its front bumper and
%the total length of the vehicle. The next step was to round the positions
%of the bumpers to whole numbers, whenever the rounded number was less than
%the original number the rounded number was incremented this was done to
%ensure the correct patches were selected for example 8.1m was rounded up
to 8m
%and would need to be incremented to 9m because 8.1m would be located on
the 124th
%patch rather than the 125th patch which contained values from 1-8m

patches=patches_table;

pos_r=pos-veh_len;

%rounding up positions to integer
int_pos=round(pos);
int_pos_r=round(pos_r);


if int_pos<pos
    rnd_pos=int_pos+1;
elseif int_pos>=pos
    rnd_pos=int_pos;
end

if int_pos_r<pos_r
    rnd_pos_r=int_pos_r+1;
elseif int_pos_r>=pos_r
    rnd_pos_r=int_pos_r;
end

%Step 2

%This step was used to find the patch associated with the rounded position.
%A MATLAB function 'find' was used to search the generated patch look up
%table for the rounded value. The function indices of the value on the look
%up table was given if found. Only the column index was of interest as it
%indicated the patch of the rounded number on the look up table. Filters
%were used to ensure only values within the range of 1 to 1000 were
%searched for and other values were assumed to be 0 (i.e. out of range)
%which could only occur when a vehicle was exiting the link or when a
%vehicle was entering the link and its rear bumper was still situated
outside the link.

if rnd_pos<1||rnd_pos>1000
    patch_find=0;
else
    [row,patch_find] = find(patches==rnd_pos);
end

if rnd_pos_r<1||rnd_pos_r>1000
    patch_find_r=0;
else
    [row,patch_find_r] = find(patches==rnd_pos_r);
end
```

Code section

```
%The array 'patches' where the designated distances were saved was 8 cells
%long and 125cells wide. The first for loop counted down from 1000 to 1 in
%steps of 8 and the value a variable 'a' was assigned as the value of the
%loop during the iterations, a variable 'patch' was also incremented during
%the iterations. The second loop ran from 2 to 8 and the value of the loop
%was used to select the rows of the array 'patches'. The loop started from
%2 because the value of
%the first loop was assigned to the first row of the corresponding column.
%In the second loop during the iterations the cell with coordinates
%corresponding to the values of the first and second loop was filled with
%the value of the variable 'a' less the value of the second loop minus 1
%since the first cell of each column was assigned the value of the first
%loop during iterations and the second loop started with the second cell.

patches=zeros(8,125);
patch=0;
a=0;

for i=1000:-8:1
a=i;
patch=patch+1;
patches(1,patch)=a;
for fil=2:8                              %cells of each patch fills up by
subtracting the cell number from the original countdown value
    patches(fil,patch)=a-(fil-1);
end
end
```

Code section

```
%The stopping time of the reference vehicle (lead or following) vehicle was
%calculated by dividing the velocity of the vehicle by its maximum
%deceleration rate.
%The maximum deceleration rate was multipled by -1 to remove the brake
negative sign
Refv_brake_time=Ref_veh_vel/(max_brake_L*(-1));

%Similarly, the stopping time of the observed vehicle
%was calculated by dividing the velocity of the vehicle by its maximum
deceleration rate.
%The maximum deceleration rate was multipled by -1 to remove the brake
negative sign
brake_time=velocity/(max_brake*(-1));

%The stopping distance of the reference vehicle (lead or following) vehicle
was
%calculated by multiplying the product of its velocity and its stopping
time by 0.5.
Refv_dist_b=0.5*Ref_veh_vel*Refv_brake_time;

%Similarly,the stopping distance of the observed vehicle was calculated by
multiplying the product
%of its velocity and its stopping time by 0.5.
dist_b=0.5*velocity*brake_time;

%If braking distance of vehicle and position of front bumper of vehicle
%would result in collision with ref veh (i.e. greater than traffic gap).
```

```
%Used with lane changing function

%A variable 'used_for_lane' was set to high when the function was being
used along with the
%lane change function and set to low when it was used as a fail proof for
the
%paramics car following function. When it was used along with the lane
%change function, the displacement of the observed vehicle was first
calculated.
%This was done because the observed driver had to assume its vehicle was in
%the target position and not its current position when determining if a
%collision would potentially occur. Although the response time of the
driver
%was considered under paramics car following function it was not considered
%under this function to reduce the complexity of the program.
%Ideally in order to take the driver's response time/awareness
%level into account, the driver of the current vehicle should have some
time
%delay when observing the parameters of the reference vehicle hence it
should
%observe the parameters at a few time steps behind the current time step.
%Since 1 time step equals 100 milliseconds (ms) a response time of 2
seconds
%would be equivalent to 20 time steps. To determine if there would
%potentially be a collision the sum of the position of the observed vehicle
front bumper,
%its displacement for the current time as well as its stopping distance was
compared to the
%sum of the reference vehicle rear and its stopping distance minus the
%minimum traffic gap. A potential collision was flagged whenever the first
%equation was greater than or equals the second or if a collision had
%already occured, it was not flagged when the first equation was less than
%the second equation or when there was no collision.
%It should be noted that the reference vehicle here referred to the lead
vehicle
%while the observed vehicle referred to the following vehicle hence the
%reference vehicle may actually be the observed vehicle if it was observing
%the following vehicle on the neighbouring lane.

if Used_for_lane==1
    % Displacement
    displ_buf= (velocity*0.1)+(1/2*(acceler*(0.1)^2));

    %Preventing negative displacements
    if displ_buf<0
        displ=0;
    elseif displ_buf>=0
        displ=displ_buf;
    end

    if (veh_fb+displ+dist_b)>=((refv_rb+Refv_dist_b)-
(traf_gap))||refv_rb<=veh_fb
        collide=1;
    elseif (veh_fb+displ+dist_b)<((refv_rb+Refv_dist_b)-
(traf_gap))&&refv_rb>veh_fb
        collide=0;
    end
```

```
%Used with Paramics function

%When the function was used along side paramics function the variable
%'used_for_lane' was to low. The next step was then to determine if the
%gap (the gap plus the minimum gap between vehicles) between the lead and
%the observed vehicle was wide enough for the observed vehicle
%to accelerate at maximum rate (desired acceleration). The term desired
%acceleration was used because the maximum acceleration rate depended on
%the maximum rate the driver was comfortable with which was a percentage of
%the actual maximum acceleration rate of the vehicle. This was further
%explained in a different function. To determine if the gap was wide enough
%a threshold gap of 200m was chosen because it was at least 2 times wider
than
%the stopping distance at maximum speed of the different vehicles featured.
The gap between
%both vehicles was compared to this threshold and if the gap was wider it
%was assumed that the observed vehicle could safely accelerate at maximum
%rate. To determine if there would potentially be a collision
%the sum of the position of the observed vehicle front bumper and its
stopping
%distance was compared to the sum of the reference vehicle rear and its
stopping
%distance minus the minimum traffic gap. A potential collision was flagged
whenever the first
%equation was greater than or equals the second or if a collision had
%already occured, it was not flagged when the first equation was less than
%the second equation or when there was no collision.
%It should be noted that the reference vehicle here was always the lead
vehicle
%on the current lane while the observed vehicle was always the actual
observed vehicle
elseif Used_for_lane==0
%used to determine if the following vehicle can accelerate at a maximum
rate
    if (((refv_rb+Refv_dist_b)-(traf_gap))-(veh_fb+dist_b))>200
        safe_acc=1;
    end
    %determine if there is a collision
    if (veh_fb+dist_b)>=((refv_rb+Refv_dist_b)-(traf_gap))||refv_rb<=veh_fb
        collide=1;
    elseif (veh_fb+dist_b)<((refv_rb+Refv_dist_b)-
(traf_gap))&&refv_rb>veh_fb
        collide=0;
    end
end
end
```

Code section

```
%Determine if the velocity of the lead vehicle is constantly reducing for 5
%clock cycles or if the lead vehicle is stationary
if (vellead_fiveago-vellead_fourago)>0&&(vellead_fourago-
vellead_threeago)>(vellead_fiveago-vellead_fourago)&&(vellead_threeago-
vellead_twoago)>(vellead_fourago-vellead_threeago)&&(vellead_twoago-
vellead_oneago)>(vellead_threeago-
vellead_twoago)||(vellead==0&&awarenes_validity>0);
    Braking_verification_Leadcar=1;
else
    Braking_verification_Leadcar=0;
end
```

Code section

```
%The array s holds the test results for the observed vehicle for each time
%step. The velocity of the lead vehicle for the 5 consecutive time steps
%been observed are fed into the function. These time steps are a total of
%the response time plus the time step number
[s(t,v_req)]=Leadcar_braking_verification(vel(t-(5+Aw_lev),ref_veh),vel(t-
(4+Aw_lev),ref_veh),vel(t-(3+Aw_lev),ref_veh),vel(t-
(2+Aw_lev),ref_veh),vel(t-(1+Aw_lev),ref_veh),vel(t-
(0+Aw_lev),ref_veh),ign);
```

Code section

```
%Power to weight ratio of the vehicle
w=P/(m*g);

%optimum speed or the speed at which the vehicle attains its full power
u0=(1164*w)-0.75;

%gear reduction factor. Accounts for the gear shift impacts at low traveling speeds when trucks (vehicle) is accelerating
B=(1/u0)*(1+min(u,u0)*(1-(1/u0)));

if veh_tp==1
    %The the engine tractive force for smaller vehicles
    FT=3600*y*(P/u);
elseif veh_tp==2
    %the engine tractive force for trucks
    FT=3600*B*y*(P/u);
end

%the mass of the vehicle on the tractive axle (kg)
Mta=Mta_F*m;

%the maximum force that can be sustained between the vehicle's tractive axle tires and the roadway surface
Fmax=Mta*g*n;

%The tractive force is then computed as the minimum of the two forces
F=min(FT,Fmax);
```

Code section

```
%Resistance forces
C1=(p/(2*3.6^2));
Ch=1-((8.5*10^-5)*H);

%The aerodynamic resistance force (drag)
Ra=C1*Cd*Ch*A*u^2;

%The rolling resistance force
Rr=Cr*(C2*u+C3)*((m*g)/1000);

%The grade resistance force
Rg=m*g*k;

%The total resistance force
R=Ra+Rr+Rg;
```

Code section

```
%maximum acceleration by raka

%The maximum acceleration the driver
%is whilling to utilise
a_rak=fp*((F-R)/m);

%The maximum acceleration the driver is willing
%to utilise under inclement weather condition
max_accel_rak=a_rak-fp*g*i;
```

Code section

```
%maximum deceleration
max_dec_rak=E*n*g*(1-(0.7758*i));
```

Code section

```
switch condition
    %dry
    case 1
        n=0.6;
        n=n*1;
        Cr=1.25;
    %light rain
    case 2
        n=0.6;
        n=n*0.90;
        Cr=1.25;
    %light snow
    case 3
        n=0.6;
        n=n*0.90;
        Cr=1.25;

    %heavy rain
    case 4
        n=0.6;
        n=n*0.90;
        Cr=1.25;
    %heavy snow
    case 5
        n=0.6;
        n=n*0.25;
        Cr=1.25;
end
```

Code section

```
switch veh_type
    case 1                  %1995 Acura Protégé
        m=1670;             %mass of vehicle
        A=1.94;             %Vehicle frontal area (m(sqr))
        P=105.932;          %Capital letter P is the Power of the vehicle in KW
        Mta_F=0.515;        %fraction of the the mass of the vehicle on the tractive axle (kg)
        Cd=0.32;            %Drag coefficient
        veh_tp=1;           %veh type i.e small or big
    case 2                  %Mazda 2001
        m=1610;
        A=2.04;
        P=96.98;
        Mta_F=0.525;
        Cd=0.34;
        veh_tp=1;
    case 3                  %1995 BMW 740I
        m=2370;
        A=2.27;
        P=210.372;
        Mta_F=0.515;
        Cd=0.32;
        veh_tp=1;

    case 4              %Semi-trailer and low mass
        m=22208;
        A=6.8;
        P=260.78;
        Mta_F=0.40;
        Cd=0.70;
        veh_tp=2;
    case 5             %Semi-trailer with No aerodynamic aids and medium
        m=34263;
        A=7.0;
        P=260.78;
        Mta_F=0.40;
        Cd=0.78;
        veh_tp=2;
    case 6              %Semi-trailer with Full aerodynamic aids and high mass
        m=43910;
        A=10.0;
        P=260.78;
        Mta_F=0.40;
        Cd=0.58;
        veh_tp=2;
end
```

Code section

```
u=(velo_array(tim,veh_reg)*18)/5;   %velocity in km/h
E=1;                                %Brake efficiency. Anti locking brake is 100% Hence 1
g=9.8066;                           %Force of gravity
i=intensity;                        %rain intensity
fp=0.62;                            %Fraction of accel driver is willing to apply
H=599;                              %Altitude in meters found in the other paper
p=1.2256;                           %small letter p is the density of air at sea level and a temperature of 15°C (59°F) (equal to 1.2256 kg/m3)
C2=0.0328;                          %vehicle tyres type constant (radial) check paper 2 for further details
C3=4.575;                           %vehicle tyres type constant (radial) check paper 2 for further details
k=0;                                %Fraction of gradient of the road. Highest gradient should be 1
```

Code section

```
%A filter was used to set the output to 0 whenever it was either not a
%number or infinite which could occur in cases where the separation or
%the gap was 0
Output_Target=(separation^2)/gap;
if isnan(Output_Target)==1||isinf(Output_Target)==1
    Output_Target=0;
end
```

Code section

```
%Target
[T(t,v_reg)]=Target_p2(s(t,v_reg),g(t,v_reg));
```

Code section

```
%The Target point overshot acceleration was first
%calculated then limited to the maximum acceleration and
%deceleration of the vehicle using a different function.
%constant_b equals 0.1.
buffer_overshot_accel= constant_b*(Leadvehicle_velocity-velocity);
```

Code section

```
%grounding the target overshot acceleration to the max accel and max dec
if buffer_overshot_accel<=maximum_deceleration
    overshot_accel=maximum_deceleration;
elseif buffer_overshot_accel>=maximum_acceleration
    overshot_accel=maximum_acceleration;
else
    overshot_accel=buffer_overshot_accel;
end
```

Code section

```
%Target point overshot
[kaA(t,v_reg)]=buffer_accel_overshot(kb,vel(t,ref_veh),vel(t,v_reg));
%Limiting aA to max accel and max dec
[aA(t,v_reg)]=accel_overshot(kaA(t,v_reg),max_dec(t,v_reg),max_accel(t,v_reg));
```

Code section

```
Output_separation= headway*(velocity_ofleadvehicle-velocity_ofvehicle);
```

Code section

```
%A filter was used to set the output to 0 whenever it was either not a
%number or infinite which could occur in cases where the Target or
%the gap was 0
bufferpullingaway_accel=(constant_B*(Leadvehicle_velocity-velocity))+(constant_A*((gap-Target/Target)));

if isnan(bufferpullingaway_accel)==1||isinf(bufferpullingaway_accel)==1
    bufferpullingaway_accel=0;
end
```

Code section

```
%grounding aB to max accel and max dec
if bufferaccel_pullingaway<=maximum_deceleration
    accel_pullingaway=maximum_deceleration;
elseif bufferaccel_pullingaway>=maximum_acceleration
    accel_pullingaway=maximum_acceleration;
else
    accel_pullingaway=bufferaccel_pullingaway;
end
```

Code section

```
%aB Lead vehicle pulling away
[kaB(t,v_reg)]=bufferaccel_pullingaway2(g(t,v_reg),T(t,v_reg),kb,vel(t,ref_veh),vel(t,v_reg),ka);
%Limiting aB to max accel and max dec
[aB(t,v_reg)]=accel_pullingaway(kaB(t,v_reg),max_dec(t,v_reg),max_accel(t,v_reg));
```

Code section

```
bunch_acc=Constant_A*((gap-traffic_gap)/gap);
```

Code section

```
%A filter was used to set the output to 0 whenever it was either not a
%number or infinite which could occur in cases where the numerator or the
%denominator equation resulted in a 0
buffercruise_accel=bunching_accel-(((Leadvehicle_velocity-vehicle_velocity)^2)/((gap-Target)));

if isnan(buffercruise_accel)==1||isinf(buffercruise_accel)==1
    buffercruise_accel=0;
end
end
```

Code section

```
%grounding aC to max accel and max dec
if buffercruise_accel<=maximum_deceleration
    cruise_accel=maximum_deceleration;
elseif buffercruise_accel>=maximum_acceleration
    cruise_accel=maximum_acceleration;
else
    cruise_accel=buffercruise_accel;
end
```

Code section

```
%Vehicles at constant speed or coming together (cruise accel)
[kaC(t,v_reg)]=bufferaccel_cruise2(vel(t,ref_veh),vel(t,v_reg),g(t,v_reg),T(t,v_reg),c(t,v_reg));
%Limiting aC to max accel and max dec
[aC(t,v_reg)]=accel_cruise(kaC(t,v_reg),max_dec(t,v_reg),max_accel(t,v_reg));
```

Code section

```
%settings
congestion=on;                  %Congestion at the end of the link?
traffic_light=off;              %Using traffic light or not using traffic light. 1=using traffic light, 0=not using traffic light
stop_line_status=off;           %If not using traffic light should the stop line be on or off?
uniform_veh=on;                 %Using uniform or mixed vehicles (uniform on or off?)
choose_veh=large;               %if using uniform vehicles then using small or large vehicles?
ratio=4;                        %If vehicles are not uniform enter the ratio of large to small vehicles. i.e. 1:ratio
condition=1;                    %Weather condition: 1 dry; 2 light rain; 3 heavy rain; 4 light snow; 5 heavy snow
no_lane=4;                      %Maximum number of lanes. Error if higher than 4 or less than 1
```

Code section

```
%first vehicle gets given a registeration number
v_reg=1;

%The Lane of the 1st vehicle for the 1st time step
lanes(t,v_reg)=1;               %the first vehicle spawns in lane one
lane_dens(1,1)=1;

%position of the 1st vehicle's front bumper for the first
%time step
posit_f(t,v_reg)=0.1;           %New vehicles appears at 0.1. i.e cell 1 pa 125
```

```
%The first vehicle gets given a vehicle type depending on
%the combination of vehicles the user selected.
if uniform_veh==on
    if choose_veh==small
        veh_len(1,v_reg)=small_L;
        veh_type(1,v_reg)=1;
    elseif choose_veh==large
        veh_len(1,v_reg)=big_L;
        veh_type(1,v_reg)=4;
    end
elseif uniform_veh==off
    veh_len(1,v_reg)=small_L;
    veh_type(1,v_reg)=1;
  %Kept track of the current small vehicle type. resetted
  %to zero when all types had been used
    L_veh_type_cnt=1;
  %counts the number of small vehicles,
  %when it is greater than the specified maximum value (ratio)
  %a larger vehicle enters and the counter resets
    veh_len_cnt=1;
end

%Position
%the position of the 1st vehicle rear bumper for the first time step
posit_r(t,v_reg)=posit_f(t,v_reg)-veh_len(1,v_reg);

%The 1st vehicle's front and rear bumpers patch locations
[p_frt,p_rer]=patch_finder2(posit_f(t,v_reg),veh_len(1,v_reg),patch_table);

%register vehicle front bumper to its current patch. The
%rear bumper would be outside the link so cannot be
%registered
patch_veh_reg(p_frt,1)=v_reg;
ref(t,v_reg)=0;

%acceleration
%The 1st vehicle maximum acceleration for the 1st time step
[max_accel(t,v_reg),max_dec(t,v_reg)]=Maximum_accelndecel_raka(v_reg,t,vel(:,:),condition,veh_type(1,v_reg),intensity);
%The 1st vehicle driver accelerates at its desired maximum acceleration
accel(t,v_reg)=max_accel(t,v_reg);

%The 1st vehicle entry time is taken into account
sta_tim(1,v_reg)=t;
%The density on the link is incremented
count_Den=count_Den+1;
%Kept account of vehicles entering and exiting the link
%If cell 1 is high a vehicle entered at that time step,
%if cell 2 high a vehicle exited at that time step
traff_flow(t,1)=1;

timer1=t;  %timer for when a vehicle last entered the link
```

Code section

```
%After the first time step
if t>1
    %search for vehicles in both front bumper registers of the current
    %patch. sw1 and sw2 change based on the current lane and accept
    %front bumber registers
    for sw=1:no_lane
        switch sw
            case 1
                sw1=1;
                sw2=2;
            case 2
                sw1=5;
                sw2=6;
            case 3
                sw1=9;
                sw2=10;
            case 4
                sw1=13;
                sw2=14;
        end
```

```
%vk changes between the current lane front bumper registers
for swb=1:2
%this loop was included for a scenario where reg b of a patch shifts
%to a after lane change and the code needs to re run a to avoid skipping
%the vehicle that shifted from b to a. the loop breaks if this shift never occured
    for shi=1:2
        shift=0;
        switch swb
            case 1
                vk=sw1;
            case 2
                vk=sw2;
        end

        %resetting parameters
        ref_veh=0;
        v_reg=0;
```

```
if patch_veh_reg(pa,vk)>0
    %to make referencing easier
    v_reg=patch_veh_reg(pa,vk);
    %run_check was used to prevent vehicles that may have switched lanes
    %(esp to d right) from running twice in the
    %same time step since the code runs from
    %the left lane to the right lane
    if run_check(t,v_reg)==0
        run_check(t,v_reg)=1;
        %Lanes maneouvering
        %The lane change function (i.e
        %overtake7) was used to determine the
        %current lane of the observed vehicle.
        %Other outputs were utilised by the
        %function to keep track of drivers
        %mindsets (e.g. interest levels)
```

```
[timer_N1(:,:),timer_N2(:,:),lanes(:,:),non_interest_counter(:,:),timer_ove
rtake(:,:),timer_change(:,:)]=overtake7(lanes(:,:),v_reg,veh,vel(:,:),max_v
el,g(:,:),t,timer_N1(:,:),timer_N2(:,:),non_interest_counter(:,:),patch_veh
_reg(:,:),pa,posit_f(:,:),posit_r(:,:),max_dec(:,:),stop_gap,
aA(:,:),aB(:,:),aC(:,:), accel(:,:),
max_accel(:,:),timer_overtake(:,:),timer_change(:,:),reset_lane_timers(:,:)
,veh_len(:,:),patch_table,no_lane);
```

```
%The OV current lane
cur_lane=lanes(t,v_reg);
%The OV previous lane
prev_lane=lanes(t-1,v_reg);
%If the current lane of the OV is
%different from its previous lane then
%increment its current lane and
%decrement its previous lane
if cur_lane~=prev_lane
    lane_dens(1,cur_lane)=lane_dens(1,cur_lane)+1;
    lane_dens(1,prev_lane)=lane_dens(1,prev_lane)-1;
end

%used to reset lane change timer for new vehicles
%after the vehicle with the same reg has exited the link
reset_lane_timers(1,v_reg)=0;
```

```
%Whenever a vehicle switched lanes the
%patch register had to be updated by
%deleting the vehicle's reg number from
%its previous patch register slot and
%entering it in its new patch register
%slot
if lanes(t,v_reg)~= lanes(t-1,v_reg)
    %Here the previous patch of the
    %vehicle was selected
    [p_frt,p_rer]=patch_finder2(posit_f(t-1,v_reg),veh_len(1,v_reg),patch_table);
    %Values were given to the
    %switch_board function, outputs were
    %based on the previous lane of the
    %observed vehicle
    [ a,b,C,d ] = switch_board(lanes(t-1,v_reg));
    %The patch register slot for the
    %previous lane front bumper was
    %reset here
    for dt=a:b
        if patch_veh_reg(p_frt,dt)==v_reg
            patch_veh_reg(p_frt,dt)=0;
            break;
        end
    end

%This step was used to move the reg no of any
%other vehicle on the previous lane
%of the observed vehicle from patch register slot 1
%to 2 i.e front bumper. Note this
%does not actually move the
%vehicle. It only allows lead
%vehicles to always be simulated
%before following vehicles on the
%same lane.
if patch_veh_reg(p_frt,a)==0
    patch_veh_reg(p_frt,a)=patch_veh_reg(p_frt,b);
    %used to determine the loop to break.
    %See above for better understanding
    if patch_veh_reg(p_frt,b)>0
        shift=1;
    end
    patch_veh_reg(p_frt,b)=0;
end

%The patch register slot for the
%previous lane rear bumper was
%reset here
for dt=C:d
    if patch_veh_reg(p_rer,dt)==v_reg
        patch_veh_reg(p_rer,dt)=0;
        break;
    end
end
```

```
%Although this may not affect the
%simulation since the front bumper
%positions were mainly used for the
%simulation, this step was done
%similar to the front bumper step
%for clarity
if patch_veh_reg(p_rer,C)==0
    patch_veh_reg(p_rer,C)=patch_veh_reg(p_rer,d);
    patch_veh_reg(p_rer,d)=0;
end

%Values were given to the
%switch_board function, outputs were
%based on the current lane of the
%observed vehicle
[ a,b,C,d ] = switch_board( lanes(t,v_reg) );
for dtt=a:b
    if patch_veh_reg(p_frt,dtt)==0
        patch_veh_reg(p_frt,dtt)=v_reg;
        break;
    end
end
```

```
    %The patch register slot for the
    %current lane front bumper was
    %updated here
    for dtt=C:d
        if patch_veh_reg(p_rer,dtt)==0
            patch_veh_reg(p_rer,dtt)=v_reg;
            break;
        end
    end
end
```

Code section

```
%A and B are variables pointing to the front bumper registers while C and D
%are pointing to the rear bumper registers. Values were assigned to the variables
%depending on the lane being observed. Each lane had 4 cells on the patch
%register with lane 1 having cells 1 to 4 etc.
A=0; B=0; C=0; D=0;
switch Lane
    case 1
        A=1;B=2;C=3;D=4;
    case 2
        A=5;B=6;C=7;D=8;
    case 3
        A=9;B=10;C=11;D=12;
    case 4
        A=13;B=14;C=15;D=16;
end
```

Code section

```
%The reference vehicle generator
%function was used to determine the OV
%lead vehicle
if v_reg>0
    [ref_veh,NTA]=ref_veh_generator3(patch_veh_reg(:,:),pa,v_reg,posit_f(:,:),posit_r(:,:),t,lanes(t,v_reg),0,0);
    ref(t,v_reg)=ref_veh;
end
```

Code section

```
% Displacement
disp_buf(t,v_reg)= (vel(t-1,v_reg)*0.1)+(1/2*(accel(t-1,v_reg)*(0.1)^2));

%Preventing negative displacements
if disp_buf(t,v_reg)<0
    disp(t,v_reg)=0;
elseif disp_buf(t,v_reg)>=0
    disp(t,v_reg)=disp_buf(t,v_reg);
end
```

Code section

```
%Calculating observed vehicle's position
%The current front bumper posiiton of the OV %was calculated as the sum of its
%previous position and its current displacement while its rear bumper
%position was calculated as the difference between its current front
%bumper position and the vehicle length
posit_f(t,v_reg)=posit_f(t-1,v_reg)+disp(t,v_reg);
posit_r(t,v_reg)=posit_f(t,v_reg)-veh_len(1,v_reg);

%Cancelling the Observed vehicle previous patch slot
[ a,b,c,d ] = switch_board( lanes(t,v_reg) );

%Its previous patches for both bumpers were obtained here
[Prevp_frt,Prevp_rer]=patch_finder2(posit_f(t-1,v_reg),veh_len(1,v_reg),patch_table);
[p_frt,p_rer]=patch_finder2(posit_f(t,v_reg),veh_len(1,v_reg),patch_table);

%This step is used when the OV previous front bumper patch is not the same as
%the current one OR when they are the same but the current lane is
%different from the previous lane
if Prevp_frt~=p_frt || (Prevp_frt==p_frt && lanes(t,v_reg)~=lanes(t-1,v_reg))
    %This loop was used to cycle through both slots of the
    %vehicle's previous patch to find the slot containing the OV's reg no
    for sk=a:b
        if Prevp_frt>0 && v_reg==patch_veh_reg(Prevp_frt,sk)
            %The slot containing the OV reg no was reset to 0
            patch_veh_reg(Prevp_frt,sk)=0;

            %finding an available front bumper slot on the OV new patch and
            %registering to the slot. The switch_board was used to find the
            %slots for the OV current lane patch
            [ a,b,c,d ] = switch_board(lanes(t,v_reg));
```

```
            %This loop was used to cycle through both slots of the
            %vehicle's current patch to find a
            %free slot to register the OV to
            for nk=a:b
                if p_frt>0 && patch_veh_reg(p_frt,nk)==0
                    %The OV was registered to the free slot found on
                    %its current patch
                    patch_veh_reg(p_frt,nk)=v_reg;
                    break;
                end
            end
            break;
        end
    end

        %If the OV previous patch is the same as its current patch and the
        %lane is the same as well then the following step is used. I.e its
        %current patch and slot remains the same as the previous one
    elseif Prevp_frt==p_frt
        if lanes(t,v_reg)==lanes(t-1,v_reg)
            patch_veh_reg(pa,vk)=v_reg;
        end
    end

    %Same as before, so that this shift doesnt cause the 2nd
    %veh in the patch reg to be skipped during
    %the vk loop
    [ a,b,C,d ] = switch_board( lanes(t,v_reg) );

    if vk==b && Prevp_frt>0
        %shifting the vehicle reg by 1 column
        if patch_veh_reg(Prevp_frt,a)==0
            patch_veh_reg(Prevp_frt,a)=patch_veh_reg(Prevp_frt,b);
            patch_veh_reg(Prevp_frt,b)=0;
        end
    end

    %cancelling previous rear bumper patch
    if posit_r(t-1,v_reg)>0
        [ a,b,C,d ] = switch_board( lanes(t,v_reg) );
        for pk=C:d
            if v_reg==patch_veh_reg(Prevp_rer,pk)
                patch_veh_reg(Prevp_rer,pk)=0;
                break
            end
        end
    end
```

```
%The next step is executed if the OV rear bumper position is greater than 0 AND its current patch is different from its previous patch OR the patch
%is the same but the lane is different or the current patch and lane are the same as the previous but the position of the rear bumper os 0.
if (posit_r(t,v_reg)>0 &&(Prevp_rer~=p_rer||(Prevp_rer==p_rer&&lanes(t,v_reg)~=lanes(t-1,v_reg))))||(Prevp_rer==p_rer&&lanes(t,v_reg)==lanes(t-1,v_reg))
    %finding an available rear bumper slot on the OV current rear bumper patch and registering to it
    [ a,b,C,d ] = switch_board( lanes(t,v_reg) );
    for rk=C:d
        if p_rer>0 && patch_veh_reg(p_rer,rk)==0
            patch_veh_reg(p_rer,rk)=v_reg;
            pa_err_r=2;
            break;
        end
    end
end
```

```
%Again the rear bumper patch slot doesn't have to be shifted but this
%was done for clarity.
if (vk==2 || vk==6 || vk==10 || vk==14) && Prevp_rer>0
    [ a,b,C,d ] = switch_board( lanes(t,v_reg) );
    %shifting the vehicle reg by 1 column
    if patch_veh_reg(Prevp_rer,C)==0
        patch_veh_reg(Prevp_rer,C)=patch_veh_reg(Prevp_rer,d);
        patch_veh_reg(Prevp_rer,d)=0;
    end
end
```

```
%When the observed vehicle gets to the end of the link
if posit_f(t,v_reg)>link
    [ a,b,C,d ] = switch_board( lanes(t,v_reg) );

    %the OV finish time is taken down
    fin_tim(1,v_reg)=t;

    %The front bumper patch slot automatically becomes 0 because the front
    %bumper position would be greater than the link but the rear bumper position
    %would have to be reset to 0
    %Resetting the rear bumper patch register
    [p_frt,p_rer]=patch_finder2(posit_f(t,v_reg),veh_len(1,v_reg),patch_table);
    if posit_r(t,v_reg)>0
        for pk=C:d
            if p_rer>0 && v_reg==patch_veh_reg(p_rer,pk)
                patch_veh_reg(p_rer,pk)=0;
            end
        end
    end
```

```
%The density of the OV lane reduces
%when the OV exits the link
lane_dens(1,cur_lane)=lane_dens(1,cur_lane)-1;

%The density of the entire link also reduces
count_Den=count_Den-1;

%If cell 1 is high a vehicle entered at that time step,
%if cell 2 high a vehicle exited at that time step
%When both are 1 or high during the same time step
%the traffic is stable.
traff_flow(t,2)=1;

%Various parameters are then
%calculated such as the total
%vehicle that have gone through the
%link, the journey time and average
%velocity of the OV that just
%exited the link.
veh_count=veh_count+1;
jon_tim(1,veh_count)=(fin_tim(1,v_reg)-sta_tim(1,v_reg))*0.1;
Veh_Av_vel(1,veh_count)=link/jon_tim(1,veh_count);

%The average velocity of all vehicles that successfully exited the link during
%simulation were summed. The sum was later divided by the total vehicle that successfully
%exited the link from the simulation start time to its termination time in order to deduce the
%average velocity on the link
Add_Av_vel=Add_Av_vel+Veh_Av_vel(1,veh_count);

%The traffic flow was stable (i.e sat) when vehicles exited and entered
%the link during the same time step. That is when both bits of
%the array traff_flow are 1.
if sat_time>0
    %The total vehicles that had gone through the link during the stable state
    veh_count_sat=veh_count_sat+1;
    %The OV journey time during the traffic flow stable state
    jon_tim_sat(1,veh_count_sat)=(fin_tim(1,v_reg)-sta_tim(1,v_reg))*0.1;
    %The OV average velocity during the traffic flow stable state
    Veh_Av_vel_sat(1,veh_count_sat)=link/jon_tim_sat(1,veh_count_sat);

    %the average velocity of all vehicles that successfully exited the link from the
    %stabled state to the simulation termination time were summed. The sum was later divided
    %by the total vehicle that successfully exited the link from the stable period to the end
    %of the simulation to deduce the average velocity on the link
    Add_Av_vel_sat=Add_Av_vel_sat+Veh_Av_vel_sat(1,veh_count_sat);
end
```

```
    %The OV parameters were then reset to to 0 including its
    %registeration number so it could be used by a new vehicle
    posit_f(t,v_reg)=0;
    posit_r(t,v_reg)=0;
    vel(t,v_reg)=0;
    accel(t,v_reg)=0;
    sta_tim(1,v_reg)=0;
    fin_tim(1,v_reg)=0;
    Veh_jou_Av_vel(1,v_reg)=0;
    h(t,v_reg)=0;
    v_reg=0;
end
```

Code section

The gap:

```
gap=Leadvehicle_rearbumperposit-vehicle_frontbumperposit;
```

The observed vehicle's velocity:

```
%velocity
buf_vel(t,v_reg)=vel(t-1,v_reg)+(accel(t-1,v_reg)*0.1);
%Limiting velocity
if buf_vel(t,v_reg)<0
    vel(t,v_reg)=0;
elseif buf_vel(t,v_reg)<max_vel
    vel(t,v_reg)=buf_vel(t,v_reg);
elseif buf_vel(t,v_reg)>=max_vel
    vel(t,v_reg)=max_vel;
end
```

The observed vehicle's headway:

```
headway_slow=0.5;

 switch change
    case 1
        headway_fast=1.5;
    case 2
        headway_fast=2;
    case 3
        headway_fast=2;
    case 4
        headway_fast=2.5;
    case 5
        headway_fast=3;
end
```

```
if ref_veh~=0
    if t>Aw_lev
        if  vel(t,v_reg)<4.5 && vel(t-Aw_lev,ref_veh)<4.5
            h(t,v_reg)=headway_slow;
        elseif vel(t,v_reg)>4.5 || vel(t-Aw_lev,ref_veh)>4.5
            h(t,v_reg)=headway_fast;
        end
    elseif t<Aw_lev
        h(t,v_reg)=headway_fast;
    end
end
```

Code section

```
%%Used to control the acceleration of the lead vehicle%%

%This function operated like the collision detector function except
%the vehicle's speed and position was compared to the position of the stopline
[ stop ] = stopline_overshoot_detector( vel(:,:),max_dec(:,:),link,t,v_reg,posit_f(:,:));

%accel_found1==0 meant acceleration mode not found

%When the OV had no lead vehicle(ref_veh==0) and no congestion was to be induced
%at the end of the link it accelerated at maximum acceleration
if ref_veh==0 && accel_found1==0 && congestion==off
        accel(t,v_reg)=max_accel(t,v_reg);
        accel_found1=1;
%When congestion was to be induced and the OV had no lead vehicle
elseif congestion==on && ref_veh==0
    %The stop line is ON and the vehicle would potentially overshoot the stop sign (i.e.stop==1)
    if stop==1 && stop_line_status==on && accel_found1==0
        accel(t,v_reg)=max_dec(t,v_reg);
        accel_found1=1;
%speed_line is a point on the link beyond which a special speed limit was required as vehicles approach
%the end of the link. jam_spd is special speed limit for the end of the link

%The OV was required to brake at max if its front bumper position was greater or equals the speed_line and its
%velocity was greater than the jam_spd
elseif posit_f(t,v_reg)>=speed_line && vel(t,v_reg)>jam_spd && accel_found1==0
    accel(t,v_reg)=max_dec(t,v_reg);
    accel_found1=1;
%Else it was required to accelerate at max if its front bumper position was greater or equals the speed_line
%and its velocity less than the jam_sp
elseif posit_f(t,v_reg)>=speed_line && vel(t,v_reg)<jam_spd && accel_found1==0
    accel(t,v_reg)=max_accel(t,v_reg);
    accel_found1=1;
%Else it was required to not accelerate if its front bumper was greater than or equals the speed_line,
%its velocity was equals the jam_spd
elseif posit_f(t,v_reg)>=speed_line && vel(t,v_reg)==jam_spd && accel_found1==0
    accel(t,v_reg)=0;
    accel_found1=1;
%Else it was required to accelerate at max if the position of its front bumper was less than the speed_line
elseif posit_f(t,v_reg)<speed_line
    accel(t,v_reg)=max_accel(t,v_reg);
    accel_found1=1;
end
```

```
%%used to safely bring the OV closer to its lead vehicle during congestion%%

%If the OV has a lead vehicle
elseif ref_veh>0 && accel_found1==0
    %If the OV is at risk of colliding with its lead vehicle it is required to brake at max
    if colli==1
        accel(t,v_reg)=max_dec(t,v_reg);
        accel_found=1;
    %Elseif the OV is not at a risk of colliding with its lead vehicle and it is within a
    %given safe threshold distance from its lead vehichle it is required to accelerate at max
    elseif acc_safe==1 && colli==0 && accel_found==0
        accel(t,v_reg)=max_accel(t,v_reg);
        accel_found=1;

    %Elseif the OV has been on the link less than the awareness time defined for all drivers
    %plus the time they require to observe the speed of their lead vehicle to determine if it is braking
    %and the OV is not at a risk of colliding with its lead vehicle

%%NOTE: if this condition is true the response time of the driver would not be included since the driver
%%would not have any memory before its journey start time
elseif (t-(Aw_lev+5))<=sta_tim(1,v_reg) && colli==0 && accel_found==0
    %If the velocity of the lead vehicle velocity is zero
    if vel(t,ref_veh)==0 && accel_found==0
        %if the gap between the OV and its lead vehicle is greater than the required gap between vehicles during
        %a traffic jam (stop_gap) and the velocity of the OV is less than the gap minus the stop_gap
        %then the preliminary acceleration is 0.1 times the gap
        %an assumption was made that the required acceleration to close the gap was proportional to the gap.
        %The acceleration was then limited to the maximum acceleration and deceleration
        if g(t,v_reg)>stop_gap && accel_found==0 && vel(t,v_reg)<(g(t,v_reg)-stop_gap)
            accel_buf=kb*g(t,v_reg);
            if accel_buf>=max_accel(t,v_reg)
                accel(t,v_reg)=max_accel(t,v_reg);
            elseif accel_buf<=max_dec(t,v_reg)
                accel(t,v_reg)=max_dec(t,v_reg);
            else
                accel(t,v_reg)=accel_buf;
            end

        accel_found=1;
    %Elseif the gap was less than the stop_gap or the OV is at a risk of colliding with its lead
    %vehicle the OV is required to decelerate at max
    elseif g(t,v_reg)<=stop_gap || colli==1 && accel_found==0
        accel(t,v_reg)=max_dec(t,v_reg);
        accel_found=1;
    end
%Elseif the velocity of the OV lead vehicle is greater than zero
elseif vel(t,ref_veh)>0 && accel_found==0
    %If the OV was within the given safe threshold distance from its lead vehicle and was not
    %at a risk of colliding with it then it was required to accelerate at max
    if acc_safe==1 && colli==0 && accel_found==0
        accel(t,v_reg)=max_accel(t,v_reg);
        accel_found=1;
    %Else if it was at a risk of colliding with its lead vehicle it was required to brake at max
    elseif colli==1
        accel(t,v_reg)=max_dec(t,v_reg);
        accel_found=1;
```

```
%Else if it was not within the given safe threshold distance from its lead vehicle and was not
%at a risk of colliding with it
elseif acc_safe==0 && colli==0 && accel_found==0
    %If its separation from its lead vehicle was less than or equals its target separation
    if s(t,v_reg)<=T(t,v_reg)
        %if its lead vehicle is not breaking (i.e. z==0) then the OV is expected to accelerate
        %at aA acceleration component
        if z(t,v_reg)==0 && accel_found==0
            accel(t,v_reg)=aA(t,v_reg);
            accel_found=1;
        %Elseif its lead vehicle is breaking (i.e. z==1) then the OV is expected to brake at max
        elseif z(t,v_reg)==1
            accel(t,v_reg)=max_dec(t,v_reg);
            accel_found=1;
        end
    %Elseif the separation is greater than the target
    elseif s(t,v_reg)>T(t,v_reg) && accel_found==0

            %If the velocity of the OV at the current time step is greater than its velocity at the
            %previous timestep then the OV is expected to accelerate at aB acceleration component
            if vel(t,veh)>vel(t-1,veh)
                accel(t,v_reg)=aB(t,v_reg);
                accel_found=1;
            %Elseif its lead vehicle is not breaking it is expected to accelerate
            %at acceleration component aC
            elseif z(t,v_reg)==0 && accel_found==0
                accel(t,v_reg)=aC(t,v_reg);
                accel_found=1;
            %Elseif its lead vehicle is breaking or it is at a risk of colliding with its lead
            %vehicle it is expected to brake at max
            elseif (z(t,v_reg)==1 || colli==1)  && accel_found==0
                accel(t,v_reg)=max_dec(t,v_reg);
                accel_found=1;
            end
        end
    end
end

%Elseif the OV has been on the link longer than the awareness time defined for all drivers
%plus the time they require to observe the speed of their lead vehicle to determine if it is braking
%and the OV is not at a risk of colliding with its lead vehicle

%%NOTE: if this condition is true the response time of the driver would be included since the driver
%%memory started during its journey start time and its memory covers its response time which is slower
%%than the actual time hence its memory is focused on a period of time in the past
%%The same steps as when the driver had insufficient memory to include its response time are then repeated
%%except the driver's response time is now taken into account
elseif (t-(Aw_lev+5))>sta_tim(1,v_reg) && colli==0 && accel_found==0
    if vel(t-Aw_lev,ref_veh)==0
        if g(t,v_reg)>stop_gap && accel_found==0 && vel(t,v_reg)<(g(t,v_reg)-stop_gap)
            accel_buf=kb*g(t,v_reg);
            if accel_buf>=max_accel(t,v_reg)
                accel(t,v_reg)=max_accel(t,v_reg);
            elseif accel_buf<=max_dec(t,v_reg)
                accel(t,v_reg)=max_dec(t,v_reg);
            else
                accel(t,v_reg)=accel_buf;
            end
            accel_found=1;
        elseif g(t,v_reg)<=stop_gap && accel_found==0
            accel(t,v_reg)=max_dec(t,v_reg);
            accel_found=1;
```

```
        elseif colli==1
            accel(t,v_reg)=max_dec(t,v_reg);
            accel_found=1;
        elseif g(t-Aw_lev,v_reg)<=stop_gap && accel_found==0
            accel(t,v_reg)=max_dec(t,v_reg);
            accel_found=1;
        end
    elseif vel(t-Aw_lev,ref_veh)>0 && accel_found==0
        if acc_safe==1 && colli==0
            accel(t,v_reg)=max_accel(t,v_reg);
            accel_found=1;
        elseif colli==1
            accel(t,v_reg)=max_dec(t,v_reg);
        elseif acc_safe==0 && colli==0 && accel_found==0
            if s(t-Aw_lev,v_reg)<=T(t-Aw_lev,v_reg)
                if z(t-Aw_lev,v_reg)==0 && accel_found==0
                    accel(t,v_reg)=aA(t,v_reg);
                    accel_found=1;
                elseif z(t-Aw_lev,v_reg)==1 && accel_found==0
                    accel(t,v_reg)=max_dec(t,v_reg);
                    accel_found=1;
                end
```

```
                elseif s(t-Aw_lev,v_reg)>T(t-Aw_lev,v_reg) && accel_found==0
                    if vel(t,veh)>vel(t-Aw_lev+5,veh)
                        accel(t,v_reg)=aB(t,v_reg);
                        accel_found=1;
                    elseif z(t-Aw_lev,v_reg)==0 && accel_found==0
                        accel(t,v_reg)=aC(t,v_reg);
                        accel_found=1;
                    elseif z(t-Aw_lev,v_reg)==1 && accel_found==0
                        accel(t,v_reg)=max_dec(t,v_reg);
                        accel_found=1;
                    elseif colli==1
                        accel(t,v_reg)=max_dec(t,v_reg);
                        accel_found=1;
                    end
                end
            end
        end
    end
end
```

Code section

```
%%Generating a new vehicle%%

%New vehicles were generated on the beginning of the link i.e patch 125
if t>1 && pa==patch
    %Generate new vehicle on patch (front bumper)
    %The vehicle to be generated was given 0.5 as a temporary registeration number. Actual vehicle registeration numbers start from 1.
    v_reg=0.5;

    %The registeration number of the lead vehicle of the new vehicle is initialised to zero
    ref_veh=0;

    if v_reg==0.5
        %The new vehicle temporary lane is initialised to zero
        temp_lane=0;
```

```
%This loop runs through all lane numbers on the link
%%NOTE that since the loop starts running from lane number 1 vehicles would first attempt to generate on the inner lanes
for la=1:no_lane
    %For each lane number selected it determines the vehicle on the lane closest to the start point.
    %This vehicle would be a potential lead vehicle of the new vehicle to be generated
    [ref_veh_D,NTA]=ref_veh_generator3(patch_veh_reg(:,:),pa,v_reg,posit_f(:,:),posit_r(:,:),t,la,0,1);
    %It then determines if there would be a collision with the potential lead vehicle if the new vehicle
    %was generated at the start of the lane
    colli=0;
    if ref_veh_D>0
        [colli,acc_safe]=collision_detector3(vel(t,ref_veh_D),max_dec(t,ref_veh_D),max_dec(t,ref_veh_D)/3,vel_init,0,posit_r(t,ref_veh_D),stop_gap,0,0);
    end
    %If the gap between the veh to be generated and the lead veh is greater than stop_gap and den is greater than 15 or entry interval has been reached
    %and If there would be no collision or there is no vehicle on the lane the scanned lane is then assigned as the temporary lane
    %of the vehicle to be generated while its lead vehicle is assigned as the detected potential lead vehicle on the lane
    %or zero if no vehicle on the lane
    if  ref_veh_D~=0 && colli==0 && ((posit_r(t,ref_veh_D)>stop_gap) && max_Den>15 ||(t-timer1)>=interval && (posit_r(t,ref_veh_D)>stop_gap)) || ref_veh_D==0
        temp_lane=la;
        ref_veh=ref_veh_D;
        break
    end
end

%if the vehicle to be generated would collide with potential lead vehicles on all lanes no vehicle is generated during this timestep

%if the vehicle to be generated has a temporary lane
if temp_lane>0
    [ a,b,C,d ] = switch_board( temp_lane );

    %an available front bumper slot on the patch (patch 125) where the vehicle is to be generated is searched for
    for jk=a:b
        %If a slot if found the slot number is then copied to a variable 'use'
        if patch_veh_reg(pa,jk)==0
            use=jk;
            break;
        end
    end

%generating a new vehicle
%if an available slot was found (i.e. use>0)
if use>0

    %selecting a registeration number for the new vehicle
    %The for loop runs from 1 to the maximum number of vehicles allowed on the link.
    for jk=1:veh
        %The patch register is looked up to see if the current value of the loop is registered on the patch register
        vr=ismember(jk, patch_veh_reg(:));       %check if v is a member of the array
        %If YES the loop keeps running but if NO the loop number is assigned as the vehicle registeration number
        %since no vehicle currently has that registeration number and the loop breaks
        if vr~=1
            v_reg=jk;
            break;
        end
    end

%If the vehicle to be generated now has a real registeration number (i.e. no longer temp reg)
if v_reg>0.5
    %The position of the vehicle on the link is set to 0.1 which is on patch 125.
    %Every newly generated vehicle starts from this point
    %posiiton
    posit_f(t,v_reg)=0.1;

    %The new vehicle journey start time is then taken as the current timestep
    sta_tim(1,v_reg)=t;

%The new vehicle type is then selected

%Small vehicles have a length of 4.7m while
%large vehicles have a length of 14m (reference)
%Uniform small vehicles were given type 1
%vehicle design while unifrom large vehicles
%were given type 4.
if uniform_veh==on
    if choose_veh==small
        veh_len(1,v_reg)=small_L;
        veh_type(1,v_reg)=1;
    elseif choose_veh==large
        veh_len(1,v_reg)=big_L;
        veh_type(1,v_reg)=4;
    end
```

```
%With uniform vehicles option off vehicle ratio
%was used. A counter was used along side the
%ratio to determine when to select small or
%large vehicles. When the counter was less than
%the ratio value selections were made
%sequentially between the 3 small vehicle
%design types. The selection got to the 3rd
%type the next selection became the first one
%and the cycle continued until the counter
%value equaled the ratio value.
elseif uniform_veh==off
    if veh_len_cnt<ratio
        veh_len(1,v_reg)=small_L;
        switch L_veh_type_cnt
            case 0
                veh_type(1,v_reg)=1;
                L_veh_type_cnt=L_veh_type_cnt+1;
            case 1
                veh_type(1,v_reg)=2;
                L_veh_type_cnt=L_veh_type_cnt+1;
            case 2
                veh_type(1,v_reg)=3;
                L_veh_type_cnt=0;
        end
        veh_len_cnt=veh_len_cnt+1;
```

```
    %When the counter equalled the ratio value
    %a large vehicle was then selected and then
    %the counter was reset so smaller vehicle
    %lengths were selected afterwards. Just like
    %the small vehicle selection procedure a
    %different counter was used to ensure the selection was
    %done sequentially and once the 3rd vehicle
    %type was selected the counter was reset so
    %that the next selection was the first
    %selection keeping the selection process in a
    %cycle.
      elseif veh_len_cnt>=ratio
          veh_len(1,v_reg)=big_L;
          switch H_veh_type_cnt
              case 0
                  veh_type(1,v_reg)=4;
                  H_veh_type_cnt=H_veh_type_cnt+1;
              case 1
                  veh_type(1,v_reg)=5;
                  H_veh_type_cnt=H_veh_type_cnt+1;
              case 2
                  veh_type(1,v_reg)=6;
                  H_veh_type_cnt=0;
          end
          veh_len_cnt=0;
      end
  end
```

```
%The position of the rear bumper of the new vehicle was calculated by
%subtracting the length of the vehicle from its front numper position
posit_r(t,v_reg)=posit_f(t,v_reg)-veh_len(1,v_reg);
%The temporary lane of the new vehicle was assigned as its lane
lanes(t,v_reg)=temp_lane;
%The density of the new vehicle's lane increased by 1
lane_dens(1,temp_lane)=lane_dens(1,temp_lane)+1;
%The lead vehicle of the new vehicle was assigned as the detected potential
%lead vehicle on the lane or zero if no vehicle on the lane
ref(t,v_reg)=ref_veh_D;
%The velocity of the new vehicle was then assigned as the predefined initial velocity
vel(t,v_reg)=vel_init;
```

```
                ref(t,v_reg)=ref_veh_D;
                %The velocity of the new vehicle was then assigned as the predefined initial velocity
                vel(t,v_reg)=vel_init;

                %find the patches the vehicle's bumpers are located
                [p_frt,rer]=patch_finder2(posit_f(t,v_reg),veh_len(1,v_reg),patch_table);
                %the vehicle's front bumper was then registered to a front bumper slot of its current patch
                patch_veh_reg(p_frt,use)=v_reg;
                %used to reset lane change timers of previous vehicle that has left when a new vehicle with the same v_reg enters
                reset_lane_timers(1,v_reg)=1;
                %density on the road increases
                count_Den=count_Den+1;
                %If cell 1 is high a vehicle entered at that time step,if cell 2 high a vehicle exited at that time step
                %When both are 1 or high during the same time step the traffic is stable.
                traff_flow(t,1)=1;
                %the time vehicle entered the link was taken, this was used to control the interval at
                %which new vehicles entered the link
                timer1=t;
            end
        end
    end
end
```

Code section

```
%Data collection
%The maximum density was updated each time the density of the link was greater than the maximum density on record
%It was saved for each time step on the first column of an array called 'data'
if count_Den>max_Den
    max_Den=count_Den;
end
data(t,1)=max_Den;

%The density, maximum density and flux for each time step were saved in data column 1, 2 and 3 respectively
density=data(t,1);
mean_velocity=data(t,2);
flux=data(t,3);
```

```
%The density, maximum density and flux for each time step were saved in data column 1, 2 and 3 respectively
density=data(t,1);
mean_velocity=data(t,2);
flux=data(t,3);

%mean velocity
%mean velocity at that time step was calculated as the sum of the average velocity of all vehicles that have
%exited the link divided by the total vehicles that have exited the link
if density>0
    mean_velocity=Add_Av_vel/veh_count;
    if Add_Av_vel==0 || veh_count==0
        mean_velocity=0;
    end
end
```

```
%mean velocity during stable traffic state
%the mean velocity at the current time step during stability was calculated as the sum
%of the average velocity of all velicles that exited the link when the traffic was stable
%divided by the total vehicles that exited the link during this period
if density>0
    mean_velocity_sat=Add_Av_vel_sat/veh_count_sat;
    if Add_Av_vel_sat==0 || veh_count_sat==0
        mean_velocity_sat=0;
    end
end
```

```
%traffic flux
%The traffic flux at the current timestep was calculated as the density
%divided by the mean velocity both at the current time step
if density>0
    flux=density*mean_velocity;
end

%The density, mean velocity and flux of the current time step were then
%saved into data column 1, 2 and 3 respectively
data(t,1)=density;
data(t,2)=mean_velocity;
data(t,3)=flux;
```

```
    %The timestep when the traffic became stable is taken
    if traff_flow(t,1)==1 && traff_flow(t,2)==1 && count_Den>=veh && prevent==0
        sat_time=t;
        prevent=1;
    end

    %%Not relevant%%
    if sat_time>0 && ((veh_count_aft>=change && change<=30)||(veh_count_aft>=30 && change>30))
        break;
    end
end

%The total simulation time in seconds from stable traffic state is calculated as the difference
%between the total time step and the time step when the traffic attained a stable state divided by 10
%since each time step is equivalent to 0.1sec
Time=(t-sat_time)/10;
%The traffic flux per hour was calculated as the quotient of the total number of vehicles that exited
%the link during the traffic stable state and the Time of the entire simulation during the stable state multiplied by 3,600
traff_flux(1,1)=(veh_count_sat/Time)*3600;
%Not relevant%
traff_flux(1,2)=(veh_count_sat/Time)*900;

%The average journey time was calculated as the mean journey time of all the vehicles that exited
%the link during the traffic stable state
mean_jon_tim_analy_sat(1,1)=mean(jon_tim_sat(1,:));

%The calculated parameters were saved into various columns of an array called 'flux_data'
flux_data(1,size)=traff_flux(1,1);
flux_data(2,size)=mean_jon_tim_analy_sat(1,1);
flux_data(3,size)=t;
flux_data(4,size)=sat_time;
flux_data(5,size)=time;
flux_data(6,size)=mean_velocity_sat;

%Not relevant%
flux_data(7,size)=change;

%The array 'flux_data' was then saved as a spreadsheet so it could be exported and used on a different program
xlswrite('classlist.xlsx',flux_data,'section2','A1');

switch change
    case 1
        data_analy(:,1)=data(:,1);
        data_analy(:,2)=data(:,2);
        data_analy(:,3)=data(:,3);
        data_analy(:,4)=traff_flow(:,1);
        data_analy(:,5)=traff_flow(:,2);

    case 2
        data_analy(:,7)=data(:,1);
        data_analy(:,8)=data(:,2);
        data_analy(:,9)=data(:,3);
        data_analy(:,10)=traff_flow(:,1);
        data_analy(:,11)=traff_flow(:,2);
    case 3
        data_analy(:,12)=data(:,1);
        data_analy(:,13)=data(:,2);
        data_analy(:,14)=data(:,3);
        data_analy(:,15)=traff_flow(:,1);
        data_analy(:,16)=traff_flow(:,2);
```

```
    case 4
        data_analy(:,18)=data(:,1);
        data_analy(:,19)=data(:,2);
        data_analy(:,20)=data(:,3);
        data_analy(:,21)=traff_flow(:,1);
        data_analy(:,22)=traff_flow(:,2);
    case 5
        data_analy(:,24)=data(:,1);
        data_analy(:,25)=data(:,2);
        data_analy(:,26)=data(:,3);
        data_analy(:,27)=traff_flow(:,1);
        data_analy(:,28)=traff_flow(:,2);
end
clear;
```

Code section

```
clear;

%maxi=3;                    %ensure when erasing you erase every infomation
from the previous simulation especially if maxi was higher than wipe. Hence
use a larger value for wipe to wipe out previous values

wipe=100;

bags=zeros(5,wipe);

xlswrite('classlist.xlsx',bags,'section2','A1');


for change=22:1:31

    max_v=31;               %must be the same as max change


    small=1;

    large=2;

    on=1;

    off=0;


    %settings

    congestion=on;                              %Congestion at the end of
the link?

    traffic_light=off;                          %Using signal or not using
signal. 1=using signal, 0=not using signal

    stop_line_status=off;                       %If not using signal should
the stop line be on or off?

    uniform_veh=on;                             %Using uniform or mixed
vehicles (uniform on or off?)
```

```
    choose_veh=large;                           %if using uniform vehicles then using small or large vehicles?

    ratio=16;                                    %If vehicles are not uniform enter the ratio of large to small vehicles. i.e. 1:ratio

    condition=1;                                %Weather condition: 1 dry; 2 light rain; 3 heavy rain; 4 light snow; 5 heavy snow

    no_lane=4;                                  %Maximum number of lanes. Error if higher than 4 or less than 1



    if condition==1

        if change==1

            time=3000;

        elseif change>1 && change<=6

            time=3000;

        elseif change>6 && change<=11          %this density simulation time has been verified. 30 was last verified

            %time=3000;

            time=10000;

        elseif change>11 && change<=16

            time=4000;

        elseif change>16 && change<=26

            time=5000;

        elseif change>26 && change<=31

            time=8000;

        elseif change>36 && change<=41

            time=30000;

        elseif change>41 && change<=46

            time=35000;

        elseif change>46 && change<=56

            time=40000;

        end

    elseif condition==2
```

```
        if change==1
            time=2700;
        elseif change>1 && change<=6
            time=2000;
        elseif change>6 && change<=16          %this density simulation
time has been verified. 30 was last verified
            time=2600;
        elseif change>16 && change<=26
            time=3600;
        elseif change>26 && change<=36
            time=4400;
        elseif change==41
            time=5600;
        elseif change==46
            time=6500;
        elseif change==51
            time=7300;
        elseif change>51 && change<=61
            time=10000;
        end
    elseif condition==3
        if change==1
            time=2300;
        elseif change>1 && change<=16
            time=2000;
        elseif change>6 && change<=31          %this density simulation
time has been verified. 30 was last verified
            time=3000;
        elseif change>16 && change<=26
            time=5000;
        elseif change==36
```

```
            time=5000;
        elseif change==41 && change<=46
            time=6300;
        elseif change==51
            time=8900;
        end
    elseif condition==5
        if change==1
            time=2700;
        elseif change>1 && change<=11
            time=2000;
        elseif change>11 && change<=16          %this density simulation
time has been verified. 30 was last verified
            time=9000;
        elseif change>16 && change<=21
            time=20000;
        elseif change>21
            time=40000;
        end
    end


    time=10000;
    veh=change;
    link = 1000;
    patch=125;
    ref_veh=0;
%Reference vehicle
    veh_len=4.7;
%remember vehicle length must be a whole number
    stop_gap=2;                                                      %gap
from ref veh when stopped in traffic. This should be 2 but we tried 4 to
avoid collision as it kept colliding
```

```
    colli_gap=10;

    mean_jon_tim_analy=zeros(1,5);

    max_accel_analy=zeros(1,5);

    headway_fast_analy=zeros(1,5);

    max_flux_analy=zeros(1,5);

    max_vel_analy=zeros(1,5);

    condition_analy=zeros(1,5);

    data_analy=zeros(time,19);

    small_L=4.7;

    big_L=14;

    jam_spd=5;

    mean_jon_tim_analy_sat=zeros(1,5);


    read_weather=0;

    if read_weather==1

        weather_data=xlsread('r_0001_scen_hly.xlsx');

    end

    %bags=zeros(1,20);

    %xlswrite('classlist.xlsx',bags,'section2','A1');




    patch_veh_reg=zeros(patch,4*no_lane);
%vehicles registered in each pa 1 and 2 are front bumpers 2 and 4 are rear
bumper

    posit_f=zeros(time,veh);
%positions of front bumper of vehicles

    posit_r=zeros(time,veh);
%positions of rear bumper of vehicles

    % count_vehin_patch=zeros(pa,4);                               %Keeps
track of the number of vehicles in a pa. 1 or 2 increments if there is a
front bumper and 3 or 4 incrememnts if there is a rear bumper

    accel=zeros(time,veh);
%Acceleration of each vehicle
```

```
    disp_buf=zeros(time,veh);                                   %Buffer
displacement
    disp=zeros(time,veh);
%Displacement
    g=zeros(time,veh);                                          %gap
    c=zeros(time,veh);
%bunching acceleration
    h=zeros(time,veh);
%headway
    s=zeros(time,veh);
%seperation
    T=zeros(time,veh);                                          %Target
    z=zeros(time,veh);
%Braking verifier
    vel=zeros(time,veh);
%Velocity
    buf_vel=zeros(time,veh);                                    %Buffer
Velocity
    aA = zeros(time,veh);
    kaA = zeros(time,veh);
    aB = zeros(time,veh);
    kaB = zeros(time,veh);
    aC = zeros(time,veh);
    kaC = zeros(time,veh);
    aD = zeros(time,veh);
    aE = zeros(time,veh);
    max_accel=zeros(time,veh);
    max_dec=zeros(time,veh);
    lanes=zeros(time,veh);
    run_check=zeros(time,veh);
%simulated vehicles checker
    fin_tim=zeros(1,veh);
    sta_tim=zeros(1,veh);
```

```
    reset_lane_timers=zeros(1,veh);                                      %used
to reset lane change timer for new vehicles after the vehicle with the same
reg has exited the link

    timer1=0;                                                            %timer
from when a vehicle last entered the link

    interval=30;
%between vehicles entry

    v_reg=0;

    %ka=0.0153769;
%constant 1

    %kb=0.09144;
%constant 2

    ka=0.01;

    kb=0.1;

    use=0;

    check=zeros(time,1);

    flag=0;

    debug_ref=zeros(time,veh);

    NTA=0;

    patch_checker=zeros(time,veh);

    patch_checker_time=zeros(1,veh);

    veh_len=zeros(1,veh);

    lane_dens=zeros(1,no_lane);


    headway_slow=0.5;

    Aw_lev=10;

    found_ref=0;

    dens=0;

    chk=0;

    chk2=0;

    Refveh_db=0;

    veh_db=0;

    H_veh_type_cnt=0;
```

```
    L_veh_type_cnt=0;

    timer_N1=zeros(1,veh);

    timer_N2=zeros(1,veh);

    timer_overtake=zeros(1,veh);

    timer_change=zeros(1,veh);

    non_interest_counter=zeros(1,veh);

    veh_type=zeros(1,veh);

    pa_err_f=0;

    pa_err_r=0;

    patch_error_f=zeros(time,veh);

    patch_error_r=zeros(time,veh);

    Veh_jou_Av_vel=zeros(1,veh);            %vehicle average speed journey
during journey. Different from the vehicle average speed after journey

    ref_veh_D=zeros(time,veh);

    traff_flow=zeros(time,2);             %Bit 1 high in 2 out while both
high

    red_cnt=0;

    green_cnt=0;

    light=zeros(time,1);

    light(1,1)=1;

    stopline_check=zeros(time,1);

    jam=0;




    %analysis

    data=zeros(time,10);                     %1=max den, 2=mean velo on
link, 3= traffic flux on the link, 5=various densities, 6=velocities of
similar densities

    veh_count=0;                            %Number of vehicles that have
exited the link

    jon_tim=zeros(1,veh_count);             %Vehicle journey time
```

```
    Veh_Av_vel=zeros(1,veh_count);          %veh average velocity

    Add_Av_vel=0;                           %summation of all vehicles
average velocity

    count_Den=0;                            %total den on the link

    max_Den=0;                              %max den on the link

    use1=0;

    use2=0;

    use3=0;

    period=9;

    sat_time=0;

    veh_count_sat=0;                        %vehicle count during stable
state

    veh_count_aft=0;

    Time=0;                                 %Duration from the start of the
stable state in seconds

    Time_DS=6000;                            %Duration from the start of
the stable state in deci seconds

    traff_flux=zeros(1,3);                            %alternative traffic
flux. 1 is veh/hr while 2 is veh/15min

    traff_fluxes=zeros(1,20);

    jon_tim_sat=zeros(1,veh_count);             %Vehicle journey time
during stable state

    Veh_Av_vel_sat=zeros(1,veh_count);          %veh average velocity
during stable state

    Add_Av_vel_sat=0;

    mean_velocity_sat=0;                    %mean velocity during
saturation

    prevent=0;

    cond1_traff_flux=546;


    flux_data = csvread('classlist.csv');

    %flux_data=xlsread('classlist.xlsx');

    for size=1:max_v

        if flux_data(1,size)==0
```

```
            break;
        end
    end

    intensity=0;
    if read_weather==1
        switch weather_data(1,5)
            case 0
                condition=1;
            case weather_data(period,5)>0 && weather_data(period,5)<=2 &&
weather_data(period,6)>0
                condition=2;
            case  weather_data(period,5)>2 && weather_data(period,6)>0
                condition=3;
            case weather_data(period,5)>0 && weather_data(period,5)<=2 &&
weather_data(period,6)<0
                condition=4;
            case weather_data(period,5)>2 && weather_data(period,6)<0
                condition=5;
        end

        intensity=weather_data(period,5);
    end



    if congestion==on
        jam_spd=jam_spd;                              %speed limit towards
the end of the link status
    elseif congestion==off
        jam_spd=max_vel;
    end
```

```
    %condition=change;


    %The variable speed_line indicated where vehicle had to start
considering the
    %special speed limit in order to avoid overshooting the stop sign since
    %their maximum deceleration rate was infuenced by the weather
conditions. The
    %variable control_vel is equivalent to the maximum speed under dry
condition
    %and the max speed of other conditions were gotten by deduction
    %specific values from this value. The variable vel_init was the initial
    %speed of vehicles entering the link, this was set to the maximum
    %speed under the specific weather condition as it was assumed that
    %the link was part of a continous Trunk Road stretch except in cases
were
    %a signal was included or were congestion was induced at the end
    %of the link but in all cases vehicles were initialised to maximum
    %speed.
    speed_line=0;                          %controls the speed limit line
    control_vel=31.2928;                   %free flow vel or speed limit
    vel_init=0;                            %initial velocity


    %Under dry condition the maximum velocity was the same as the speed
    %limit of the link (i.e. 70mph or 31.293m/s) and the speed line is at
the
    %highest position on the link compared to other weather conditions(i.e.
    %700m)
    if condition==1
        max_vel = control_vel;
        speed_line=700;
        vel_init=max_vel;
```

```
    %Under light rain and light snow conditions the maximum speed was
    %2.778m/s (or 6.214mph) less than the speed limit. The speed line
    %remained the same as the maximum deceleration rate was not impacted much enough to
    %have a significant impact on their stopping distances.
    elseif condition==2
        max_vel = control_vel-2.778;
        speed_line=700;
        vel_init=max_vel*1;
    elseif condition==3
        max_vel = control_vel-2.778;
        speed_line=700;
        vel_init=max_vel;
    %Under heavy rain condition the maximum speed was 5.556m/s (or 12.427mph)
    %less than the speed limit while the speed line was reduced to 650m to
    %compensate for the impact of the weather conditon on the maximum deceleration rate.
    elseif condition==4
        max_vel = control_vel-5.556;
        speed_line=650;
        vel_init=max_vel;
    %Under heavy snow condition the maximum speed was 13.889m/s (or 31.0686mph)
    %less than the speed limit while the speed line was reduced to 500m to
    %compensate for the impact of the weather conditon on the maximum deceleration rate.
    elseif condition==5
        max_vel = control_vel-13.889;
        speed_line=500;
        vel_init=max_vel;
    end
```

```
%jam_spd=7;


%Generates the look up table for the patch finder function
patch_table=patch_lookup_table();

for t=1:time
    %signal
    %The light array kept track of the state of the signal for
    %each time step. Both states had counter variables which were
    %red_cnt and green_cnt. Whenever a state was active its counter was
    %incremented during each time step. After its maximum active time
    %had elapsed its counter was reset and the signal state was
    %switched to the next state.
    if light(t,1)==1 || red_cnt>0
        red_cnt=red_cnt+1;
        light(t,1)=1;
        if red_cnt>=300
            red_cnt=0;
            light(t,1)=2;
            if t<time
                light(t+1,1)=2;
            end
        end
    end
    if light(t,1)==2 || green_cnt>0
        green_cnt=green_cnt+1;
        light(t,1)=2;
        if green_cnt>=600
```

```
                green_cnt=0;
                light(t,1)=1;
                if t<time
                    light(t+1,1)=1;
                end
            end
        end

        for pa=1:patch
            if t==1 && pa==patch                                        %At
the start of the simulation. Remember pa 125 holds cells 1:8
                %first vehicle gets given a registeration number
                v_reg=1;

                %The Lane of the 1st vehicle for the 1st time step
                lanes(t,v_reg)=1;                 %the first vehicle
spawns in lane one
                lane_dens(1,1)=1;

                %position of the 1st vehicle's front bumper for the first
                %time step
                posit_f(t,v_reg)=0.1;             %New vehicles appears at
0.1. i.e cell 1 pa 125

                %The first vehicle gets given a vehicle type depending on
                %the combination of vehicles the user selected.
                if uniform_veh==on
                    if choose_veh==small
                        veh_len(1,v_reg)=small_L;
                        veh_type(1,v_reg)=1;
                    elseif choose_veh==large
```

```
                veh_len(1,v_reg)=big_L;
                veh_type(1,v_reg)=4;
            end
        elseif uniform_veh==off
            veh_len(1,v_reg)=small_L;
            veh_type(1,v_reg)=1;
          %Kept track of the current small vehicle type. resetted
          %to zero when all types had been used
            L_veh_type_cnt=1;
          %counts the number of small vehicles,
          %when it is greater than the specified maximum value
(ratio)
          %a larger vehicle enters and the counter resets
            veh_len_cnt=1;
        end

        %Position
        %the position of the 1st vehicle rear bumper for the first
time step
        posit_r(t,v_reg)=posit_f(t,v_reg)-veh_len(1,v_reg);

        %The 1st vehicle's front and rear bumpers patch locations

[p_frt,p_rer]=patch_finder2(posit_f(t,v_reg),veh_len(1,v_reg),patch_table);

        %register vehicle front bumper to its current patch. The
        %rear bumper would be outside the link so cannot be
        %registered
        patch_veh_reg(p_frt,1)=v_reg;
        ref(t,v_reg)=0;
```

```
            %acceleration
            %The 1st vehicle maximum acceleration for the 1st time step

[max_accel(t,v_reg),max_dec(t,v_reg)]=Maximum_accelndecel_raka(v_reg,t,vel(
:,:),condition,veh_type(1,v_reg),intensity);
            %The 1st vehicle driver accelerates at its desired maximum
acceleration
            accel(t,v_reg)=max_accel(t,v_reg);


            %The 1st vehicle gets given an initial velocity which
            %depends on the weather condition
            vel(t,v_reg)=vel_init;


            %The 1st vehicle entry time is taken into account
            sta_tim(1,v_reg)=t;
            %The density on the link is incremented
            count_Den=count_Den+1;
            %Kept account of vehicles entering and exiting the link
            %If cell 1 is high a vehicle entered at that time step,
            %if cell 2 high a vehicle exited at that time step
            traff_flow(t,1)=1;


            timer1=t;  %timer for when a vehicle last entered the link
        end



        %After the first time step
        if t>1
            %search for vehicles in both front bumper registers of the
current
```

```
                %patch. sw1 and sw2 change based on the current lane and
accept
                %front bumber registers
                for sw=1:no_lane
                    switch sw
                        case 1
                            sw1=1;
                            sw2=2;
                        case 2
                            sw1=5;
                            sw2=6;
                        case 3
                            sw1=9;
                            sw2=10;
                        case 4
                            sw1=13;
                            sw2=14;
                    end

                    %vk changes between the current lane front bumper
registers
                    for swb=1:2
                    %this loop was included for a scenario where reg b of a
patch shifts
                    %to a after lane change and the code needs to re run a
to avoid skipping
                    %the vehicle that shifted from b to a. the loop breaks
if this shift never occured
                        for shi=1:2
                            shift=0;
                            switch swb
                                case 1
```

```
                    vk=sw1;
                case 2
                    vk=sw2;
            end

            %resetting parameters
            ref_veh=0;
            v_reg=0;

            if patch_veh_reg(pa,vk)>0
                %to make referencing easier
                v_reg=patch_veh_reg(pa,vk);
                %run_check was used to prevent vehicles
that may have switched lanes
                %(esp to d right) from running twice in the
                %same time step since the code runs from
                %the left lane to the right lane
                if run_check(t,v_reg)==0
                    run_check(t,v_reg)=1;
                    %Lanes maneouvering
                    %The lane change function (i.e
                    %overtake7) was used to determine the
                    %current lane of the observed vehicle.
                    %Other outputs were utilised by the
                    %function to keep track of drivers
                    %mindsets (e.g. interest levels)

[timer_N1(:,:),timer_N2(:,:),lanes(:,:),non_interest_counter(:,:),timer_ove
rtake(:,:),timer_change(:,:)]=overtake7(lanes(:,:),v_reg,veh,vel(:,:),max_v
el,g(:,:),t,timer_N1(:,:),timer_N2(:,:),non_interest_counter(:,:),patch_veh
_reg(:,:),pa,posit_f(:,:),posit_r(:,:),max_dec(:,:),stop_gap,
aA(:,:),aB(:,:),aC(:,:), accel(:,:),
max_accel(:,:),timer_overtake(:,:),timer_change(:,:),reset_lane_timers(:,:)
,veh_len(:,:),patch_table,no_lane);
```

```
%The OV current lane
cur_lane=lanes(t,v_reg);
%The OV previous lane
prev_lane=lanes(t-1,v_reg);
%If the current lane of the OV is
%different from its previous lane then
%increment its current lane and
%decrement its previous lane
if cur_lane~=prev_lane

lane_dens(1,cur_lane)=lane_dens(1,cur_lane)+1;

lane_dens(1,prev_lane)=lane_dens(1,prev_lane)-1;
end

%used to reset lane change timer for
new vehicles
%after the vehicle with the same reg
has exited the link
reset_lane_timers(1,v_reg)=0;

%Whenever a vehicle switched lanes the
%patch register had to be updated by
%deleting the vehicle's reg number from
%its previous patch register slot and
%entering it in its new patch register
%slot
if lanes(t,v_reg)~= lanes(t-1,v_reg)
    %Here the previous patch of the
    %vehicle was selected

[p_frt,p_rer]=patch_finder2(posit_f(t-
1,v_reg),veh_len(1,v_reg),patch_table);
```

```
                                        %Values were given to the
                                        %switch_board function, outputs
were
                                        %based on the previous lane of the
                                        %observed vehicle
                                        [ a,b,C,d ] = switch_board(lanes(t-
1,v_reg));
                                        %The patch register slot for the
                                        %previous lane front bumper was
                                        %reset here
                                        for dt=a:b
                                            if
patch_veh_reg(p_frt,dt)==v_reg
                                                patch_veh_reg(p_frt,dt)=0;
                                                break;
                                            end
                                        end


                                        %This step was used to move the reg
no of any
                                        %other vehicle on the previous lane
                                        %of the observed vehicle from patch
register slot 1
                                        %to 2 i.e front bumper. Note this
                                        %does not actually move the
                                        %vehicle. It only allows lead
                                        %vehicles to always be simulated
                                        %before following vehicles on the
                                        %same lane.
                                        if patch_veh_reg(p_frt,a)==0

patch_veh_reg(p_frt,a)=patch_veh_reg(p_frt,b);
```

```
        %used to determine the loop to
brake.
        %See above for better
understanding
        if patch_veh_reg(p_frt,b)>0
            shift=1;
        end
        patch_veh_reg(p_frt,b)=0;
    end

    %The patch register slot for the
    %previous lane rear bumper was
    %reset here
    for dt=C:d
        if
patch_veh_reg(p_rer,dt)==v_reg
            patch_veh_reg(p_rer,dt)=0;
            break;
        end
    end

    %Although this may not affect the
    %simulation since the front bumper
    %positions were mainly used for the
    %simulation, this step was done
    %similar to the front bumper step
    %for clarity
    if patch_veh_reg(p_rer,C)==0

patch_veh_reg(p_rer,C)=patch_veh_reg(p_rer,d);
        patch_veh_reg(p_rer,d)=0;
    end
```

```
            %Values were given to the
            %switch_board function, outputs
were
            %based on the current lane of the
            %observed vehicle
            [ a,b,C,d ] = switch_board(
lanes(t,v_reg) );
            for dtt=a:b
                if patch_veh_reg(p_frt,dtt)==0

patch_veh_reg(p_frt,dtt)=v_reg;
                    break;
                end
            end

            %The patch register slot for the
            %current lane front bumper was
            %updated here
            for dtt=C:d
                if patch_veh_reg(p_rer,dtt)==0

patch_veh_reg(p_rer,dtt)=v_reg;
                    break;
                end
            end
        end

        %The reference vehicle generator
        %function was used to determine the OV
        %lead vehicle
        if v_reg>0
```

```
[ref_veh,NTA]=ref_veh_generator3(patch_veh_reg(:,:),pa,v_reg,posit_f(:,:),p
osit_r(:,:),t,lanes(t,v_reg),0,0);
                                        ref(t,v_reg)=ref_veh;
                                    end


                                    % Displacement
                                    disp_buf(t,v_reg)= (vel(t-
1,v_reg)*0.1)+(1/2*(accel(t-1,v_reg)*(0.1)^2));


                                    %Preventing negative displacements
                                    if disp_buf(t,v_reg)<0
                                        disp(t,v_reg)=0;
                                    elseif disp_buf(t,v_reg)>=0
                                        disp(t,v_reg)=disp_buf(t,v_reg);
                                    end


                                    %Calculating observed vehicle's
position
                                    %The current front bumper posiiton of
the OV %was calculated as the sum of its
                                    %previous position and its current
displacement while its rear bumper
                                    %position was calculated as the
difference between its current front
                                    %bumper position and the vehicle length
                                    posit_f(t,v_reg)=posit_f(t-
1,v_reg)+disp(t,v_reg);
                                    posit_r(t,v_reg)=posit_f(t,v_reg)-
veh_len(1,v_reg);


                                    %Cancelling the Observed vehicle
previous patch slot
                                    [ a,b,C,d ] = switch_board(
lanes(t,v_reg) );
```

```
                                        %Its previous patches for both bumpers
were obtained here

[Prevp_frt,Prevp_rer]=patch_finder2(posit_f(t-
1,v_reg),veh_len(1,v_reg),patch_table);

[p_frt,p_rer]=patch_finder2(posit_f(t,v_reg),veh_len(1,v_reg),patch_table);


                                        %This step is used when the OV previous
front bumper patch is not the same as
                                        %the current one OR when they are the
same but the current lane is
                                        %different from the previous lane
                                        if Prevp_frt~=p_frt ||
(Prevp_frt==p_frt && lanes(t,v_reg)~=lanes(t-1,v_reg))
                                            %This loop was used to cycle
through both slots of the
                                            %vehicle's previous patch to find
the slot containing the OV's reg no
                                            for sk=a:b
                                                if Prevp_frt>0 &&
v_reg==patch_veh_reg(Prevp_frt,sk)
                                                    %The slot containing the OV
reg no was reset to 0

patch_veh_reg(Prevp_frt,sk)=0;


                                                    %finding an available front
bumper slot on the OV new patch and
                                                    %registering to the slot.
The switch_board was used to find the
                                                    %slots for the OV current
lane patch
                                                    [ a,b,C,d ] =
switch_board(lanes(t,v_reg));
```

```
                                        %This loop was used to
cycle through both slots of the
                                        %vehicle's current patch to
find a
                                        %free slot to register the
OV to
                                        for nk=a:b
                                            if p_frt>0 &&
patch_veh_reg(p_frt,nk)==0
                                                %The OV was
registered to the free slot found on
                                                %its current patch

patch_veh_reg(p_frt,nk)=v_reg;
                                                break;
                                            end
                                        end
                                        break;
                                    end
                                end
                                %If the OV previous patch is the
same as its current patch and the
                                %lane is the same as well then the
following step is used. I.e its
                                %current patch and slot remains the
same as the previous one
                            elseif Prevp_frt==p_frt
                                if lanes(t,v_reg)==lanes(t-1,v_reg)
                                    patch_veh_reg(pa,vk)=v_reg;
                                end
                            end

                            %Same as before, so that this shift
doesnt cause the 2nd
```

```
                                    %veh in the patch reg to be skipped
during
                                    %the vk loop
                                    [ a,b,C,d ] = switch_board(
lanes(t,v_reg) );


                                    if vk==b && Prevp_frt>0
                                        %shifting the vehicle reg by 1
column
                                        if patch_veh_reg(Prevp_frt,a)==0

patch_veh_reg(Prevp_frt,a)=patch_veh_reg(Prevp_frt,b);
                                            patch_veh_reg(Prevp_frt,b)=0;
                                        end
                                    end


                                    %cancelling previous rear bumper patch
                                    if posit_r(t-1,v_reg)>0
                                        [ a,b,C,d ] = switch_board(
lanes(t,v_reg) );
                                        for pk=C:d
                                            if
v_reg==patch_veh_reg(Prevp_rer,pk)

patch_veh_reg(Prevp_rer,pk)=0;
                                                break
                                            end
                                        end
                                    end


                                    %The next step is executed if the OV
rear bumper position is greater than 0 AND its current patch is different
from its previous patch OR the patch
```

```
                                    %is the same but the lane is different
or the current patch and lane are the same as the previous but the position
of the rear bumper os 0.

                                    if (posit_r(t,v_reg)>0
&&(Prevp_rer~=p_rer||(Prevp_rer==p_rer&&lanes(t,v_reg)~=lanes(t-
1,v_reg))))||(Prevp_rer==p_rer&&lanes(t,v_reg)==lanes(t-1,v_reg))

                                        %finding an available rear bumper
slot on the OV current rear bumper patch and registering to it

                                        [ a,b,C,d ] = switch_board(
lanes(t,v_reg) );

                                        for rk=C:d

                                            if p_rer>0 &&
patch_veh_reg(p_rer,rk)==0

patch_veh_reg(p_rer,rk)=v_reg;

                                                pa_err_r=2;

                                                break;

                                            end

                                        end

                                    end




                                    %Again the rear bumper patch slot
doesn't have to be shifted but this                                    %

                                    %was done for clarity.

                                    if (vk==2 || vk==6 || vk==10 || vk==14)
&& Prevp_rer>0

                                        [ a,b,C,d ] = switch_board(
lanes(t,v_reg) );

                                        %shifting the vehicle reg by 1
column

                                        if patch_veh_reg(Prevp_rer,C)==0

patch_veh_reg(Prevp_rer,C)=patch_veh_reg(Prevp_rer,d);

                                            patch_veh_reg(Prevp_rer,d)=0;

                                        end
```

```
                                    end

                                    %When the observed vehicle gets to the
end of the link
                                    if posit_f(t,v_reg)>link
                                        [ a,b,C,d ] = switch_board(
lanes(t,v_reg) );

                                        %the OV finish time is taken down
                                        fin_tim(1,v_reg)=t;

                                        %The front bumper patch slot
automatically becomes 0 because the front
                                        %bumper position would be greater
than the link but the rear bumper position
                                        %would have to be reset to 0
                                        %Resetting the rear bumper patch
register

[p_frt,p_rer]=patch_finder2(posit_f(t,v_reg),veh_len(1,v_reg),patch_table);
                                        if posit_r(t,v_reg)>0
                                            for pk=C:d
                                                if p_rer>0 &&
v_reg==patch_veh_reg(p_rer,pk)

patch_veh_reg(p_rer,pk)=0;
                                                end
                                            end
                                        end

                                        %The density of the OV lane reduces
                                        %when the OV exits the link

lane_dens(1,cur_lane)=lane_dens(1,cur_lane)-1;
```

```
                                        %The density of the entire link
also reduces
                                        count_Den=count_Den-1;


                                        %If cell 1 is high a vehicle
entered at that time step,
                                        %if cell 2 high a vehicle exited at
that time step
                                        %When both are 1 or high during the
same time step
                                        %the traffic is stable.
                                        traff_flow(t,2)=1;


                                        %Various parameters are then
                                        %calculated such as the total
                                        %vehicle that have gone through the
                                        %link, the journey time and average
                                        %velocity of the OV that just
                                        %exited the link.
                                        veh_count=veh_count+1;

jon_tim(1,veh_count)=(fin_tim(1,v_reg)-sta_tim(1,v_reg))*0.1;

Veh_Av_vel(1,veh_count)=link/jon_tim(1,veh_count);


                                        %The average velocity of all
vehicles that successfully exited the link during
                                        %simulation were summed. The sum
was later divided by the total vehicle that successfully
                                        %exited the link from the
simulation start time to its termination time in order to deduce the
                                        %average velocity on the link
```

```
Add_Av_vel=Add_Av_vel+Veh_Av_vel(1,veh_count);

                                        %The traffic flow was stable (i.e
sat) when vehicles exited and entered
                                        %the link during the same time
step. That is when both bits of
                                        %the array traff_flow are 1.
                                        if sat_time>0
                                            %The total vehicles that had
gone through the link during the stable state
                                            veh_count_sat=veh_count_sat+1;
                                            %The OV journey time during the
traffic flow stable state

jon_tim_sat(1,veh_count_sat)=(fin_tim(1,v_reg)-sta_tim(1,v_reg))*0.1;
                                            %The OV average velocity during
the traffic flow stable state                                            %

Veh_Av_vel_sat(1,veh_count_sat)=link/jon_tim_sat(1,veh_count_sat);


                                            %the average velocity of all
vehicles that successfully exited the link from the
                                            %stabled state to the
simulation termination time were summed. The sum was later divided
                                            %by the total vehicle that
successfully exited the link from the stable period to the end
                                            %of the simulation to deduce
the average velocity on the link

Add_Av_vel_sat=Add_Av_vel_sat+Veh_Av_vel_sat(1,veh_count_sat);


                                            veh_count_aft=veh_count_sat-1;
%dont include
                                        end
```

```
                                        %The OV parameters were then reset
to to 0 including its
                                        %registeration number so it could
be used by a new vehicle
                                        posit_f(t,v_reg)=0;
                                        posit_r(t,v_reg)=0;
                                        vel(t,v_reg)=0;
                                        accel(t,v_reg)=0;
                                        sta_tim(1,v_reg)=0;
                                        fin_tim(1,v_reg)=0;
                                        Veh_jou_Av_vel(1,v_reg)=0;
                                        h(t,v_reg)=0;
                                        v_reg=0;
                                    end



                                    if v_reg>0
                                        %gap
                                        if ref_veh~=0

[g(t,v_reg)]=Vehicle_gap(posit_r(t,ref_veh),posit_f(t,v_reg));
%Since it is a lead vehicle
                                        end

                                        %bunching acceleration

[c(t,v_reg)]=bunching_accel2(ka,g(t,v_reg),stop_gap);

                                        %velocity
                                        buf_vel(t,v_reg)=vel(t-
1,v_reg)+(accel(t-1,v_reg)*0.1);
                                        %Limiting velocity
```

```
if buf_vel(t,v_reg)<0
    vel(t,v_reg)=0;
elseif buf_vel(t,v_reg)<max_vel
    vel(t,v_reg)=buf_vel(t,v_reg);
elseif buf_vel(t,v_reg)>=max_vel
    vel(t,v_reg)=max_vel;
end

%headway
%http://odd.topslab.wisc.edu/publications/2011/Modeling%20Highway%20Safety%20and%20Simulation%20in%20Rainy%20Weather%20(2237-15).pdf%
%Vehicle average velocity while in
%journey. Dont use for analysis
if ref_veh~=0
    %Vehicle average velocity
Veh_jou_Av_vel(1,v_reg)=posit_f(t,v_reg)/((t-sta_tim(1,v_reg))*0.1);
    %Average spacing on the link
av_spacing=link/lane_dens(1,cur_lane);
    %Estimated headway
h(t,v_reg)=av_spacing/Veh_jou_Av_vel(1,v_reg);
end

%Seperation
if ref_veh~=0
[s(t,v_reg)]=separation(h(t,v_reg),vel(t,ref_veh),vel(t,v_reg));
end

%Target
```

```
[T(t,v_reg)]=Target_p2(s(t,v_reg),g(t,v_reg));



                                        %acceleration components

[max_accel(t,v_reg),max_dec(t,v_reg)]=Maximum_accelndecel_raka(v_reg,t,vel(
:,:),condition,veh_type(1,v_reg),intensity);
                                        if ref_veh~=0
                                            %Target point overshot

[kaA(t,v_reg)]=buffer_accel_overshot(kb,vel(t,ref_veh),vel(t,v_reg));
                                            %Limiting aA to max accel and
max dec

[aA(t,v_reg)]=accel_overshot(kaA(t,v_reg),max_dec(t,v_reg),max_accel(t,v_re
g));


                                            %aB Lead vehicle pulling away

[kaB(t,v_reg)]=bufferaccel_pullingaway2(g(t,v_reg),T(t,v_reg),kb,vel(t,ref_
veh),vel(t,v_reg),ka);
                                            %Limiting aB to max accel and
max dec

[aB(t,v_reg)]=accel_pullingaway(kaB(t,v_reg),max_dec(t,v_reg),max_accel(t,v
_reg));


                                            %Vehicles at constant speed or
coming together (cruise accel)

[kaC(t,v_reg)]=bufferaccel_cruise2(vel(t,ref_veh),vel(t,v_reg),g(t,v_reg),T
(t,v_reg),c(t,v_reg));
                                            %Limiting aC to max accel and
max dec

[aC(t,v_reg)]=accel_cruise(kaC(t,v_reg),max_dec(t,v_reg),max_accel(t,v_reg)
);
```

```
end

%lead car braking verification. 1 is true 0 is false
if ref_veh~=0
    if t>15
        %determine if the leadvehicle entered the link before or after the cur time minus the cur veh awreness time plus 5
        ord=(t-(5+Aw_lev));
        ort=sta_tim(1,ref_veh);
        orl=ord-ort;
        if  orl>0
            ign=1;
        else
            ign=0;
        end
        %The array z holds the test results for the observed vehicle for each time step. The velocity of the lead vehicle for the 5 consecutive time steps been observed are fed into the function. These time steps are a total of the response time plus the time step number

[z(t,v_reg)]=Leadcar_braking_verification(vel(t-(5+Aw_lev),ref_veh),vel(t-(4+Aw_lev),ref_veh),vel(t-(3+Aw_lev),ref_veh),vel(t-(2+Aw_lev),ref_veh),vel(t-(1+Aw_lev),ref_veh),vel(t-(0+Aw_lev),ref_veh),ign);
    end
end

%accelerate vehicle
%Detect collision
acc_safe=0;
if ref_veh~=0
```

```
[colli,acc_safe]=collision_detector3(vel(t,ref_veh),max_dec(t,ref_veh),max_dec(t,v_reg),vel(t,v_reg),posit_f(t,v_reg),posit_r(t,ref_veh),stop_gap,accel(t-1,v_reg),0);
end

%Determine acceleration mode
%Stop_line response
%The stop sign (i.e. stop_line_status)
%was on when the light was red (1)
%during the current time step and
%was off when the light was green
%(2) during the current time step
if traffic_light==on
    if light(t,1)==1
        stop_line_status=on;                    %ON=1, OFF=0
        stopline_check(t,1)=on;
    elseif light(t,1)==2
        stop_line_status=off;                   %ON=1, OFF=0
        stopline_check(t,1)=off;
    end
end

accel_found=0;
accel_found1=0;

%%Used to control the acceleration of the lead vehicle%%
```

```
                                        %This function operated like the
collision detector function except
                                        %the vehicle's speed and position
was compared to the position of the stopline
                                        [ stop ] =
stopline_overshoot_detector(
vel(:,:),max_dec(:,:),link,t,v_reg,posit_f(:,:));


                                        %accel_found1==0 meant acceleration
mode not found


                                        %When the OV had no lead
vehicle(ref_veh==0) and no congestion was to be induced
                                        %at the end of the link it
accelerated at maximum acceleration
                                        if ref_veh==0 && accel_found1==0 &&
congestion==off

accel(t,v_reg)=max_accel(t,v_reg);
                                                accel_found1=1;
                                        %When congestion was to be induced
and the OV had no lead vehicle
                                        elseif congestion==on && ref_veh==0
                                            %The stop line is ON and the
vehicle would potentially overshoot the stop sign (i.e.stop==1)
                                            if stop==1 &&
stop_line_status==on && accel_found1==0

accel(t,v_reg)=max_dec(t,v_reg);
                                                accel_found1=1;
                                        %speed_line is a point on the link
beyound which a special speed limit was required as vehicles approach
                                        %the end of the link. jam_spd is
special speed limit for the end of the link
```

```
                                            %The OV was required to brake
at max if its front bumper position was greater or equals the speed_line
and its
                                            %velocity was greater than the
jam_spd
                                            elseif
posit_f(t,v_reg)>=speed_line && vel(t,v_reg)>jam_spd && accel_found1==0

accel(t,v_reg)=max_dec(t,v_reg);
                                                accel_found1=1;
                                            %Else it was required to
accelerate at max if its front bumper position was greater or equals the
speed_line
                                            %and its velocity less than the
jam_sp
                                            elseif
posit_f(t,v_reg)>=speed_line && vel(t,v_reg)<jam_spd && accel_found1==0

accel(t,v_reg)=max_accel(t,v_reg);
                                                accel_found1=1;
                                            %Else it was required to not
accelerate if its front bumper was greater than or equals the speed_line,
                                            %its velocity was equals the
jam_spd
                                            elseif
posit_f(t,v_reg)>=speed_line && vel(t,v_reg)==jam_spd && accel_found1==0
                                                accel(t,v_reg)=0;
                                                accel_found1=1;
                                            %Else it was required to
accelerate at max if the position of its front bumper was less than the
speed_line
                                            elseif
posit_f(t,v_reg)<speed_line

accel(t,v_reg)=max_accel(t,v_reg);
                                                accel_found1=1;
                                            end
```

```
                                        %%used to safely bring the OV
closer to its lead vehicle during congestion%%

                                        %If the OV has a lead vehicle
                                        elseif ref_veh>0 && accel_found1==0
                                            %If the OV is at risk of
colliding with its lead vehicle it is required to brake at max
                                            if colli==1

accel(t,v_reg)=max_dec(t,v_reg);
                                                accel_found=1;
                                            %Elseif the OV is not at a risk
of colliding with its lead vehicle and it is within a
                                            %given safe threshold distance
from its lead vehichle it is required to accelerate at max
                                            elseif acc_safe==1 && colli==0
&& accel_found==0

accel(t,v_reg)=max_accel(t,v_reg);
                                                accel_found=1;


                                            %Elseif the OV has been on the
link less than the awareness time defined for all drivers
                                            %plus the time they require to
observe the speed of their lead vehicle to determine if it is braking
                                            %and the OV is not at a risk of
colliding with its lead vehicle


                                            %%NOTE: if this condition is
true the response time of the driver would not be included since the driver
                                            %%would not have any memory
before its journey start time
                                            elseif (t-
(Aw_lev+5))<=sta_tim(1,v_reg) && colli==0 && accel_found==0
                                                %If the velocity of the
lead vehicle velocity is zero
```

```
                                                    if vel(t,ref_veh)==0 &&
accel_found==0
                                                        %if the gap between the
OV and its lead vehicle is greater than the required gap between vehicles
during
                                                        %a traffic jam
(stop_gap) and the velocity of the OV is less than the gap minus the
stop_gap
                                                        %then the preliminary
acceleration is 0.1 times the gap
                                                        %an assumption was made
that the required acceleration to close the gap was proportional to the
gap.
                                                        %The acceleration was
then limited to the maximum acceleration and deceleration
                                                        if g(t,v_reg)>stop_gap
&& accel_found==0 && vel(t,v_reg)<(g(t,v_reg)-stop_gap)

accel_buf=kb*g(t,v_reg);
                                                            if
accel_buf>=max_accel(t,v_reg)

accel(t,v_reg)=max_accel(t,v_reg);
                                                            elseif
accel_buf<=max_dec(t,v_reg)

accel(t,v_reg)=max_dec(t,v_reg);
                                                            else

accel(t,v_reg)=accel_buf;
                                                            end
                                                            accel_found=1;
                                                        %Elseif the gap was
less than the stop_gap or the OV is at a risk of colliding with its lead
                                                        %vehicle the OV is
required to decelerate at max
                                                        elseif
g(t,v_reg)<=stop_gap || colli==1 && accel_found==0
```

```
accel(t,v_reg)=max_dec(t,v_reg);
                                                                    accel_found=1;
                                                                end
                                                            %Elseif the velocity of the
OV lead vehicle is greater than zero
                                                            elseif vel(t,ref_veh)>0 &&
accel_found==0
                                                                %If the OV was within
the given safe threshold distance from its lead vehicle and was not
                                                                %at a risk of colliding
with it then it was required to accelerate at max
                                                                if acc_safe==1 &&
colli==0 && accel_found==0

accel(t,v_reg)=max_accel(t,v_reg);
                                                                    accel_found=1;
                                                                %Else if it was at a
risk of colliding with its lead vehicle it was required to brake at max
                                                                elseif colli==1

accel(t,v_reg)=max_dec(t,v_reg);
                                                                    accel_found=1;


                                                                %Else if it was not
within the given safe threshold distance from its lead vehicle and was not
                                                                %at a risk of colliding
with it
                                                                elseif acc_safe==0 &&
colli==0 && accel_found==0
                                                                    %If its separation
from its lead vehicle was less than or equals its target separation
                                                                    if
s(t,v_reg)<=T(t,v_reg)
                                                                        %if its lead
vehicle is not breaking (i.e. z==0) then the OV is expected to accelerate
```

```
                                                    %at aA
acceleration component
                                                    if
z(t,v_reg)==0 && accel_found==0

accel(t,v_reg)=aA(t,v_reg);

accel_found=1;
                                                    %Elseif its
lead vehicle is breaking (i.e. z==1) then the OV is expected to brake at
max
                                                    elseif
z(t,v_reg)==1

accel(t,v_reg)=max_dec(t,v_reg);

accel_found=1;
                                                    end
                                                %Elseif the
separation is greater than the target
                                                elseif
s(t,v_reg)>T(t,v_reg) && accel_found==0


                                                    %If the
velocity of the OV at the current time step is greater than its velocity at
the
                                                    %previous
timestep then the OV is expected to accelerate at aB acceleration component
                                                    if
vel(t,veh)>vel(t-1,veh)

accel(t,v_reg)=aB(t,v_reg);

accel_found=1;
                                                    %Elseif its
lead vehicle is not breaking it is expected to accelerate
                                                    %at
acceleration component aC
```

```
                                                        elseif
z(t,v_reg)==0 && accel_found==0

accel(t,v_reg)=aC(t,v_reg);

accel_found=1;
                                                        %Elseif its
lead vehicle is breaking or it is at a risk of colliding with its lead
                                                        %vehicle it is
expected to brake at max
                                                        elseif
(z(t,v_reg)==1 || colli==1)  && accel_found==0

accel(t,v_reg)=max_dec(t,v_reg);

accel_found=1;
                                                        end
                                                    end
                                                end
                                            end

                                            %Elseif the OV has been on the
link longer than the awareness time defined for all drivers
                                            %plus the time they require to
observe the speed of their lead vehicle to determine if it is braking
                                            %and the OV is not at a risk of
colliding with its lead vehicle

                                            %%NOTE: if this condition is
true the response time of the driver would be included since the driver
                                            %%memory started during its
journey start time and its memory covers its response time which is slower
                                            %%than the actual time hence
its memory is focused on a period of time in the past
                                            %%The same steps as when the
driver had insufficient memory to include its response time are then
repeated
```

```
                                                    %%except the driver's response
time is now taken into account
                                                    elseif (t-
(Aw_lev+5))>sta_tim(1,v_reg) && colli==0 && accel_found==0
                                                        if vel(t-Aw_lev,ref_veh)==0
                                                            if g(t,v_reg)>stop_gap
&& accel_found==0 && vel(t,v_reg)<(g(t,v_reg)-stop_gap)

accel_buf=kb*g(t,v_reg);
                                                                if
accel_buf>=max_accel(t,v_reg)

accel(t,v_reg)=max_accel(t,v_reg);
                                                                elseif
accel_buf<=max_dec(t,v_reg)

accel(t,v_reg)=max_dec(t,v_reg);
                                                                else

accel(t,v_reg)=accel_buf;
                                                                end
                                                                accel_found=1;
                                                            elseif
g(t,v_reg)<=stop_gap && accel_found==0

accel(t,v_reg)=max_dec(t,v_reg);
                                                                accel_found=1;

                                                            elseif colli==1

accel(t,v_reg)=max_dec(t,v_reg);
                                                                accel_found=1;
                                                            elseif g(t-
Aw_lev,v_reg)<=stop_gap && accel_found==0

accel(t,v_reg)=max_dec(t,v_reg);
```

```
                                                            accel_found=1;
                                                        end
                                                    elseif vel(t-
Aw_lev,ref_veh)>0 && accel_found==0
                                                        if acc_safe==1 &&
colli==0

accel(t,v_reg)=max_accel(t,v_reg);
                                                            accel_found=1;
                                                        elseif colli==1

accel(t,v_reg)=max_dec(t,v_reg);
                                                        elseif acc_safe==0 &&
colli==0 && accel_found==0
                                                            if s(t-
Aw_lev,v_reg)<=T(t-Aw_lev,v_reg)
                                                                if z(t-
Aw_lev,v_reg)==0 && accel_found==0

accel(t,v_reg)=aA(t,v_reg);

accel_found=1;
                                                                elseif z(t-
Aw_lev,v_reg)==1 && accel_found==0

accel(t,v_reg)=max_dec(t,v_reg);

accel_found=1;
                                                                end

                                                            elseif s(t-
Aw_lev,v_reg)>T(t-Aw_lev,v_reg) && accel_found==0
                                                                if
vel(t,veh)>vel(t-Aw_lev+5,veh)

accel(t,v_reg)=aB(t,v_reg);
```

```
accel_found=1;
                                                            elseif z(t-
Aw_lev,v_reg)==0 && accel_found==0
accel(t,v_reg)=aC(t,v_reg);
accel_found=1;
                                                            elseif z(t-
Aw_lev,v_reg)==1 && accel_found==0
accel(t,v_reg)=max_dec(t,v_reg);
accel_found=1;
                                                            elseif colli==1
accel(t,v_reg)=max_dec(t,v_reg);
accel_found=1;
                                                            end
                                                        end
                                                    end
                                                end
                                            end
                                        end
                                    end
                                end
                            end
                            if shift==0 %Exits loop if no shift occurred or
b wasnt greater than zero see above for proper understanding
                                break;
                            end
                        end
                    end
                end
```

```
            end


            %%Generating a new vehicle%%


            %New vehicles were generated on the beginning of the link i.e
patch 125
            if t>1 && pa==patch
                %Generate new vehicle on patch (front bumper)
                %The vehicle to be generated was given 0.5 as a temporary
registeration number. Actual vehicle registeration numbers start from 1.
                v_reg=0.5;


                %The registeration number of the lead vehicle of the new
vehicle is initialised to zero
                ref_veh=0;


                if v_reg==0.5
                    %The new vehicle temporary lane is initialised to zero
                    temp_lane=0;


                    %This loop runs through all lane numbers on the link
                    %%NOTE that since the loop starts running from lane
number 1 vehicles would first attempt to generate on the inner lanes
                    for la=1:no_lane
                        %For each lane number selected it determines the
vehicle on the lane closest to the start point.
                        %This vehicle would be a potential lead vehicle of
the new vehicle to be generated

[ref_veh_D,NTA]=ref_veh_generator3(patch_veh_reg(:,:),pa,v_reg,posit_f(:,:)
,posit_r(:,:),t,la,0,1);
                        %It then determines if there would be a collision
with the potential lead vehicle if the new vehicle
                        %was generated at the start of the lane
```

```
                        colli=0;
                        if ref_veh_D>0

[colli,acc_safe]=collision_detector3(vel(t,ref_veh_D),max_dec(t,ref_veh_D),
max_dec(t,ref_veh_D)/3,vel_init,0,posit_r(t,ref_veh_D),stop_gap,0,0);
                        end
                        %If the gap between the veh to be generated and the
lead veh is greater than stop_gap and den is greater than 15 or entry
interval has been reached
                        %and If there would be no collision or there is no
vehicle on the lane the scanned lane is then assigned as the temporary lane
                        %of the vehicle to be generated while its lead
vehicle is assigned as the detected potential lead vehicle on the lane
                        %or zero if no vehicle on the lane
                        if  ref_veh_D~=0 && colli==0 &&
((posit_r(t,ref_veh_D)>stop_gap) && max_Den>15 ||(t-timer1)>=interval &&
(posit_r(t,ref_veh_D)>stop_gap)) || ref_veh_D==0
                            temp_lane=la;
                            ref_veh=ref_veh_D;
                            break
                        end
                    end
                end
                %if the vehicle to be generated would collide with
potential lead vehicles on all lanes no vehicle is generated during this
timestep


                %if the vehicle to be generated has a temporary lane
                if temp_lane>0
                    [ a,b,C,d ] = switch_board( temp_lane );


                    %an available front bumper slot on the patch (patch
125) where the vehicle is to be generated is searched for
                    for jk=a:b
```

```
                        %If a slot if found the slot number is then copied
to a variable 'use'
                        if patch_veh_reg(pa,jk)==0
                            use=jk;
                            break;
                        end
                    end

                    %generating a new vehicle
                    %if an available slot was found (i.e. use>0)
                    if use>0

                        %selecting a registeration number for the new
vehicle
                        %The for loop runs from 1 to the maximum number of
vehicles allowed on the link.
                        for jk=1:veh
                            %The patch register is looked up to see if the
current value of the loop is registered on the patch register
                            vr=ismember(jk, patch_veh_reg(:));       %check
if v is a member of the array
                            %If YES the loop keeps running but if NO the
loop number is assigned as the vehicle registeration number
                            %since no vehicle currently has that
registeration number and the loop breaks
                            if vr~=1
                                v_reg=jk;
                                break;
                            end
                        end

                        %If the vehicle to be generated now has a real
registeration number (i.e. no longer temp reg)
```

```
                    if v_reg>0.5
                        %The position of the vehicle on the link is set
to 0.1 which is on patch 125.
                        %Every newly generated vehicle starts from this
point
                        %posiiton
                        posit_f(t,v_reg)=0.1;

                        %The new vehicle journey start time is then
taken as the current timestep
                        sta_tim(1,v_reg)=t;

                        %The new vehicle type is then selected

                        %Small vehicles have a length of 4.7m while
                        %large vehicles have a length of 14m
(reference)
                        %Uniform small vehicles were given type 1
                        %vehicle design while unifrom large vehicles
                        %were given type 4.
                        if uniform_veh==on
                            if choose_veh==small
                                veh_len(1,v_reg)=small_L;
                                veh_type(1,v_reg)=1;
                            elseif choose_veh==large
                                veh_len(1,v_reg)=big_L;
                                veh_type(1,v_reg)=4;
                            end
                        %With uniform vehicles option off vehicle ratio
                        %was used. A counter was used along side the
                        %ratio to determine when to select small or
                        %large vehicles. When the counter was less than
```

```
                    %the ratio value selections were made
                    %sequentially between the 3 small vehicle
                    %design types. The selection got to the 3rd
                    %type the next selection became the first one
                    %and the cycle continued until the counter
                    %value equaled the ratio value.
                    elseif uniform_veh==off
                        if veh_len_cnt<ratio
                            veh_len(1,v_reg)=small_L;
                            switch L_veh_type_cnt
                                case 0
                                    veh_type(1,v_reg)=1;
L_veh_type_cnt=L_veh_type_cnt+1;
                                case 1
                                    veh_type(1,v_reg)=2;
L_veh_type_cnt=L_veh_type_cnt+1;
                                case 2
                                    veh_type(1,v_reg)=3;
                                    L_veh_type_cnt=0;
                            end
                            veh_len_cnt=veh_len_cnt+1;
                      %When the counter equalled the ratio value
                      %a large vehicle was then selected and then
                      %the counter was reset so smaller vehicle
                      %lengths were selected afterwards. Just like
                      %the small vehicle selection procedure a
                      %different counter was used to ensure the
selection was
                      %done sequentially and once the 3rd vehicle
                      %type was selected the counter was reset so
```

```
                                        %that the next selection was the first
                                        %selection keeping the selection process in a
                                        %cycle.
                                          elseif veh_len_cnt>=ratio
                                              veh_len(1,v_reg)=big_L;
                                              switch H_veh_type_cnt
                                                  case 0
                                                      veh_type(1,v_reg)=4;

H_veh_type_cnt=H_veh_type_cnt+1;
                                                  case 1
                                                      veh_type(1,v_reg)=5;

H_veh_type_cnt=H_veh_type_cnt+1;
                                                  case 2
                                                      veh_type(1,v_reg)=6;
                                                      H_veh_type_cnt=0;
                                              end
                                              veh_len_cnt=0;
                                          end
                                      end

                                      %The position of the rear bumper of the new
vehicle was calculated by
                                      %subtracting the length of the vehicle from its
front numper position
                                      posit_r(t,v_reg)=posit_f(t,v_reg)-
veh_len(1,v_reg);
                                      %The temporary lane of the new vehicle was
assigned as its lane
                                      lanes(t,v_reg)=temp_lane;
                                      %The density of the new vehicle's lane
increased by 1
```

```
lane_dens(1,temp_lane)=lane_dens(1,temp_lane)+1;
                            %The lead vehicle of the new vehicle was
assigned as the detected potential
                            %lead vehicle on the lane or zero if no vehicle
on the lane
                            ref(t,v_reg)=ref_veh_D;
                            %The velocity of the new vehicle was then
assigned as the predefined initial velocity
                            vel(t,v_reg)=vel_init;


                            %find the patches the vehicle's bumpers are
located

[p_frt,rer]=patch_finder2(posit_f(t,v_reg),veh_len(1,v_reg),patch_table);
                            %the vehicle's front bumper was then registered
to a front bumper slot of its current patch
                            patch_veh_reg(p_frt,use)=v_reg;
                            %used to reset lane change timers of previous
vehicle that has left when a new vehicle with the same v_reg enters
                            reset_lane_timers(1,v_reg)=1;
                            %density on the road increases
                            count_Den=count_Den+1;
                            %If cell 1 is high a vehicle entered at that
time step,if cell 2 high a vehicle exited at that time step
                            %When both are 1 or high during the same time
step the traffic is stable.
                            traff_flow(t,1)=1;
                            %the time vehicle entered the link was taken,
this was used to control the interval at
                            %which new vehicles entered the link
                            timer1=t;
                        end
                    end
                end
```

```
        end
    end

    %Data collection
    %The maximum density was updated each time the density of the link
was greater than the maximum density on record
    %It was saved for each time step on the first column of an array
called 'data'
    if count_Den>max_Den
        max_Den=count_Den;
    end
    data(t,1)=max_Den;

    %The density, maximum density and flux for each time step were
saved in data column 1, 2 and 3 respectively
    density=data(t,1);
    mean_velocity=data(t,2);
    flux=data(t,3);

    %mean velocity
    %mean velocity at that time step was calculated as the sum of the
average velocity of all vehicles that have
    %exited the link divided by the total vehicles that have exited the
link
    if density>0
        mean_velocity=Add_Av_vel/veh_count;
        if Add_Av_vel==0 || veh_count==0
            mean_velocity=0;
        end
    end

    %mean velocity during stable traffic state
```

```
        %the mean velocity at the current time step during stability was
calculated as the sum

        %of the average velocity of all velicles that exited the link when
the traffic was stable

        %divided by the total vehicles that exited the link during this
period

        if density>0

            mean_velocity_sat=Add_Av_vel_sat/veh_count_sat;

            if Add_Av_vel_sat==0 || veh_count_sat==0

                mean_velocity_sat=0;

            end

        end



        %traffic flux

        %The traffic flux at the current timestep was calculated as the
density

        %divided by the mean velocity both at the current time step

        if density>0

            flux=density*mean_velocity;

        end



        %The density, mean velocity and flux of the current time step were
then

        %saved into data column 1, 2 and 3 respectively

        data(t,1)=density;

        data(t,2)=mean_velocity;

        data(t,3)=flux;



        %The timestep when the traffic became stable is taken

        if traff_flow(t,1)==1 && traff_flow(t,2)==1 && count_Den>=veh &&
prevent==0

            sat_time=t;

            prevent=1;
```

```
        end


        %%Not relevant%%

        if sat_time>0 && ((veh_count_aft>=change &&
change<=30)||(veh_count_aft>=30 && change>30))

            break;

        end

    end

    %The total simulation time in seconds from stable traffic state is
calculated as the difference

    %between the total time step and the time step when the traffic
attained a stable state divided by 10

    %since each time step is equivalent to 0.1sec

    Time=(t-sat_time)/10;

    %The traffic flux per hour was calculated as the quotient of the total
number of vehicles that exited

    %the link during the traffic stable state and the Time of the entire
simulation during the stable state multiplied by 3,600

    traff_flux(1,1)=(veh_count_sat/Time)*3600;

    %Not relevant%

    traff_flux(1,2)=(veh_count_sat/Time)*900;


    %The average journey time was calculated as the mean journey time of
all the vehicles that exited

    %the link during the traffic stable state

    mean_jon_tim_analy_sat(1,1)=mean(jon_tim_sat(1,:));


    %The calculated parameters were saved into various columns of an array
called 'flux_data'

    flux_data(1,size)=traff_flux(1,1);

    flux_data(2,size)=mean_jon_tim_analy_sat(1,1);

    flux_data(3,size)=t;

    flux_data(4,size)=sat_time;
```

```
    flux_data(5,size)=time;

    flux_data(6,size)=mean_velocity_sat;


    %Not relevant%

    flux_data(7,size)=change;


    %The array 'flux_data' was then saved as a spreadsheet so it could be
exported and used on a different program

    xlswrite('classlist.xlsx',flux_data,'section2','A1');


    switch change

        case 1

            data_analy(:,1)=data(:,1);

            data_analy(:,2)=data(:,2);

            data_analy(:,3)=data(:,3);

            data_analy(:,4)=traff_flow(:,1);

            data_analy(:,5)=traff_flow(:,2);


        case 2

            data_analy(:,7)=data(:,1);

            data_analy(:,8)=data(:,2);

            data_analy(:,9)=data(:,3);

            data_analy(:,10)=traff_flow(:,1);

            data_analy(:,11)=traff_flow(:,2);

        case 3

            data_analy(:,12)=data(:,1);

            data_analy(:,13)=data(:,2);

            data_analy(:,14)=data(:,3);

            data_analy(:,15)=traff_flow(:,1);

            data_analy(:,16)=traff_flow(:,2);
```

```
        case 4
            data_analy(:,18)=data(:,1);
            data_analy(:,19)=data(:,2);
            data_analy(:,20)=data(:,3);
            data_analy(:,21)=traff_flow(:,1);
            data_analy(:,22)=traff_flow(:,2);
        case 5
            data_analy(:,24)=data(:,1);
            data_analy(:,25)=data(:,2);
            data_analy(:,26)=data(:,3);
            data_analy(:,27)=traff_flow(:,1);
            data_analy(:,28)=traff_flow(:,2);
    end
   clear;

end
```

The edited code to accommodate autonomous vehicles

The main code

```
clear;
%maxi=3;                   %ensure when erasing you erase every infomation from the previous simulation especially if maxi was higher than wipe. Hence use a larger value for wipe to wipe out previous values
wipe=100;
bags=zeros(5,wipe);
xlswrite('classlist.xlsx',bags,'section2','A1');


for change=22:1:31
    max_v=31;               %must be the same as max change


    small=1;
```

```
    large=2;

    on=1;

    off=0;


    %settings

    congestion=on;                                %Congestion at the end of
the link?

    traffic_light=off;                            %Using traffic light or not
using traffic light. 1=using traffic light, 0=not using traffic light

    stop_line_status=off;                         %If not using traffic light
should the stop line be on or off?

    uniform_veh=on;                               %Using uniform or mixed
vehicles (uniform on or off?)

    choose_veh=large;                             %if using uniform vehicles
then using small or large vehicles?

    ratio=4;                                      %If vehicles are not
uniform enter the ratio of large to small vehicles. i.e. 1:ratio

    condition=1;                                  %Weather condition: 1 dry;
2 light rain; 3 heavy rain; 4 light snow; 5 heavy snow

    no_lane=4;                                    %Maximum number of lanes.
Error if higher than 4 or less than 1


    if condition==1

        if change==1

            time=3000;

        elseif change>1 && change<=6

            time=3000;

        elseif change>6 && change<=11            %this density simulation
time has been verified. 30 was last verified

            %time=3000;

            time=10000;

        elseif change>11 && change<=16

            time=4000;

        elseif change>16 && change<=26
```

```
            time=5000;
        elseif change>26 && change<=31
            time=8000;
        elseif change>36 && change<=41
            time=30000;
        elseif change>41 && change<=46
            time=35000;
        elseif change>46 && change<=56
            time=40000;
        end
    elseif condition==2
        if change==1
            time=2700;
        elseif change>1 && change<=6
            time=2000;
        elseif change>6 && change<=16          %this density simulation
time has been verified. 30 was last verified
            time=2600;
        elseif change>16 && change<=26
            time=3600;
        elseif change>26 && change<=36
            time=4400;
        elseif change==41
            time=5600;
        elseif change==46
            time=6500;
        elseif change==51
            time=7300;
        elseif change>51 && change<=61
            time=10000;
        end
```

```
    elseif condition==3
        if change==1
            time=2300;
        elseif change>1 && change<=16
            time=2000;
        elseif change>6 && change<=31          %this density simulation
time has been verified. 30 was last verified
            time=3000;
        elseif change>16 && change<=26
            time=5000;
        elseif change==36
            time=5000;
        elseif change==41 && change<=46
            time=6300;
        elseif change==51
            time=8900;
        end
    elseif condition==5
        if change==1
            time=2700;
        elseif change>1 && change<=11
            time=2000;
        elseif change>11 && change<=16          %this density simulation
time has been verified. 30 was last verified
            time=9000;
        elseif change>16 && change<=21
            time=20000;
        elseif change>21
            time=40000;
        end
    end
```

```
    time=10000;

    veh=change;

    link = 1000;

    patch=125;

    ref_veh=0;
%Reference vehicle

    veh_len=4.7;
%remember vehicle length must be a whole number

    stop_gap=2;                                                     %gap
from ref veh when stopped in traffic. This should be 2 but we tried 4 to
avoid collision as it kept colliding

    colli_gap=10;

    mean_jon_tim_analy=zeros(1,5);

    max_accel_analy=zeros(1,5);

    headway_fast_analy=zeros(1,5);

    max_flux_analy=zeros(1,5);

    max_vel_analy=zeros(1,5);

    condition_analy=zeros(1,5);

    data_analy=zeros(time,19);

    small_L=4.7;

    big_L=14;

    jam_spd=5;

    mean_jon_tim_analy_sat=zeros(1,5);


    read_weather=0;

    if read_weather==1

        weather_data=xlsread('r_0001_scen_hly.xlsx');

    end

    %bags=zeros(1,20);

    %xlswrite('classlist.xlsx',bags,'section2','A1');
```

```
    patch_veh_reg=zeros(patch,4*no_lane);
%vehicles registered in each pa 1 and 2 are front bumpers 2 and 4 are rear
bumper

    posit_f=zeros(time,veh);
%positions of front bumper of vehicles

    posit_r=zeros(time,veh);
%positions of rear bumper of vehicles

    % count_vehin_patch=zeros(pa,4);                              %Keeps
track of the number of vehicles in a pa. 1 or 2 increments if there is a
front bumper and 3 or 4 incrememnts if there is a rear bumper

    accel=zeros(time,veh);
%Acceleration of each vehicle

    disp_buf=zeros(time,veh);                                      %Buffer
displacement

    disp=zeros(time,veh);
%Displacement

    g=zeros(time,veh);                                             %gap

    c=zeros(time,veh);
%bunching acceleration

    h=zeros(time,veh);
%headway

    s=zeros(time,veh);
%seperation

    T=zeros(time,veh);                                             %Target

    z=zeros(time,veh);
%Braking verifier

    vel=zeros(time,veh);
%Velocity

    buf_vel=zeros(time,veh);                                       %Buffer
Velocity

    aA = zeros(time,veh);

    kaA = zeros(time,veh);

    aB = zeros(time,veh);

    kaB = zeros(time,veh);

    aC = zeros(time,veh);

    kaC = zeros(time,veh);
```

```
    aD = zeros(time,veh);

    aE = zeros(time,veh);

    max_accel=zeros(time,veh);

    max_dec=zeros(time,veh);

    lanes=zeros(time,veh);

    auto=zeros(time,veh);                    %register for the type of
vehicles (i.e. autonomous or not autonomous

    auto_level=1;                            %The fraction of autonomous
vehicles on the link. 1=1/3, 2=2/3, 3=3/3.

    run_check=zeros(time,veh);
%simulated vehicles checker

    fin_tim=zeros(1,veh);

    sta_tim=zeros(1,veh);

    reset_lane_timers=zeros(1,veh);                              %used
to reset lane change timer for new vehicles after the vehicle with the same
reg has exited the link

    timer1=0;                                                    %timer
from when a vehicle last entered the link

    interval=30;
%between vehicles entry

    v_reg=0;

    %ka=0.0153769;
%constant 1

    %kb=0.09144;
%constant 2

    ka=0.01;

    kb=0.1;

    use=0;

    check=zeros(time,1);

    flag=0;

    debug_ref=zeros(time,veh);

    NTA=0;

    patch_checker=zeros(time,veh);

    patch_checker_time=zeros(1,veh);
```

```
    veh_len=zeros(1,veh);

    lane_dens=zeros(1,no_lane);


    headway_slow=0.5;

    Aw_lev=10;

    found_ref=0;

    dens=0;

    chk=0;

    chk2=0;

    Refveh_db=0;

    veh_db=0;

    H_veh_type_cnt=0;

    L_veh_type_cnt=0;

    timer_N1=zeros(1,veh);

    timer_N2=zeros(1,veh);

    timer_overtake=zeros(1,veh);

    timer_change=zeros(1,veh);

    non_interest_counter=zeros(1,veh);

    veh_type=zeros(1,veh);

    pa_err_f=0;

    pa_err_r=0;

    patch_error_f=zeros(time,veh);

    patch_error_r=zeros(time,veh);

    Veh_jou_Av_vel=zeros(1,veh);            %vehicle average speed journey
during journey. Different from the vehicle average speed after journey

    ref_veh_D=zeros(time,veh);

    traff_flow=zeros(time,2);             %Bit 1 high in 2 out while both
high

    red_cnt=0;

    green_cnt=0;

    light=zeros(time,1);
```

```
    light(1,1)=1;

    stopline_check=zeros(time,1);

    jam=0;




    %analysis

    data=zeros(time,10);                     %1=max den, 2=mean velo on
link, 3= traffic flux on the link, 5=various densities, 6=velocities of
similar densities

    veh_count=0;                            %Number of vehicles that have
exited the link

    jon_tim=zeros(1,veh_count);             %Vehicle journey time

    Veh_Av_vel=zeros(1,veh_count);          %veh average velocity

    Add_Av_vel=0;                           %summation of all vehicles
average velocity

    count_Den=0;                            %total den on the link

    max_Den=0;                              %max den on the link

    use1=0;

    use2=0;

    use3=0;

    period=9;

    sat_time=0;

    veh_count_sat=0;                        %vehicle count during stable
state

    veh_count_aft=0;

    Time=0;                                 %Duration from the start of the
stable state in seconds

    Time_DS=6000;                            %Duration from the start of
the stable state in deci seconds

    traff_flux=zeros(1,3);                            %alternative traffic
flux. 1 is veh/hr while 2 is veh/15min

    traff_fluxes=zeros(1,20);
```

```
    jon_tim_sat=zeros(1,veh_count);             %Vehicle journey time
during stable state

    Veh_Av_vel_sat=zeros(1,veh_count);          %veh average velocity
during stable state

    Add_Av_vel_sat=0;

    mean_velocity_sat=0;                    %mean velocity during
saturation

    prevent=0;

    cond1_traff_flux=546;


    flux_data = csvread('classlist.csv');

    %flux_data=xlsread('classlist.xlsx');

    for size=1:max_v

        if flux_data(1,size)==0

            break;

        end

    end


    intensity=0;

    if read_weather==1

        switch weather_data(1,5)

            case 0

                condition=1;

            case weather_data(period,5)>0 && weather_data(period,5)<=2 &&
weather_data(period,6)>0

                condition=2;

            case  weather_data(period,5)>2 && weather_data(period,6)>0

                condition=3;

            case weather_data(period,5)>0 && weather_data(period,5)<=2 &&
weather_data(period,6)<0

                condition=4;

            case weather_data(period,5)>2 && weather_data(period,6)<0
```

```
                condition=5;
        end

        intensity=weather_data(period,5);
    end



    if congestion==on
        jam_spd=jam_spd;                              %speed limit towards
the end of the link status
    elseif congestion==off
        jam_spd=max_vel;
    end

    %condition=change;

    %The variable speed_line indicated where vehicle had to start
considering the
    %special speed limit in order to avoid overshooting the stop sign since
    %their maximum deceleration rate was infuenced by the weather
conditions. The
    %variable control_vel is equivalent to the maximum speed under dry
condition
    %and the max speed of other conditions were gotten by deduction
    %specific values from this value. The variable vel_init was the initial
    %speed of vehicles entering the link, this was set to the maximum
    %speed under the specific weather condition as it was assumed that
    %the link was part of a continous Trunk Road stretch except in cases
were
    %a traffic light was included or were congestion was induced at the end
    %of the link but in all cases vehicles were initialised to maximum
    %speed.
```

```
    speed_line=0;                           %controls the speed limit line
    control_vel=31.2928;                    %free flow vel or speed limit
    vel_init=0;                             %initial velocity

    %Under dry condition the maximum velocity was the same as the speed
    %limit of the link (i.e. 70mph or 31.293m/s) and the speed line is at 
the
    %highest position on the link compared to other weather conditions(i.e.
    %700m)
    if condition==1
        max_vel = control_vel;
        speed_line=700;
        vel_init=max_vel;
    %Under light rain and light snow conditions the maximum speed was
    %2.778m/s (or 6.214mph) less than the speed limit. The speed line
    %remained the same as the maximum deceleration rate was not impacted 
much enough to
    %have a significant impact on their stopping distances.
    elseif condition==2
        max_vel = control_vel-2.778;
        speed_line=700;
        vel_init=max_vel*1;
    elseif condition==3
        max_vel = control_vel-2.778;
        speed_line=700;
        vel_init=max_vel;
    %Under heavy rain condition the maximum speed was 5.556m/s (or 
12.427mph)
    %less than the speed limit while the speed line was reduced to 650m to
    %compensate for the impact of the weather conditon on the maximum 
deceleration rate.
    elseif condition==4
```

```
        max_vel = control_vel-5.556;
        speed_line=650;
        vel_init=max_vel;
    %Under heavy snow condition the maximum speed was 13.889m/s (or 
31.0686mph)
    %less than the speed limit while the speed line was reduced to 500m to
    %compensate for the impact of the weather conditon on the maximum 
deceleration rate.
    elseif condition==5
        max_vel = control_vel-13.889;
        speed_line=500;
        vel_init=max_vel;
    end


    %jam_spd=7;



    %Generates the look up table for the patch finder function
    patch_table=patch_lookup_table();


    for t=1:time
        %traffic light
        %The light array kept track of the state of the traffic light for
        %each time step. Both states had counter variables which were
        %red_cnt and green_cnt. Whenever a state was active its counter was
        %incremented during each time step. After its maximum active time
        %had elapsed its counter was reset and the traffic light state was
        %switched to the next state.
        if light(t,1)==1 || red_cnt>0
            red_cnt=red_cnt+1;
            light(t,1)=1;
```

```
            if red_cnt>=300
                red_cnt=0;
                light(t,1)=2;
                if t<time
                    light(t+1,1)=2;
                end
            end
        end
        if light(t,1)==2 || green_cnt>0
            green_cnt=green_cnt+1;
            light(t,1)=2;
            if green_cnt>=600
                green_cnt=0;
                light(t,1)=1;
                if t<time
                    light(t+1,1)=1;
                end
            end
        end


        for pa=1:patch
            if t==1 && pa==patch                                       %At
the start of the simulation. Remember pa 125 holds cells 1:8
                %first vehicle gets given a registeration number
                v_reg=1;


                %The Lane of the 1st vehicle for the 1st time step
                lanes(t,v_reg)=1;                    %the first vehicle
spawns in lane one
                auto(t,v_reg)=1;                      %The first vehicle is
made autonomous because it apawns on lane 1
```

```
                lane_dens(1,1)=1;


                %position of the 1st vehicle's front bumper for the first
                %time step
                posit_f(t,v_reg)=0.1;                %New vehicles appears at
0.1. i.e cell 1 pa 125


                %The first vehicle gets given a vehicle type depending on
                %the combination of vehicles the user selected.
                if uniform_veh==on
                    if choose_veh==small
                        veh_len(1,v_reg)=small_L;
                        veh_type(1,v_reg)=1;
                    elseif choose_veh==large
                        veh_len(1,v_reg)=big_L;
                        veh_type(1,v_reg)=4;
                    end
                elseif uniform_veh==off
                    veh_len(1,v_reg)=small_L;
                    veh_type(1,v_reg)=1;
                  %Kept track of the current small vehicle type. resetted
                  %to zero when all types had been used
                    L_veh_type_cnt=1;
                  %counts the number of small vehicles,
                  %when it is greater than the specified maximum value
(ratio)
                  %a larger vehicle enters and the counter resets
                    veh_len_cnt=1;
                end


                %Position
```

```
                %the position of the 1st vehicle rear bumper for the first
time step
                posit_r(t,v_reg)=posit_f(t,v_reg)-veh_len(1,v_reg);

                %The 1st vehicle's front and rear bumpers patch locations
[p_frt,p_rer]=patch_finder2(posit_f(t,v_reg),veh_len(1,v_reg),patch_table);

                %register vehicle front bumper to its current patch. The
                %rear bumper would be outside the link so cannot be
                %registered
                patch_veh_reg(p_frt,1)=v_reg;
                ref(t,v_reg)=0;



                %acceleration
                %The 1st vehicle maximum acceleration for the 1st time step
[max_accel(t,v_reg),max_dec(t,v_reg)]=Maximum_accelndecel_raka(v_reg,t,vel(
:,:),condition,veh_type(1,v_reg),intensity);
                %The 1st vehicle driver accelerates at its desired maximum
acceleration
                accel(t,v_reg)=max_accel(t,v_reg);

                %The 1st vehicle gets given an initial velocity which
                %depends on the weather condition
                vel(t,v_reg)=vel_init;

                %The 1st vehicle entry time is taken into account
                sta_tim(1,v_reg)=t;
                %The density on the link is incremented
                count_Den=count_Den+1;
```

```
        %Kept account of vehicles entering and exiting the link
        %If cell 1 is high a vehicle entered at that time step,
        %if cell 2 high a vehicle exited at that time step
        traff_flow(t,1)=1;

        timer1=t;  %timer for when a vehicle last entered the link
    end



    %After the first time step
    if t>1
        %search for vehicles in both front bumper registers of the
current
        %patch. sw1 and sw2 change based on the current lane and
accept
        %front bumber registers
        for sw=1:no_lane
            switch sw
                case 1
                    sw1=1;
                    sw2=2;
                case 2
                    sw1=5;
                    sw2=6;
                case 3
                    sw1=9;
                    sw2=10;
                case 4
                    sw1=13;
                    sw2=14;
            end
```

```
                    %vk changes between the current lane front bumper
registers
                    for swb=1:2
                    %this loop was included for a scenario where reg b of a
patch shifts
                    %to a after lane change and the code needs to re run a
to avoid skipping
                    %the vehicle that shifted from b to a. the loop breaks
if this shift never occured
                        for shi=1:2
                            shift=0;
                            switch swb
                                case 1
                                    vk=sw1;
                                case 2
                                    vk=sw2;
                            end

                            %resetting parameters
                            ref_veh=0;
                            v_reg=0;

                            if patch_veh_reg(pa,vk)>0
                                %to make referencing easier
                                v_reg=patch_veh_reg(pa,vk);
                                %run_check was used to prevent vehicles
that may have switched lanes
                                %(esp to d right) from running twice in the
                                %same time step since the code runs from
                                %the left lane to the right lane
                                if run_check(t,v_reg)==0
```

```
                                run_check(t,v_reg)=1;

                                %Lanes maneouvering

                                %The lane change function (i.e

                                %overtake7) was used to determine the

                                %current lane of the observed vehicle.

                                %Other outputs were utilised by the

                                %function to keep track of drivers

                                %mindsets (e.g. interest levels)

                                %autonomous
edit***************************************************************************
*******************************************************************************
*******************************************************************************
*******************************************************************************
*******************************************************************************
***************************************************************

                                %Each vehicle on the link were assigned
cells in an array register which held the autonomy

                                %capabilities of each vehicle and was
updated at every time step

                                %If the vehicle is autonomous then its
lane at the previous time step

                                %(which was the designated autonomous
vehicles lane i.e. lane 1) remains its current lane

                                %while the manual vehicles go through
the lane change algorithm where they may select any

                                %lane except the designated autonomous
vehicles lanes

                                auto(t,v_reg)=auto(t-1,v_reg);

                                if auto(t,v_reg)==0

[timer_N1(:,:),timer_N2(:,:),lanes(:,:),non_interest_counter(:,:),timer_ove
rtake(:,:),timer_change(:,:)]=overtake7_auto(lanes(:,:),v_reg,veh,vel(:,:),
max_vel,g(:,:),t,timer_N1(:,:),timer_N2(:,:),non_interest_counter(:,:),patc
h_veh_reg(:,:),pa,posit_f(:,:),posit_r(:,:),max_dec(:,:),stop_gap,
aA(:,:),aB(:,:),aC(:,:), accel(:,:),
max_accel(:,:),timer_overtake(:,:),timer_change(:,:),reset_lane_timers(:,:)
,veh_len(:,:),patch_table,no_lane,auto_level);

                                elseif auto(t,v_reg)==1

                                    lanes(t,v_reg)=lanes(t-1,v_reg);
```

```
end
%The OV current lane
cur_lane=lanes(t,v_reg);
%The OV previous lane
prev_lane=lanes(t-1,v_reg);
%If the current lane of the OV is
%different from its previous lane then
%increment its current lane and
%decrement its previous lane
if cur_lane~=prev_lane

lane_dens(1,cur_lane)=lane_dens(1,cur_lane)+1;

lane_dens(1,prev_lane)=lane_dens(1,prev_lane)-1;
end


%used to reset lane change timer for
new vehicles

%after the vehicle with the same reg
has exited the link

reset_lane_timers(1,v_reg)=0;


%Whenever a vehicle switched lanes the
%patch register had to be updated by
%deleting the vehicle's reg number from
%its previous patch register slot and
%entering it in its new patch register
%slot
if lanes(t,v_reg)~= lanes(t-1,v_reg)
    %Here the previous patch of the
    %vehicle was selected
```

```
[p_frt,p_rer]=patch_finder2(posit_f(t-
1,v_reg),veh_len(1,v_reg),patch_table);
                                        %Values were given to the
                                        %switch_board function, outputs
were
                                        %based on the previous lane of the
                                        %observed vehicle
                                        [ a,b,C,d ] = switch_board(lanes(t-
1,v_reg));
                                        %The patch register slot for the
                                        %previous lane front bumper was
                                        %reset here
                                        for dt=a:b
                                            if
patch_veh_reg(p_frt,dt)==v_reg
                                                patch_veh_reg(p_frt,dt)=0;
                                                break;
                                            end
                                        end

                                        %This step was used to move the reg
no of any
                                        %other vehicle on the previous lane
                                        %of the observed vehicle from patch
register slot 1
                                        %to 2 i.e front bumper. Note this
                                        %does not actually move the
                                        %vehicle. It only allows lead
                                        %vehicles to always be simulated
                                        %before following vehicles on the
                                        %same lane.
                                        if patch_veh_reg(p_frt,a)==0
```

```
patch_veh_reg(p_frt,a)=patch_veh_reg(p_frt,b);
                                            %used to determine the loop to
brake.
                                            %See above for better
understanding
                                            if patch_veh_reg(p_frt,b)>0
                                                shift=1;
                                            end
                                            patch_veh_reg(p_frt,b)=0;
                                        end

                                        %The patch register slot for the
                                        %previous lane rear bumper was
                                        %reset here
                                        for dt=C:d
                                            if
patch_veh_reg(p_rer,dt)==v_reg
                                                patch_veh_reg(p_rer,dt)=0;
                                                break;
                                            end
                                        end

                                        %Although this may not affect the
                                        %simulation since the front bumper
                                        %positions were mainly used for the
                                        %simulation, this step was done
                                        %similar to the front bumper step
                                        %for clarity
                                        if patch_veh_reg(p_rer,C)==0

patch_veh_reg(p_rer,C)=patch_veh_reg(p_rer,d);
```

```
            patch_veh_reg(p_rer,d)=0;
        end

        %Values were given to the
        %switch_board function, outputs
were
        %based on the current lane of the
        %observed vehicle
        [ a,b,C,d ] = switch_board(
lanes(t,v_reg) );
        for dtt=a:b
            if patch_veh_reg(p_frt,dtt)==0

patch_veh_reg(p_frt,dtt)=v_reg;
                break;
            end
        end

        %The patch register slot for the
        %current lane front bumper was
        %updated here
        for dtt=C:d
            if patch_veh_reg(p_rer,dtt)==0

patch_veh_reg(p_rer,dtt)=v_reg;
                break;
            end
        end
    end

    %The reference vehicle generator
    %function was used to determine the OV
```

```
%lead vehicle
if v_reg>0
[ref_veh,NTA]=ref_veh_generator3(patch_veh_reg(:,:),pa,v_reg,posit_f(:,:),posit_r(:,:),t,lanes(t,v_reg),0,0);
    ref(t,v_reg)=ref_veh;
end

% Displacement
disp_buf(t,v_reg)= (vel(t-1,v_reg)*0.1)+(1/2*(accel(t-1,v_reg)*(0.1)^2));

%Preventing negative displacements
if disp_buf(t,v_reg)<0
    disp(t,v_reg)=0;
elseif disp_buf(t,v_reg)>=0
    disp(t,v_reg)=disp_buf(t,v_reg);
end

%Calculating observed vehicle's position
%The current front bumper posiiton of the OV %was calculated as the sum of its
%previous position and its current displacement while its rear bumper
%position was calculated as the difference between its current front
%bumper position and the vehicle length
posit_f(t,v_reg)=posit_f(t-1,v_reg)+disp(t,v_reg);
posit_r(t,v_reg)=posit_f(t,v_reg)-veh_len(1,v_reg);
```

```
                                    %Cancelling the Observed vehicle
previous patch slot
                                    [ a,b,C,d ] = switch_board(
lanes(t,v_reg) );


                                    %Its previous patches for both bumpers
were obtained here

[Prevp_frt,Prevp_rer]=patch_finder2(posit_f(t-
1,v_reg),veh_len(1,v_reg),patch_table);

[p_frt,p_rer]=patch_finder2(posit_f(t,v_reg),veh_len(1,v_reg),patch_table);


                                    %This step is used when the OV previous
front bumper patch is not the same as
                                    %the current one OR when they are the
same but the current lane is
                                    %different from the previous lane
                                    if Prevp_frt~=p_frt ||
(Prevp_frt==p_frt && lanes(t,v_reg)~=lanes(t-1,v_reg))
                                        %This loop was used to cycle
through both slots of the
                                        %vehicle's previous patch to find
the slot containing the OV's reg no
                                        for sk=a:b
                                            if Prevp_frt>0 &&
v_reg==patch_veh_reg(Prevp_frt,sk)
                                                %The slot containing the OV
reg no was reset to 0

patch_veh_reg(Prevp_frt,sk)=0;


                                                %finding an available front
bumper slot on the OV new patch and
                                                %registering to the slot.
The switch_board was used to find the
```

```
                                        %slots for the OV current
lane patch
                                        [ a,b,C,d ] =
switch_board(lanes(t,v_reg));

                                        %This loop was used to
cycle through both slots of the
                                        %vehicle's current patch to
find a
                                        %free slot to register the
OV to
                                        for nk=a:b
                                            if p_frt>0 &&
patch_veh_reg(p_frt,nk)==0
                                                %The OV was
registered to the free slot found on
                                                %its current patch

patch_veh_reg(p_frt,nk)=v_reg;

                                                break;
                                            end
                                        end
                                        break;
                                    end
                                end
                                %If the OV previous patch is the
same as its current patch and the
                                %lane is the same as well then the
following step is used. I.e its
                                %current patch and slot remains the
same as the previous one
                            elseif Prevp_frt==p_frt
                                if lanes(t,v_reg)==lanes(t-1,v_reg)
                                    patch_veh_reg(pa,vk)=v_reg;
                                end
```

```
                                    end

                                    %Same as before, so that this shift
doesnt cause the 2nd
                                    %veh in the patch reg to be skipped
during
                                    %the vk loop
                                    [ a,b,C,d ] = switch_board(
lanes(t,v_reg) );

                                    if vk==b && Prevp_frt>0
                                        %shifting the vehicle reg by 1
column
                                        if patch_veh_reg(Prevp_frt,a)==0

patch_veh_reg(Prevp_frt,a)=patch_veh_reg(Prevp_frt,b);
                                            patch_veh_reg(Prevp_frt,b)=0;
                                        end
                                    end

                                    %cancelling previous rear bumper patch
                                    if posit_r(t-1,v_reg)>0
                                        [ a,b,C,d ] = switch_board(
lanes(t,v_reg) );
                                        for pk=C:d
                                            if
v_reg==patch_veh_reg(Prevp_rer,pk)

patch_veh_reg(Prevp_rer,pk)=0;
                                                break
                                            end
                                        end
                                    end
```

```
                                    %The next step is executed if the OV
rear bumper position is greater than 0 AND its current patch is different
from its previous patch OR the patch

                                    %is the same but the lane is different
or the current patch and lane are the same as the previous but the position
of the rear bumper os 0.

                                    if (posit_r(t,v_reg)>0
&&(Prevp_rer~=p_rer||(Prevp_rer==p_rer&&lanes(t,v_reg)~=lanes(t-
1,v_reg))))||(Prevp_rer==p_rer&&lanes(t,v_reg)==lanes(t-1,v_reg))

                                        %finding an available rear bumper
slot on the OV current rear bumper patch and registering to it

                                        [ a,b,C,d ] = switch_board(
lanes(t,v_reg) );

                                        for rk=C:d

                                            if p_rer>0 &&
patch_veh_reg(p_rer,rk)==0


patch_veh_reg(p_rer,rk)=v_reg;

                                                pa_err_r=2;

                                                break;

                                            end

                                        end

                                    end




                                    %Again the rear bumper patch slot
doesn't have to be shifted but this                                    %

                                    %was done for clarity.

                                    if (vk==2 || vk==6 || vk==10 || vk==14)
&& Prevp_rer>0

                                        [ a,b,C,d ] = switch_board(
lanes(t,v_reg) );

                                        %shifting the vehicle reg by 1
column

                                        if patch_veh_reg(Prevp_rer,C)==0
```

```
patch_veh_reg(Prevp_rer,C)=patch_veh_reg(Prevp_rer,d);
                                             patch_veh_reg(Prevp_rer,d)=0;
                                         end
                                     end


                                     %When the observed vehicle gets to the
end of the link
                                     if posit_f(t,v_reg)>link
                                         [ a,b,C,d ] = switch_board(
lanes(t,v_reg) );


                                         %the OV finish time is taken down
                                         fin_tim(1,v_reg)=t;


                                         %The front bumper patch slot
automatically becomes 0 because the front
                                         %bumper position would be greater
than the link but the rear bumper position
                                         %would have to be reset to 0
                                         %Resetting the rear bumper patch
register

[p_frt,p_rer]=patch_finder2(posit_f(t,v_reg),veh_len(1,v_reg),patch_table);
                                         if posit_r(t,v_reg)>0
                                             for pk=C:d
                                                 if p_rer>0 &&
v_reg==patch_veh_reg(p_rer,pk)

patch_veh_reg(p_rer,pk)=0;
                                                 end
                                             end
                                         end
```

```
                                        %The density of the OV lane reduces
                                        %when the OV exits the link
lane_dens(1,cur_lane)=lane_dens(1,cur_lane)-1;

                                        %The density of the entire link
also reduces
                                        count_Den=count_Den-1;

                                        %If cell 1 is high a vehicle
entered at that time step,
                                        %if cell 2 high a vehicle exited at
that time step
                                        %When both are 1 or high during the
same time step
                                        %the traffic is stable.
                                        traff_flow(t,2)=1;

                                        %Various parameters are then
                                        %calculated such as the total
                                        %vehicle that have gone through the
                                        %link, the journey time and average
                                        %velocity of the OV that just
                                        %exited the link.
                                        veh_count=veh_count+1;
jon_tim(1,veh_count)=(fin_tim(1,v_reg)-sta_tim(1,v_reg))*0.1;
Veh_Av_vel(1,veh_count)=link/jon_tim(1,veh_count);

                                        %The average velocity of all
vehicles that successfully exited the link during
                                        %simulation were summed. The sum
was later divided by the total vehicle that successfully
```

```
                                        %exited the link from the
simulation start time to its termination time in order to deduce the
                                        %average velocity on the link

Add_Av_vel=Add_Av_vel+Veh_Av_vel(1,veh_count);


                                        %The traffic flow was stable (i.e
sat) when vehicles exited and entered
                                        %the link during the same time
step. That is when both bits of
                                        %the array traff_flow are 1.
                                        if sat_time>0
                                            %The total vehicles that had
gone through the link during the stable state
                                            veh_count_sat=veh_count_sat+1;
                                            %The OV journey time during the
traffic flow stable state

jon_tim_sat(1,veh_count_sat)=(fin_tim(1,v_reg)-sta_tim(1,v_reg))*0.1;
                                            %The OV average velocity during
the traffic flow stable state                                             %

Veh_Av_vel_sat(1,veh_count_sat)=link/jon_tim_sat(1,veh_count_sat);


                                            %the average velocity of all
vehicles that successfully exited the link from the
                                            %stabled state to the
simulation termination time were summed. The sum was later divided
                                            %by the total vehicle that
successfully exited the link from the stable period to the end
                                            %of the simulation to deduce
the average velocity on the link

Add_Av_vel_sat=Add_Av_vel_sat+Veh_Av_vel_sat(1,veh_count_sat);
```

```
                                                    veh_count_aft=veh_count_sat-1;
%dont include
                                                end

                                                %The OV parameters were then reset
to to 0 including its
                                                %registeration number so it could
be used by a new vehicle
                                                posit_f(t,v_reg)=0;
                                                posit_r(t,v_reg)=0;
                                                vel(t,v_reg)=0;
                                                accel(t,v_reg)=0;
                                                sta_tim(1,v_reg)=0;
                                                fin_tim(1,v_reg)=0;
                                                Veh_jou_Av_vel(1,v_reg)=0;
                                                h(t,v_reg)=0;
                                                v_reg=0;
                                                lanes(t,v_reg)=0;
                                                auto(t,v_reg)=0;          %Resets
the vehicle from autonomous to the default
                                            end


                                            if v_reg>0
                                                %gap
                                                if ref_veh~=0

[g(t,v_reg)]=Vehicle_gap(posit_r(t,ref_veh),posit_f(t,v_reg));
%Since it is a lead vehicle
                                                end


                                                %bunching acceleration
```

```
[c(t,v_reg)]=bunching_accel2(ka,g(t,v_reg),stop_gap);

                                        %velocity
                                        buf_vel(t,v_reg)=vel(t-
1,v_reg)+(accel(t-1,v_reg)*0.1);
                                        %Limiting velocity
                                        if buf_vel(t,v_reg)<0
                                            vel(t,v_reg)=0;
                                        elseif buf_vel(t,v_reg)<max_vel
                                            vel(t,v_reg)=buf_vel(t,v_reg);
                                        elseif buf_vel(t,v_reg)>=max_vel
                                            vel(t,v_reg)=max_vel;
                                        end


                                        %headway

%http://odd.topslab.wisc.edu/publications/2011/Modeling%20Highway%20Safety%
20and%20Simulation%20in%20Rainy%20Weather%20(2237-15).pdf%
                                        %Vehicle average velocity while in
                                        %journey. Dont use for analysis
                                        if ref_veh~=0
                                            %Vehicle average velocity

Veh_jou_Av_vel(1,v_reg)=posit_f(t,v_reg)/((t-sta_tim(1,v_reg))*0.1);
                                            %Average spacing on the link

av_spacing=link/lane_dens(1,cur_lane);
                                            %Estimated headway

h(t,v_reg)=av_spacing/Veh_jou_Av_vel(1,v_reg);
                                        end
```

```
                                        %Seperation
                                        if ref_veh~=0

[s(t,v_reg)]=separation(h(t,v_reg),vel(t,ref_veh),vel(t,v_reg));
                                        end


                                        %Target

[T(t,v_reg)]=Target_p2(s(t,v_reg),g(t,v_reg));



                                        %acceleration components

[max_accel(t,v_reg),max_dec(t,v_reg)]=Maximum_accelndecel_raka(v_reg,t,vel(
:,:),condition,veh_type(1,v_reg),intensity);
                                        if ref_veh~=0
                                            %Target point overshot

[kaA(t,v_reg)]=buffer_accel_overshot(kb,vel(t,ref_veh),vel(t,v_reg));
                                            %Limiting aA to max accel and
max dec

[aA(t,v_reg)]=accel_overshot(kaA(t,v_reg),max_dec(t,v_reg),max_accel(t,v_re
g));


                                            %aB Lead vehicle pulling away

[kaB(t,v_reg)]=bufferaccel_pullingaway2(g(t,v_reg),T(t,v_reg),kb,vel(t,ref_
veh),vel(t,v_reg),ka);
                                            %Limiting aB to max accel and
max dec

[aB(t,v_reg)]=accel_pullingaway(kaB(t,v_reg),max_dec(t,v_reg),max_accel(t,v
_reg));
```

```
                                       %Vehicles at constant speed or
coming together (cruise accel)

[kaC(t,v_reg)]=bufferaccel_cruise2(vel(t,ref_veh),vel(t,v_reg),g(t,v_reg),T
(t,v_reg),c(t,v_reg));

                                       %Limiting aC to max accel and
max dec

[aC(t,v_reg)]=accel_cruise(kaC(t,v_reg),max_dec(t,v_reg),max_accel(t,v_reg)
);

                                   end



                                   %lead car braking verification. 1
is true 0 is false

                                   if ref_veh~=0

                                       if t>15

                                           %determine if the
leadvehicle entered the link before or after the cur time minus the cur veh
awreness time plus 5

                                           ord=(t-(5+Aw_lev));

                                           ort=sta_tim(1,ref_veh);

                                           orl=ord-ort;

                                           if  orl>0

                                               ign=1;

                                           else

                                               ign=0;

                                           end

                                           %The array z holds the test
results for the observed vehicle for each time step. The velocity of the
lead vehicle for the 5 consecutive time steps been observed are fed into
the function. These time steps are a total of the response time plus the
time step number


[z(t,v_reg)]=Leadcar_braking_verification(vel(t-(5+Aw_lev),ref_veh),vel(t-
(4+Aw_lev),ref_veh),vel(t-(3+Aw_lev),ref_veh),vel(t-
(2+Aw_lev),ref_veh),vel(t-(1+Aw_lev),ref_veh),vel(t-
(0+Aw_lev),ref_veh),ign);

                                       end
```

```
end

%accelerate vehicle
%Detect collision
acc_safe=0;
if ref_veh~=0
[colli,acc_safe]=collision_detector3(vel(t,ref_veh),max_dec(t,ref_veh),max_dec(t,v_reg),vel(t,v_reg),posit_f(t,v_reg),posit_r(t,ref_veh),stop_gap,accel(t-1,v_reg),0);
end

%Determine acceleration mode
%Stop_line response
%The stop sign (i.e. stop_line_status)
%was on when the light was red (1)
%during the current time step and
%was off when the light was green
%(2) during the current time step
if traffic_light==on
    if light(t,1)==1
        stop_line_status=on;                    %ON=1, OFF=0
        stopline_check(t,1)=on;
    elseif light(t,1)==2
        stop_line_status=off;                   %ON=1, OFF=0
        stopline_check(t,1)=off;
    end
end
```

```
                                        accel_found=0;

                                        accel_found1=0;


                                        %%Used to control the acceleration
of the lead vehicle%%


                                        %This function operated like the
collision detector function except

                                        %the vehicle's speed and position
was compared to the position of the stopline

                                        [ stop ] =
stopline_overshoot_detector(
vel(:,:),max_dec(:,:),link,t,v_reg,posit_f(:,:));


                                        %accel_found1==0 meant acceleration
mode not found


                                        %When the OV had no lead
vehicle(ref_veh==0) and no congestion was to be induced

                                        %at the end of the link it
accelerated at maximum acceleration

                                        if ref_veh==0 && accel_found1==0 &&
congestion==off


accel(t,v_reg)=max_accel(t,v_reg);

                                                accel_found1=1;

                                        %When congestion was to be induced
and the OV had no lead vehicle

                                        elseif congestion==on && ref_veh==0

                                            %The stop line is ON and the
vehicle would potentially overshoot the stop sign (i.e.stop==1)

                                            if stop==1 &&
stop_line_status==on && accel_found1==0


accel(t,v_reg)=max_dec(t,v_reg);
```

```
                                                  accel_found1=1;
                                          %speed_line is a point on the link
beyound which a special speed limit was required as vehicles approach
                                          %the end of the link. jam_spd is
special speed limit for the end of the link


                                              %The OV was required to brake
at max if its front bumper position was greater or equals the speed_line
and its
                                              %velocity was greater than the
jam_spd
                                              elseif
posit_f(t,v_reg)>=speed_line && vel(t,v_reg)>jam_spd && accel_found1==0

accel(t,v_reg)=max_dec(t,v_reg);
                                                  accel_found1=1;
                                              %Else it was required to
accelerate at max if its front bumper position was greater or equals the
speed_line
                                              %and its velocity less than the
jam_sp
                                              elseif
posit_f(t,v_reg)>=speed_line && vel(t,v_reg)<jam_spd && accel_found1==0

accel(t,v_reg)=max_accel(t,v_reg);
                                                  accel_found1=1;
                                              %Else it was required to not
accelerate if its front bumper was greater than or equals the speed_line,
                                              %its velocity was equals the
jam_spd
                                              elseif
posit_f(t,v_reg)>=speed_line && vel(t,v_reg)==jam_spd && accel_found1==0
                                                  accel(t,v_reg)=0;
                                                  accel_found1=1;
                                              %Else it was required to
accelerate at max if the position of its front bumper was less than the
speed_line
```

```
                                        elseif
posit_f(t,v_reg)<speed_line

accel(t,v_reg)=max_accel(t,v_reg);
                                            accel_found1=1;
                                        end

                                    %%used to safely bring the OV
closer to its lead vehicle during congestion%%

                                    %If the OV has a lead vehicle
                                    elseif ref_veh>0 && accel_found1==0
                                        %If the OV is at risk of
colliding with its lead vehicle it is required to brake at max
                                        if colli==1

accel(t,v_reg)=max_dec(t,v_reg);
                                            accel_found=1;
                                            %autonomous
edit***************************************************************************
******************************
                                            %This is used to override
the acceleration of the vehicle if the vehicle is autonomous
                                            %The autonomous system
kicks in when the following vehicle is at most 6m away from its lead
vehicle
                                            %Note that the response
system does not use the response of the driver but rather the response of
                                            %the autonomous system and
the autonomous system was assumed to be as fast as possible hence the
                                            %minimum response time was
used which is 0.1sec which appears to be instantaneous hence no
                                            %need for a response time
lapse
                                        elseif auto(t,v_reg)==1 &&
g(t,v_reg)<=100 && vel(t,v_reg)<=vel(t,ref_veh)
```

```
                                                %converting velo from m/s
to kph so that Hee et al.(2015) gap can be used

vel_mph=vel(t,v_reg)*2.23694;
                                                vel_kph=vel_mph*1.60934;
                                                Hee_gap=(5/112)*vel_kph;
                                                %If the speed of the
vehicle is less than or equals the speed of the lead vehicle and the gap is
greater
                                                %than the gap suggested by
Hee et al.(2015) then the acceleration of the velicle is increased by
0.2m/s(2)
                                                %if the increase wont be
greater than its maximum acceleration else the maximum acceleration is
used.
                                                %Iif the autonomous system
kicks in and the gap is less than the Hee_gap then the acceleration is
                                                %reduced by 0.2m/s(2).
Elseif the gap equalse the Hee_gap then the following vehicle uses the
                                                %acceleration of its lead
vehicle.
                                                if
vel(t,v_reg)<=vel(t,ref_veh) && g(t,v_reg)>Hee_gap
                                                    if
(accel(t,ref_veh)+0.2)< max_accel(t,v_reg)

accel(t,v_reg)=accel(t,ref_veh)+0.2;
                                                    elseif
(accel(t,ref_veh)+0.2)>= max_accel(t,v_reg)

accel(t,v_reg)=max_accel(t,v_reg);
                                                    end
                                                elseif
vel(t,v_reg)<=vel(t,ref_veh) && g(t,v_reg)<Hee_gap

accel(t,v_reg)=accel(t,ref_veh)-0.2;
                                                elseif
accel(t,ref_veh)<=max_accel(t,v_reg)
```

```
accel(t,v_reg)=accel(t,ref_veh);
                                        else
accel(t,v_reg)=max_accel(t,v_reg);
                                        end
                                        accel_found=1;
                                     %Elseif the OV is not at a risk
of colliding with its lead vehicle and it is within a
                                     %given safe threshold distance
from its lead vehichle it is required to accelerate at max
                                     elseif acc_safe==1 && colli==0
&& accel_found==0
accel(t,v_reg)=max_accel(t,v_reg);
                                        accel_found=1;

                                     %Elseif the OV has been on the
link less than the awareness time defined for all drivers
                                     %plus the time they require to
observe the speed of their lead vehicle to determine if it is braking
                                     %and the OV is not at a risk of
colliding with its lead vehicle

                                     %%NOTE: if this condition is
true the response time of the driver would not be included since the driver
                                     %%would not have any memory
before its journey start time
                                     elseif (t-
(Aw_lev+5))<=sta_tim(1,v_reg) && colli==0 && accel_found==0
                                        %If the velocity of the
lead vehicle velocity is zero
                                        if vel(t,ref_veh)==0 &&
accel_found==0
                                           %if the gap between the
OV and its lead vehicle is greater than the required gap between vehicles
during
```

```
                                          %a traffic jam
(stop_gap) and the velocity of the OV is less than the gap minus the
stop_gap
                                          %then the preliminary
acceleration is 0.1 times the gap
                                          %an assumption was made
that the required acceleration to close the gap was proportional to the
gap.
                                          %The acceleration was
then limited to the maximum acceleration and deceleration
                                          if g(t,v_reg)>stop_gap
&& accel_found==0 && vel(t,v_reg)<(g(t,v_reg)-stop_gap)

accel_buf=kb*g(t,v_reg);
                                              if
accel_buf>=max_accel(t,v_reg)

accel(t,v_reg)=max_accel(t,v_reg);
                                              elseif
accel_buf<=max_dec(t,v_reg)

accel(t,v_reg)=max_dec(t,v_reg);
                                              else

accel(t,v_reg)=accel_buf;
                                              end
                                              accel_found=1;
                                          %Elseif the gap was
less than the stop_gap or the OV is at a risk of colliding with its lead
                                          %vehicle the OV is
required to decelerate at max
                                          elseif
g(t,v_reg)<=stop_gap || colli==1 && accel_found==0

accel(t,v_reg)=max_dec(t,v_reg);
                                              accel_found=1;
                                          end
```

```
                                                  %Elseif the velocity of the
OV lead vehicle is greater than zero
                                                  elseif vel(t,ref_veh)>0 &&
accel_found==0
                                                      %If the OV was within
the given safe threshold distance from its lead vehicle and was not
                                                      %at a risk of colliding
with it then it was required to accelerate at max
                                                      if acc_safe==1 &&
colli==0 && accel_found==0

accel(t,v_reg)=max_accel(t,v_reg);
                                                          accel_found=1;
                                                      %Else if it was at a
risk of colliding with its lead vehicle it was required to brake at max
                                                      elseif colli==1

accel(t,v_reg)=max_dec(t,v_reg);
                                                          accel_found=1;

                                                      %Else if it was not
within the given safe threshold distance from its lead vehicle and was not
                                                      %at a risk of colliding
with it
                                                      elseif acc_safe==0 &&
colli==0 && accel_found==0
                                                          %If its separation
from its lead vehicle was less than or equals its target separation
                                                          if
s(t,v_reg)<=T(t,v_reg)
                                                              %if its lead
vehicle is not breaking (i.e. z==0) then the OV is expected to accelerate
                                                              %at aA
acceleration component
                                                              if
z(t,v_reg)==0 && accel_found==0

accel(t,v_reg)=aA(t,v_reg);
```

```
accel_found=1;
                                                            %Elseif its
lead vehicle is breaking (i.e. z==1) then the OV is expected to brake at
max
                                                            elseif
z(t,v_reg)==1

accel(t,v_reg)=max_dec(t,v_reg);

accel_found=1;
                                                            end
                                                        %Elseif the
separation is greater than the target
                                                        elseif
s(t,v_reg)>T(t,v_reg) && accel_found==0

                                                            %If the
velocity of the OV at the current time step is greater than its velocity at
the
                                                            %previous
timestep then the OV is expected to accelerate at aB acceleration component
                                                            if
vel(t,veh)>vel(t-1,veh)

accel(t,v_reg)=aB(t,v_reg);

accel_found=1;
                                                            %Elseif its
lead vehicle is not breaking it is expected to accelerate
                                                            %at
acceleration component aC
                                                            elseif
z(t,v_reg)==0 && accel_found==0

accel(t,v_reg)=aC(t,v_reg);

accel_found=1;
```

```
                                                      %Elseif its
lead vehicle is breaking or it is at a risk of colliding with its lead
                                                      %vehicle it is
expected to brake at max
                                                      elseif
(z(t,v_reg)==1 || colli==1)  && accel_found==0

accel(t,v_reg)=max_dec(t,v_reg);

accel_found=1;
                                                      end
                                                  end
                                              end
                                          end


                                        %Elseif the OV has been on the
link longer than the awareness time defined for all drivers
                                        %plus the time they require to
observe the speed of their lead vehicle to determine if it is braking
                                        %and the OV is not at a risk of
colliding with its lead vehicle


                                        %%NOTE: if this condition is
true the response time of the driver would be included since the driver
                                        %%memory started during its
journey start time and its memory covers its response time which is slower
                                        %%than the actual time hence
its memory is focused on a period of time in the past
                                        %%The same steps as when the
driver had insufficient memory to include its response time are then
repeated
                                        %%except the driver's response
time is now taken into account
                                        elseif (t-
(Aw_lev+5))>sta_tim(1,v_reg) && colli==0 && accel_found==0
                                            if vel(t-Aw_lev,ref_veh)==0
```

```
                                                if g(t,v_reg)>stop_gap
&& accel_found==0 && vel(t,v_reg)<(g(t,v_reg)-stop_gap)

accel_buf=kb*g(t,v_reg);
                                                    if
accel_buf>=max_accel(t,v_reg)

accel(t,v_reg)=max_accel(t,v_reg);
                                                    elseif
accel_buf<=max_dec(t,v_reg)

accel(t,v_reg)=max_dec(t,v_reg);
                                                    else

accel(t,v_reg)=accel_buf;
                                                    end
                                                    accel_found=1;
                                                elseif
g(t,v_reg)<=stop_gap && accel_found==0

accel(t,v_reg)=max_dec(t,v_reg);
                                                    accel_found=1;

                                                elseif colli==1

accel(t,v_reg)=max_dec(t,v_reg);
                                                    accel_found=1;
                                                elseif g(t-
Aw_lev,v_reg)<=stop_gap && accel_found==0

accel(t,v_reg)=max_dec(t,v_reg);
                                                    accel_found=1;
                                                end
                                            elseif vel(t-
Aw_lev,ref_veh)>0 && accel_found==0
```

```
if acc_safe==1 &&
colli==0
accel(t,v_reg)=max_accel(t,v_reg);
    accel_found=1;
elseif colli==1
accel(t,v_reg)=max_dec(t,v_reg);
elseif acc_safe==0 &&
colli==0 && accel_found==0
    if s(t-
Aw_lev,v_reg)<=T(t-Aw_lev,v_reg)
        if z(t-
Aw_lev,v_reg)==0 && accel_found==0
accel(t,v_reg)=aA(t,v_reg);
accel_found=1;
        elseif z(t-
Aw_lev,v_reg)==1 && accel_found==0
accel(t,v_reg)=max_dec(t,v_reg);
accel_found=1;
        end
    elseif s(t-
Aw_lev,v_reg)>T(t-Aw_lev,v_reg) && accel_found==0
        if
vel(t,veh)>vel(t-Aw_lev+5,veh)
accel(t,v_reg)=aB(t,v_reg);
accel_found=1;
        elseif z(t-
Aw_lev,v_reg)==0 && accel_found==0
accel(t,v_reg)=aC(t,v_reg);
```

```
accel_found=1;
                                                            elseif z(t-
Aw_lev,v_reg)==1 && accel_found==0

accel(t,v_reg)=max_dec(t,v_reg);

accel_found=1;
                                                            elseif colli==1

accel(t,v_reg)=max_dec(t,v_reg);

accel_found=1;
                                                            end
                                                        end
                                                    end
                                                end
                                            end
                                        end
                                    end
                                end
                            end
                            if shift==0 %Exits loop if no shift occurred or
b wasnt greater than zero see above for proper understanding
                                break;
                            end
                        end
                    end
                end
            end

            %%Generating a new vehicle%%
```

```
            %New vehicles were generated on the beginning of the link i.e
patch 125

            if t>1 && pa==patch

                %Generate new vehicle on patch (front bumper)

                %The vehicle to be generated was given 0.5 as a temporary
registeration number. Actual vehicle registeration numbers start from 1.

                v_reg=0.5;


                %The registeration number of the lead vehicle of the new
vehicle is initialised to zero

                ref_veh=0;


                if v_reg==0.5

                    %The new vehicle temporary lane is initialised to zero

                    temp_lane=0;


                    %This loop runs through all lane numbers on the link

                    %%NOTE that since the loop starts running from lane
number 1 vehicles would first attempt to generate on the inner lanes

                    for la=1:no_lane

                        %For each lane number selected it determines the
vehicle on the lane closest to the start point.

                        %This vehicle would be a potential lead vehicle of
the new vehicle to be generated


[ref_veh_D,NTA]=ref_veh_generator3(patch_veh_reg(:,:),pa,v_reg,posit_f(:,:)
,posit_r(:,:),t,la,0,1);

                        %It then determines if there would be a collision
with the potential lead vehicle if the new vehicle

                        %was generated at the start of the lane

                        colli=0;

                        if ref_veh_D>0


[colli,acc_safe]=collision_detector3(vel(t,ref_veh_D),max_dec(t,ref_veh_D),
max_dec(t,ref_veh_D)/3,vel_init,0,posit_r(t,ref_veh_D),stop_gap,0,0);
```

```
                        end
                        %If the gap between the veh to be generated and the lead veh is greater than stop_gap and den is greater than 15 or entry interval has been reached
                        %and If there would be no collision or there is no vehicle on the lane the scanned lane is then assigned as the temporary lane
                        %of the vehicle to be generated while its lead vehicle is assigned as the detected potential lead vehicle on the lane
                        %or zero if no vehicle on the lane
                        if  ref_veh_D~=0 && colli==0 && ((posit_r(t,ref_veh_D)>stop_gap) && max_Den>15 ||(t-timer1)>=interval && (posit_r(t,ref_veh_D)>stop_gap)) || ref_veh_D==0
                            temp_lane=la;
                            ref_veh=ref_veh_D;
                            break
                        end
                    end
                end
                %if the vehicle to be generated would collide with potential lead vehicles on all lanes no vehicle is generated during this timestep


                %if the vehicle to be generated has a temporary lane
                if temp_lane>0
                    [ a,b,C,d ] = switch_board( temp_lane );


                    %an available front bumper slot on the patch (patch 125) where the vehicle is to be generated is searched for
                    for jk=a:b
                        %If a slot if found the slot number is then copied to a variable 'use'
                        if patch_veh_reg(pa,jk)==0
                            use=jk;
                            break;
```

```
                    end
                end

                %generating a new vehicle
                %if an available slot was found (i.e. use>0)
                if use>0

                    %selecting a registeration number for the new
vehicle
                    %The for loop runs from 1 to the maximum number of
vehicles allowed on the link.
                    for jk=1:veh
                        %The patch register is looked up to see if the
current value of the loop is registered on the patch register
                        vr=ismember(jk, patch_veh_reg(:));       %check
if v is a member of the array
                        %If YES the loop keeps running but if NO the
loop number is assigned as the vehicle registeration number
                        %since no vehicle currently has that
registeration number and the loop breaks
                        if vr~=1
                            v_reg=jk;
                            break;
                        end
                    end

                    %If the vehicle to be generated now has a real
registeration number (i.e. no longer temp reg)
                    if v_reg>0.5
                        %The position of the vehicle on the link is set
to 0.1 which is on patch 125.
                        %Every newly generated vehicle starts from this
point
                        %posiiton
```

```
                            posit_f(t,v_reg)=0.1;

                            %The new vehicle journey start time is then
taken as the current timestep
                            sta_tim(1,v_reg)=t;

                            %The new vehicle type is then selected

                            %Small vehicles have a length of 4.7m while
                            %large vehicles have a length of 14m
(reference)
                            %Uniform small vehicles were given type 1
                            %vehicle design while unifrom large vehicles
                            %were given type 4.
                            if uniform_veh==on
                                if choose_veh==small
                                    veh_len(1,v_reg)=small_L;
                                    veh_type(1,v_reg)=1;
                                elseif choose_veh==large
                                    veh_len(1,v_reg)=big_L;
                                    veh_type(1,v_reg)=4;
                                end
                            %With uniform vehicles option off vehicle ratio
                            %was used. A counter was used along side the
                            %ratio to determine when to select small or
                            %large vehicles. When the counter was less than
                            %the ratio value selections were made
                            %sequentially between the 3 small vehicle
                            %design types. The selection got to the 3rd
                            %type the next selection became the first one
                            %and the cycle continued until the counter
```

```
                                    %value equaled the ratio value.
                                    elseif uniform_veh==off
                                        if veh_len_cnt<ratio
                                            veh_len(1,v_reg)=small_L;
                                            switch L_veh_type_cnt
                                                case 0
                                                    veh_type(1,v_reg)=1;

L_veh_type_cnt=L_veh_type_cnt+1;
                                                case 1
                                                    veh_type(1,v_reg)=2;

L_veh_type_cnt=L_veh_type_cnt+1;
                                                case 2
                                                    veh_type(1,v_reg)=3;
                                                    L_veh_type_cnt=0;
                                            end
                                            veh_len_cnt=veh_len_cnt+1;
                                      %When the counter equalled the ratio value
                                      %a large vehicle was then selected and then
                                      %the counter was reset so smaller vehicle
                                      %lengths were selected afterwards. Just like
                                      %the small vehicle selection procedure a
                                      %different counter was used to ensure the
selection was
                                      %done sequentially and once the 3rd vehicle
                                      %type was selected the counter was reset so
                                      %that the next selection was the first
                                      %selection keeping the selection process in a
                                      %cycle.
                                        elseif veh_len_cnt>=ratio
                                            veh_len(1,v_reg)=big_L;
```

```
                                        switch H_veh_type_cnt
                                            case 0
                                                veh_type(1,v_reg)=4;
H_veh_type_cnt=H_veh_type_cnt+1;
                                            case 1
                                                veh_type(1,v_reg)=5;
H_veh_type_cnt=H_veh_type_cnt+1;
                                            case 2
                                                veh_type(1,v_reg)=6;
                                                H_veh_type_cnt=0;
                                        end
                                        veh_len_cnt=0;
                                    end
                                end

                                %The position of the rear bumper of the new
vehicle was calculated by
                                %subtracting the length of the vehicle from its
front numper position
                                posit_r(t,v_reg)=posit_f(t,v_reg)-
veh_len(1,v_reg);
                                %The temporary lane of the new vehicle was
assigned as its lane
                                lanes(t,v_reg)=temp_lane;

                                %Autonomous
edit*****************************************************
                                %Vehicles were made autonomous depending on
whether they were generated
                                %on a designated autonomous vehicles lane or
not. If the percentage of
```

```
                            %autonomous vehicles was 33% or 1/3 then only
vehicles generated on the
                            %first lane were made autonomous. If it was 2/3
only vehicles generated
                            %on the 1st and second lanes were made
autonomous while if it was 3/3 or
                            %100% all new vehicles were made autonomous.
                            if auto_level==1
                                if lanes(t,v_reg)==1
                                    auto(t,v_reg)=1;
                                end
                            elseif auto_level==2
                                if lanes(t,v_reg)==1 || lanes(t,v_reg)==2
                                    auto(t,v_reg)=1;
                                end
                            elseif auto_level==3
                                if lanes(t,v_reg)==1 || lanes(t,v_reg)==2
|| lanes(t,v_reg)==3
                                    auto(t,v_reg)=1;
                                end
                            end

                            %The density of the new vehicle's lane
increased by 1

lane_dens(1,temp_lane)=lane_dens(1,temp_lane)+1;
                            %The lead vehicle of the new vehicle was
assigned as the detected potential
                            %lead vehicle on the lane or zero if no vehicle
on the lane
                            ref(t,v_reg)=ref_veh_D;
                            %The velocity of the new vehicle was then
assigned as the predefined initial velocity
                            vel(t,v_reg)=vel_init;
```

```
                            %find the patches the vehicle's bumpers are
located

[p_frt,rer]=patch_finder2(posit_f(t,v_reg),veh_len(1,v_reg),patch_table);

                            %the vehicle's front bumper was then registered
to a front bumper slot of its current patch

                            patch_veh_reg(p_frt,use)=v_reg;

                            %used to reset lane change timers of previous
vehicle that has left when a new vehicle with the same v_reg enters

                            reset_lane_timers(1,v_reg)=1;

                            %density on the road increases

                            count_Den=count_Den+1;

                            %If cell 1 is high a vehicle entered at that
time step,if cell 2 high a vehicle exited at that time step

                            %When both are 1 or high during the same time
step the traffic is stable.

                            traff_flow(t,1)=1;

                            %the time vehicle entered the link was taken,
this was used to control the interval at

                            %which new vehicles entered the link

                            timer1=t;

                        end

                    end

                end

            end

        end



        %Data collection

        %The maximum density was updated each time the density of the link
was greater than the maximum density on record

        %It was saved for each time step on the first column of an array
called 'data'

        if count_Den>max_Den
```

```
            max_Den=count_Den;

        end

        data(t,1)=max_Den;


        %The density, maximum density and flux for each time step were
saved in data column 1, 2 and 3 respectively

        density=data(t,1);

        mean_velocity=data(t,2);

        flux=data(t,3);


        %mean velocity

        %mean velocity at that time step was calculated as the sum of the
average velocity of all vehicles that have

        %exited the link divided by the total vehicles that have exited the
link

        if density>0

            mean_velocity=Add_Av_vel/veh_count;

            if Add_Av_vel==0 || veh_count==0

                mean_velocity=0;

            end

        end


        %mean velocity during stable traffic state

        %the mean velocity at the current time step during stability was
calculated as the sum

        %of the average velocity of all velicles that exited the link when
the traffic was stable

        %divided by the total vehicles that exited the link during this
period

        if density>0

            mean_velocity_sat=Add_Av_vel_sat/veh_count_sat;

            if Add_Av_vel_sat==0 || veh_count_sat==0

                mean_velocity_sat=0;
```

```
        end
    end

    %traffic flux
    %The traffic flux at the current timestep was calculated as the
density
    %divided by the mean velocity both at the current time step
    if density>0
        flux=density*mean_velocity;
    end

    %The density, mean velocity and flux of the current time step were
then
    %saved into data column 1, 2 and 3 respectively
    data(t,1)=density;
    data(t,2)=mean_velocity;
    data(t,3)=flux;

    %The timestep when the traffic became stable is taken
    if traff_flow(t,1)==1 && traff_flow(t,2)==1 && count_Den>=veh &&
prevent==0
        sat_time=t;
        prevent=1;
    end

    %%Not relevant%%
    if sat_time>0 && ((veh_count_aft>=change &&
change<=30)||(veh_count_aft>=30 && change>30))
        break;
    end
end
```

```
    %The total simulation time in seconds from stable traffic state is calculated as the difference

    %between the total time step and the time step when the traffic attained a stable state divided by 10

    %since each time step is equivalent to 0.1sec

    Time=(t-sat_time)/10;

    %The traffic flux per hour was calculated as the quotient of the total number of vehicles that exited

    %the link during the traffic stable state and the Time of the entire simulation during the stable state multiplied by 3,600

    traff_flux(1,1)=(veh_count_sat/Time)*3600;

    %Not relevant%

    traff_flux(1,2)=(veh_count_sat/Time)*900;


    %The average journey time was calculated as the mean journey time of all the vehicles that exited

    %the link during the traffic stable state

    mean_jon_tim_analy_sat(1,1)=mean(jon_tim_sat(1,:));


    %The calculated parameters were saved into various columns of an array called 'flux_data'

    flux_data(1,size)=traff_flux(1,1);

    flux_data(2,size)=mean_jon_tim_analy_sat(1,1);

    flux_data(3,size)=t;

    flux_data(4,size)=sat_time;

    flux_data(5,size)=time;

    flux_data(6,size)=mean_velocity_sat;


    %Not relevant%

    flux_data(7,size)=change;


    %The array 'flux_data' was then saved as a spreadsheet so it could be exported and used on a different program
```

```
xlswrite('classlist.xlsx',flux_data,'section2','A1');

switch change
    case 1
        data_analy(:,1)=data(:,1);
        data_analy(:,2)=data(:,2);
        data_analy(:,3)=data(:,3);
        data_analy(:,4)=traff_flow(:,1);
        data_analy(:,5)=traff_flow(:,2);

    case 2
        data_analy(:,7)=data(:,1);
        data_analy(:,8)=data(:,2);
        data_analy(:,9)=data(:,3);
        data_analy(:,10)=traff_flow(:,1);
        data_analy(:,11)=traff_flow(:,2);
    case 3
        data_analy(:,12)=data(:,1);
        data_analy(:,13)=data(:,2);
        data_analy(:,14)=data(:,3);
        data_analy(:,15)=traff_flow(:,1);
        data_analy(:,16)=traff_flow(:,2);
    case 4
        data_analy(:,18)=data(:,1);
        data_analy(:,19)=data(:,2);
        data_analy(:,20)=data(:,3);
        data_analy(:,21)=traff_flow(:,1);
        data_analy(:,22)=traff_flow(:,2);
    case 5
        data_analy(:,24)=data(:,1);
```

```
            data_analy(:,25)=data(:,2);

            data_analy(:,26)=data(:,3);

            data_analy(:,27)=traff_flow(:,1);

            data_analy(:,28)=traff_flow(:,2);

    end

   clear;


end
```

The lane change function

```
function [
timer_N1_array,timer_N2_array,Lanes_array,non_interest_counter_array,timer_
overtake_array,timer_change_array ] = overtake7_auto(
Lanes_array,veh_reg,veh,velo_array,max_velo,gap_array,time,timer_N1_array,t
imer_N2_array,non_interest_counter_array,patch_regis_array,patch,posit_frt_
array,posit_r_array,max_brake_array,traffic_gap,
aA_array,aB_array,aC_array, accel_array,
max_accel_array,timer_overtake_array,timer_change_array,reset_lane_timers_a
rray,veh_length_array,patch_table_array,max_lane,auton_level )

%UNTITLED Summary of this function goes here

%   Detailed explanation goes here


total_vel=0;

no_of_veh=0;

mean_velo_cur=0;

total_vel_N2=0;

mean_velo_N1=0;

mean_velo_N2=0;

collision_N1=0;

collision_N2=0;

colli_N1a=0;

colli_N1b=0;

colli_N2a=0;

colli_N2b=0;
```

```
no_of_veh_N1=0;
no_of_veh_N2=0;
total_vel_N1=0;
total_vel_N2=0;
Rcur=0;
ch2=0;
ch3=0;
set1=0;
set2=0;
neigh_state=0;
RN1a=0;
RN2a=0;
RN1b=0;
RN2b=0;
N_A=0;
lane_checker_mode_set=1;
lane_checker_mode_set2=0;
N2f_avail=0;
N1f_avail=0;
N2r_avail=0;
N1r_avail=0;
N2_avail=0;
N1_avail=0;
po_frt=0;
po_rer=0;
a=0;b=0;C=0;d=0;
disp_buf_fol=0;
disp_fol=0;
posit_f_fol=0;
change1=0;
```

```
change2=0;

ref=0;

accel_safe=0;


%resetting lane change timers for new vehicle

if reset_lane_timers_array(1,veh_reg)==1

    timer_N2_array(1,veh_reg)=0;

    timer_N1_array(1,veh_reg)=0;

    non_interest_counter_array(1,veh_reg)=0;

    timer_overtake_array(1,veh_reg)=0;

    timer_change_array(1,veh_reg)=0;

end


%Updating lane to previous lane before processing

Lanes_array(time,veh_reg)=Lanes_array(time-1,veh_reg);


%current lane of the vehicle

current_lane=Lanes_array(time,veh_reg);


% to prevent the driver from changing his mind rapidly when conditions

% suddenly become favourable

if timer_overtake_array(1,veh_reg)==20

    if (timer_overtake_array(1,veh_reg)>0 && (accel_array(time-
1,veh_reg)>=aB_array(time-1,veh_reg)||accel_array(time-
1,veh_reg)==max_accel_array(time-1,veh_reg))||velo_array(time-
1,veh_reg)==max_velo) && timer_change_array(1,veh_reg)<=10

        timer_change_array(1,veh_reg)=timer_change_array(1,veh_reg)+1;

    elseif timer_overtake_array(1,veh_reg)<20 && velo_array(time-
1,veh_reg)<max_velo && ((accel_array(time-1,veh_reg)<=aA_array(time-
1,veh_reg)&&aA_array(time-1,veh_reg)<max_accel_array(time-
1,veh_reg))||(accel_array(time-1,veh_reg)<=aC_array(time-
1,veh_reg)&&aC_array(time-1,veh_reg)<max_accel_array(time-
1,veh_reg))||accel_array(time-1,veh_reg)<aB_array(time-1,veh_reg))
```

```
        timer_change_array(1,veh_reg)=0;

    end

end


%checking driving conditions. Driver's Driving conditions perception only change if the driver

%has not decided to check a different lane for better conditions or 10 mind

%levels (see above) after he has decided to check other lanes


%Decision to change lane (interest levels)

if (timer_overtake_array(1,veh_reg)==20 && timer_change_array(1,veh_reg)==10)||(timer_overtake_array(1,veh_reg)<20)

    if timer_overtake_array(1,veh_reg)<20 && velo_array(time-1,veh_reg)<max_velo && ((accel_array(time-1,veh_reg)<=aA_array(time-1,veh_reg)&&aA_array(time-1,veh_reg)<max_accel_array(time-1,veh_reg))||(accel_array(time-1,veh_reg)<=aC_array(time-1,veh_reg)&&aC_array(time-1,veh_reg)<max_accel_array(time-1,veh_reg))||accel_array(time-1,veh_reg)<aB_array(time-1,veh_reg))

        timer_overtake_array(1,veh_reg)=timer_overtake_array(1,veh_reg)+1;

    elseif timer_overtake_array(1,veh_reg)>0 && (accel_array(time-1,veh_reg)>=aB_array(time-1,veh_reg)||accel_array(time-1,veh_reg)==max_accel_array(time-1,veh_reg))||velo_array(time-1,veh_reg)==max_velo

        timer_overtake_array(1,veh_reg)=timer_overtake_array(1,veh_reg)-1;

    end

end


%finding current lane neighbouring lanes

right=0;left=0;

if max_lane~=1 && current_lane==1

    right=0;left=2;

    neigh_state=1.1;

elseif max_lane==1 && current_lane==1

    right=0;left=0;
```

```
    neigh_state=1.2;
elseif max_lane~=2 && current_lane==2
    right=1;left=3;
    neigh_state=2.1;
elseif max_lane==2 && current_lane==2
    right=1;left=0;
    neigh_state=2.2;
elseif max_lane~=3 && current_lane==3
    right=2;left=4;
    neigh_state=3.1;
elseif max_lane==3 && current_lane==3
    right=2;left=0;
    neigh_state=3.2;
elseif max_lane==4 && current_lane==4
    right=3;left=0;
    neigh_state=4;
end



%calculating total velocity for vehicles on the same lane
for ch=1:veh
    %calculating the velocity for current lane
    if Lanes_array(time-1,ch)==current_lane
        no_of_veh=no_of_veh+1;
        total_vel=total_vel+velo_array(time-1,ch);
    end
    %calculating the velocity for the neighbouring lanes
    switch neigh_state
        %if current lane is 1
        case 1.1
```

```
    if Lanes_array(time-1,ch)==2
        no_of_veh_N2=no_of_veh_N2+1;
        total_vel_N2=total_vel_N2+velo_array(time-1,ch);
    end
    no_of_veh_N1=0;
    total_vel_N1=0;
    %if current lane is 2
case 1.2
    no_of_veh_N2=0;
    total_vel_N2=0;

    no_of_veh_N1=0;
    total_vel_N1=0;

case 2.1
    if Lanes_array(time-1,ch)==1
        no_of_veh_N1=no_of_veh_N1+1;
        total_vel_N1=total_vel_N1+velo_array(time-1,ch);
    end
    if Lanes_array(time-1,ch)==3
        no_of_veh_N2=no_of_veh_N2+1;
        total_vel_N2=total_vel_N2+velo_array(time-1,ch);
    end
case 2.2
    if Lanes_array(time-1,ch)==1
        no_of_veh_N1=no_of_veh_N1+1;
        total_vel_N1=total_vel_N1+velo_array(time-1,ch);
    end
    no_of_veh_N2=0;
    total_vel_N2=0;
```

```
            %if current lane is 3
        case 3.1
            if Lanes_array(time-1,ch)==2
                no_of_veh_N1=no_of_veh_N1+1;
                total_vel_N1=total_vel_N1+velo_array(time-1,ch);
            end
            if Lanes_array(time-1,ch)==4
                no_of_veh_N2=no_of_veh_N2+1;
                total_vel_N2=total_vel_N2+velo_array(time-1,ch);
            end
        case 3.2
            if Lanes_array(time-1,ch)==2
                no_of_veh_N1=no_of_veh_N1+1;
                total_vel_N1=total_vel_N1+velo_array(time-1,ch);
            end
            no_of_veh_N2=0;
            total_vel_N2=0;
            %if current lane is 4
        case 4
            if Lanes_array(time-1,ch)==3
                no_of_veh_N1=no_of_veh_N1+1;
                total_vel_N1=total_vel_N1+velo_array(time-1,ch);
            end
            no_of_veh_N2=0;
            total_vel_N2=0;
    end
end

%average velocity of vehicles on the current lane
if total_vel>0 && no_of_veh>0
```

```
    mean_velo_cur=total_vel/no_of_veh;
end

%average velocity of vehicles on the Neighbouring lane 1 (N1) lane
if total_vel_N1>0 && no_of_veh_N1>0
    mean_velo_N1=total_vel_N1/no_of_veh_N1;
end

%average velocity of vehicles on the Neighbouring lane 2 (N2) lane
if total_vel_N2>0 && no_of_veh_N2>0
    mean_velo_N2=total_vel_N2/no_of_veh_N2;
end

%Reference vehicle on current lane
%[ Rcur ] =
ref_veh_generator(patch_regis_array(:,:),patch,veh_reg,posit_frt_array(:,:)
,posit_r_array(:,:),time,current_lane);
[Rcur,N_A]=ref_veh_generator3(patch_regis_array(:,:),patch,veh_reg,posit_fr
t_array(:,:),posit_r_array(:,:),time,current_lane,lane_checker_mode_set2,0)
;

%Interest on neighbouring lanes
%The Inner lane
%Before observing the inner lane the driver does not need to be unsatisfied
with its current lane
%Increased Interest in the Inner lane
if current_lane>1&& timer_N1_array(1,veh_reg)<40 &&
((mean_velo_N1>=max_velo-10||mean_velo_N1>=mean_velo_cur-2||
RN1a==0)||(Rcur==0 && velo_array(time-1,veh_reg)<mean_velo_N1-2))
    timer_N1_array(1,veh_reg)=timer_N1_array(1,veh_reg)+1;
    ch3=1;
%Reduced Interest in the Inner lane
```

```
elseif current_lane>1 && timer_N1_array(1,veh_reg)>0 &&
(mean_velo_N1<max_velo-10&&mean_velo_N1<=mean_velo_cur-2) && ch3==0

    timer_N1_array(1,veh_reg)=timer_N1_array(1,veh_reg)-1;

    set2=1;

end

%Before observing the outer lane lane the driver needs to be unsatisfied
with its current lane

%No Interest in the Outer lane

if timer_overtake_array(1,veh_reg)==20

    if current_lane<max_lane && Rcur==0

        timer_N2_array(1,veh_reg)=0;

        if non_interest_counter_array(1,veh_reg)>=0


non_interest_counter_array(1,veh_reg)=non_interest_counter_array(1,veh_reg)
+1;

        end

        ch2=1;

        %Increased Interest in the Outer lane

    elseif current_lane<max_lane && timer_N2_array(1,veh_reg)<40 && ch2==0
&& gap_array(time-1,veh_reg)<70 &&Rcur~=0

        if (mean_velo_N2>mean_velo_cur+2 ) || RN1a==0 || velo_array(time-
1,Rcur)<mean_velo_N2-2

            timer_N2_array(1,veh_reg)=timer_N2_array(1,veh_reg)+1;

            non_interest_counter_array(1,veh_reg)=0;

            ch2=1;

        end

        %Reduced Interest in the Outer lane

    elseif current_lane<max_lane && ch2==0 && Rcur~=0

        if (mean_velo_N2<mean_velo_cur+2 || gap_array(time-1,veh_reg)>70)
&& timer_N2_array(1,veh_reg)>0

            timer_N2_array(1,veh_reg)=timer_N2_array(1,veh_reg)-1;


non_interest_counter_array(1,veh_reg)=non_interest_counter_array(1,veh_reg)
+1;
```

```
            set1=1;
        end
    end
end

if timer_N2_array(1,veh_reg)>=40
    %ref generator right lane(N2)
    switch current_lane
        case 1
            if neigh_state==1.1
[RN2a,RN2b]=ref_veh_generator3(patch_regis_array(:,:),patch,veh_reg,posit_frt_array(:,:),posit_r_array(:,:),time,2,lane_checker_mode_set,0);
            elseif neigh_state==1.2
                RN2a=0;RN2b=0;
            end
        case 2
            if neigh_state==2.1
[RN2a,RN2b]=ref_veh_generator3(patch_regis_array(:,:),patch,veh_reg,posit_frt_array(:,:),posit_r_array(:,:),time,3,lane_checker_mode_set,0);
            elseif neigh_state==2.2
                RN2a=0;RN2b=0;
            end
        case 3
            if neigh_state==3.1
[RN2a,RN2b]=ref_veh_generator3(patch_regis_array(:,:),patch,veh_reg,posit_frt_array(:,:),posit_r_array(:,:),time,4,lane_checker_mode_set,0);
            elseif neigh_state==3.2
                RN2a=0;RN2b=0;
            end
        case 4
```

```
            RN2a=0;RN2b=0;
    end

    if RN2a>0
        %detect collision
        [colli_N2a,accel_safe] = collision_detector3( velo_array(time-
1,RN2a),max_brake_array(time-1,RN2a),max_brake_array(time-
1,veh_reg),velo_array(time-1,veh_reg),posit_frt_array(time-
1,veh_reg),posit_r_array(time-1,RN2a),traffic_gap,accel_array(time-
1,veh_reg),1);
    end
    if RN2b>0
        %current veh is ref veh
        [colli_N2b,accel_safe]=collision_detector3(velo_array(time-
1,veh_reg),max_brake_array(time-1,veh_reg),max_brake_array(time-
1,RN2b),velo_array(time-1,RN2b),posit_frt_array(time-
1,RN2b),posit_r_array(time-1,veh_reg),traffic_gap,accel_array(time-
1,RN2b),1);
    end
    if colli_N2a==1 || colli_N2b==1
        collision_N2=1;
    end
end

if timer_N1_array(1,veh_reg)>=40
    %ref generator left lane(N1)
    switch current_lane
        case 1
            RN1a=0;RN1b=0;
        case 2

[RN1a,RN1b]=ref_veh_generator3(patch_regis_array(:,:),patch,veh_reg,posit_f
rt_array(:,:),posit_r_array(:,:),time,1,lane_checker_mode_set,0);
        case 3
```

```
[RN1a,RN1b]=ref_veh_generator3(patch_regis_array(:,:),patch,veh_reg,posit_f
rt_array(:,:),posit_r_array(:,:),time,2,lane_checker_mode_set,0);

        case 4

[RN1a,RN1b]=ref_veh_generator3(patch_regis_array(:,:),patch,veh_reg,posit_f
rt_array(:,:),posit_r_array(:,:),time,3,lane_checker_mode_set,0);

    end



    if RN1a>0

        %detect collision

        [colli_N1a,accel_safe]=collision_detector3(velo_array(time-
1,RN1a),max_brake_array(time-1,RN1a),max_brake_array(time-
1,veh_reg),velo_array(time-1,veh_reg),posit_frt_array(time-
1,veh_reg),posit_r_array(time-1,RN1a),traffic_gap,accel_array(time-
1,veh_reg),1);

    end

    if RN1b>0

        %current veh is ref veh

        [colli_N1b,accel_safe]=collision_detector3(velo_array(time-
1,veh_reg),max_brake_array(time-1,veh_reg),max_brake_array(time-
1,RN1b),velo_array(time-1,RN1b),posit_frt_array(time-
1,RN1b),posit_r_array(time-1,veh_reg),traffic_gap,accel_array(time-
1,RN1b),1);

    end



    if colli_N1a==1 || colli_N1b==1

        collision_N1=1;

    end

end



%Determine if velo of the Ref veh in the neigh lane is lower than

%current lane mean velo

if current_lane<max_lane && ch2==0 && Rcur~=0 && set1==0 && RN2a>0
```

```
    if  velo_array(time-1,RN2a)<mean_velo_cur+2

        timer_N2_array(1,veh_reg)=timer_N2_array(1,veh_reg)-1;

non_interest_counter_array(1,veh_reg)=non_interest_counter_array(1,veh_reg)
+1;

    end

end


if RN1a>0 && velo_array(time-1,RN1a)<=mean_velo_cur-2 && set2==0 && ch3==0

    timer_N1_array(1,veh_reg)=timer_N1_array(1,veh_reg)-1;

end


%determine if the patch registers on the neighbouring lanes are available

for sh=1:2

    if sh==1 && current_lane<max_lane

        [ a,b,C,d ] = switch_board( Lanes_array(time,veh_reg)+1 );

    elseif sh==2 && current_lane>1

        [ a,b,C,d ] = switch_board( Lanes_array(time,veh_reg)-1);

    end

    [po_frt,po_rer]=patch_finder2(posit_frt_array(time-
1,veh_reg),veh_length_array(1,veh_reg),patch_table_array);


    if a>0 && b>0

        for gk=a:b

            if po_frt>0

                if
patch_regis_array(po_frt,a)==0||patch_regis_array(po_frt,b)==0

                    if sh==1

                        N2f_avail=1;

                    elseif sh==2

                        N1f_avail=1;

                    end
```

```
                    break;
                end
            end
        end
    end

    if po_rer>0
        if C>0 && d>0
        for gk=C:d
            if
patch_regis_array(po_rer,C)==0||patch_regis_array(po_rer,d)==0
                if sh==1
                    N2r_avail=1;
                elseif sh==2
                    N1r_avail=1;
                end
                break;
            end
        end
        end
    elseif po_rer<0
        if sh==1
            N2r_avail=1;
        elseif sh==2
            N1r_avail=1;
        end
    end

    if sh==1
        if N2f_avail==1 && N2r_avail==1
            N2_avail=1;
```

```
        end
    elseif sh==2
        if N1f_avail==1 && N1r_avail==1
            N1_avail=1;
        end
    end
end

%projecting the future position of its following vehicle

for gh=1:2
    if gh==1
        ref=RN1b;
    elseif gh==2
        ref=RN2b;
    end

    if ref>0
        % Displacement
        disp_buf_fol= (velo_array(time-
1,ref)*0.1)+(1/2*(max_accel_array(time-1,ref)*(0.1)^2));

        %Preventing negative displacements
        if disp_buf_fol<0
            disp_fol=0;
        elseif disp_buf_fol>=0
            disp_fol=disp_buf_fol;
        end

        %position
```

```
        posit_f_fol=posit_frt_array(time-1,ref)+disp_fol;

        switch gh
            case 1
                if posit_f_fol>=posit_r_array(time-1,veh_reg)
                    change1=0;
                else
                    change1=1;
                end
            case 2
                if posit_f_fol>=posit_r_array(time-1,veh_reg)
                    change2=0;
                else
                    change2=1;
                end
        end
    elseif ref==0
        switch gh
            case 1
                change1=1;
            case 2
                change2=1;
        end
    end
end

%Change to the Outer lane
if collision_N2==0 && change2==1 && N2_avail==1 &&
timer_N2_array(1,veh_reg)>=40 && current_lane<max_lane
    Lanes_array(time,veh_reg)=Lanes_array(time,veh_reg)+1;
    timer_N2_array(1,veh_reg)=0;
```

```
    timer_N1_array(1,veh_reg)=0;

    non_interest_counter_array(1,veh_reg)=0;

    timer_overtake_array(1,veh_reg)=0;

    timer_change_array(1,veh_reg)=0;

    %Change to the Inner lane

    %autonomous
edit***************************************************************************
*************************************************************************

elseif collision_N1==0 && change1==1 && N1_avail==1 &&
timer_N1_array(1,veh_reg)>=40 && (timer_N2_array(1,veh_reg)==0 ||
non_interest_counter_array(1,veh_reg)>20)&& current_lane>1

    %Vehicles remain on their current lane if their target lane is a
designated autonomous lane.

    if auton_level==1 && current_lane==2

        Lanes_array(time,veh_reg)=Lanes_array(time,veh_reg);

    elseif auton_level==2 && current_lane==3

        Lanes_array(time,veh_reg)=Lanes_array(time,veh_reg);

    else

        Lanes_array(time,veh_reg)=Lanes_array(time,veh_reg)-1;

        timer_N2_array(1,veh_reg)=0;

        timer_N1_array(1,veh_reg)=0;

        non_interest_counter_array(1,veh_reg)=0;

        timer_overtake_array(1,veh_reg)=0;

        timer_change_array(1,veh_reg)=0;

    end

    %Stay in the current lane

else

    Lanes_array(time,veh_reg)=Lanes_array(time,veh_reg);

end

end
```