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A systematic approach to evaluating operations of virtually coupled trains

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Abstract

Railway transport holds prominence as a viable alternative to road and air modes. With the demand for rail expected to continue its upward trend, stakeholders are seeking innovative solutions to boost rail traffic volume. Virtual Coupling (VC) has been proposed as a concept that enables trains to run closer than existing operations. This can be achieved in a way that two or more trains become engaged with each other so much that they move like a single unit via synchronous acceleration and braking. VC operations, when deployed, are expected to increase line capacity. However, rail lines are so complex that capacity enhancement is not simple and straightforward. Some studies and projects have conducted research on VC, but a systematic approach to evaluating the capacity enhancement of VC operations has not yet been developed. This study has made an original contribution to VC research by developing an evaluation framework for assessing the VC operational performance.

As a step of concept exploration, VC was defined from an operations perspective. The study categorised VC operations from two viewpoints including convoy formation and safe distance principle. Two types were defined through the convoy formation: In inter-consist one, two or more trains are virtually coupled with each other, whereas in intra-consist one, one train is split into smaller sub-trains. From the viewpoint of braking principle, VC operations were defined on the basis of either Absolute Braking (AB) or Relative Braking (RB).

The study has defined four basic operational scenarios depending on where coupling and/or uncoupling occur: at stations or around junctions and then, has developed a simulation architecture to assess capacity performance for these scenarios. The simulation results indicate that under ideal conditions, VC on RB can deliver a capacity of 240 train per hour for a plain line, but this performance is confined by switch processing times for the scenarios including diverging or converging route. VC on AB deliver a capacity ranging from 60 to 70 train per hour for all the scenarios. Also, it was found that intra-consist operation reduces energy use and travel time, especially for express high-speed train services. In addition, the study has investigated influencing factors on VC performance by conducting sensitivity analysis. The following factors were found effective on capacity performance and important in creating a VC operational plan: braking capability, adhesion, fleet heterogeneity, station layout and platform length, relativity index, number of trains in a convoy, virtual interlocking type.

The evaluation framework, developed by this study and presented with the IDEF0 notation, is the first one that creates a systematic approach to evaluating VC operations on a rail line against its existing performance. The framework has been demonstrated through a case study. The London Waterloo to Surbiton line section was analysed over a VC operational plan of nine scenarios with varying safety levels and convoy types. The simulation results indicate a potential capacity increase of two to four times, contingent on fleet expansion with additional 40 to 80 stocks. However, delay propagation is an issue as per deterministic perturbation scenarios, suggesting reducing convoy sizes and increasing time intervals between them as a resilience strategy.

Acknowledgements

بزرگی سراسر به گفتار نیست

دو صد گفته چون نیم کردار نیست

Greatness is not solely in speech's domain,

Two hundred words lack half an action's gain.

(Ferdowsi, Persian Poet)

Embarking on a PhD is akin to traversing a path filled with peaks and valleys, offering not a peaceful voyage, but a vibrantly turbulent one. Reflecting upon UoB's Latin Motto, "Per Ardua ad Alta" – meaning 'through hard work, great things achieved' – it seems perfectly tailored for the pursuit of a doctorate degree. Similarly, as suggested in the epigraph using different phrasing, it is a tangible action, excessive discourse does not help us gain comprehension, only experiencing does!

While it is impossible to mention every individual by name due to the constraints of this space, I would like to express my gratitude to my Turkish friends, many of whom have also confronted the challenges of a PhD journey. Their unwavering friendship has created a natural community that has been a wellspring of assistance whenever I needed it. A special thanks is reserved for my friends and colleagues within BCRRE. Their support has transformed them into a familial unit, and I have been always happy for being a part of it.

I must give a special thanks to the Turkish Ministry of Education for its financial backing, which not only facilitated my PhD research but also enabled the pursuit of my MSc degree, and ultimately, my expertise on railway systems. I would like to give my deepest appreciation to my supervisors, Clive Roberts and Lei Chen, for their all guidance, support and feedback. I would also like to acknowledge Marcelo Blumenfeld, whose voluntary supervision improved my progress across all stages of research.

Lastly, but with utmost significance, my deepest gratitude is reserved for my family, particularly my self-sacrificing mother. Their steady support has been the cornerstone of my achievements.

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Glossary of Terms / List of Abbreviations

Term	Explanation / Meaning / Definition
AB	Absolute Braking
ACC	Adaptive Cruise Control
ATC	Automatic Train Control
ATO	Automatic Train Operation
ATP	Automatic Train Protection
CACC	Cooperative Adaptive Cruise Control
CBI	Computer-based Interlocking
CBTC	Communication-based Train Control System
CC	Cruise Control
CR	Closer Running
DMI	Driver Machine Interface
EC	European Commission
ETCS	European Train Control System
EU	European Union
GA	Genetic Algorithm
GoA	Grade of Automation
GPS	Global Positioning System
GSM-R	Global System for Mobile Communication – Railway
HDT	Headway Time
IPO	Input-Process-Output
KPI	Key Performance Indicator
L	Level (used with ETCS)
LMA	Limit of Movement Authority
MPC	Model Predictive Control
MTS	Multi-train Simulator
OS	Operational Scenario
pphpd	Passenger per hour per direction
RB	Relative Braking
RBC	Radio Block Centre
SE	Systems Engineering
SM	Safety Margin
STPA	Systems Theoretic Process Analysis

Term	Explanation / Meaning / Definition
SWOT	Strengths, Weaknesses, Opportunities, and Threats
tph	Train per hour
V2V	Vehicle-to-Vehicle Communication
VC	Virtual Coupling
VCI	Virtual Coupling Interaction
VI	Virtual Interlocking

Chapter 1 Introduction

1.1 Research Motivation

Railway transport has been holding an important position among the modes of transport. This position is being empowered by investments and incentives underpinned by both governments and industry itself. It is anticipated that railway systems will be increasingly functional for transporting passengers and goods. European Commission has proposed 2021 to be the European Year of Rail in order to increase the pace of 'rail'isation across Europe and the share of rail lines between transport options(European Commission, 2020). In the UK, the rail mode has been increasingly used since 2002 according to the National Travel Survey (Figure 1). In addition, railway transport has not been regarded as an alternative to only road transport anymore. As per a research conducted by UBS, travellers will switch from air to high speed line in the post Covid-19 period due to the environmental-friendly performance of rail systems at carbon emissions and increasing the popularity of high-speed rail lines(Railway Gazette News, 2020). According to a more recent report about EU targets, it has been planned to double HSR traffic in the EU Zone by 2030, triple by 2050 through Trans-European Transport Network by constructing new HSR lines and upgrading existing ones (EU-Rail JU, 2023).

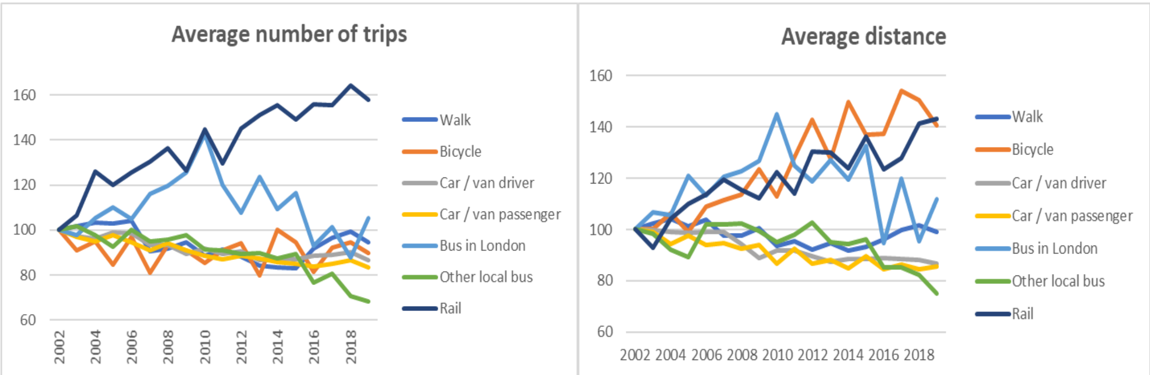


Figure 1: UK National Travel Survey (Index:2002=100) a) average number of trips by selected transport modes, b) average distance travelled by selected transport modes.

Increasing demand for the railway transport has always made the railway sector to seek solutions in order to regulate the rail traffic to accommodate more train services on the same line (Woodland, 2004b). In the early days of railway services, traditional signalling systems helped increase train numbers per unit time as of their use in the early 1800s. On those days, train services were controlled through solely on-sight-operation in which the driver was responsible for controlling braking and traction responding to lineside signals and the signalman was responsible for setting the route by switching points via manual handling as mentioned in Charles Dicken's story *The Signalman*. The ever-increasing demand for rail transport quickly made on-sight operation insufficient, pushing for technology-based solutions that could run more services in a safe, efficient, and timely manner. Today, we have modern railway control systems which are developed using high technological solutions such as Communication-based Train Control System (CBTC) and European Train Control System (ETCS). These two famous instances of these systems include subsystems such as Radio communication, Automation Train Operation (ATO) /Driverless Operation, Computer-based Interlocking (CBI) system etc.

In the recent landscape of rail transport, there is—will be more and more—a need to fit more trains on busy rail networks where bottleneck sections are fully occupied, and capacity cannot be increased any more (UIC, 2019; RSSB, 2020). For this reason, Virtual Coupling (VC), as a novel concept and a potential solution, has been discussed among both academy and industry stakeholders. VC is a type of operation in which successive trains on a line traffic could be running closer to each other than conventional operations. This can be achieved in a way of that the trains move as if they are only one single unit by following each other's pattern of acceleration/deceleration. Thus, following the meaning of 'coupling' in railway terminology, that is, physical connection between two cars/wagons, VC Operations would establish a 'virtual' coupling between two or more trains. Several projects from the Shift2Rail Joint Undertaking under Horizon 2020 have focused on researching VC. Shift2Rail is based on 5 Innovation Programmes (IP). Each IP consists of numerous Technical Demonstrator (TD)s. IP2 represents Advanced Traffic Management & Control Systems, under which TD 2.8 focuses on Virtually- Coupled Train Sets (VCTS). The projects MovingRail and X2Rail-3 have contributed to the work packages of TD 2.8 with their outputs.

Any approach to addressing the complexity of railway systems is required to understand the 'whole' as a combination of many 'parts' that work together towards a single purpose. In this context, even though VC is anticipated to make trains run closer and increase the capacity on rail lines, its implementation is not entirely straightforward. Each rail line has its own characteristics and needs, which directly affects potential benefit of any upgrade. In the literature, studies have not yet covered how to evaluate the capacity enhancement enabled by running VC operations on a rail line. From the principle that the *raison d'etre of* railway systems' is to carry passengers and/or goods from a location to another one in a safely and timely manner rather than proving the application of technologies, this study aims to develop an evaluation framework to help planners and engineers to establish whether VC would generate benefits or not against baseline operations. This study's contribution can help the decision-makers who are under the circumstances of trying to answer the question of "Whether VC coupling operations are sensible on the line in question?".

1.2 Aims, Objectives and Research Questions

As above mentioned, each rail line is a *sui generis* entity of which different characteristics constitute a unique specification. It is most likely that a VC operation would have distinct outcomes on different lines. Most importantly, VC operations do not necessarily mean an improvement on the capacity of a rail line. In this context, the evaluation framework, to be developed by this study, would be potentially useful for the relevant stakeholders and decision-makers. The framework would be beneficial whilst conducting a feasibility analysis of running the VC operations onto a specific line.

The main aim of this research is stated as follows:

- To develop an evaluation framework that establishes a systematic approach to assessing VC operational performance on a specific rail line.

In order to fulfil the aim, the following objectives are pursued:

- To define a terminology for VC operational concepts and scenarios.
- To develop a simulation structure utilised to assess VC operations.
- To investigate and measure factors that affect VC operational performance.

- To produce a framework by synthetising the evaluative steps and effective factors.
- To demonstrate the framework applying it to a case study.

Each objective is followed to answer several specific research questions. The research questions are investigated in the thesis chapters. Each answer constitutes a specific chapter content. The relationship between objectives, research questions and chapters are indicated in Table 1.

Table 1: Objectives and Research Questions

Objectives		**Research Questions**		**Thesis Chapters**
1	To define VC Concept Terminology and Operational Scenarios.	a.	What is the definition of VC from an operational perspective?	2, 4
		b.	How is VC related to existing systems?	
		c.	Which technologies will enable to implement VC on railway transport?	
		d.	What are VC types and operational scenarios?	
2	To develop a simulation structure utilised to assess VC operations.	e.	How to model train motions for VC operations?	4
		f.	What is a simulation structure that enables to observe VC operational performance?	
3	To investigate effective factors upon VC operational	g.	What are the simulation outputs of VC types and operational scenarios?	5
		h.	Which factors are effective on VC operational	

	performance.		performance?	
4	To synthetise the evaluative steps for forming the framework	j.	Which technical language is used to visualise the framework?	6
		k.	Which steps are required to follow for an evaluation process?	
		l.	What are outcomes of an evaluation process?	
5	To demonstrate the framework applying to a case study	m.	How can the framework be applicable to case studies in practice?	7
		n.	How to compare outputs of the VC Operations to baselines?	
		o.	What are outcomes of applying the framework?	

1.3 Approach

Figure 2 illustrates a Vee model that is one of the renowned life cycle representations for technological developments. The system or product is decomposed throughout the left-hand side of the model with an increasing level of details from deciding on stakeholder needs at a conceptual level to technical specifications of each component including hardware and software at a design and implementation level. On the right-hand side of the model, components and subsystems are integrated to each other passing through testing, verification, and validation stages.

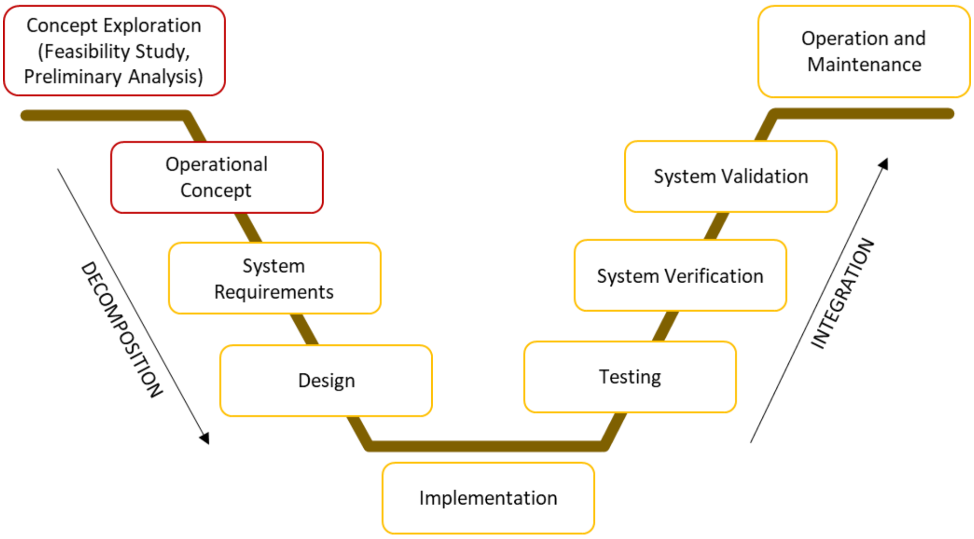


Figure 2: Vee lifecycle model. The red boxes indicate the stages this study is related to.

This study aims to contribute to realisation of VC operations focusing on the early steps of Vee Model at left-hand side including feasibility/preliminary study and operational concepts. The approach has two aspects:

- Feasibility studies comprise mostly several aspects of an engineering project such as finance, organisational, technical etc. To clarify the scope, it is meant by feasibility whether or not operational improvement of a rail line is feasible thanks to running VC scenarios in terms of capacity and capacity-related indicators. In the place of feasibility, preliminary can be interchangeably used as a more correct term that points out an analysis is required at early stages of a decision-making process.
- In addition to preliminary study, as this study analyses the VC operational performance, operational concept is the second aspect of this study's approach. Defining VC operations, simulating, and analysis them are among the objectives of the study. This is conducted at a high-level by running computer-based simulations and observing their impact upon operational performance over rail line timetables.

1.4 Scope

As the study focuses on Preliminary Analysis and Operational Concept, technological design such as developing systems or components, either hardware or software, is out of the scope. Since controller design is the most common focused area in the literature, it deserves to make an explanation herein: it is a limited subject matter within the study. The study devotes itself to contributing to understanding of operational benefits of VC operations.

As for the technical depth of simulation architecture, the study does not use a microscopic one which contains an increased level of detail for infrastructures with precise measurements. The simulation is used to observe operational performance in terms of capacity-related performance indicators and investigate influencing factors conducting a sensitivity analysis from a strategic decision perspective that does not require a detailed simulation architecture.

1.5 Thesis Structure

The thesis is structured in order to fulfil the aim and objectives by replying to the research questions above-mentioned as follows:

Chapter 2 provides a fundamental knowledge about the existing technologies mostly in the rail domain and signalling systems, shortly in the automotive domain. Chapter 3 contains a panoramic literature review that discusses the existing studies on VC from a general perspective. Additionally, based on the findings, Chapter 3 prepares the operational concept of VC by providing the operational definition and types of VC, and their scenarios. Chapter 4 builds a simulation architecture that enables to run simulations for the operational concept. Chapter 5 conducts evaluation of the operations from two sides: (i) running simulations of operational scenarios and types defined in the previous chapter and (ii) investigating effective factors on capacity performance through a sensitivity analysis. Chapter 6 produces the framework that draws on findings of the previous chapters using a IDEF0 notation. Chapter 7 applies the framework to a case study in order to demonstrate its useability.

Chapter 8 concludes the research by discussing the findings in line with the aim and objectives, pointing out the further studies, and making recommendations for further works.

Chapter 2 Preliminaries and Technological Background

In this chapter, the fundamental terms and systems are explained in order to help the reader understand the context into which VC fits. The chapter explains the enabling systems of VC in both rail and automotive domains. Section 1 illustrates all the systems, giving an overview. Section 2 gives a foundation about train control systems to understand the existing technologies on which VC can be built. Section 3 explores the different technologies across the automotive industry that are important for understanding similar or complementary applications needed in the rail domain, in order to realise VC implementation.

2.1 Systems Enabling Virtual Coupling

Both automotive and rail technologies are important in understanding the foundation of a VC system. Figure 3 illustrates these enabling technologies. In the rail domain, modern train control systems use radio communication and moving-block systems: the European Train Control System (ETCS), one of the most famous main line systems that is mainly used across the European zone, and the Communication-Based Train Control System (CBTC), which has a similar architecture to ETCS but is implemented on urban rail lines. Furthermore, CBTC and ETCS have important subsystems such as Automatic Train Protection (ATP), Automatic Train Operation (ATO), Automatic Train Control (ATC) radio communication and moving blocks that deserve to be touched on in this context. In addition, as VC is anticipated to reduce headway distance, a discussion on minimum distance calculation is carried out. The terms full or absolute braking and relative braking are explained to contribute to clarification of the VC context.

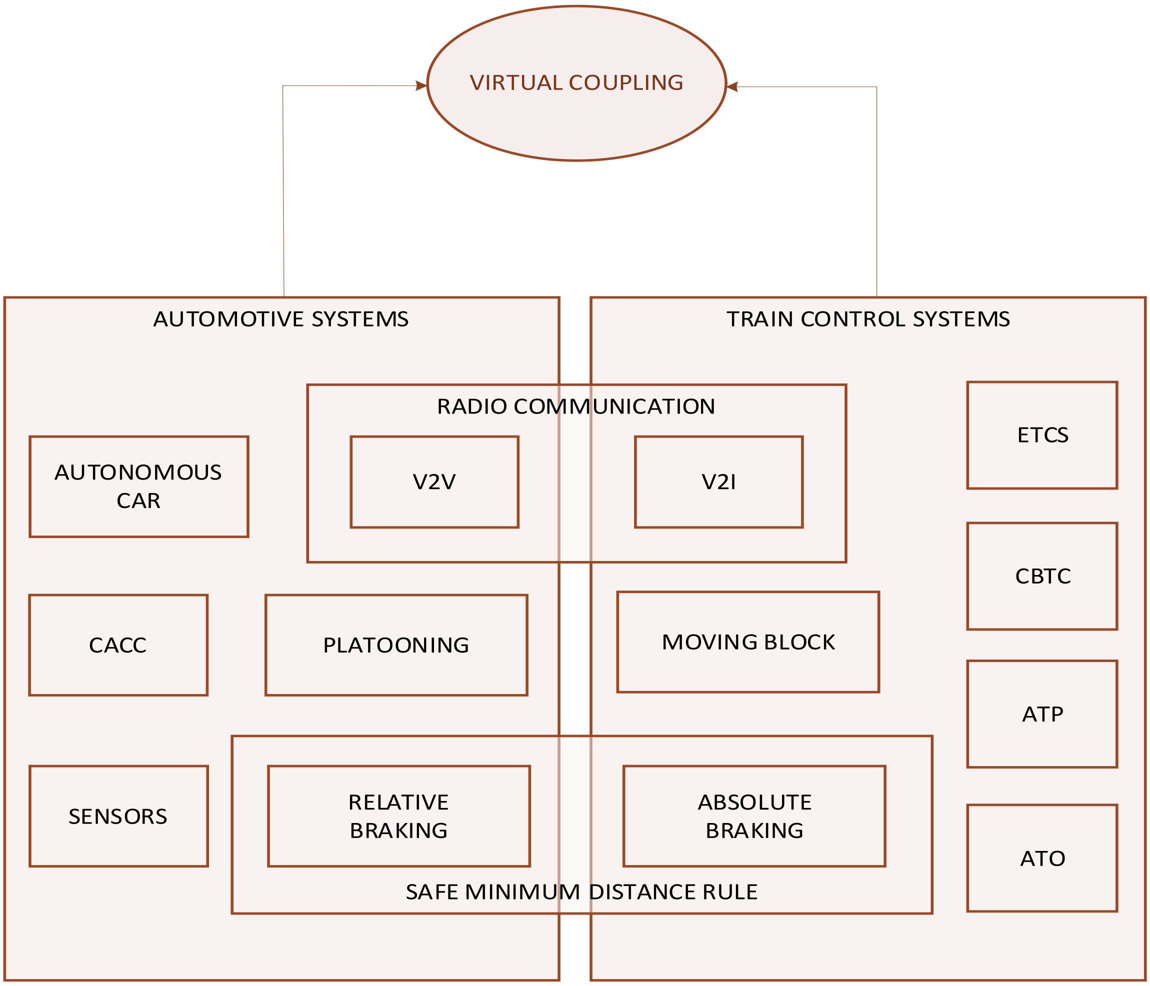


Figure 3: Virtual Coupling Enablers across automotive and rail transport domains

In the automotive domain, up-to-date systems can contribute to our understanding: Autonomous Cars and Platooning, similar concepts to VC, are enabled by automated driving, Vehicle-to-Vehicle Communication (V2V) and advanced sensing technologies. V2V and Relative Braking have been applied in the automotive domain but not yet in the rail domain. These are two of the most key elements being discussed in the VC context.

2.2 Rail Domain: Train Control Systems

Train control systems ensure that trains run safely and efficiently in order to meet the requirement of regulations imposed by rail authorities, the line performance needed by rail operators business and the customer expectations (Woodland, 2004a). As a railway system is primarily defined as one transferring passengers and/or goods from one location to another (Connor, Harris and Schmid, 2015), the main functionalities of a train control system are related to controlling the positions of trains running on the rail line (Woodland, 2004a), and are briefly listed as follows:

- Ensure a safe distance between two consecutive trains on the same track.
- Protect trains whilst crossing junctions.
- Control the train movement on approaching and departing from stations.
- Regulate train services according to the service frequency, pre-planned timetable and speed regulations (Woodland, 2004a).

The terms train control system and railway control system are interchangeably used in some places but there exists a nuance from the operational view. To clarify the choice preferred, a railway control system has a more comprehensive meaning by including network planning and control, station control and line control systems (Woodland, 2004a), which are not included in the scope, whereas a train control system is about controlling the train movement.

2.2.1 Traditional Systems: Fixed-Block Aspect Signalling

Fixed-block signalling systems still exist as the most dominant system across the world, which makes it conventional, too, not only traditional. While they are not 'real' VC enablers, they are relevant to understanding the basics required whilst comparing the performance of different systems with VC operations.

In fixed-block signalling, the line track is separated into many sections i.e., blocks. Each block must be occupied by only one train at the same time (Farooq and Soler, 2017). Each block has a signal ahead of itself which displays an operation order to the train driver. In this system, when a train enters a section, the section becomes occupied. The train's exact location along the section is not known. The section becomes free again whenever the train leaves it.

The signals have different types depending on the number of colours they have. In a 2-aspect signal, there are only green—proceed order—and red—danger order—indications. A 3-aspect signal has one additional indication, and a 4-aspect signal has two additional yellow signals with caution orders. With these additional aspects, the signalling systems provide earlier warnings to the drivers to slow down, as trains operating at high speeds need a longer braking distance (Zhao, 2013). Also, the block length can be shortened in a such a way that running times between two signals or two blocks are reduced, and the line capacity increases.

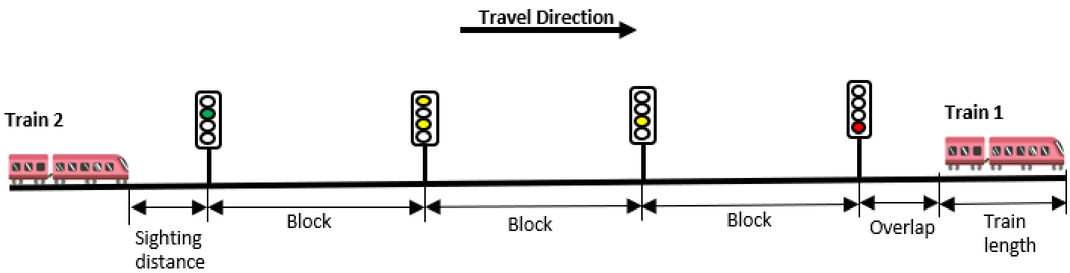


Figure 4: 4-aspect signalling layout.

Figure 4 shows the 4-aspect signalling layout. The driver occupies track sections as long as the signal is green. When the driver sees double yellow—preliminary caution—they start to slow down. If the next signal is yellow, the driver keeps braking until stopping the train completely just before the red signal. The length of the track section should be equal to or greater than half of the braking distance. This is because the train must be able to stop in the length of two sections. Furthermore, there are additional safety measures in the signalling structure due to the possibility of driver error or system failure causing a train to proceed over a red signal. The overlap distance enables the system to prevent the signal from changing to a proceed aspect from a danger one until the train traverses the distance inside the next section. The overlap distance is assigned a nominal length of 180 m in the UK (Woodland, 2004a). In addition to the overlap, another measure ensuring the train can stop before it is desirable is due to the human reaction time. The driver needs to see the signal at a specific distance prior to reaching the signal. The distance between the point at which the driver observes the signal and the location at which the trains must start braking is included as the sighting distance in calculating minimum headway distance.

Including the constituents above mentioned, the headway distance is calculated by:

$$HD = 3d + S + O + TL$$

When d is equal to half of the braking distance, the formula becomes:

$$HD = \frac{3}{2}BD + S + O + TL$$

2.2.2 Modern Advanced Rail Control Systems

The traditional signalling systems are mostly based on human reaction and abilities, which increases the size of human error outcomes that cause system failures, train accidents and dangerous incidents. In order to eliminate the problems caused by human errors, the advent of technological abilities led to the utilisation of radio transmission and automation in train control systems.

2.2.2.1 CBTC

CBTC technology has enabled urban rail transport to have vehicle-centred control systems and be independent of track-based-solutions such as track circuits, axle counters, lineside signalling, etc. In IEEE Standard 1474 (2004), CBTC is defined as *"A continuous automatic train control system utilizing high-resolution train location determination, independent of track circuits; continuous, high capacity, bidirectional train-to-wayside data communications; and train-borne and wayside processors capable of implementing vital functions*". CBTC systems determine a train's location on a vehicle-centred architecture, employing some of the devices like tachometers, accelerometers, gyroscopes, global positioning system (GPS), transponders, radar, lasers, etc. rather than track circuits (Pascoe and Eichorn, 2009). The onboard train equipment transfers continuously the train speed, location and direction to the wayside over radio communication. Based on the data received, the wayside control centre calculates the maximum speed the train can go up to and the maximum distance the train is allowed to traverse in safety, then sends the information to the train as the Limit of Movement Authority (LMA). The onboard train equipment evaluates the LMA and controls the movement, keeping the train at a safe distance from any preceding trains.

2.2.2.1.1 Moving Blocks

As discussed above, the rail tracks in a fixed-block system are divided into sections, in which each section has a fixed length and no real-time communication. When a train enters a track section, the section becomes occupied without knowing the exact location and no other train is allowed to enter the same section. The system works regardless of train length, braking capability and exact location. However, in the moving-block technology of CBTC, the train location stays exact within a limit of accuracy over continuous radio communication (Farooq and Soler, 2017). Since the train separation is not based on track circuits, the separation blocks move with trains and are updated with real-time information. Figure 5 shows the differences between the two types of system.

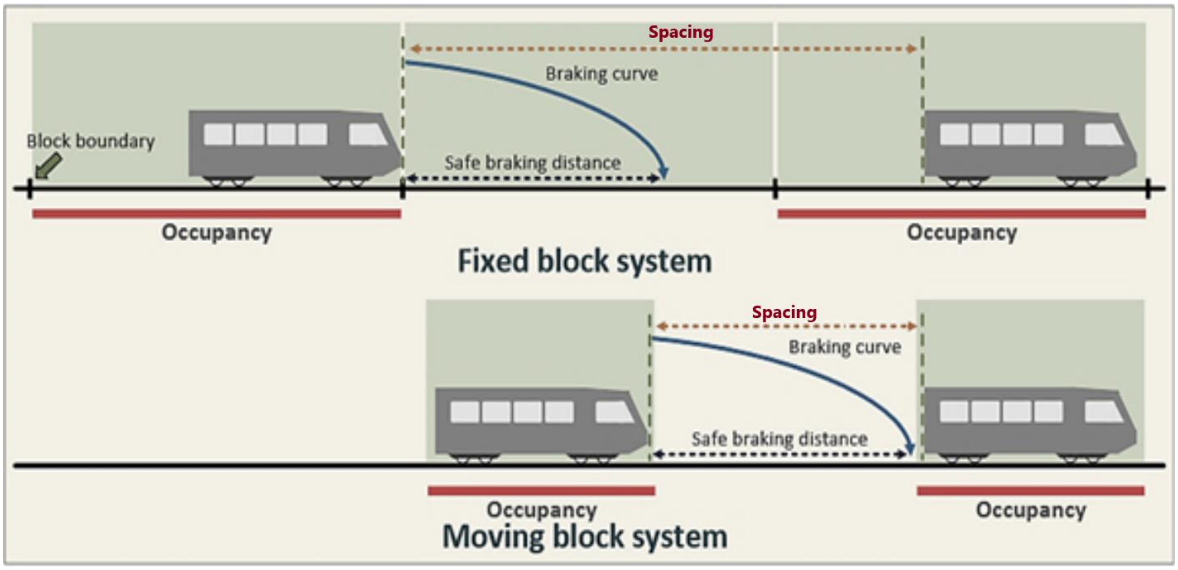


Figure 5: Fixed-block vs moving-block system (Farooq and Soler, 2017)

Moving-block technology reduces the spacing between two trains by bi-directional communication between the wayside and train-borne systems. The spacing depends on only instantaneous braking distance and safety margin, whereas the braking distance is calculated with the line speed to determine the section length in a fixed-block signalling system.

In addition to moving blocks, CBTC has two important system features, ATP and ATO.

2.2.2.1.2 ATP

The human errors that cause safety problems have been eliminated with automation technologies. The ATP functionality holds a safety-critical role that protects the train movement from collisions by overriding the driver's erroneous driving. The train receives the LMA over the wayside devices. The older ATP systems, called intermittent ATP, receive the LMA intermittently in a specific update interval by passing over beacons distributed at short intervals throughout the track (Woodland, 2004a). The novel, continuous ATP, systems have continuous radio communication with the Zone Controller (ZC) and wayside controller so that the LMA update interval is very short. The train receives a speed profile restricted by the LMA from the ZC that determines the LMA, making a calculation with the location and speed parameters of both trains—rear and front. If the rear train does not stay in the LMA, ATP applies the emergency brakes and stops the train.

2.2.2.1.3 ATO

ATO is a method of operation in place of the manual operation performed by a train driver. As ATO controls the train movement, it controls the train traction and braking as long as there is not a safety issue. Under circumstances that affect the system's safety, ATO is overridden by the ATP intervention. ATO is not safety-critical whereas ATP is, which ensures the train stops without any collision if ATO makes the rear train approach the front train closer than the safe distance (Woodland, 2004a).

ATO is classified into different levels of automation. Table 2 shows the grades of automation (GoA) in which the human involvement diminishes from lower to upper ones.

Table 2: Automation levels of ATO functionality (Villalba, 2016)

Grade of Automation	**Train Operation**	**Setting Train in Motion**	**Stopping Train**	**Closing Doors**	**Operation in the Event of Disruption**
GoA 1	ATP with driver	Driver	Driver	Driver	Driver
GoA 2	ATO with driver	Automatic	Automatic	Driver	Driver
GoA 3	Driverless	Automatic	Automatic	Train attendant	Train attendant
GoA 4	Unattended	Automatic	Automatic	Automatic	Automatic

2.2.2.2 ETCS

The European Commission (EC) initiated the development of the ERTMS (European Railway Traffic Management System) in order to produce a standard solution for the incompatibility issue caused by different train control systems of each country throughout cross-border operations over the European rail network (Abed, 2010; Ngai, 2017). The decision to create a standard to implement an interoperable system across the EU was made by European institutions in the late 1980s. The ERTMS, which took many years to develop and test before it was published with the initial specifications in 2000, marked the culmination of this decision and effort.

2.2.2.2.1 Subsystems

ERTMS comprises two main components: the ETCS and Global System for Mobile Communications-Railway (GSM-R). ETCS has in-cab signalling—depending on ETCS level—and an ATP system that supervises train movement with its onboard and trackside elements and supplies continuous real-time information to both drivers and controllers (Sniady and Soler, 2012). The Driver Machine Interface (DMI), an interactive screen, is used for in-cab signalling in place of the traditional trackside signals. It provides the driver with all the information required for the train motion. Additionally, compared to the traditional trackside aspect signalling, all information provided by the DMI is far more thorough and accurate. As a result, misinterpreting a signal is not a possible case for in-cab signalling. In particular, when a train runs at high speed, the sighting distance and reaction time can be very high for the traditional system (Sniady and Soler, 2012). As previously mentioned, the ATP system is in charge of monitoring train movement to determine whether the driver is operating the train appropriately for the braking curve. At every location along the route, the train's top speed is determined by the braking curve. If the driver exceeds the braking curve profile limits, the ATP system compares the actual speed and calculated speed, and then, if necessary, applies automatic braking (Sniady and Soler, 2012). GSM-R is a radio communication system that provides voice and data transmission between the train and trackside equipment using specified frequencies allocated for railway applications (Abed, 2010).

2.2.2.2.2 ETCS Levels

ETCS has three application levels, each of which has different functionalities depending on the onboard and trackside equipment used (Abed, 2010):

<u>ETCS Level 1</u>

The lineside signalling is retained, thereby the ETCS is easily superimposed on the existing signalling system (Railway Signalling, 2014). Eurobalises, which are installed intermittently on the track, transmit signal aspects from the lineside signals for the train as the LMA with route data. The onboard component receives the LMA and route data from the balise when the onboard balise antenna faces the balise. The onboard ETCS component uses the data to calculate the maximum speed and braking curve. Because of the intermittent communication between the train and trackside, the train must pass over a balise to update the LMA. Figure 6 illustrates ETCS Level 1.

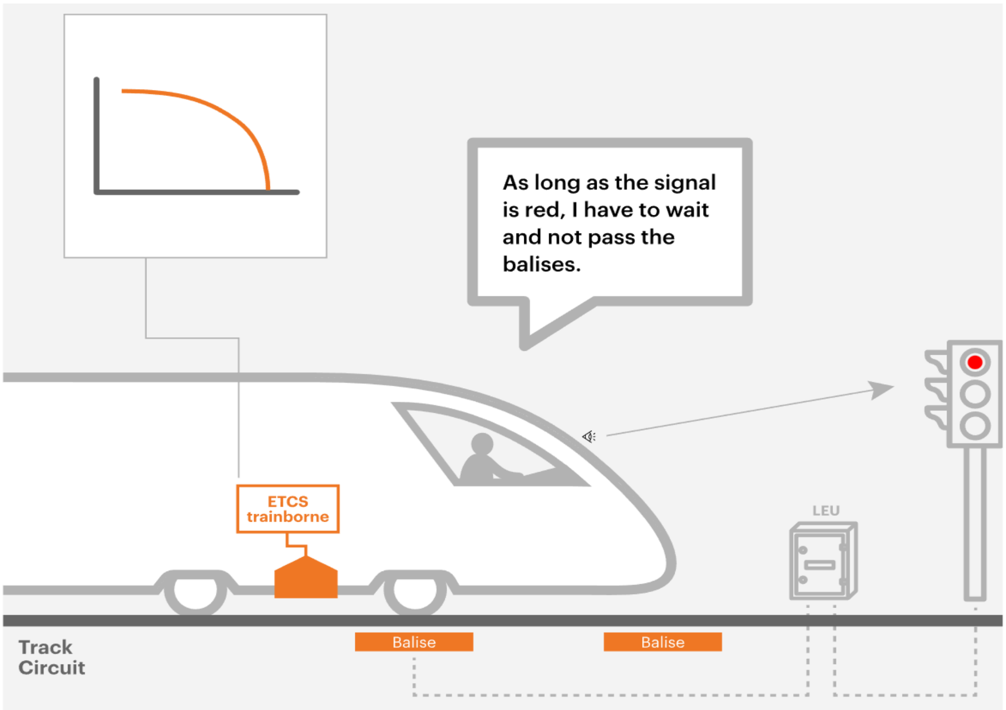


Figure 6: ETCS Level 1 (UNIFE, 2022)

ETCS Level 2

In Level 2, the radio communication provides continuous update of the LMA. The lineside signalling is not needed but can be used as backup system, except that some trackside indicators remind the driver of the start location and end location of Level 2. The train communicates with the Radio Block Centre (RBC) bi-directionally via GSM-R. The train sends its location and direction of travel to the RBC at regular intervals and the RBC transmits the LMA to the train. Balises are used as for passive positioning beacons(Ngai, 2017). The onboard sensors determine the train location between two balises. The train integrity is still supervised by the trackside devices like track circuits.

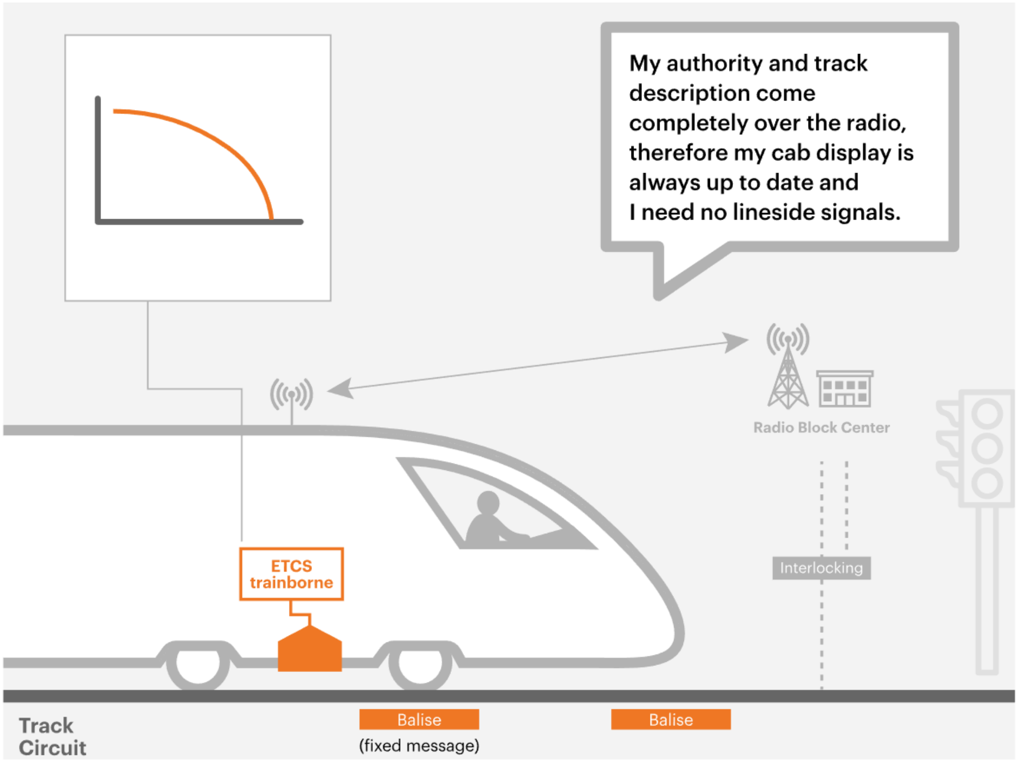


Figure 7: ETCS Level 2 (UNIFE, 2022)

<u>ETCS Level 3</u>

Level 3 replaces the need for the lineside signalling and trackside detection devices. With the train integrity, train location is determined by the train itself and transmitted to the RBC via GSM-R. Train headways reduce down to the full braking distance with a full independence from fixed blocks, using moving-block technology (Ngai, 2017).

Since ETCS Level 3 has not yet been implemented on any rail track, moving-block technology is not a proven technology for main line operations. Also, ATO does not have a place within ERTMS architecture. In contrast, moving block signalling and ATO have been already applied for urban rail transport.

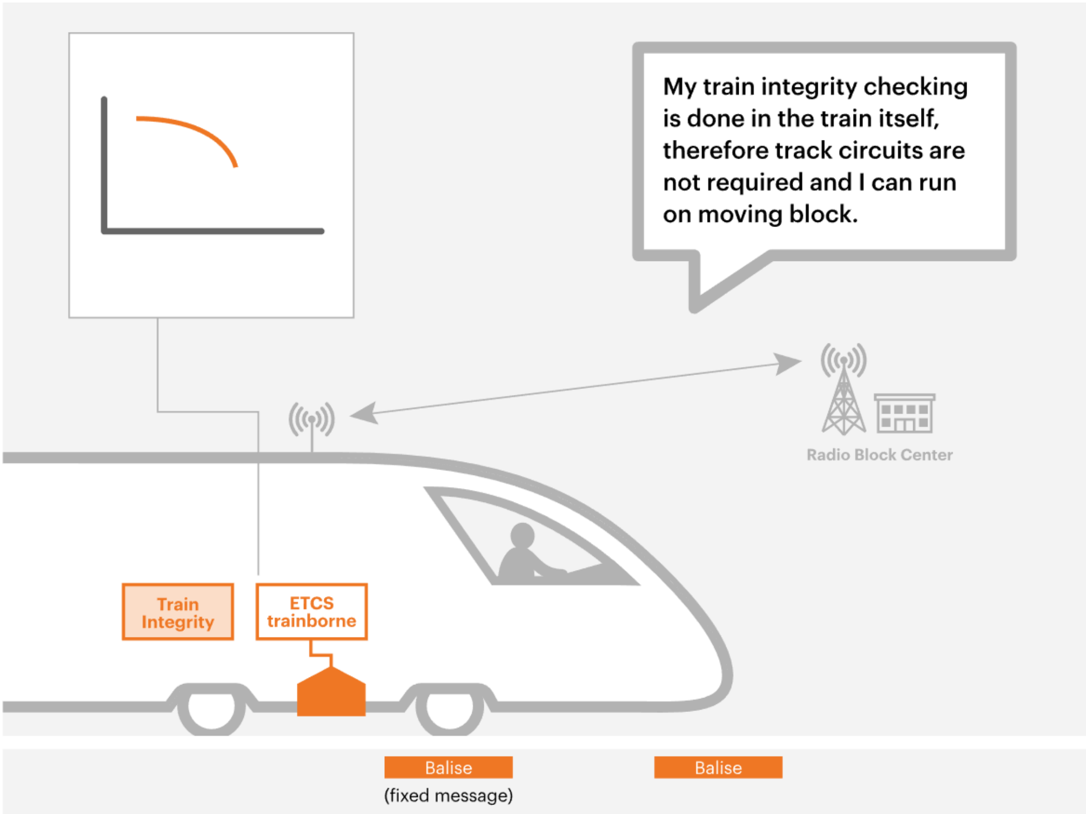


Figure 8: ETCS Level 3 (UNIFE, 2022)

2.2.2.3 Safe Distance Rule – Braking Principle

With the use of moving blocks and other complementary advanced systems, trains have started to move closer to each other. The trains can follow each other just as far away as the distance demarcated by the braking capability and safety margins. In the railway context, the train in front is considered as a fixed obstacle so the minimum distance is determined by calculating the rear train's braking capability. This is called the *full braking* or *absolute braking* (AB) distance principle based on the assumption that the leading one of two consecutive trains can stop instantaneously i.e., a 'concrete block' scenario (RSSB, 2016). However, the following reasons have triggered the consideration of an alternative approach:

- The adhesion between wheel and rail is not as high as the friction between tyre and road on motorways. The braking distance can increase by up to several kilometres on high-speed lines (Mitchell, 2016).
- Additionally, the AB assumption is conservative in terms of considering the front train that is moving at a speed as a fixed obstacle, thereby assuming that the first train can

stop suddenly without going further even though it had speed just a moment ago (RSSB, 2016).

Alternatively, the *relative braking* (RB) principle has a different perspective that reduces the braking distance by considering the speed and location of the front train. Although a few studies discussed RB a long time ago (Ning, 1998), it has started to be articulated in relation to VC discussions. The principle can allow measurement of the distance it will take the front train to slow down to a standstill. The AB distance of the following train is partly occupied by the front train under the RB principle. Since the current principle, AB, was structured in around 1870 (RSSB, 2016), it would be a breakthrough to implement RB in railway operations which requires a strong change in the solid safety consensus. Figure 9 illustrates both principles in one diagram.

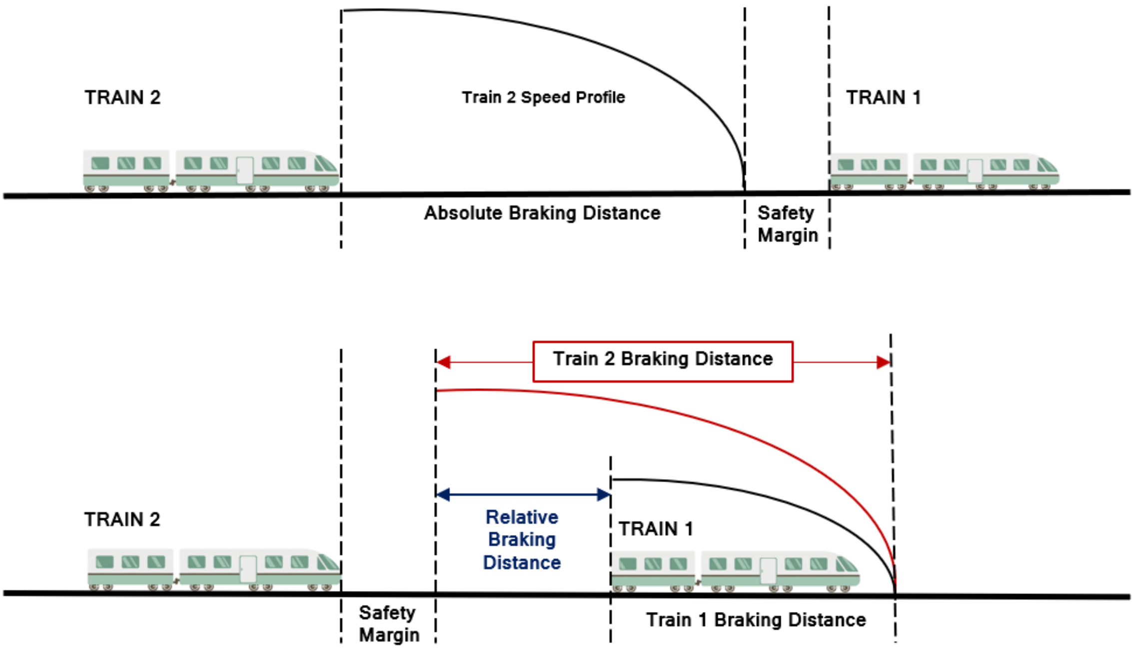


Figure 9: Comparison of Absolute Braking Distance (top) with Relative Braking Distance (bottom)

2.3 Automotive Technologies

The automotive industry has been implementing advanced automation technologies and strongly supporting research on their development. These are useful to the rail sector in the sense that knowledge transfer between the two domains could be fruitful for furthering the technological development of VC. Two automotive technologies related to the VC context deserve mention here:

2.3.1 Autonomous Cars

The term 'autonomous vehicle' refers to a vehicle that has been fitted with a system that enables it to sense its surroundings and navigate on its own without the assistance of a human. Inputs from numerous systems, such as radar, lidar, GPS, odometers and cameras are used by the vehicles to create a map of their surroundings and choose an appropriate course of travel (RSSB, 2016). The term 'autonomous' has the meaning of 'self-governing', implying that the vehicle itself is in control of driving. However, the term is controversial since there are various automation levels and few of them would correspond to that meaning in a real sense (SAE International, 2021). SAE International has classified driving automation systems (DAS) into six levels and revises the definitions periodically. Table 2 shows a summary of the latest version updated in 2021.

Table 3: Summary of levels of driving automation

Level	Name	Definition
0	No Driving Automation	All driving tasks are undertaken by a human driver.
1	Driver Assistance	One driving task – steering, lateral motion, or accelerating, longitudinal motion – is executed by DAS. Cruise control qualifies as Level 1.
2	Partial Driving Automation	Both lateral and longitudinal motion is executed by DAS; along with that, the human driver supervises vehicle motion and is ready to take control of the vehicle.
3	Conditional Driving Automation	All driving tasks are executed by the Automated Driving System (ADS) with environmental detection capabilities. The human driver must be

		ready to take control once the system issues an intervention request.
4	High Driving Automation	All driving tasks are executed by ADS without any human intervention requests. The automation is conditioned to specific environments. The human driver can override ADS.
5	Full Driving Automation	All driving tasks are executed by ADS without any specification for operational environment. The vehicle does not have a steering wheel or acceleration/braking pedals.

Rail vehicles do not need lateral motion control thanks to the single degree of freedom. It can be considered as one of the reasons why automated driving operations has a longer history of use in the rail domain as well as one of the reasons why sensing technologies have been developed to a larger extent in the automotive domain. Knowledge transfer from the automotive industry can help increase the use of novel sensors specifically for monitoring the distance between two trains.

2.3.2 Platooning or Convoying

Vehicle platooning is a process where a collection of vehicles travel together in a coordinated formation (Bergenhem *et al.*, 2012). The platooning concept may vary among different projects. This is because each project uses different technological solutions following the project's strategy and goals. The major differences that affect the concept implications can be summarised in two points:

- the platoon leader is fully automated or manually driven.
- lateral control is included in the automated driving of the platoon followers or not i.e., only longitudinal control is included.

Platooning has been trialled in some projects such as SARTRE, a European project which demonstrated a platoon comprising a lead truck and 4 following vehicles. The project findings showed that platooning technology has the potential to bring some important benefits such as decreasing congestion, improved capacity, improved journey times and improved fuel efficiency (RSSB, 2016).

V2V enables collaboration among vehicles that is a must for platooning operations. The lead vehicle can directly transmit data, including any movement commands, to the following vehicles via V2V. In SARTRE, the ITS-G5 system, a 5.9 GHz band licensed by the European Telecommunications Standards Institute, was used for the wireless communication (Bergenhem, Hedin and Skarin, 2012). This system uses IEEE 802.11p which is an amendment to the famous 802.11 standard to add Wireless Access Environments. ITS-G5 has a short range of approximately 300 m in areas surrounded by high buildings. To increase the coverage, there are ongoing studies such as those developing heterogenous architecture that uses cellular networks like 4G or 5G with ITS-G5 (CAR2CAR Communication Consortium, 2022).

Another important system enabling platooning is Cooperative Adaptive Cruise Control (CACC), a longitudinal control system that has emerged as the extent of Driver Assistant Systems in the automotive industry has increased (Qi Sun, 2016). The system originated from Cruise Control (CC) that allows velocity to be maintained at a specific value. Whilst CC is applied, the driver does not use the accelerator pedal and focuses only on the steering. CC is switched off automatically when the driver presses the brake pedal. After CC, Adaptive Cruise Control (ACC) was developed. ACC works in a similar way to the CC system, if there is not another vehicle in front of the vehicle. Otherwise, ACC utilises numerous sensors to calculate the distance and the relative velocity to the front vehicle. A vehicle operating on ACC adjusts its speed and acceleration to follow the front vehicle safely by controlling the brake and throttle. However, ACC is not sufficiently successful to provide string stability, especially when the number of vehicles in the platoon increases. A platoon has string stability only if disturbances propagated from the leading vehicle are attenuated to the tail of the platoon (Qi Sun, 2016) . Thus, CACC has been developed to provide string stability in a platoon via V2V communication. V2V communication enables information about the speed and location of the front vehicle to be shared, thus increasing efficiency and safety in the platoon.

2.4 Summary

This chapter has introduced the technological background that can enable VC technology in the future. In the rail domain, ETCS and CBTC technologies have been proved to implementation level. These modern systems that use radio communication and moving-block technologies have reached a maturity level that could be furthered for realising VC by the transfer of technology and knowledge from the automotive domain. Platooning and autonomous car concepts have been demonstrated at some level. Also, some protocols and standards have been developed for V2V technology. These await to be addressed from a rail-specific approach. After describing the background, the next chapter will review the studies on VC in the literature.

Chapter 3 Understanding of VC: From Literature Review to Conceptualisation

This chapter aims to produce a VC system concept by reviewing published studies in the literature and the project deliverables related to VC. Section 1 explains findings through an overlooking perspective in order to capture a holistic picture of VC. Section 2 develops a terminology of VC and the operational concept. In Section 2, the terminology draws on the findings of LR, and the relevant references are given by producing the terminology.

3.1 A Panoramic Literature Review

The section explores the studies on VC through reviewing research outputs to give a panorama of the concept. Thus, academic papers were reviewed to obtain an overview of VC and extract the research themes. Most of the papers are about designing controllers using different methods and techniques. Thus, these papers were reviewed to understand the challenges in developing controllers. However, the technical details in the context of controller design were not taken into consideration since they are out of the PhD scope. In addition to these findings from the literature, deliverables of the relevant projects were added to the sources.

3.1.1 Demand for VC and its future

In X2Rail-3 and MovingRail projects, supported by EU Shift2Rail, VC has been researched as part of their objectives. Approaches to VC has been different in a such way that MovingRail analysed VC as a next level of ETCS Level 3 but X2Rail-3 explored VC from a technology-independent viewpoint (X2Rail-3, 2021). In MovingRail, Aoun et al. (2021) assessed the impact of railway signalling innovations using the Delphi method. They compared ETCS Level 3 with moving blocks to VC from the perspective of multiple criteria including quantitative ones such as costs, capacity, etc. and qualitative ones such as safety and regulatory approval for different market segments including high-speed, mainline, regional, urban and freight corridors. The results showed that VC outperforms moving blocks. However, the technological maturity and potential safety concerns are considered as challenging barriers to the implementation of VC. In a later study, Aoun et al. (2023) proposed a method for forecasting the deployment of VC considering the outputs of SWOT and multi-criteria analysis conducted to assess the above-mentioned different market segment needs of VC and ETCS L3. Gap analysis between current and future states of operational, technological and business domains was explored. Further actions and their time plan were laid out for the VC implementation. As per the results, the deployment of VC for each market segment could be completed by 2050 in both optimistic and pessimistic scenarios except for the mainline segment in the pessimistic scenario which could be completed slightly later than 2050. In X2Rail-3 D6.1, VC is explained at the conceptual system level with its potential applications and operational scenarios. The operational scenarios are described textually, thus their performance measurement is not analysed (X2Rail-3, 2020).

3.1.2 Capacity enhancement

As mentioned in the introduction, VC operations are anticipated to reduce headway time between trains, thereby increasing line capacity. The capacity enhancement needs to be analysed and compared against conventional signalling and train control systems. Quaglietta et al. (2020) developed a train-following model including operational states such as coupling, decoupling and coupled running for the VC signalling and compared the VC capacity performance with that of other signalling systems: ETCS levels and fixed-block signalling in a case study. VC can deliver better capacity performance with 77% and 43% shorter headways when compared to ETCS Level 2 and Level 3, respectively. Schumann (2017) evaluated a VC scenario on the Shinkansen line from Tokyo to Osaka through timetable analysis. They found that the infrastructure components including stopping patterns, platform length and track layout impact VC performance. The result showed that the seating capacity is increased from 15,000 to 23,000.

3.1.3 Operational Flexibility

Some studies analyse VC from a different viewpoint in a such way that VC can provide operational flexibility in terms of changing the number of carriages in an efficient way or splitting a long train into smaller units. Gallo et al. (2020) proposed managing the number of carriages in train convoys dynamically by making it possible for the trains to leave or pick up new carriages at stations. Some trains are parked in the siding area of specific stations to join the convoy. The paper's aim was to arrange operational flexibility in meeting dynamic passenger demand by applying mathematical programming. Similarly, Qianqian and Hongwei (2019) developed a leader-follower control mechanism applying the artificial potential field theory for VC in order to cope with unbalanced passenger flow in rush hour over Beijing Subway Batong Line. The study showed that VC can contribute to resource allocation by reducing waste of capacity caused by the tidal characteristics of passenger flow. Thus, the service quality is enhanced by VC. Chen et al. (2022) suggested an integrated train scheduling method with a coupling strategy that determines whether a train should be part of a VC convoy or not. Train scheduling includes selecting the operation level, departure time and arrival time. A multi-objective optimisation was conducted to optimise the train re-scheduling under perturbations, the number of stranded passengers and the energy consumption. Additionally, Wang et al. (2020) suggested a method for calculating carrying capacity for flexible train formations, analysing technical details of multiple formations and variable formations based on physical coupling and on VC. They found that variable formations based on VC have the lowest impact on carrying capacity while addressing the imbalance in the distribution of passenger flow through regional rail networks.

3.1.4 A Novel Train Control System

The most studies related to VC in the literature have considered the controller design for VC applying a lot of different control methods and approaches. Xun *et al.* (2022) conducted a survey on these control methods and approaches.

The train control system is one of the challenging parts that carries a high priority in the implementation plan (Aoun, Quaglietta and Goverde, 2023). The challenges originate from the following major reasons:

The low-level adhesion makes trains have a longer braking distance, especially in high-speed ranges due to the nature of the wheel–rail interface (Liu *et al.*, 2021; Stickel *et al.*, 2022). This is different from the situation on motorways where the friction between tyres and the ground is so much higher that the braking distance is shorter and the relative braking distance with high braking capability does not produce as many safety problems. In contrast, the migration to relative braking from full braking carries a lot of safety concerns in the rail domain.

The nonlinear and time-varying elements in safe distance calculation are another challenge that motorways do not share. The automation in a motorway scenario can apply a constant-time or constant-distance spacing policy which makes the controller design easier. In the railway case, the safe distance is nonlinear, i.e., it depends on the braking capability of two successive trains. Su et al. (2023) designed a control scheme for VC with heterogenous braking capability based on a relative braking separation/spacing principle whereas constant gap- and time-based policies are common in other studies (Felez, Kim and Borrelli, 2019; Liu *et al.*, 2021). The paper analysed the impact of heterogenous braking dynamics capability on string stability in the frequency domain by using Laplacian transformation. The braking capability changes throughout the journey, being affected by the actual speed, actual adhesion, gradient, curvature, etc.; thereby, the safe distance changes regularly. Felez et al. (2022) developed a decentralised Robust Model Predictive Control (MPC) controller by introducing two uncertainties in train positioning and adhesion loss that changes the braking capability, whereas the nominal MPC controllers do not address uncertainties. Robustness is required when dynamic disturbance or error has a large impact on behaviour controller.

String stability is one of the focus points in convoying in car platooning and VC. The decentralised controllers look to control only two successive trains, providing local stability by attenuating and recovering from disturbances created by the leading train (Su *et al.*, 2023). In case of any disturbance or uncertainty, the controller keeps two trains in their virtually coupled state. However, if considering more than two trains in convoy, you need to develop a centralised controller that ensures string stability by guaranteeing that any disturbance gradually dissipates while propagating through the string (Su *et al.*, 2023). Liu et al. (2021) proposed an analytical optimal linear feedback control method for both local and string stability under variant manoeuvres of high-speed rail operations. Mathematical proof for string stability considering both homogenous and heterogenous convoy formation was conducted. Local stability was proved by eigenvalue analysis; a sufficient condition for string stability was derived by the frequency-domain method. Numerical simulations were conducted to prove stabilities on the rail section.

Replacing a physical coupler with a virtual connection is not straightforward. A physical coupler keeps two carriages or wagons together by balancing a lot of unseen in-train mechanical forces. In other words, the rail vehicles have mechanical push-pull forces throughout the convoy. All of these must be balanced virtually. This point also indicates a must for developing a digital twin to achieve realistic simulation results for VC operations. Previous studies have modelled trains as mass points so the simulation results with this simple model cannot bring about realistic results. There are a few studies focusing on this gap. Wu et al. (2022) developed a simulation method including inter-vehicle actions whereas other studies model trainsets as a single mass. Their paper presented high-fidelity models in which train dynamics were remodelled with more realistic vehicle dynamics including nonlinearities caused by in-train forces. The simulation method enabled better validation of the VC control algorithm. Also, vehicle dynamics were solved via a parallel computing technique: each vehicle assigned to another computer. Wang et al. (2022) proposed a semi-physical and semi-simulation testing scheme by designing a cloud-based platform to carry a simulated testing environment as an alternative to on-site testing by which it is challenging to discover the defects and hidden dangers of VC systems.

3.1.5 Safety and anti-collision

VC will enable trains to run closer to each other, but this may come at a cost to safety. In particular, changing the braking principle is an important controversial upgrade and against the common understanding of minimum distance calculation in which the train in front is considered as a fixed obstacle. There is an inevitable need for strong research and technical discussions on the safety side of VC. Hao et al. (2020) approached VC from the viewpoint of a relatively new safety method, so-called Systems Theoretic Process Analysis (STPA). Their paper suggested an STPA method, which utilises control theory to treat accidents as a control problem, helping to understand complex processes underlying the system in order to assist decision-making in safety design of the VC system, whereas traditional safety analysis methods cannot do this since they treat accidents as a failure problem as if only originated from chain of events. In a similar study, Kim et al. (2019) applied two different safety approaches—a novel process model e.g., STPA and a traditional model e.g., Event Tree Analysis—to the relative braking principle considering the obstacle collision scenario. Other studies in the literature mostly focus on the anti-collision design of the train control system without applying safety methods and techniques such as Fault Tree Analysis, Failure Modes Effects and Criticality Analysis, Common Safety Method for Risk Assessment, etc.—see Barnatt and Jack (2018) for more details.

Xun et al. (2020) studied two aspects of the overspeed protection mechanism by calculating the limit speed for trains in convoy and safely controlling trains in the convoy when overspeed happens. An algorithm was proposed to calculate speed limit differences considering the relative braking performance of the follower to the leading train. Xun et al. (2020) proposed a collision mitigation approach that minimises the relative kinetic energy by adopting MPC. The performance of MPC was compared with that of adaptive cruise control and directly maximum braking control. MPC was found to be the best at reducing the relative kinetic energy in the scenarios including emergency braking for heterogenous and homogenous fleets. A similar but more complex study was conducted by Su et al. (2022) who designed a collision-avoidance control methodology applying reinforcement methodology. It was found that ensuring the safety, the minimum distance between the successive trains was reduced by 70.23% on average.

Zhang (2015) proposed a formal definition for safety analysis of VC based on a topological modelling method. It enabled the modelling of many different control processes for switch control and train order under the same mathematical framework, which means an integrated train control concept. General formalism was used for modelling the physical elements of train control systems on; safety analysis was conducted over the location of railway equipment in the topological view considering dynamic train parameters of speed and location. The topological view helps implement the VC logic in a mathematical format as a way of abstraction. Manifold-based protection logic was developed in order to include the dynamic behaviour of train movement rather than the discrete representation used in other works.

3.1.6 Discussion

In the literature, most of the studies have focused on the controller design for VC, with MPC controllers being the most popular choice. Additionally, safety and anti-collision discussions are mostly an extension of that in the controller context. Other discussions related to VC benefits and performance outcomes such as operational flexibility and capacity enhancement have approached it from a ‘ready-to-go’ perspective. However, the overall understanding of VC at conceptual and operational levels has not yet reached maturity. For example, it is still unclear what factors should be taken into consideration while creating an operational plan of VC, which is essential to comprehend the capabilities and limitations of VC.

Therefore, this study has analysed the major factors influencing VC capacity performance through modelling and simulation. Based on these findings, a generic evaluation framework has been developed to allow stakeholders to explore the potential benefits of VC implementation on specific rail lines. To validate the framework's applicability, this study applied it to a case study involving VC potential assessment through timetabling for VC operations. The systematic approach employed in the case study is demonstrated to explore the capabilities of VC operations.

3.2 Conceptualisation

This section deliberately takes a step back and remains at the conceptual level, providing an essential foundation for understanding VC with the development of explicit definitions, types, and terminology for VC from an operational perspective. While previous projects may have partially addressed these aspects, there is still no consensus, and the terminology introduced in this study offers a novel perspective.

3.2.1 A Semantic Induction: From Physical to Virtual

This section tries to define VC from a semantic perspective. VC is linguistically formed as the combination of two words: *virtual* and *coupling.* In the dictionary, coupling means an action of joining or combining two things (Oxford English Dictionary, 2022). From a general perspective, coupling requires an interaction between two objects. In railway terminology, coupling is a term used for joining two rail vehicles such as carriages or wagons physically (X2Rail-3, 2020; Nold and Corman, 2021). Mechanical couplers are used to build the physical connection of coupling. The couplers implement two main functions (X2Rail-3, 2020):

- The basic function is to keep the relative position stable between the coupled units by transferring push and pull forces.

- The second one is to transmit the information of braking and/or traction via wires or pipes between the coupled units in a coordinated way.

In this sense, VC has the meaning implying a kind of special interaction in which rail vehicles or trains interact with each other *virtually* rather than physically. The function of the virtual coupling interaction (VCI) is to fulfil two main functions of the mechanical coupler through a real-time collaboration among trains by transmitting the real-time data of vehicle dynamics such as speed, acceleration, location etc via reliable communication and sensing systems(Stickel *et al.*, 2022). VCI enables multiple trains to replicate each other's motion pattern in terms of velocity and acceleration/braking so that they move like a single train together. In other words, considering a convoy of trains, once the train in front accelerates or brakes, the follower(s) make the same change while on the move, which is enabled by VCI. The question of how the virtual interaction can be established is more dependent on different technological topologies such Vehicle-to-Vehicle Communication (V2V), Vehicle-to-Infrastructure-to-Vehicle Communication and different technology standards such as 5G, ITS-G5 etc. (Unterhuber, Lehner and de Ponte Müller, 2016; Homay *et al.*, 2017; Gomez *et al.*, 2018; He *et al.*, 2018).

Another term that deserves mention is "auto-coupling," which refers to the physical coupling of two train carriages automatically. Auto-coupling is achievable when trains are in a standstill position. However, VC (virtual coupling) can be defined as a form of auto-coupling in extreme cases: when trains can automatically couple while in motion, with zero distance between them.

It is worth noting that the term Closer Running (CR) can be seen as associated with VC, especially in the UK context (Mitchell, 2016; Kim *et al.*, 2019). However, CR should be differentiated from VC in the sense that it is an umbrella term having the meaning of any upgrades, development or advances in order to operate trains in a closer form than existing applications. With this meaning, the term includes Virtual Coupling and more so that it deserves to be freed from being demarcated only to the VC context. Figure 10 indicates the relation of CR to VC.

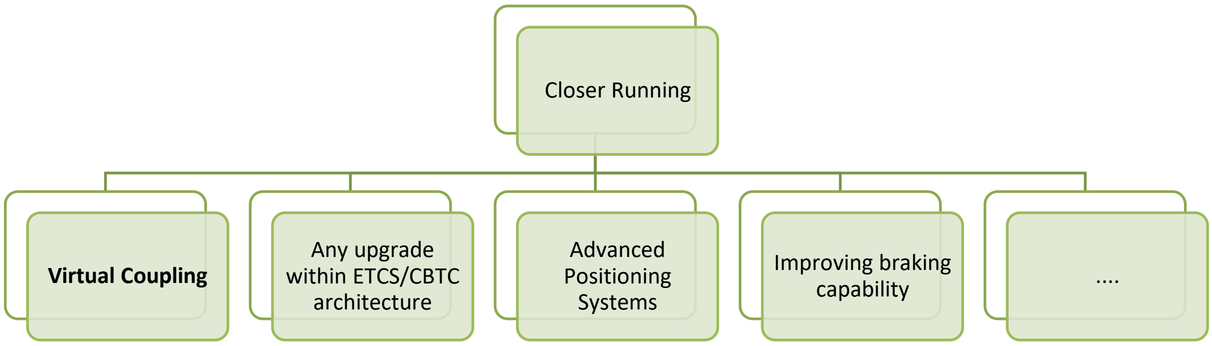


Figure 10: 'Closer running' meaning includes VC but is not peculiar to only the VC context.

3.2.2 A Formal Definition

Giving the semantic background, the term VC is defined as follows:

"*Virtual Coupling is a railway operation with a special kind of interaction that enables two or more trains to represent the same or very similar move patterns to such an extent that they move together as a single unit, or they behave as two units of the same train*."

To clarify meaning of the definition, the other terms related to VC are explained in Table 4. Trains can perform a VC operation via the special functionality *Virtual Interlocking (VI)* that sustains the same movement pattern among *Virtually Coupled Trains*. A convoy of Virtually Coupled Trains forms *Virtual Consist.* VI has two types: the primary-secondary one in which preceding train follows leading one via unidirectional communication and the multi-agent one in which trains decide on movement in collaboration via bidirectional communication.

Table 4: Glossary of Virtual Coupling terminology

Term	**Definition**

Decoupled	Railway vehicles with cut or lost *virtual interlocking* in *virtual coupling* operation for any reason.
Non-virtually coupled	Trains do not have *virtual interlocking* between each other.
Rail operating unit	A vehicle used for carrying passengers or goods on the rail track. e.g., carriage, wagon.
Train	A consist of one or more *rail operating unit*s.
Virtual Consist	A convoy of two or more *virtually coupled train*s having *virtual interlocking* among each other.
Virtual Coupling	A railway operation of two or more trains to form a *virtual consist* via *virtual interlocking*.
Virtual Interlocking	An interaction of rail vehicles or trains peculiar to *virtual coupling* operation in which they are engaged with each other and replicate the same movement patterns. It has two types: - Primary-secondary: master train leads follower one(s) via unidirectional communication. - Multi-agent: two or more trains decide on movement in collaboration via bidirectional communication.
Virtually Coupled Trains	Trains interact via *virtual interlocking.*

The formal definition developed by this study has distinguishing features from the ones existing in the literature: VC was defined mostly from a technology-based perspective or, less commonly, a generic transport aspect. In the former case, VC brings some add-ons to the existing systems. For instance, Aoun et al. (2020; 2021; 2023) defined the VC concept as an upgrade of ETCS L3 with additional V2V and RB-enabling technologies. In the latter case, Nold (2021) defined VC from a more general transport perspective, i.e., not considering rail-focused systems, as an intermediate step moving from manual mechanical coupling to dynamic automatic coupling. Although X2Rail-3 Project (2020) approached VC from a more operational perspective, some aspects taken in this study differentiate it: In the project, the system definition was made only in the master-slave form neglecting the multi-agent one. Secondly, VI is not considered between rail operating units but only between trains, thereby ignoring some scenarios enabled by that.

3.2.3 Classification

VC can be divided into two types depending on the minimum safety distance. The absolute or full braking principle is so solid a safety topic among railway stakeholders that changing the safety principle would be a breakthrough. As a migration strategy, a VC system deserves to be defined and developed with full braking principle at the outset—even though all studies in the literature define it with only relative one. Thus, it is a good point from which two types of VC can be defined. This differentiation can make it easier to understand the impacts of changing a safety principle and to observe outcomes separately within the VC context.

Another viewpoint is the convoy formation. Railway transport has several vehicle types such as carriage, wagon and multiple units. They are generally called trains. However, once we try to decide on what the transport unit is in railway transport, the answer becomes tricky. A complete train can be regarded as transport unit but so can a carriage or a multiple unit. Furthermore, if the old-fashioned slip coach operations are taken into consideration, this point makes more sense: a slip coach was a carriage attached at the end of a train by a special form of physical coupling, which could be easily uncoupled around the station and stopped by only braking (Acworth, 1900). Slip coach operation, which existed between 1858 and 1960 in Britain and Ireland ('Slip coach', 2021), enabled a carriage to be split from a train and stopped at a station without stopping the whole train. That should be in consideration within the VC context as a novel modern operation style, which is aligned with studies in literature discussed in 3.1.3. Operational Flexibility. Ultimately, from the convoy formation aspect, VC can be divided into two more types, intra-consist and inter-consist.

Figure 11 shows the VC classification from the two aspects discussed above.

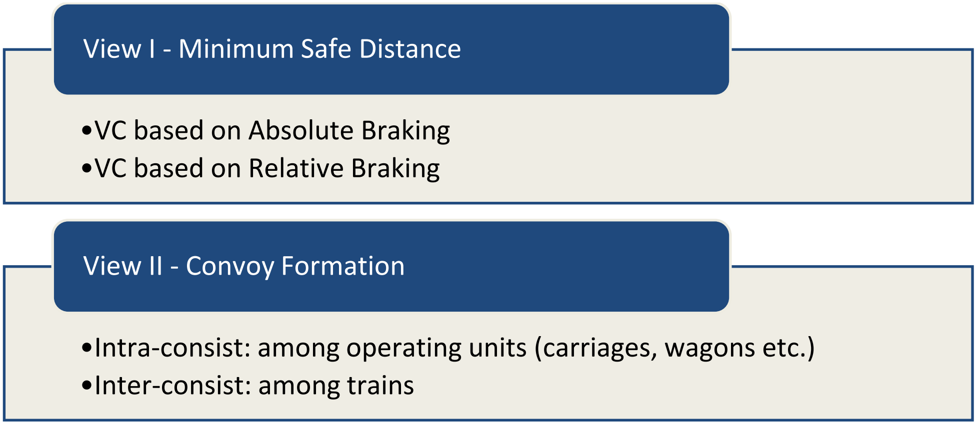


Figure 11: VC classification

Following the definitions, the classification can be better understood by an example of two trains with three carriages as shown in Figure 12. The trains can be virtually coupled to each other in four formations by virtually coupling them directly as an instance of *inter-convoy* formation or splitting them into smaller trains as instances of *intra-convoy* formation.

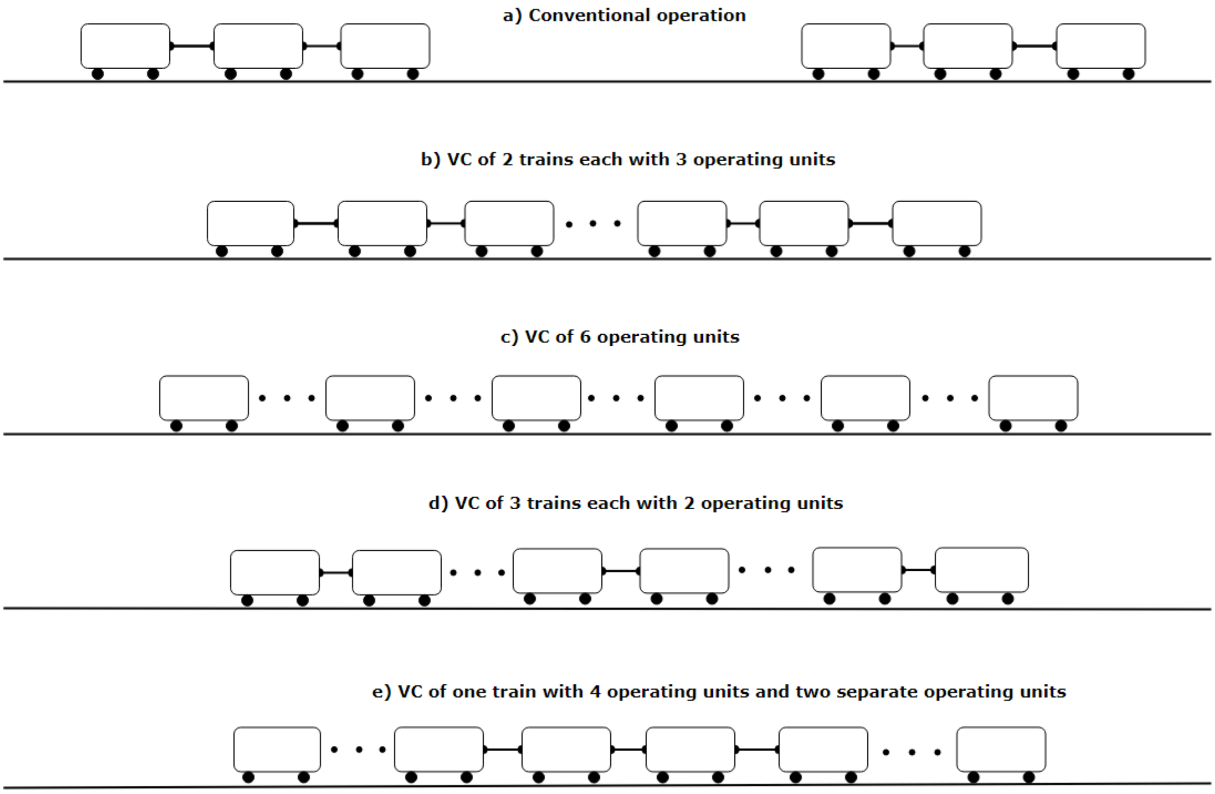


Figure 12: Different VC formations of two trains. Each train has three carriages a) conventional operation, VC operation of 2 trains b) without splitting them into sub-trains, c) split into six sub-trains, d) split into three sub-trains with even number of carriages, e) split into three sub-trains with uneven number of carriages.

3.2.4 Operational Scenarios

VC can run on rail lines with many types of Operational Scenarios (OS). These OS depend on when coupling and uncoupling happens. The simplest one is coupling trains at a standstill and keeping the VC interaction until they stop. When the trains need to be separated intentionally in order to move through different routes, the trains stop virtual interlocking before the diverging junction. There may be unintentional uncoupling due to some errors like communication failure, but these cases do not form an operational scenario because there is not a planned action. Also, the front train coming from a previous station can slow down towards a new station without stopping, then the second train can catch on and be engaged with it. In other scenarios, trains can get into the virtually coupled mode whilst moving. In this case, the front train may need to slow down, and/or the rear train may need to accelerate. This coupling process can be started on a plain line or around a converging junction. Also, the trains can decouple as in the previous cases intentionally or unintentionally after they are coupled with each other. Table 5 summarises the cases discussed here:

Table 5: Virtual Coupling basic operational scenarios

ID	Operational scenario	Suitable track layout type	Coupling point	Uncoupling point
OS1	Coupling at standstill/station and keeping it	Plain line	Station	N/A
OS2	Coupling at standstill/station and uncoupling in motion	Diverging line	Station	Prior to junction
OS3	Coupling in motion and keeping it	Converging line	After junction	N/A
OS4	Coupling in motion and uncoupling in motion	Line with both converging and diverging aspects	After junction	Prior to junction

3.2.5 Summary

By building upon the findings from the literature review, this chapter has completed the conceptualisation of VC with the following steps in each section successively: discussing VC from a semantic perspective, defining VC more technically and systematically along with its own terminology, classifying VC into different types from two views: safe distance and convoy formation, and lastly, providing operational scenarios. The next chapter will explain the tools and techniques required to model train motions and run simulations for VC operations which are necessary to implement this study's evaluation plan.

Chapter 4 Modelling and Simulation

This chapter gives an explanation of the mathematical modelling and simulation techniques required for observing VC operations. Section 1 and 2 explains the simulation structure as well as the mathematical models of vehicle dynamics, train motion modes and braking principles. Sections 3 and 4 cover the driving strategy with the optimisation technique and controller design for the train following model, respectively.

4.1 Mathematical Model

This section explains the details of modelling train motions, which includes longitudinal dynamics, train motion modes, braking distances.

4.1.1 Longitudinal Vehicle Dynamics

Longitudinal vehicle dynamics is mathematically modelled by Zhao (2013) as follows:

$$M_{eff}a = F_T - F_R - F_{grad} \qquad \textit{Eq. 1}$$

$$M_{eff} = M(1+\lambda) \qquad \textit{Eq. 2}$$

$$F_R = A + Bv + Cv^2 \qquad \textit{Eq. 3}$$

$$F_{grad=}M_{eff}\, g \sin\theta \qquad \textit{Eq. 4}$$

where M_{eff} is the effective mass that carries the impact of rotational inertia on the vehicle mass, F_T is the traction force of the vehicle, F_R is the resistance force that is formulated with the Davis equation (7c), F_{grad} is the force exerted by gradient, M is the vehicle mass, λ is the rotary allowance that is usually less than 0.2 depending on the vehicle type (Steimel, 2007), A, B and C are the Davis constant parameters that depend on the vehicle design (Rochard and Schmid, 2000), g is gravity and θ is the slope angle.

The maximum tractive effort is confined by the normal force exerted from wheel to rail and adhesion, the friction coefficient between rail and wheel, μ, as well as the proportion of powered axles, ρ:

$$F_{Tmax} = \rho M\, g\, \mu \qquad \textit{Eq. 5}$$

where g is the gravity rate. Following the tractive effort constraint, the maximum acceleration can be expressed as follows:

$$a_{max} = \frac{F_{Tmax}}{M_{eff}} \qquad \textit{Eq. 6}$$

The formula is important to explore impact of change in adhesion upon capacity performance in Section 5.2.2.4.

In addition to the forward tractive effort, backward braking effort is required to slow down train. The braking effort is modelled with a constant braking rate as follows:

$$F_B = M_{eff}\, b \qquad \textit{Eq. 7}$$

where b is the constant braking rate and F_B is the braking effort.

4.1.2 Train Motion Modes

A typical train has four motion modes throughout its journey: motoring, cruising, coasting, and braking (Zhao *et al.*, 2017). In this study, coasting mode is ignored as it is not relevant to the scope. Figure 13 indicates three modes, which are explained as follows:

- Motoring/acceleration: Train accelerates by applying tractive effort.
- Cruising: Train keeps the same velocity by applying a small amount of tractive effort to offset the force exerted by gradient and rolling resistance.
- Braking: Train applies backward braking effort to slow down train.

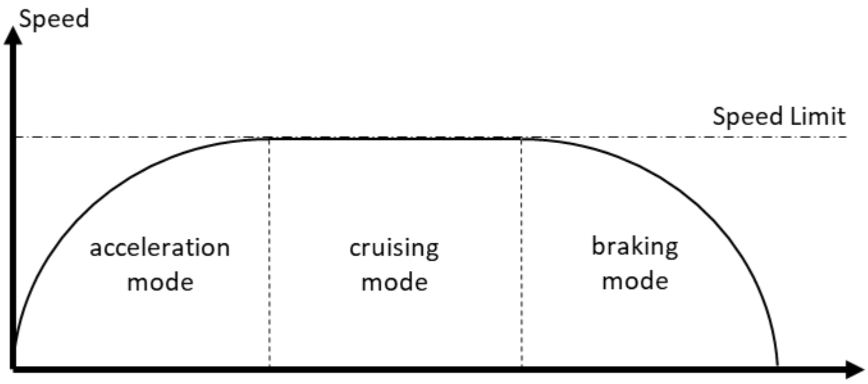


Figure 13: Train motion modes

The mathematical expressions of these modes can be seen in Table 6.

Table 6: Motion mode equations

Modes	**Mathematical Expressions**
Motoring	$a > 0, \quad a = \frac{(F_T - F_R - F_{grad})}{Meff}$
Cruising	$a = 0\,, \quad (F_T - F_R - F_{grad}) = 0$
Braking	$a < 0, \quad a = \frac{(-F_B - F_R - F_{grad})}{Meff}$

4.1.3 Energy consumption

The train consumes energy over the course of its journey. Energy consumption is calculated as follows:

$$\mathrm{E} = \int_0^T P(t)\,dt \qquad \textit{Eq. 8}$$

T is journey time and $P(t)$ is train power. The power equation is shown as follows:

$$P(t) \;\; = F_T(t)v(t) \qquad \textit{Eq. 9}$$

When the power formula is inserted into Eq. 8, energy consumption is calculated with the following equation:

$$\mathrm{E} \;\; = \int_0^T F_T(t)v(t)\, dt \qquad \textit{Eq. 10}$$

4.1.4 Braking Distance and Calculations

The braking principle is a critical factor in calculating the minimum distance between two trains. We have two principles:

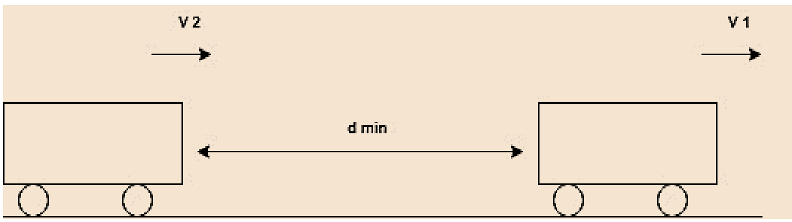


Figure 14: The minimum distance (d_{min}) between the trains is affected by train velocities (V_1 and V_2) and braking principle.

4.1.4.1 Absolute Braking (AB)

The first train is considered as a fixed obstacle. Then, the minimum distance equals the follower train's full braking distance.

$$d_{min} = \frac{V_2^2}{2b_2} + SM \qquad \textit{Eq. 11}$$

where d_{min} is the minimum distance, V_2 is the follower train's speed, b_2 is the follower train's braking rate and SM is the safety margin. SM includes all system delays (onboard systems and communication latency) and is calculated as:

$$SM = V_2 T_{delay} \qquad \textit{Eq. 12}$$

where T_{delay} is the total system delay.

4.1.4.2 Relative Braking (RB)

The first train is not considered as a fixed obstacle. When calculating the minimum distance, the first train's speed becomes an input into the equation:

$$d_{min} = \frac{V_2^2}{2b_2} - \frac{V_1^2}{2b_1} + SM \qquad \textit{Eq. 13}$$

where d_{min} is the minimum distance, V_2 is the follower train's speed, V_1 is the leading train's speed, b_2 is the second train's braking rate, b_1 is the first train's braking rate and SM is the safety margin. As intuitively understood, d_{min} can depend only on SM in the VC operation, in which $v_2 = v_1$ and $b_2 = b_1$, if the trains are sufficiently homogenous. That result suggests we should focus more on the SM analysis.

4.1.4.3 Safety Margin (SM)

In the literature, SM has been calculated by taking into account the maximum operational speed on the line (Durmus *et al.*, 2013; European Railway Agency, 2016). In that case, SM becomes conservative when calculated as if the train always operates at the maximum speed throughout the whole journey. However, since it would be possible to transfer instantaneous data between trains via V2V communication during VC operations, additional capacity can be gained by calculating the SM over actual speeds rather than at maximum operational speeds.

Table 7 shows the SM elements and their values. Constant SM and Dynamic SM equations are given in (5) and (6).

4.1.4.3.1 Constant SM

Conventionally, SM is calculated as a constant value considering the maximum operational speed.

$$SM_{constant} = (v_{max} + \Delta v).T_{delay} + \Delta s \qquad \textit{Eq. 14}$$

where v_{max} is maximum operational speed, Δv is the inaccuracy of speed measurement, T_{delay} is the total system delays and Δs is the location inaccuracy.

4.1.4.3.2 Dynamic SM

It is suggested that SM should be calculated as a dynamic speed-dependent value for VC operations.

$$SM_{dynamic} = (v_{ins} + \Delta v).T_{delay} + \Delta s \qquad \textit{Eq. 15}$$

where v_{ins} is the instantaneous speed, Δv is the inaccuracy of speed measurement, T_{delay} is the total system delays and Δs is the location inaccuracy. A difference between dynamic one and constant SM occurs in acceleration and braking modes. In cruising mode, there is not any difference between them as the train reaches operational speed limit.

SM elements and their values are shown in Table 7.

Table 7: Safety Margin elements and values.

SM Element Names	Variable	Values
Brake build-up time		2.5sec
Onboard system reaction time		1sec
Communication latency		1sec
Total delays	$\boldsymbol{T_{delay}}$	**5.5sec**
Speed measurement inaccuracy	$\Delta\boldsymbol{v}$	**2.5%**
Location inaccuracy	$\Delta\boldsymbol{s}$	**5%**

4.2 Multi-train Simulator

In this thesis, train movements are simulated utilising the Multi-train Simulator (MTS) which was built in BCRRE. MTS simulates multiple trains via time-based discrete modelling through specific route data with different stopping patterns. The simulator gives outputs for distance–time, velocity–time and velocity–distance diagrams for each train. MTS is useful for analysing line capacity and observing the impact of different signalling systems. Figure 15 shows the input-process-output (IPO) diagram of MTS. The simulator produces line timetable with necessary graphs using train and tack data along with operational information. The driving style affects each train's motion depending on whether the optimisation is applied. Train control/signalling systems control rail traffic intensity and line capacity. The conventional signalling systems were ready in the simulator (Zhao *et al.*, 2017). In order to enable VC operations in this study's scope, a new train control/signalling type of VC is developed and embedded into MTS designing a controller to make trains follow each other. The controller design is explained in 4.4.

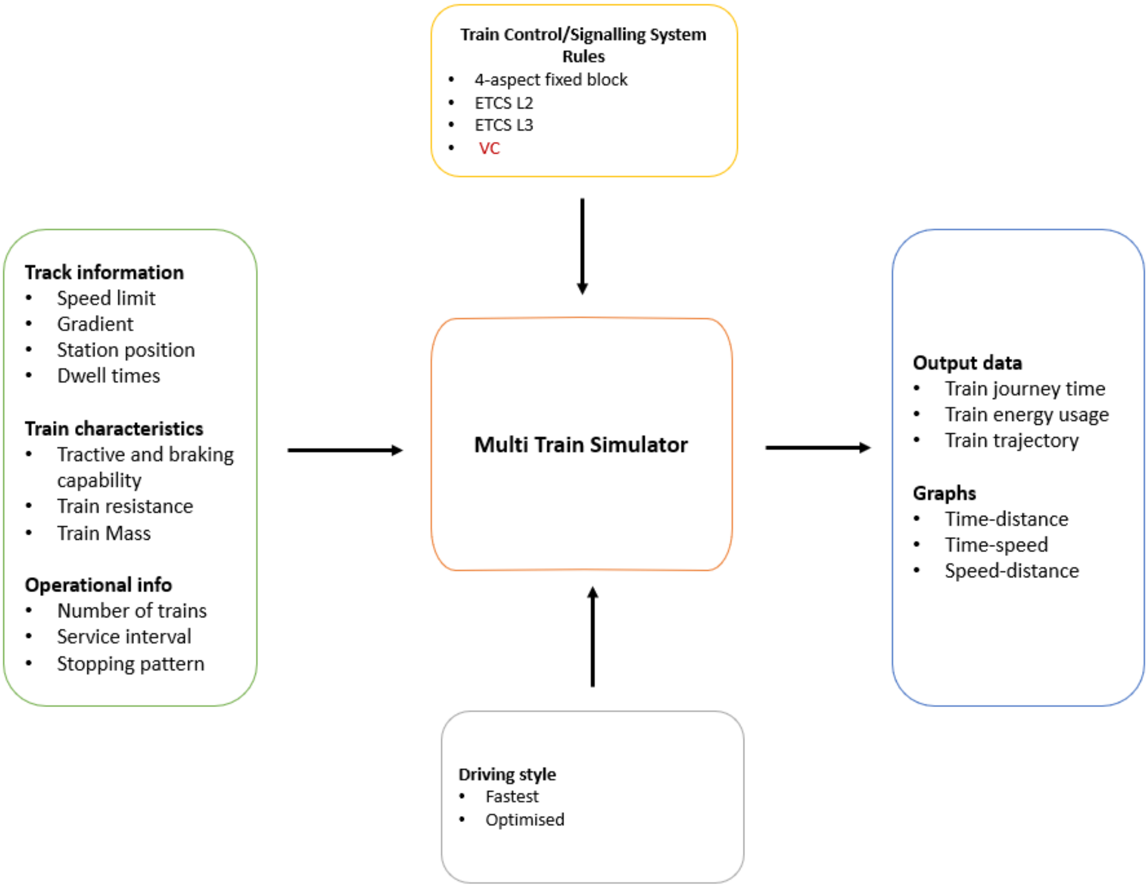


Figure 15: MTS IPO diagram

The simulator runs each train's movement separately by completing the first train's motion from initial stop to last one, then, starting the next one. The mechanism for the first one is illustrated with the flowchart as shown in Figure 16. The data from input files, including train position, speed limit, gradient, station location, and dwell time at each station, are imported by the simulator. MTS determines the speed limit and gradient for the current position at each time-step and calculates power and energy consumption at the end of each iteration. Once the train arrives at the last station, the process is complete.

The simulator selects the necessary mode to run the train from initial position to final destination. *Choose mode* action works through the following principles:

- The train is accelerated by motoring mode until the train reaches the maximum line speed.

- Once the speed limit is reached, MTS switches to cruising mode and the train keeps its speed.
- While approaching a station or a line section with a lower line speed limit, MTS activates the braking mode in order to bring the train to a complete stop at the station or to slow the train down to the lower speed limit.
- MTS calculates power and energy consumption at the end of each iteration. Once the train arrives at the last station, the process is complete.

The follower train must be running at a specific distance from the first train that is determined by the train control/signalling system. The movement authorities, or permission to proceed, are calculated at each step. The distance to the train in front that the following train is allowed to travel is specified by the movement authority. As seen in Figure 17, the train determines the distance to LMA at each time step and compares its value to the braking distance. If the train position is closer than the point determined by LMA, the train is decelerated to keep the train in a safe separation. In this circumstance, the simulator records this event as an *ATP activation* or *interference* between two successive trains. To measure the maximum capacity that a train control/signalling system allows, the service interval between two consecutive trains is determined with the minimum value that does not lead any interference between them. After the simulator completes the run process for each train, all data are saved in the appropriate arrays, and different graphical outputs are produced.

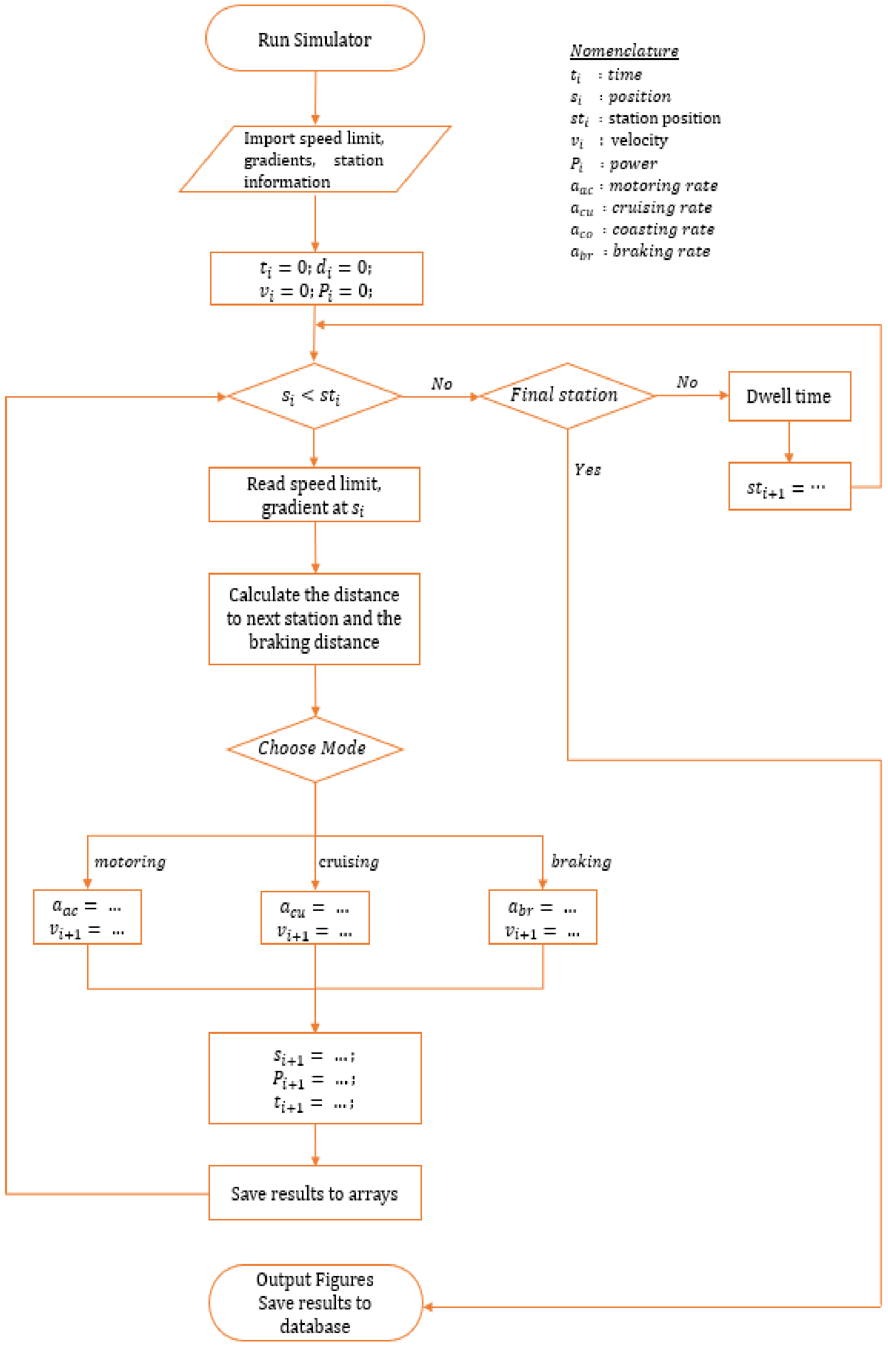


Figure 16: Flow chart of the first train in MTS

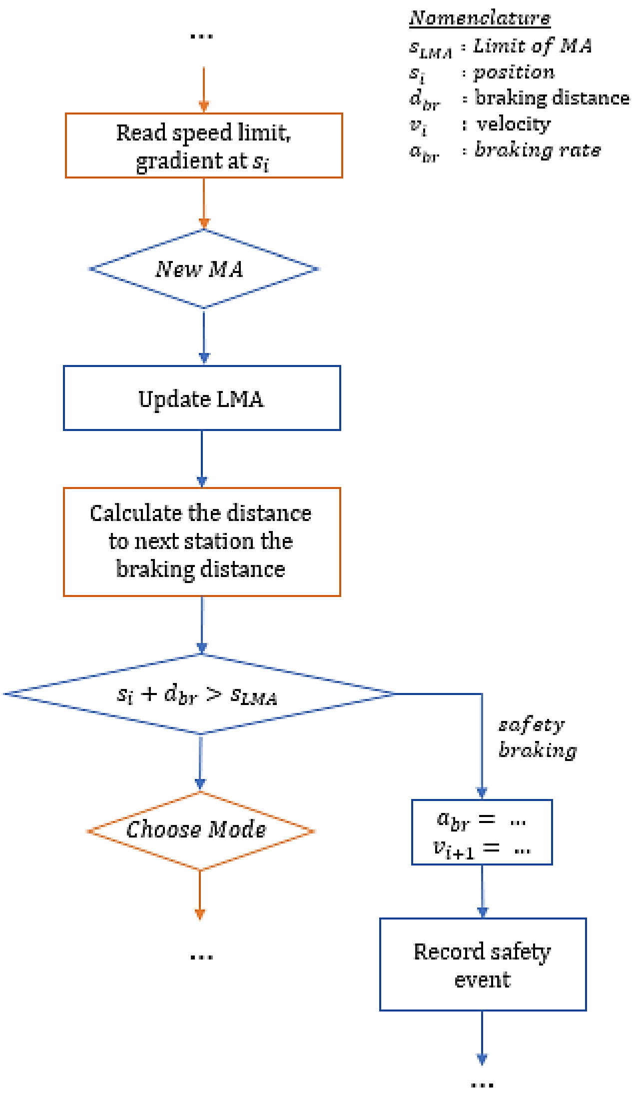


Figure 17: Flowchart of the following train in MTS. The blue boxes are additional to the previous flowchart.

4.3 Driving Strategy

A driving strategy enables us to set optimised speed levels and tractive effort, i.e., forward acceleration, during train journeys in order to reduce energy consumption at the cost of increased journey time. Therein lies a trade-off between energy consumption and journey time. Two levels of driving strategy can be considered:

(i) Fastest Driving: Minimising journey time regardless of energy consumption

(ii) Optimised Driving: Conducting a balanced driving style, spending less energy than (i).

The optimisation problem for energy-time trade-off can be formulated as multi-objective by the following expression:

$$min \;\; J = W_1 \, E_{run} + W_2 \, T_{run} \qquad \textit{Eq. 16}$$

where $\mathrm{E_{run}}$, $\mathrm{T_{run}}$, W_1 and W_2 are energy consumption, total journey time and their weighting coefficients, respectively. However, $\mathrm{T_{run}}$ can be defined as a constraint to a single objective function for minimising energy consumption rather than solving the multi-objective function defined above. Stating journey time as a constraint is more suitable since trains are allowed to complete their services in a time interval. With this approach, $\mathrm{E_{run}}$ and $\mathrm{T_{run}}$ can be calculated by the following formulation (Din *et al.*, 2021):

$$E_{run} = f(a, V_t) \; if \;\; T_{min} < T_{run} < T_{max} \qquad \textit{Eq. 17}$$

$$T_{run} = g(a, V_t) \qquad \textit{Eq. 18}$$

where T_{min} and T_{max} are the maximum and minimum scheduled journey times, and V_t is a series of target speeds that limits the peak value of speed profile for each inter-station section. Figure 18 shows the optimisation process:

- The algorithm changes the target speeds by lowering speed limits and then, give them as inputs to the simulator.
- The simulator is run, and the output values of journey time and energy consumption are fed into the algorithm.
- The algorithm checks the values to compare them with previous results.
- The algorithm repeats the process until finding optimum speed targets.
- When the output values are not changed significantly, the algorithm terminates the process.

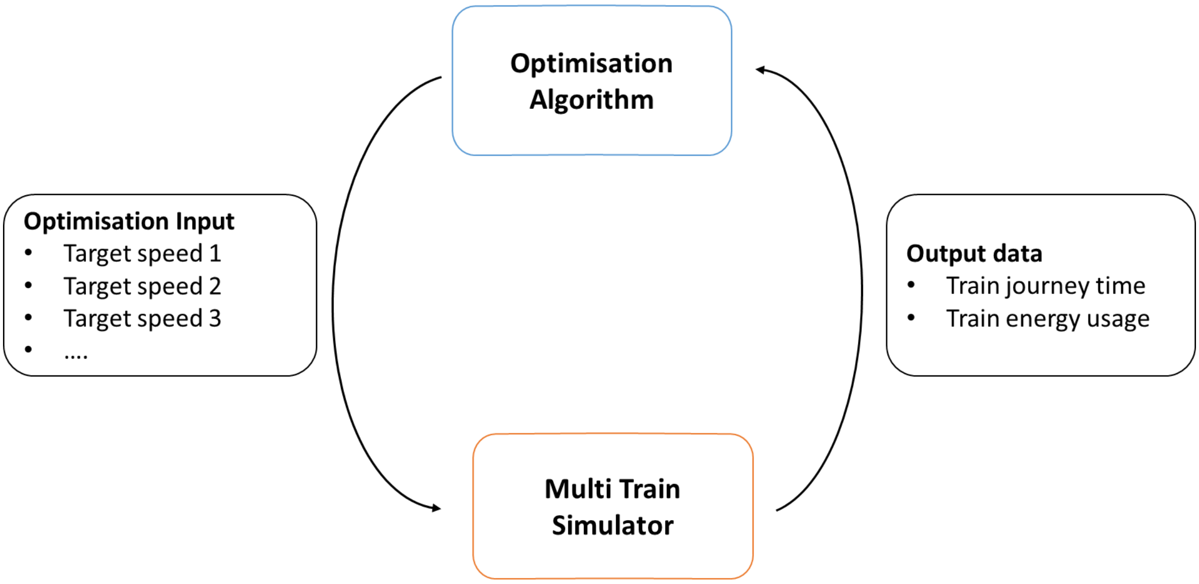


Figure 18: Optimisation Process

In order to optimise speed profile with the process seen in Figure 18, different algorithms have been used in the literature: some researchers applied algorithms to solve the optimisation problem such as brute force, genetic, ant colony and dynamic programming. Genetic algorithms have been proved as an efficient method of finding trajectory optimisation (Söylemez and Açıkbaş, 2008; Zhao, 2013). Following the discussions in the literature, in this study, a genetic algorithm (GA) has been applied to solve the optimisation problem. GA is explained in the next subsection.

4.3.1 Genetic Algorithm (GA)

GA is one of the population methods in which an optimisation problem is solved with a collection of design points, called individuals (Kochenderfer and Wheeler, 2019). A great variety of individuals are spread across the design space in order not to converge into a local minimum. It has a stochastic nature by which information sharing between different points is conducted to find a globally optimum point. GA received inspiration from the theory of evolution in biology. An individual's fitness value has the greatest impact on its passing over to the next generations. Each individual has a chromosome that represents the design point identified by the individual. In each generation, the chromosomes of the fitter individuals give birth to the next generation by going through some genetic operations such as crossover, mutation and selection.

The GA steps conducted for trajectory optimisation are as follows (Zhao, 2013):

I. Initialisation: the GA initiates the optimisation process by randomly generating an initial population of solutions. A solution or an individual is defined as the targets of maximum speed and coasting speed for each interstation section. The population in each generation represents a series of speed targets.
II. All speed targets are fed into MTS in order to find the fittest individuals in the populations, i.e., the best target speed series in terms of minimising energy consumption and journey time per interstation section.
III. Selection: Selection is the process of deciding which chromosomes are to be used as parents for generating the next population. There are different selection methods. *Truncation selection* is preferred here, in which each individual carries a value of the objective function and a specific value of individuals having minimum values are selected.
IV. Crossover: The top-ranked individuals are matched in pairs to be parents that give birth to new individuals of the next generation. Each parent has two genomes, so crossover is the process in which one of these genomes is randomly selected to carry the parent genome over to the new individual.
V. Mutation: During crossover, genome selection is implemented by taking one of the parent genomes. In mutation, new genes are injected into the chromosome by making the algorithm explore more of the state space.
VI. Termination: The algorithm runs the optimal search until two stopping conditions are satisfied. The program stops if
    a. the cumulative change in the fitness function is smaller than the tolerance value, or

b. the maximum number of generations is reached.

The process is represented in Figure 19. The fitness function is the objective function defined earlier.

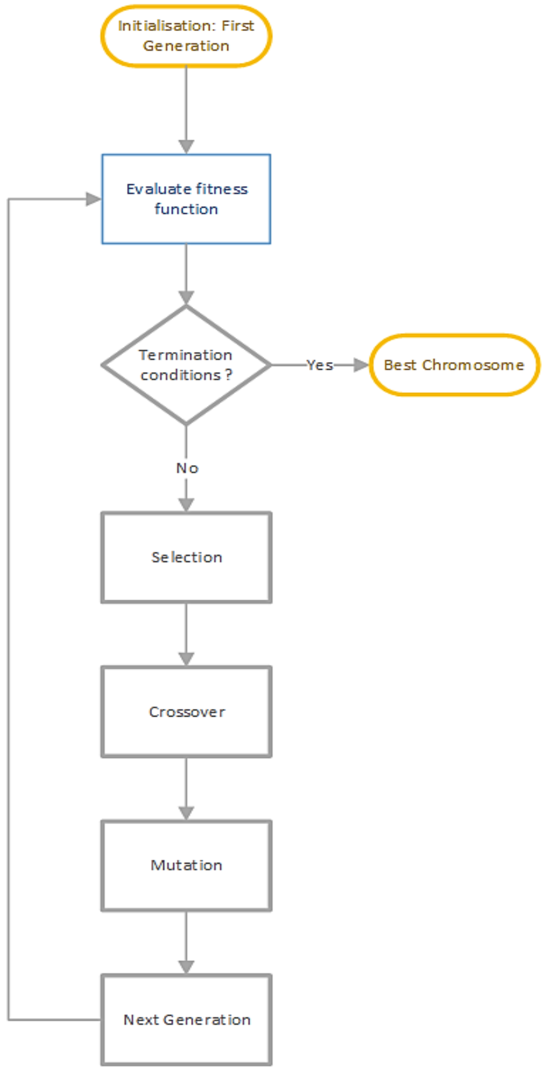


Figure 19: Genetic Algorithm flow chart

4.4 Controller Design for Train Following

To enable following behaviour between two trains, a controller was built. In the literature, controller design is based on different approaches such as adaptive PID, neural networks, fuzzy control, and Model Predictive Control (MPC). MPC has better performance than conventional PID control (Salem and Mosaad, 2015; Felez, Kim and Borrelli, 2019). In this study, MPC is preferred. MPC has the ability to predict the plant's behaviour in the future by following an online optimisation process (Orukpe, 2012). The optimisation maximises performance under specific constraints. It was designed in MATLAB/Simulink with the characteristics explained in the following subsections.

4.4.1 Model Predictive Control (MPC)

MPC solves an optimum control problem over a receding horizon within system boundaries and constraints to choose the subsequent control action. At each subsequent timestep, this optimisation is repeated, and the control rule is updated. The receding horizon control problem determines the optimal sequence of control inputs over the control horizon by minimising a cost function, defined by the controller goals, over the prediction horizon. Only the first optimal control value is executed at each time step. At each timestep, the same process, optimisation and applying the first value, is reiterated.

4.4.2 Control Problem Goals

Control design has two major aims:

- To converge the intervehicle distance following error to zero:

$$\Delta d \rightarrow 0 \qquad \textit{Eq. 19}$$

$$\Delta d = d - d_r \qquad \textit{Eq. 20}$$

$$d = s_1 - s_2 - l \qquad \textit{Eq. 21}$$

where d is the actual separation between two trains, d_r is the desired distance, s_1 is the first train's location, s_2 is the second train's location and l is the train length.

- To converge the speed following error to zero:

$$\Delta v \rightarrow 0 \qquad \textit{Eq. 22}$$

$$\Delta v = v_2 - v_1 \qquad \textit{Eq. 23}$$

where v_2 is the follower train's speed and v_1 is the leader train's speed.

4.4.3 State-Space Model

The train's longitudinal dynamics are mathematically nonlinear due to the resistance force and gradient effect. Consequently, the complexity of control design increases with this nonlinearity. However, thanks to the MPC Controller, which predicts how the controller's input will affect the train's future steps through discrete modelling within a specific horizon, the nonlinear factors—resistance and gradient—can be incorporated into a linear system model as measured disturbances since these factors are known (Bemporad, Ricker and Morari, 2023, pp. 1–3). In other words, the train's motion dynamics can be formulated as a linear state-space model, but with the addition of disturance inputs from resistance force and gradient at each step. This is established with the following equations:

$$\begin{cases} \dot{x} = Ax + Bu + B_d z \\ y = Cx \end{cases} \qquad \textit{Eq. 24}$$

The state variables of the plant are defined as $x = [x_1 \quad x_2]^T \in \mathbb{R}^2$ with $x_1 = v_2, x_2 = s_2$ and $x_2 = s_2$ where s_2, v_2 are, in order, the distance, speed of the follower train. The input and the output of the plant are, respectively, $u = F_T$ and $y = [y_1 \quad y_2]^T \in \mathbb{R}^2$ with $y_1 = v_2$ and $y_2 = s_2$. The measurable disturbance is $z = F_R + F_{grad}$.

The discretised model with T_s as the sampling rate is designed as:

$$\left\{ \begin{matrix} \mathrm{x}(k+1) = \mathrm{A}\mathrm{x}(k) + \mathrm{B}\mathrm{u}(k) + \mathrm{B_d}\mathrm{z}(k) \\ \mathrm{y}(k) = \mathrm{C}\mathrm{x}(k) \end{matrix} \right\} \qquad \textit{Eq. 25}$$

The model matrices are as follows:

$$\mathrm{A} = \begin{bmatrix} 1 & 0 \\ T_s & 1 \end{bmatrix} \in R^{2x2},\ \ \mathrm{B} = \begin{bmatrix} T_s/M_{eff} \\ 0 \end{bmatrix} \in R^{2x1},\ \mathrm{C} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}\ \in R^{2x2},$$

$$\mathrm{B_d} = [-T_s/M_{eff} \quad 0]^T \in R^{2x1}.$$

4.4.4 Prediction Equation

The prediction model enables one to predict a future state from the current measured system state, input and output. This is supported by the observability principle in control theory. Let the prediction horizon be p and the controller horizon be m, and $X(k)$ and $Y(k)$ are prediction sequences of the system state and output within prediction horizon $[k+1{:}\, k+p]$. Let $U(k)$ be the system input sequence, i.e., the controller output sequence, within prediction horizon $[k{:}\, k+m-1]$. Since $m \leq p$, the system input is held constant for the remaining prediction horizon steps from $k+m$ through $k+p-1$ such that $u(k+p-m|k) = u(k+p-m-1|k) = \cdots = u(k+m|k)$.

$x(k+i|k)$ is the i^{th} estimated step of state vector at step k. The estimation values of the system state can be calculated through the following iterations:

$$\begin{cases} x(k+1|k) = Ax(k) + Bu(k) + B_d z(k) \\ x(k+2|k) = A^2x(k) + ABu(k) + Bu(k+1) + AB_d z(k) \\ \vdots \\ \mathrm{x}(k+p|k) = A^p\mathrm{x}(k) + A^{p-1}\mathrm{Bu}(k) + A^{p-2}\mathrm{Bu}(k+1) + \\ \qquad\qquad + \mathrm{Bu}(p-1) + A^{p-1}B_d\mathrm{z}(k) \end{cases} \qquad \textit{Eq. 26}$$

The prediction sequences for the system output can be expressed as follows:

$$X(k) = [x(k+1|k)\, x(k+2|k)\ \cdots\ x(k+p|k)]^T \qquad \textit{Eq. 27}$$

$$U(k) = [u(k+1|k)\, u(k+2|k)\ \cdots\ u(k+p|k)]^T \qquad \textit{Eq. 28}$$

$$Y(k) = [y(k+1|k)\, y(k+2|k)\ \cdots\ y(k+p|k)]^T \qquad \textit{Eq. 29}$$

The prediction model in matrix form can be summarised as follows:

$$X(k) = Fx(k) + GU(k) \qquad \textit{Eq. 30}$$

$$Y(k) = Kx(k) + LU(k) \qquad \textit{Eq. 31}$$

where $F = [AA^2A^3 \cdots A^p]^T$, $\mathrm{G} = \begin{bmatrix} \mathrm{B} & 0 & 0 & \cdots & 0 \\ \mathrm{AB} & B & 0 & \cdots & 0 \\ A^2B & AB & B & \cdots & 0 \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ A^{p-1}B & A^{p-2}B & A^{p-2}B & \cdots & B \end{bmatrix}$, $\mathrm{K} = \begin{bmatrix} CA \\ CA^2 \\ \cdots \\ CA^p \end{bmatrix}$, and

$$\mathrm{H} = \begin{bmatrix} \mathrm{CB} & 0 & 0 & \cdots & 0 \\ \mathrm{CAB} & CB & 0 & \cdots & 0 \\ CA^2B & CAB & CB & \cdots & 0 \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ CA^{p-1}B & CA^{p-2}B & CA^{p-2}B & \cdots & CB \end{bmatrix}.$$

4.4.5 Optimisation Problem

MPC controller performance has a quadratic objective junction including inter-distance error and inter-velocity error:

$$\min J = \qquad \textit{Eq. 32}$$

$$\sum_{i=1}^{p} |\, W_1[d_r(k+i \mid k) - d_{act}(k+i \mid k)]|^2 + |W_2[v_1(k+i \mid k) - v_2(k+i \mid k)]|^2$$

where W_1 and W_2 are coefficients of the inter-distance and inter-velocity errors, respectively. The optimisation problem is solved via active-set method that is a bult-in algorithm in MATLAB MPC Toolbox (Bemporad, Ricker and Morari, 2023, pp. 1–17).

4.4.6 Constraints

The control parameters are subject to the following constraints:

- Rail vehicle capability:

$$a_{i\,min} \leq u_i(k) \leq a_{i\,max} \qquad \textit{Eq. 33}$$

$$j_{i\,min} \leq \Delta u_i(k) \leq j_{i\,max} \qquad \textit{Eq. 34}$$

$$j_i(k) = a_i(k) - a_i(k-1)/T_s \qquad \textit{Eq. 35}$$

where $a_{i\,min}$ is the maximum braking rate, $a_{i\,max}$ is the maximum braking rate, and $j_{i\,min}$ and $j_{i\,max}$ are the minimum and maximum jerk rates of the trains, respectively. These parameters are limited by the vehicle design and capability.

- Line speed limitation:

v_{line} is the maximum operational speed depending on the train's location. At each step k, the maximum allowable speed can change.

$$0 \leq v_i(k) \leq v_{line}(k) \qquad \textit{Eq. 36}$$

- Safety Distance:

For safety-critical issues, d cannot be less than d_{min} at any time during the journey. In order to keep the distance within safe bounds, the small number ε is defined as:

$$d_r = d_{min} + \varepsilon \qquad \textit{Eq. 37}$$

$$d \geq d_{min} + \varepsilon \qquad \textit{Eq. 38}$$

If the trains are closer than d_r, ATP is activated, and the follower train immediately stops.

4.5 Demonstration of embedding VC into MTS

This section shows the simulation results for the control design with optimised driving strategy in order to demonstrate that MTS can be utilised for VC operations. VC operations are the subject matter of the next chapter and are therefore simulated in the next chapter.

4.5.1 Results for Optimised Driving

This subsection indicates the simulation results for optimum driving. The train is simulated on a 17 km test track with four stations. The parameters are tabulated in Table 8. In the fastest driving strategy, the train is run without considering energy consumption. In the optimum driving strategy, the train is run by reducing energy consumption. For this, the maximum allowed journey times are put into the optimisation problem as the constraints: the train can increase the station arrival times up to a maximum of 45 seconds for each one. So, the train can reach the second station 45 seconds later, the third one 90 seconds later and the terminal one 135 seconds later.

Table 8: Parameters for comparing driving styles

Parameter	Notation	Value
Maximum acceleration rate	$a_{i\,max}$	0.8 m/s^2
Maximum braking rate	$a_{i\,\min}$	−0.675 m/s^2
Davis parameters	A B C	5.4215 0.069031 0.0103
Train mass	M	408 tonnes
Number of stations	-	4
Track length	-	17 km

Sample rate	T_s	1 sec
Dwell time	-	30 sec
Train length	l	220 m
GA population size	-	10
GA generation number	-	50
GA crossover fraction	-	0.7
GA function tolerance	-	0.01

The simulation results are shown in Figure 20. The diagrams indicate the time–distance, speed–time and distance–speed of the fastest and optimised driving strategies. The outputs of energy consumption and journey time are represented in Table 9. The results show that optimised driving leads to 15% less energy consumption with the cost of a 5% longer total journey time.

Table 9: Comparison of energy and journey times for fastest and optimum driving

Outputs	**Fastest Driving**	**Optimised Driving**
Speed targets (m/s)	As per line speed limit	[43.14, 55.20, 44.43]
Station arrival times (sec)	[266, 442, 599]	[297, 472, 629]
Energy consumption (kWh)	138.61	118.18

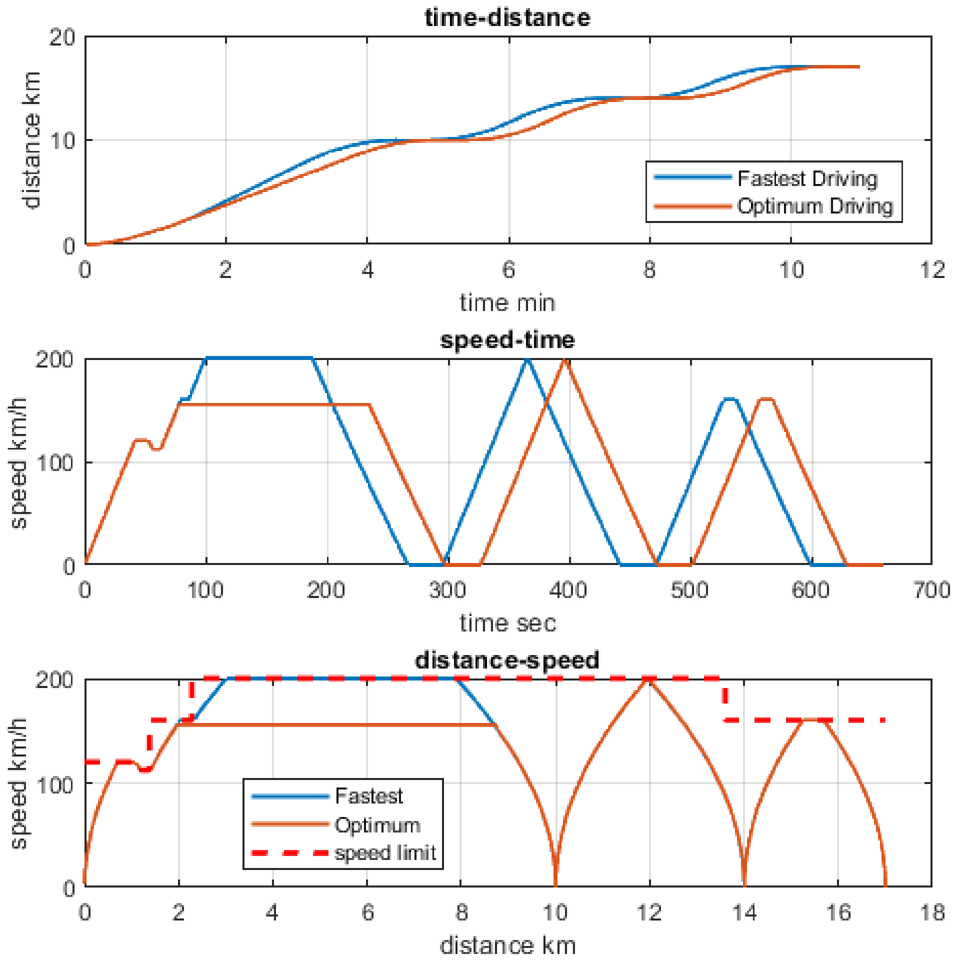


Figure 20: Comparison of the simulation results for the fastest and optimum driving

4.5.2 Results for Controller Design

This subsection indicates the simulation results for the controller design. The rail line is a generic track of 17 km with five stations. All parameters are given in Table 10. For the sake of simplicity here, the trains are modelled with constant acceleration and braking rates.

Table 10: Parameters for controller design

Parameter	Notation	Value
Maximum acceleration rate	$a_{i\,max}$	0.8 m/s^2
Maximum braking rate	$a_{i\,\min}$	−0.675 m/s^2

Davis parameters	A B C	5.4215 0.069031 0.0103
MPC distance error coefficient	W_1	0.5
MPC velocity error coefficient	W_2	0.5
Number of stations	-	4
Track length	-	17 km
Sample rate	T_s	0.2 sec
Dwell time	-	30 sec
Train length	l	220 m
Minimum spacing at stations	-	50 m
System delays	T_{delay}	5 sec

Figure 21 indicates the simulation results after completing the controller design. In this simulation, the second train follows the first train based upon the data of position and velocity. The results show that the designed controller can implement a successful train following model with a small range of velocity and spacing errors. The errors appear when the lead train is accelerating or decelerating. When the train runs at constant speed, the errors disappear.

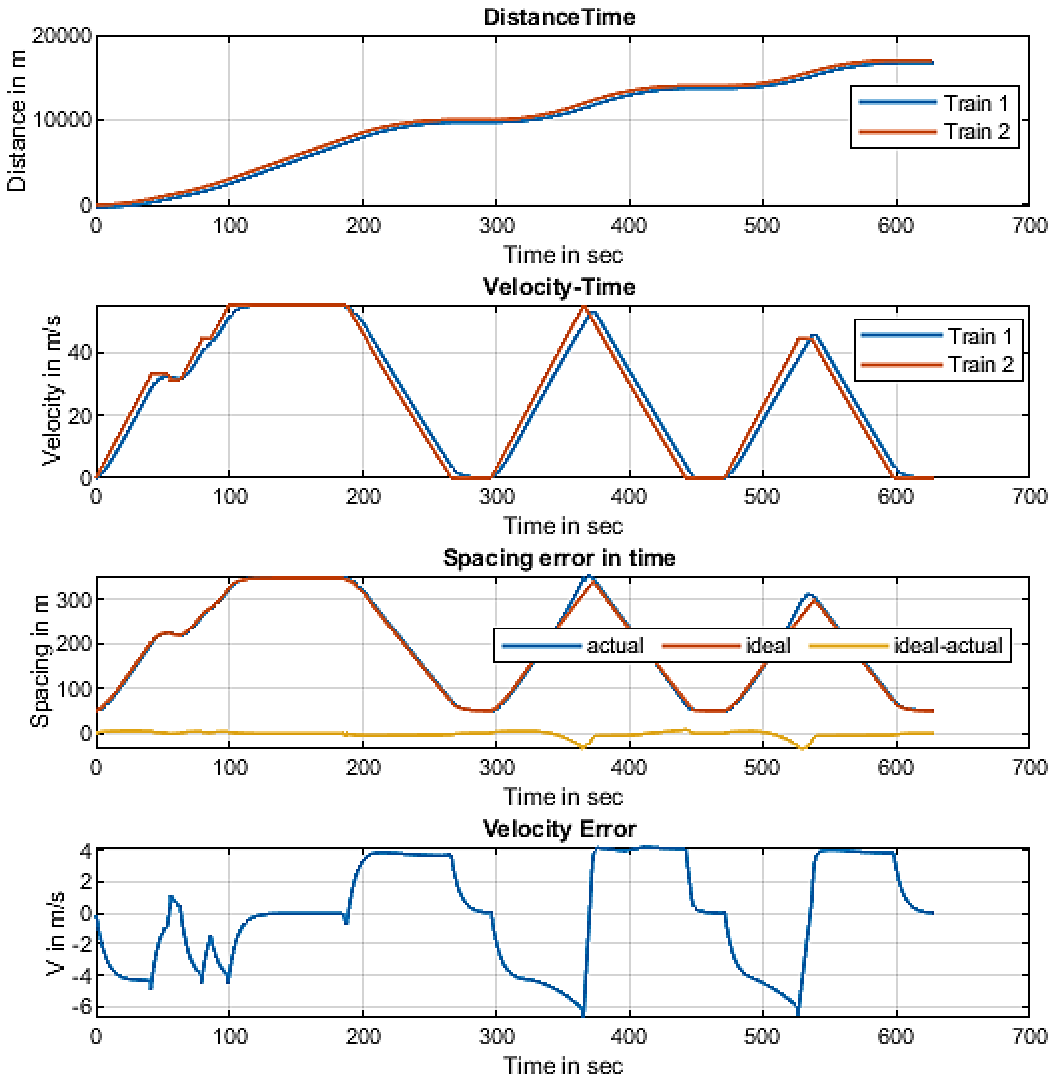


Figure 21: Controller design outputs, from top to bottom: a) distance–time; b) velocity–time; c) spacing between trains over time; d) velocity error over time

4.6 Summary

This chapter has introduced the mathematical modelling and simulation tools that enable observation of VC operations. These cover the simulation structure, including MTS, along with the driving strategy by optimisation with GA, and the controller design applying the MPC theory. After covering this technical foundation, the next chapter will run the simulations for the VC operations.

Chapter 5 Evaluation of VC Operations Performance

In this chapter, Section 1 performs simulations for the VC OSs defined in Chapter 4 through the simulation structure with the model and methods explained in Chapter 5. The simulations are conducted over the same rail line data for the different scenarios that include the inter-consist and intra-consist types by comparing the different braking principles to each other.

Section 2 aims to understand that what should be taken into account whilst making an operational plan for VC. The section explores the influencers that affect the VC operational performance. The factors are regarded under three major components of a railway operation: rolling stock, infrastructure, and signalling & control system. This section analyses how their different factors impact the capacity outcome by varying them over a range of typical values.

5.1 Simulation of VC Operations

In this section, the VC OSs were simulated over track data of the West Coast Main Line Section from Rugby to Birmingham International. The speed limitation and altitude profile of the line section are shown in Figure 22 and Figure 23. The line is length is 37km. As vehicle on the line section, Class 390/1 Pendolino is run. The train parameters are listed in Table 11. The tractive effort and resistive force curve are shown in Figure 24. The tractive effort represents the directional force of the train motor or engine at the wheels that varies depending on the train speed. The tractive effort diagram has two regions constant force and constant power region (Douglas et al., 2016):

- Horizontal/Constant Force region: This is the maximum effort limited by adhesion and friction force as per Eq. 5. More than this value makes train start slipping.
- Curve/Constant Power region: Train power limits the tractive effort as per the formula: $Tractive\ effort = {}^{Maximum\ power}/_{Speed}$. If speed increases, tractive effort decreases.

The resistive force curve created by using the Davis equation as given in Eq. 3.

Table 11: Train Parameters

Parameter	Value
Davis parameters (A, B, C)	5.4215, 0.069031, 0.0103
Maximum speed (km/h)	225
Tractive system efficiency	85%
Train length (m)	217.5
Maximum power (kW)	600
Train Mass (tonne)	592.8
Proportion of powered axles	50%
Seating capacity	469
Number of carriages per train	9

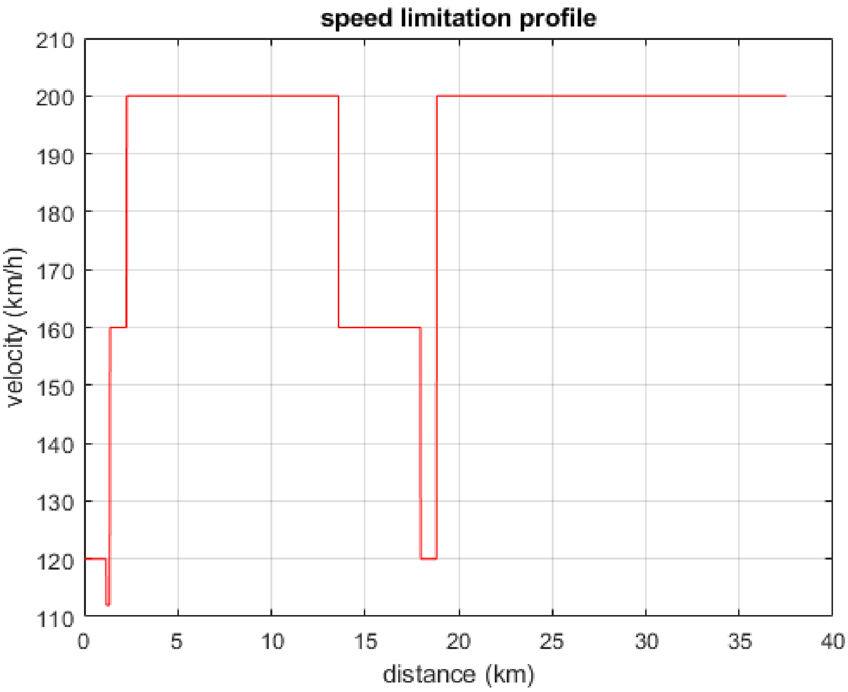


Figure 22: Speed limitation profile

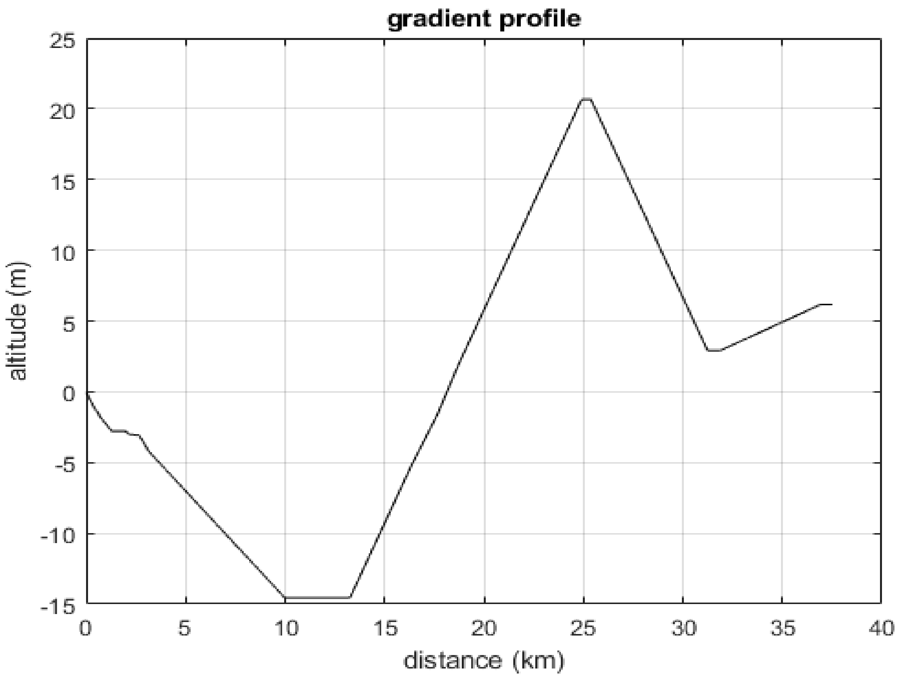


Figure 23: Gradient profile

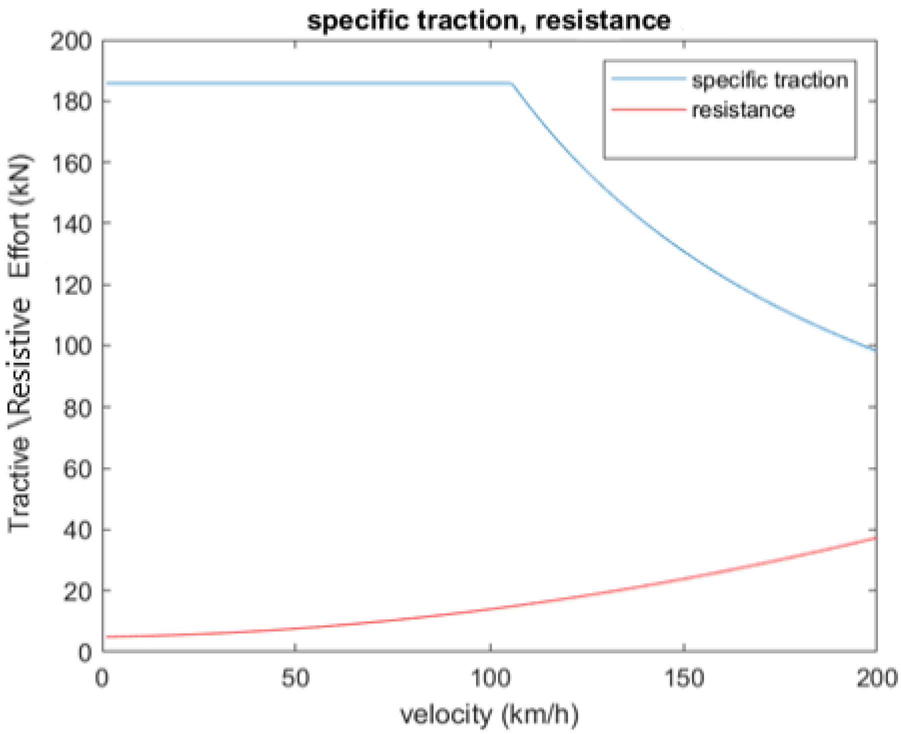


Figure 24:Train tractive effort and resistance

5.1.1 Simulation for VC types and OSs

As defined in Chapter 3, different VC types are defined through the following views:

- View I – Safety Rule: Two types of VC based on braking principle:
  - Absolute braking
  - Relative braking
- View II – Consist Formation: Other two types based on consist formation:
  - Between trains – *inter-consist*
  - Between single rail units – *intra-consist*

Table 12 shows VC OS. These scenarios will be simulated for VC View I and View II types.

Table 12: Virtual Coupling Operational Scenarios

ID	Operational Scenarios	Suitable track layout type	Coupling point	Uncoupling point
OS1	Coupling at standstill/station and keeping it	Plain Line	Station	N/A
OS2	Coupling at standstill/station and uncoupling in motion	Diverging line	Station	Prior to junction
OS3	Coupling in motion and keeping it	Converging line	After junction	N/A
OS4	Coupling in motion and uncoupling in motion	Line needs	N/A	N/A

5.1.2 Assumptions

The simulations were carried out based on the following assumptions:

i) The virtually coupled trains can start their journeys at the same platform. In this case, it is assumed that the platform can accommodate all the trains in the convoy.

The minimum platform length is calculated by considering the number of trains and the minimum distance between trains at stationary position.

ii) The optimised driving is not considered in this section. The trains, therefore, run at the fastest driving regardless of reducing the energy consumption.

iii) VI has two types as defined in Chapter 3: primary-secondary and multi-agent one. If there is not any explicit explanation, the simulations are based on the primary-secondary in which the lead train does not move in collaboration with the following one. Otherwise, it is explicitly stated.

Changing these assumptions can change the results. In Section 2, these assumptions are discussed by changing them to understand their effects on the VC performance, the same assumptions apply to the simulation plan.

Hourly capacity for a specific section is measured in relation to headway time between two consecutive trains (Abril *et al.*, 2008) as given in Eq. 39:

$$Capacity = \frac{3600}{Headway\ Time} \qquad \textit{Eq. 39}$$

Headway time is the time difference between two trains that pass over the same location consecutively. Line capacity is calculated with the maximum of all headway times which determines the weakest part of rail line(Abril *et al.*, 2008). This is because extra capacity generated algebraically by lowering headway time during journey cannot be used by additional trains straightforwardly. The number of trains (n) required to run train services with a specific capacity is calculated as given in Eq. 40(Hasegawa, 2014):

$$n \leq \frac{2(Journey\ time + Turnaround\ time)}{Headway\ Time}, n \in \mathbb{N} \qquad \textit{Eq. 40}$$

5.1.3 Simulation results

The section has two sub-parts: In Section 5.1.3.1, the results for the inter-consist operations are provided whereas in Section 5.1.3.1.2, the results for the intra-consist operations are provided.

5.1.3.1 Inter-consist VC Operations

The section shows the simulation results for the inter-consist operations for two braking principles separately, that is, relative and absolute one: Section 5.1.3.1.1 provides the results of the operational scenarios for simulating the trains following the RB principle. In Section 5.1.3.1.2, the simulations of the same operational scenarios based on the AB principle are carried out.

5.1.3.1.1 Results for Relative braking

The simulation results of the VC operations for the RB are given in the following sections:

5.1.3.1.1.1 RESULTS FOR OS1 RB

In this simulation, the trains start their motion at the initial station keeping the VC mode on until they complete the whole journey. Figure 25 indicates the train motions with time-distance, time-velocity, and distance-speed graphs. Figure 26 shows the instant headway time and distance values. Trains have longer headway times around both initial and final stations. This is because their speeds are lower until they reach the maximum allowable speed. Conversely, the trains have shorter headway distances around the stations. This is because the minimum distance depends on the actual speed. Once the trains rise up their speed, the headway distance increases. Figure 26c shows the hourly capacity that depends on the instant headway time. As seen, hourly capacity is maximum once headway time is the minimum.

Table 13 shows the performance outputs. The line capacity is determined by the weakest section of the line that is the longest headway time. As per results, VC OS 1 has a line capacity of 240 train per hour(tph) with more than 100,000 passenger per hour per direction(pphpd). Train 2 has a longer journey time than Train 1 since the actual distance varies as per the actual speed. Around the stations, the minimum distance reduces, and Train 2 arrives at the final station later than the lead train. Train 2 consumes lower energy than Train 1. Virtual Train Length is the sum of the headway distance and the train lengths that varies over the time since the actual separation between two trains changes depending on the speed. The number of trains that the fleet requires to enable this operation is 73.

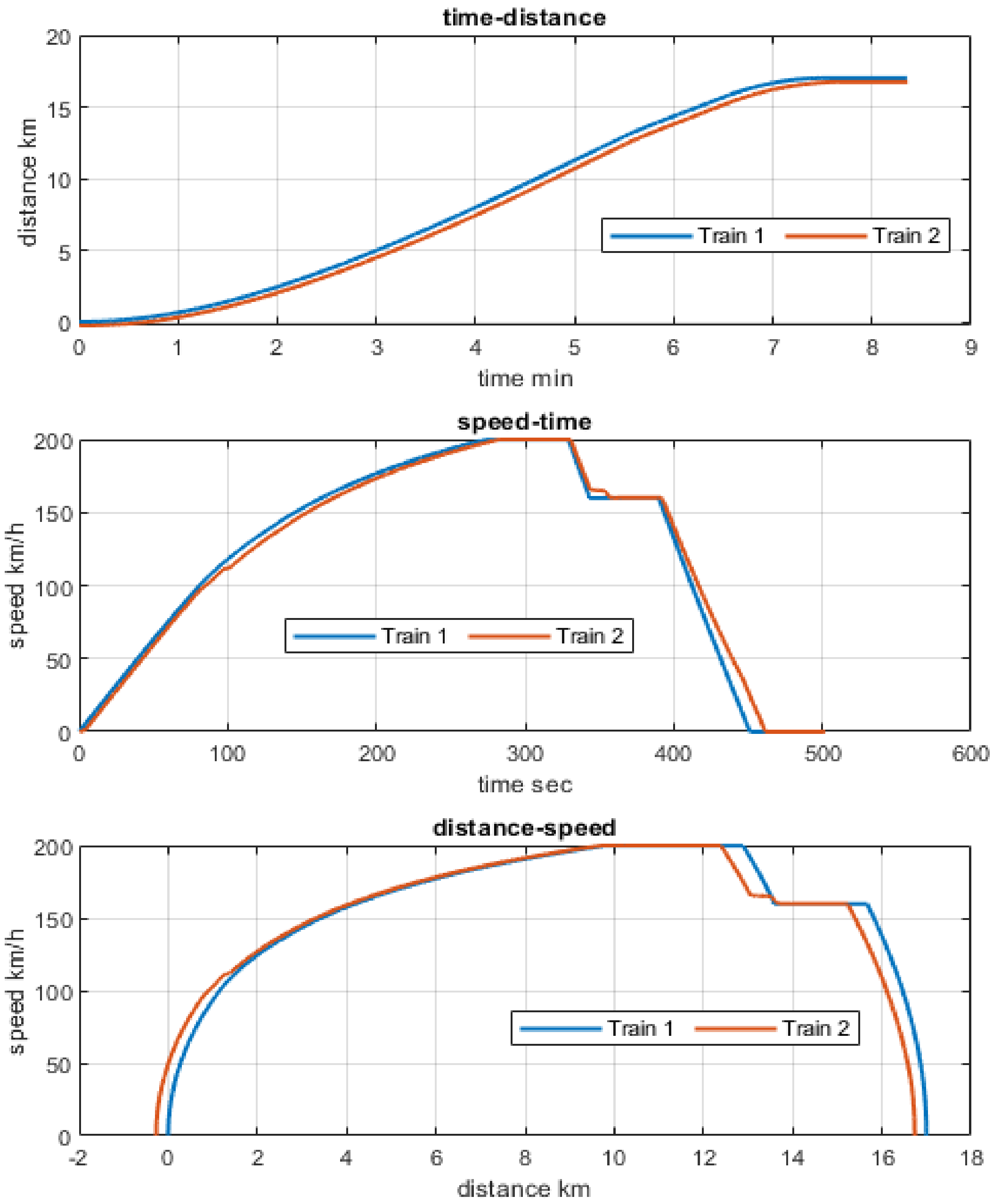


Figure 25: OS1 RB Train Motion Outputs: a) time-distance; b) speed-time; c) distance-speed.

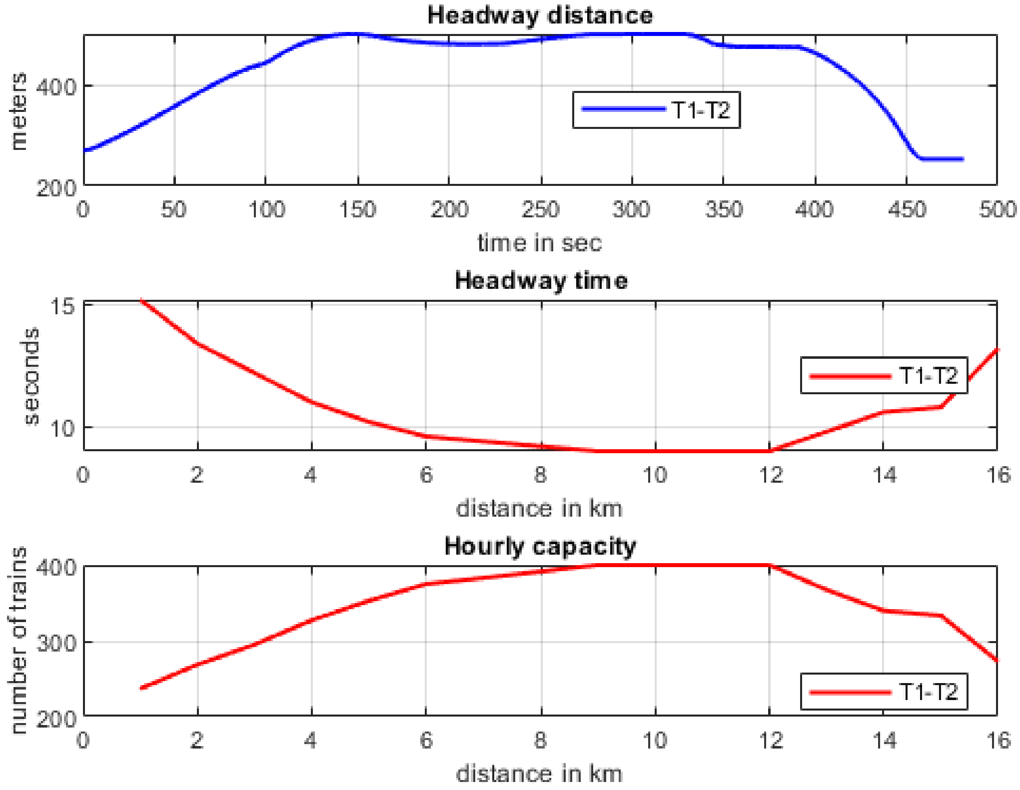


Figure 26: OS1 RB Capacity Outputs: a) Headway distance; b) Headway time; c) Hourly capacity.

Table 13: Performance Outputs for OS1 RB

Metric	**Value**	**Commentary**
Capacity	240tph 112,560pphpd	The weakest section or longest headway time determines the line capacity.
Number of trains required	73	Turnaround 180sec
Journey Time	T1:451sec T2:460sec	
Energy consumption	T1: 355kWh T2: 330 kWh	

Virtual Train Length	min: 495m max: 720m	Two train length added to min and max headway distance

5.1.3.1.1.2 RESULTS FOR OS2 RB

In the simulation of OS2, a turnout is placed at 10km. The follower train diverges at the turnout. A time of 60sec is allocated to the switch processing for safety. In other words, the follower train decouples from the leader train and passes through the turnout one minute later after the moment the leader train passes over it. Figure 27 indicates the train motions with time-distance, time-velocity, and distance-speed graphs. Figure 28 shows the graphs of headway time over location and headway distance over time. The follower train decouples from the lead train at 227sec in 6.82km. The headway time and distance increases towards the junction area until reaching 60sec which equals to the safety time allocated to the switch processing.

Table 14 shows the performance outputs. The line capacity is limited by the weakest section that is apparently the junction area. As per results, VC OS 2 has a line capacity of 60tph with more than 25,000 pphpd. The capacity reduces by 75% as compared to the outcome produced by OS1 RB. Train 2 consumes lower energy than Train 1. Virtual train length varies from 490m to 700m prior to the decoupling. The number of trains required for the fleet is 17, which is quite lower than that required for OS1 RB.

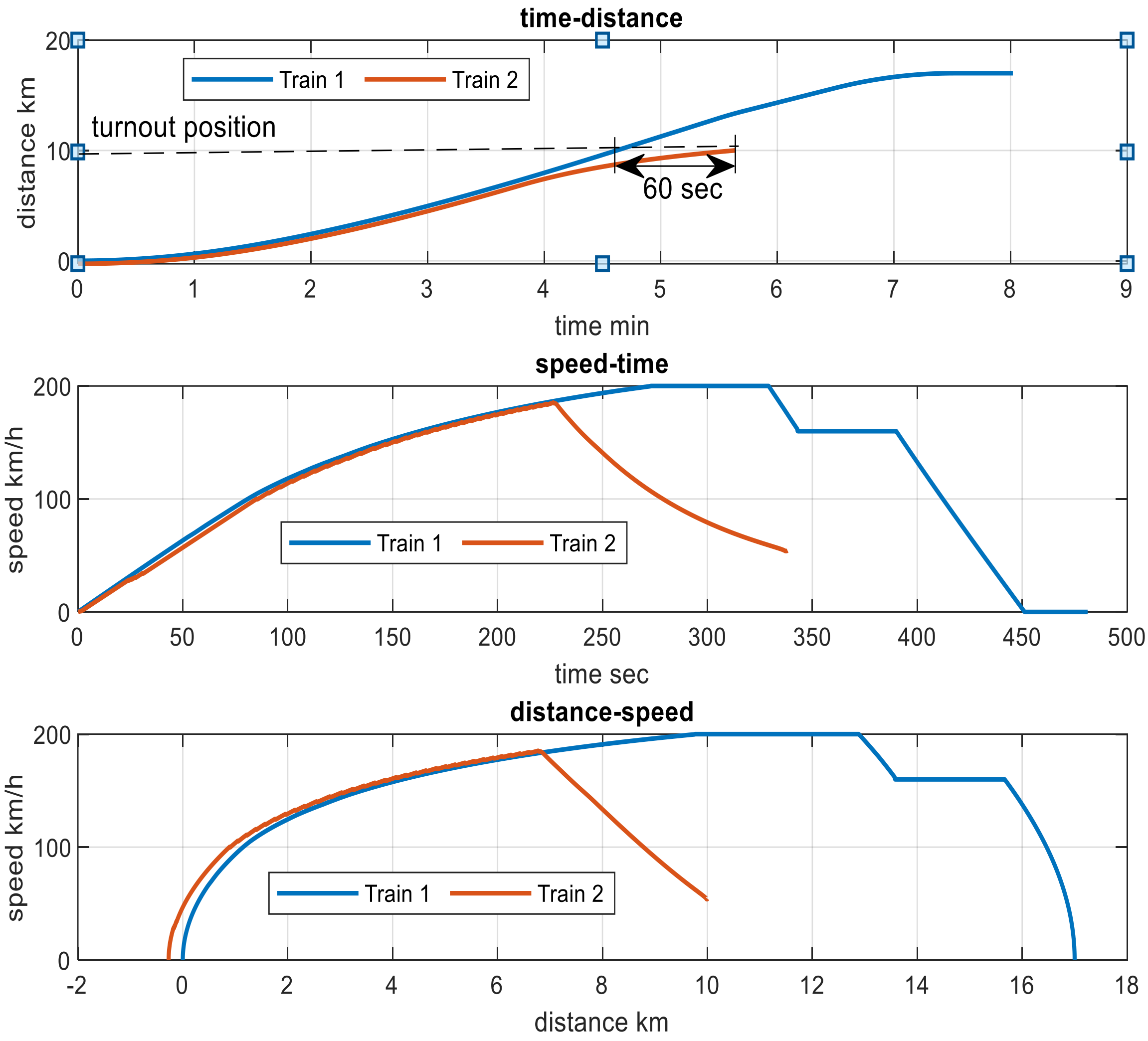


Figure 27: OS2 RB Train Motion Outputs: a) time-distance; b) speed-time; c) distance-speed.

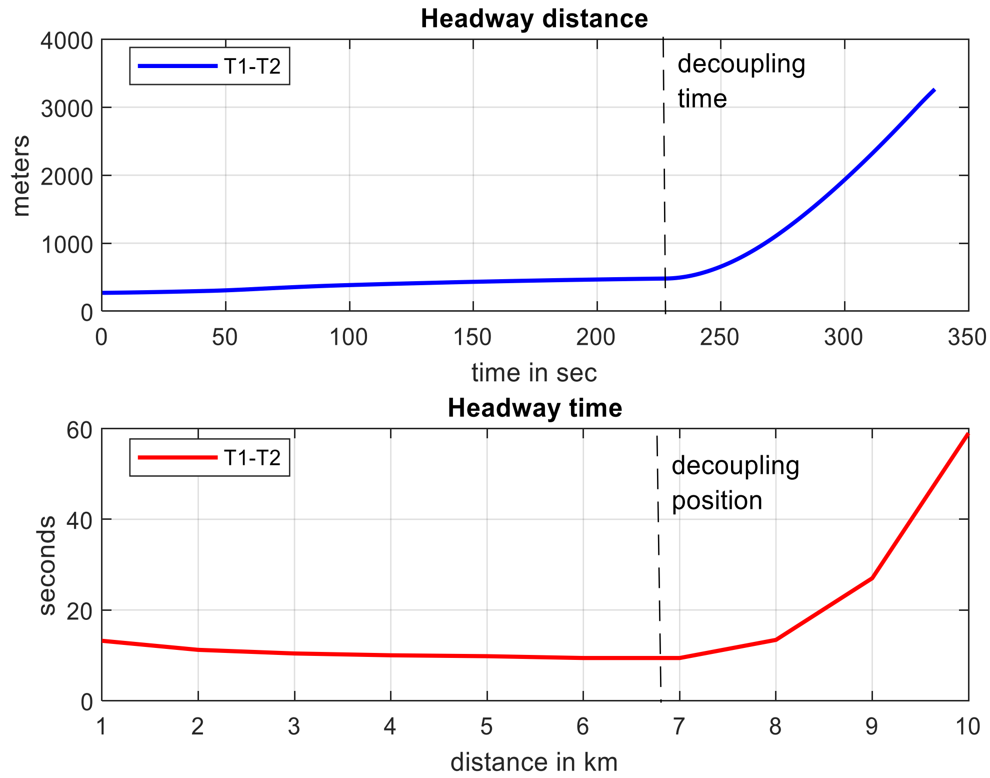


Figure 28: OS2 RB Capacity Outputs: a) Headway distance; b) Headway time.

Table 14: Performance Outputs for OS2 RB

Metric	Value - Rate	Commentary
Capacity	60tph 28,140pphpd	
Number of trains required	17	Turnaround 180sec
Journey Time	T1:451sec T2:338sec	
Energy consumption	T1: 355kWh T2: 224kWh	
Virtual train length	min: 490m max: 700m	

Decoupled time - position	227sec 6.82km	

5.1.3.1.1.3 RESULTS FOR OS3 RB

In the simulation of OS3, a turnout is placed at 5km. The follower train converges to the plain line through the turnout. A time of 60sec is allocated to the switch processing for safety. In other words, the follower train enters the plain line passing through the turnout one minute later after the moment the leader train has passed over it. Figure 29 indicates the train motions with time-distance, time-velocity, and distance-speed graphs. Figure 30 shows the graphs of headway time over location and headway distance over time. The follower train initiates the coupling process at 240sec and 6.82km and completes it after taking 6.65km in 165sec. To enable the coupling process, the leader train reduces its speed down to 30m/s from 5th km until 10th km. This slowdown is essential, otherwise the follower one cannot get closer to the lead one since they are homogenous in the tractive effort. Therein lies an assumption that the slowdown is conducted in collaboration with the follower one thanks to the multi-agent VI. The headway time starts to reduce from 60sec, which equals to the safety time allocated to the switch processing, around the junction area down to approximately 15sec. Virtual train length reduces from 700m to 490m after the coupling process is completed.

Table 15 shows the performance outputs. The line capacity is limited by the weakest section that is apparently the junction area. As per results, VC OS3 RB has a line capacity of 60tph with more than 25,000pphpd. The capacity reduces by 75% as compared to the outcome produced by OS1 RB but is the same with OS2 RB. The number of trains required for the fleet is 17, which is the same with that required for OS2 RB.

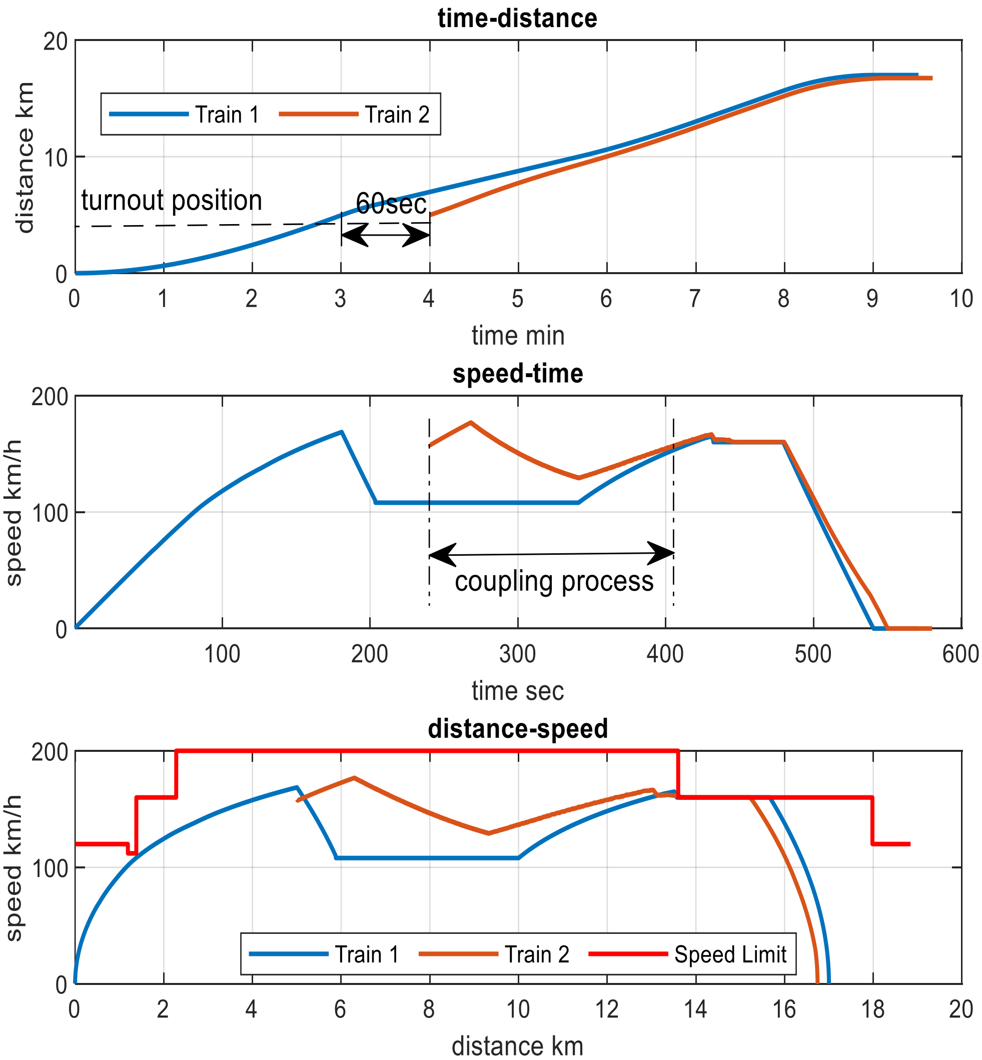


Figure 29: OS3 RB Train Motion Outputs: a) time-distance; b) speed-time; c) distance-speed.

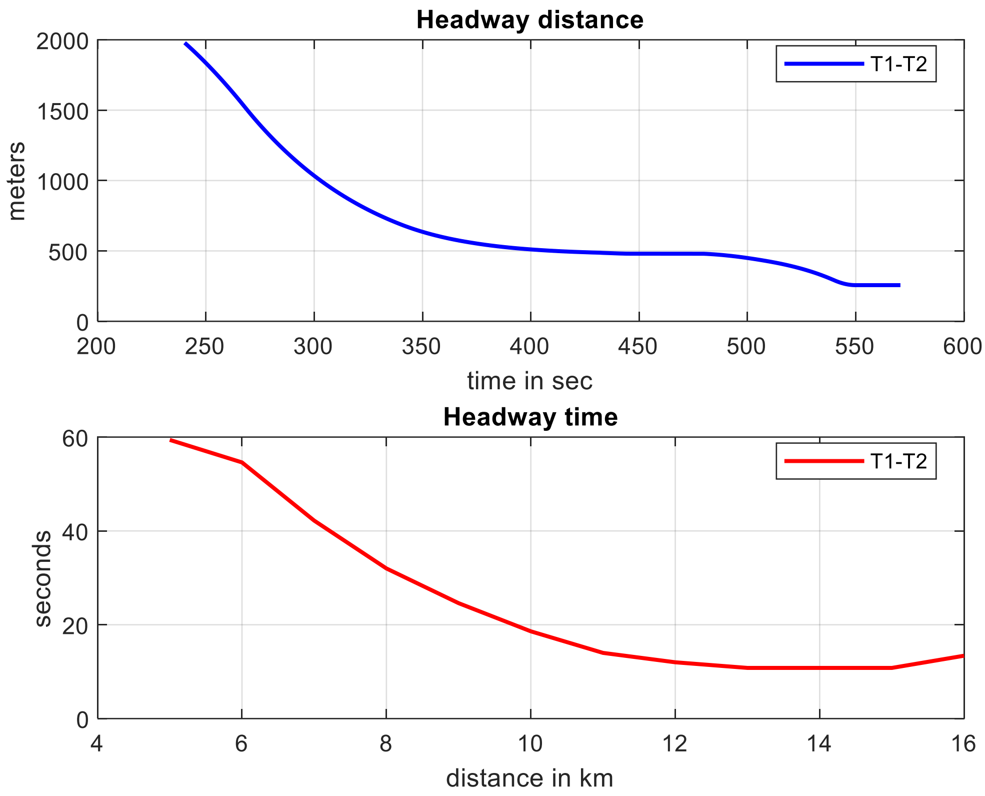


Figure 30: OS2 RB Capacity Outputs: a) Headway distance; b) Headway time.

Table 15: Performance Outputs for OS3 RB

Metric	Value	Comment
Capacity	60tph 28,140pphpd	Switch processing limits the capacity.
Number of trains required	17	Turnaround 180sec
Journey Time	T1:541sec T2:310sec	
Energy consumption	T1: 323kWh T2: 196 kWh	
Virtual Train Length	min: 490m max: 700m	

Coupling time - position	240 sec – 405 sec (165sec) 5km – 11.85km (6.65km)	
Train 1 slowdown	5km – 10 km @30m/s	Assumed enabled by Multiagent VI

5.1.3.1.1.4 RESULTS FOR OS 4 RB

This scenario is the combination of OS2 and OS3. For the simulation, two turnouts are placed at 5km and 30km. The follower train converges to the plain line through the first turnout. Then later, the follower train diverges from the plain line through the second turnout. A time of 60sec is allocated to the switch processing for safety. In other words, the follower train enters the plain line passing through the turnout one minute later after the moment the leader train passed over it and decouples from the leader train and passes through the turnout one minute later after the moment the leader train passed over it.

Figure 31 indicates the train motions with time-distance, time-velocity, and distance-speed graphs. Figure 32 shows the graphs of headway time over location and headway distance over time. The follower train initiates the coupling process at 240sec and 6.82km and completes it after taking 6.65km in 165sec. To enable the coupling process, the leader train reduces its speed down to 30m/s from 5th km until 10th km. The slowdown is essential, otherwise the follower one cannot get closer to the lead one since they are homogenous in the tractive effort. Therein lies an assumption that the slowdown is conducted in collaboration with the follower one thanks to the multi-agent VI. The follower train decouples from the lead train at 749sec and in 27th km. The headway time starts to reduce from 60sec, which equals to the safety time allocated to the switch processing, around the junction area down to approximately 15sec and increases towards the junction area until reaching 60sec. Virtual train length varies between 490m and 700m.

Table 16 shows the performance outputs. The line capacity is limited by the weakest section that is apparently the junction area. As per results, VC OS4 RB has a line capacity of 60tph with more than 25,000pphpd. The capacity reduces by 75% as compared to the outcome produced by OS1 RB but is the same with OS2 RB and OS3 RB. The number of trains required for the fleet is 17, which is the same with that required for OS2 RB and OS3 RB.

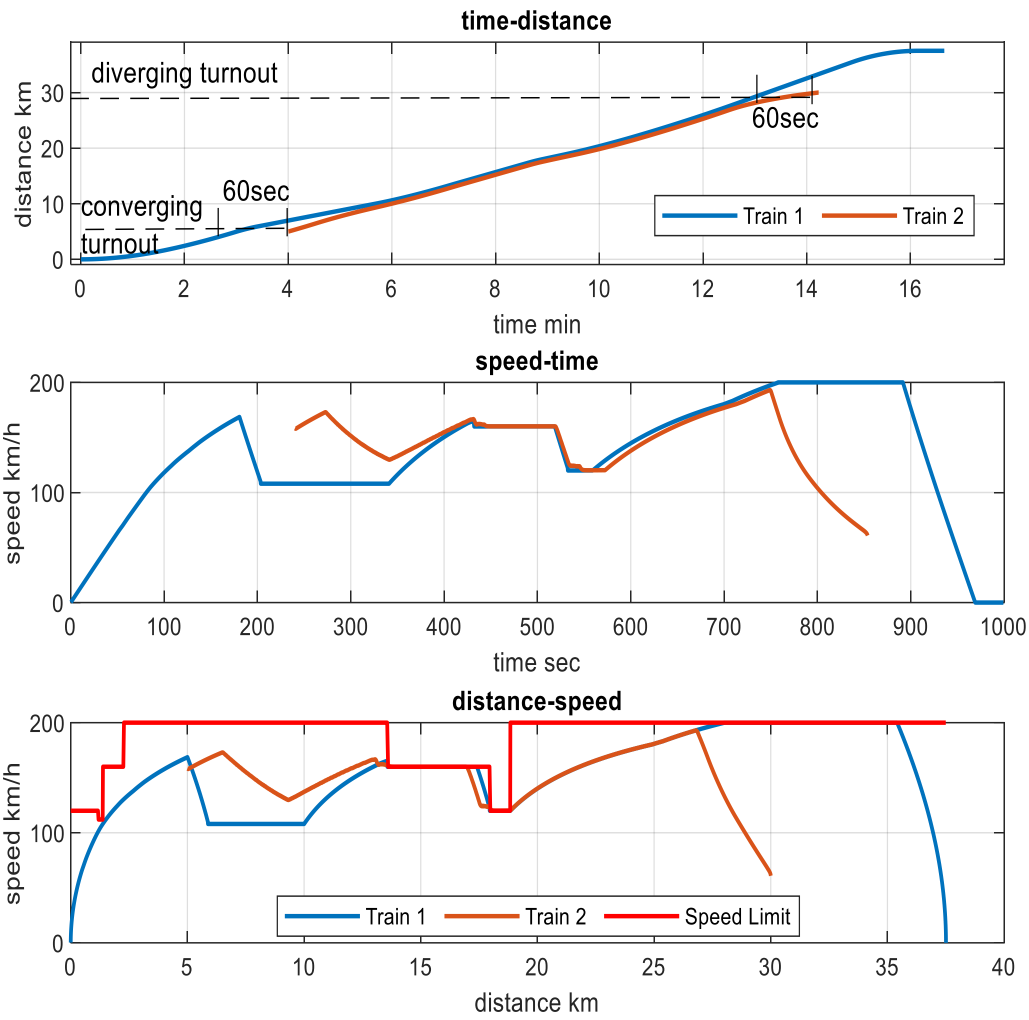


Figure 31: OS4 RB Train Motion Outputs: a) time-distance; b) speed-time; c) distance-speed.

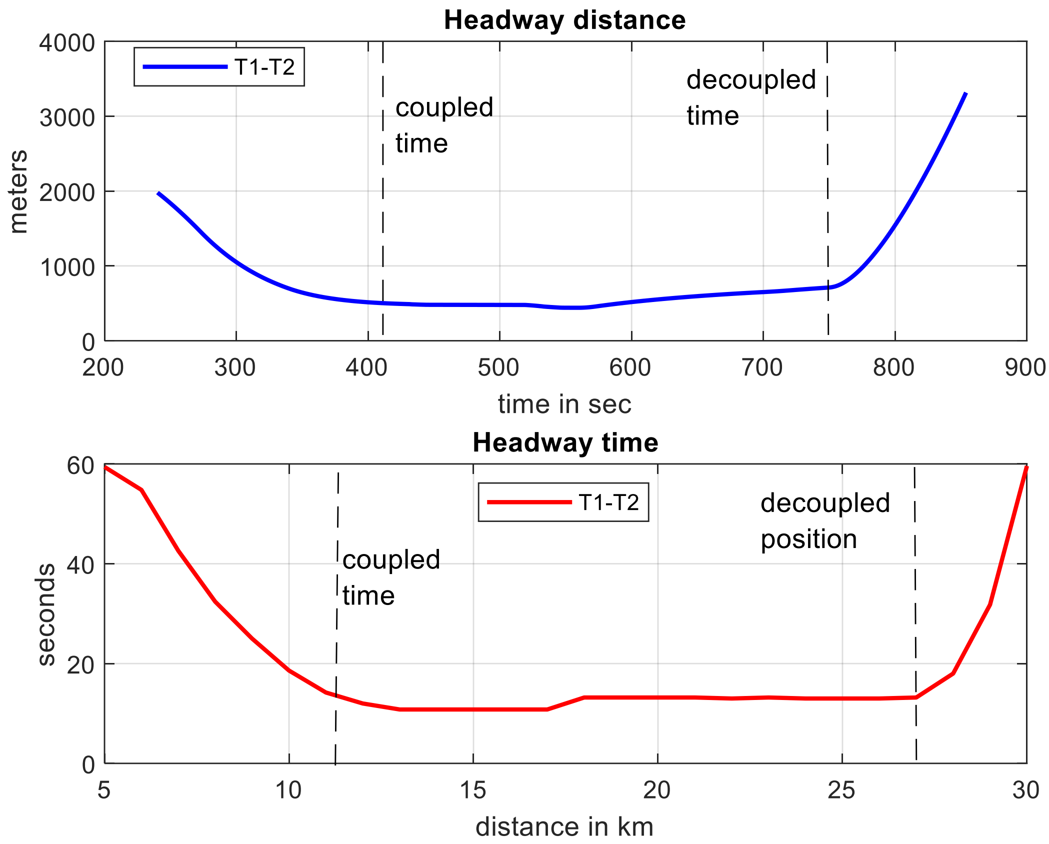


Figure 32: OS4 RB Capacity Outputs: a) Headway distance; b) Headway time; c) Hourly capacity.

Table 16: Performance Outputs for OS4 RB

Metric	**Value**	**Comment**
Capacity	60tph 28,140pphpd	Switch processing limits the capacity.
Number of trains required	17	Turnaround 180sec
Journey Time	T1:970sec T2:614sec	
Energy consumption	T1: 692kWh T2: 397kWh	

Virtual Train Length	min: 490m max: 700m	
Coupling time - location	240 sec – 405 sec (165sec) 5km – 11.85km (6.65km)	
Train 1 slowdown	5km – 10 km @30m/s	
Decoupled time – location	749sec 26787m	

5.1.3.1.2 Results for Absolute Braking

The simulation results of the VC operations for the AB are given in the following sections:

5.1.3.1.2.1 RESULTS FOR OS 1 AB

In this simulation, the trains start their motion at the initial station keeping the VC mode on until they complete the whole journey. Figure 33 indicates the train motions with time-distance, time-velocity, and distance-speed graphs. Figure 34 shows the instant headway time and distance values. The Trains have longer heady times around both initial and final stations. This is because their speeds are lower until they reach the maximum allowable speed. Conversely, the trains have shorter headway distances around the stations. This is because the minimum distance depends on the actual speed of the trains. Once the trains rise up their speed, the headway distance increases. Table 17 shows the performance outputs. The line capacity is determined by the weakest section of the line that is the longest headway time. As per results, OS 1 AB has a line capacity of 70tph with more than 30,000pphpd. Train 2 has a longer journey time than Train 1 since the actual distance varies as per the actual speed. Around the stations, the minimum distance reduces, and Train 2 arrives at the final station later than the lead train. Train 2 consumes lower energy than Train 1. Virtual Train Length varies between 577m and 2624m over the time since the actual separation between two trains changes depending on the speed. The number of trains that the fleet requires to enable this operation is 23.

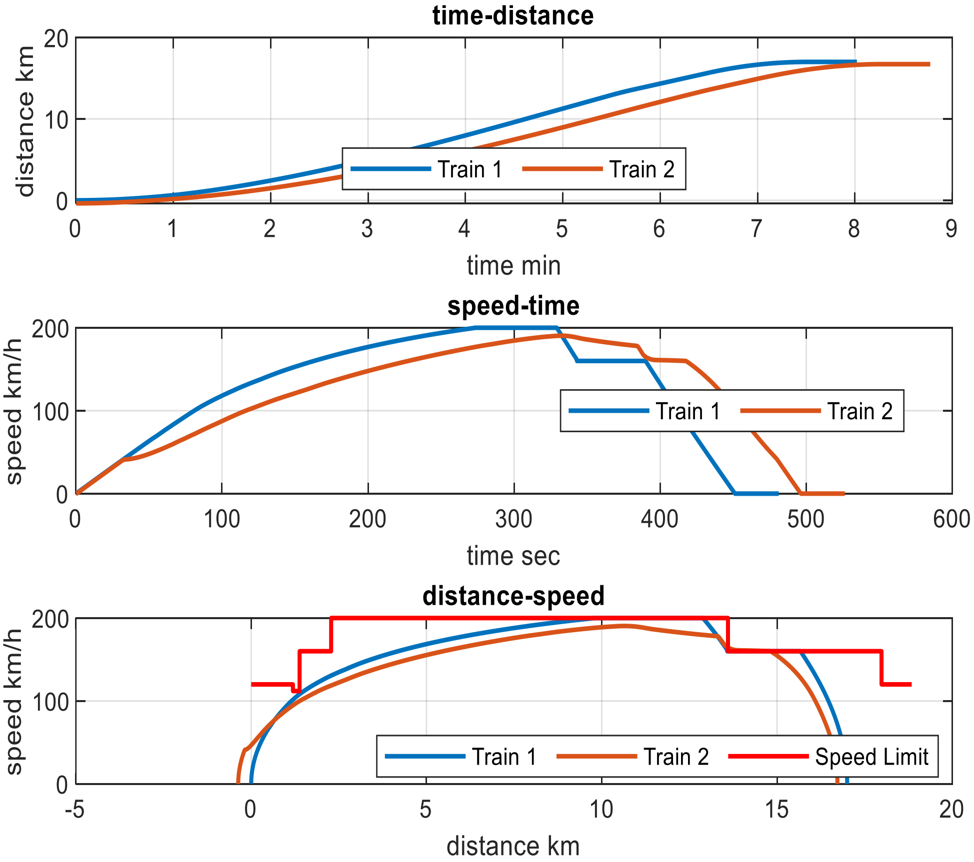


Figure 33: OS1 AB Train Motion Outputs: a) time-distance; b) speed-time; c) distance-speed.

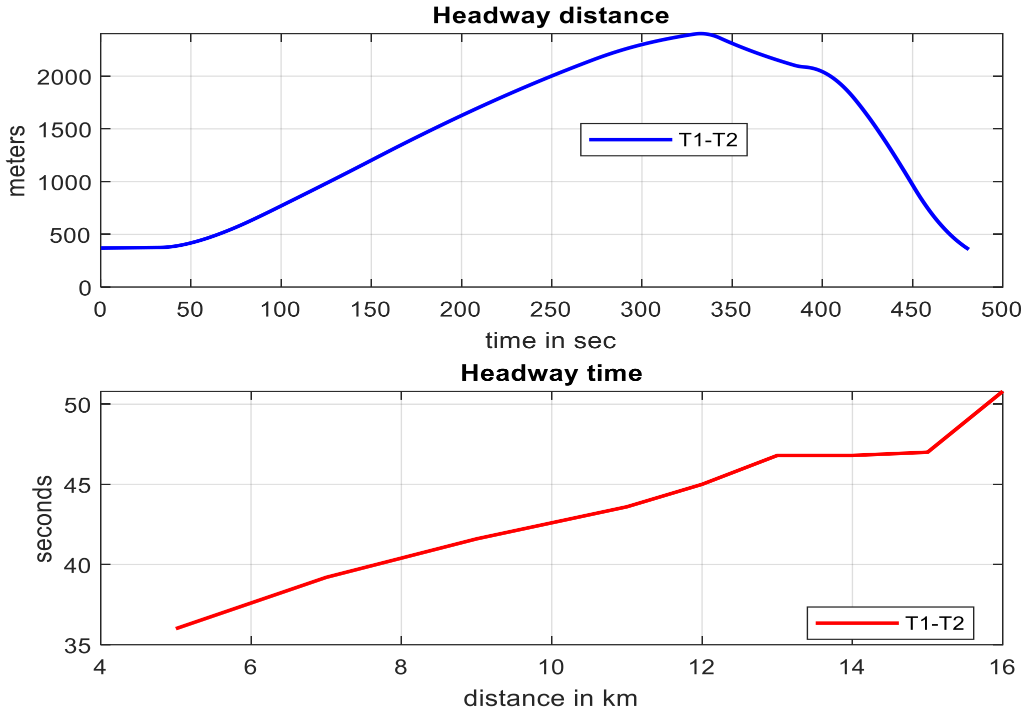


Figure 34: OS1 AB Capacity Outputs: a) Headway distance; b) Headway time.

Table 17: Performance Outputs for OS1 AB

Metric	Value	Commentary
Capacity	70tph 32,830pphpd	
Number of trains required	23	Turnaround 180sec
Journey Time	T1:451sec T2:496sec	
Energy consumption	T1: 356kWh T2: 285kWh	
Virtual Train Length	min: 577m max: 2624m	100m between two trains at station

5.1.3.1.2.2 RESULTS FOR OS2 AB

In the simulation for OS2 AB, a turnout is placed at 10km. The follower train diverges from the plain line through the turnout. A time of 60sec is allocated to the switch processing for safety. In other words, the follower train decouples from the leader train and passes through the turnout one minute later after the moment the leader train passed over it. Figure 35 indicates the train motions with time-distance, time-velocity, and distance-speed graphs. Figure 36 shows the graphs of headway time over location and headway distance over time. The follower train decouples from the lead train at 282sec in 8km. The headway time and distance increases towards the junction area until reaching 60sec which equals to the safety time allocated to the switch processing.

Table 18 shows the performance outputs. The line capacity is limited by the weakest section that is apparently the junction area. As per results, VC OS 2 has a line capacity of 60tph with more than 25,000 pphpd. The capacity reduces by 15% as compared to the outcome produced by OS1 AB. Train 2 consumes lower energy than Train 1. Virtual train length varies from 577m to 2624m prior to the decoupling. The number of trains required for the fleet is 17, which is a similar value to that required for OS1 RB.

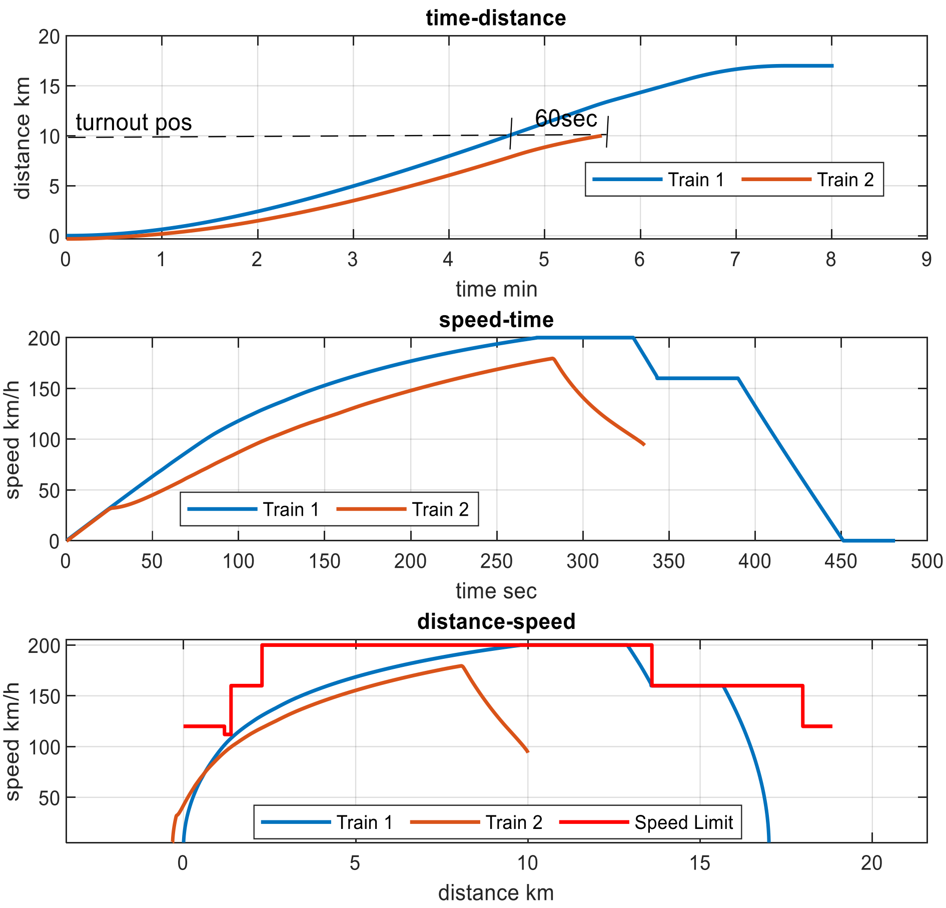


Figure 35: OS2 AB Train Motion Outputs: a) time-distance; b) speed-time; c) distance-speed.

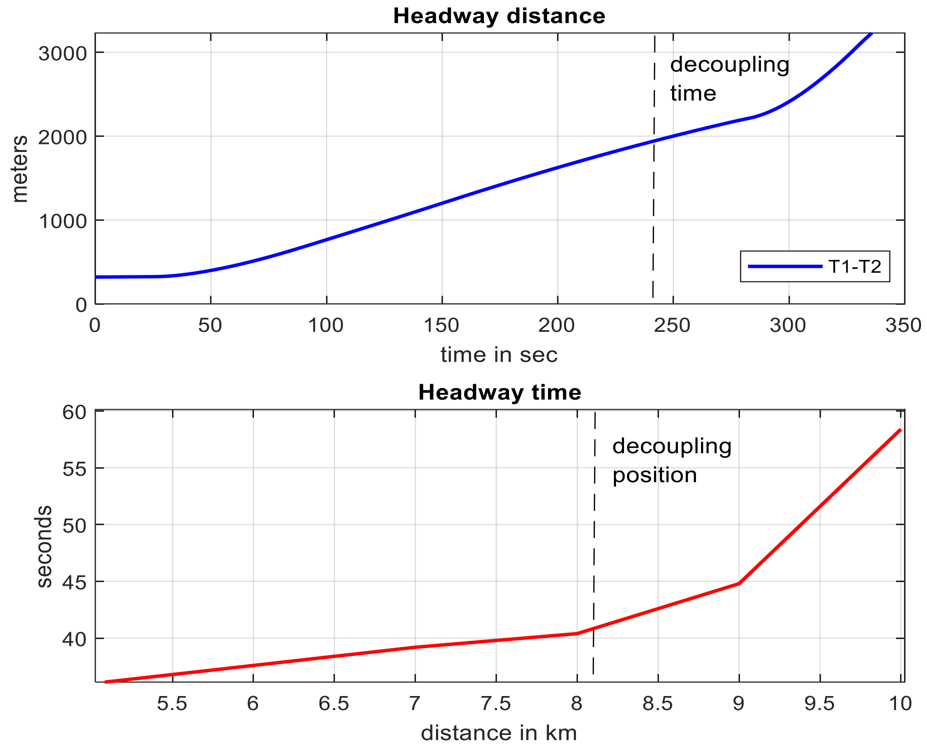


Figure 36: OS2 AB Capacity Outputs: a) Headway distance; b) Headway time.

Table 18: Performance Outputs for OS2 AB

Metric	Value	Commentary
Capacity	60tph 28,140pphpd	Switch processing limits the capacity.
Number of trains required	17	Turnaround 180sec
Journey Time	T1:451sec T2:336sec	
Energy consumption	T1: 356kWh T2: 215kWh	
Virtual Train Length	min: 577m max: 2624m	150m between two trains at station

Decoupling time and location	282sec 8064m	

5.1.3.1.2.3 RESULTS FOR OS3 AB

In the simulation for OS3 AB, a turnout is placed at 5km. The follower train converges to the plain line through the turnout. A time of 60sec is allocated to the switch processing for safety. In other words, the follower train enters the plain line passing through the turnout one minute later after the moment the leader train passed over it. Figure 37 indicates the train motions with time-distance, time-velocity, and distance-speed graphs. Figure 38 shows the graphs of headway time over location and headway distance over time. The follower train initiates the coupling process at 240sec and 5 km and completes it after taking 6.65km in 165sec. To enable the coupling process, the leader train reduces its speed down to 30m/s from 5th km until 10th km. The slowdown is essential, otherwise the follower one cannot get closer to the lead one since they are homogenous in the tractive effort. Therein lies an assumption that the slowdown is conducted in collaboration with the follower one thanks to the multi-agent VI. The headway time starts to reduce from 60sec, which equals to the safety time allocated to the switch processing, around the junction area down to approximately 45sec. Virtual train length reduces from 2200m to 573m after the coupling process is completed.

Table 19 shows the performance outputs. The line capacity is limited by the weakest section that is apparently the junction area. As per results, VC OS3 RB has a line capacity of 60tph with more than 25,000pphpd. The capacity reduces by 15% as compared to the outcome produced by OS1 AB but is the same with OS2 AB, OS2 and OS3 RB. The number of trains required for the fleet is 17, which is the same with that required for OS2 RB.

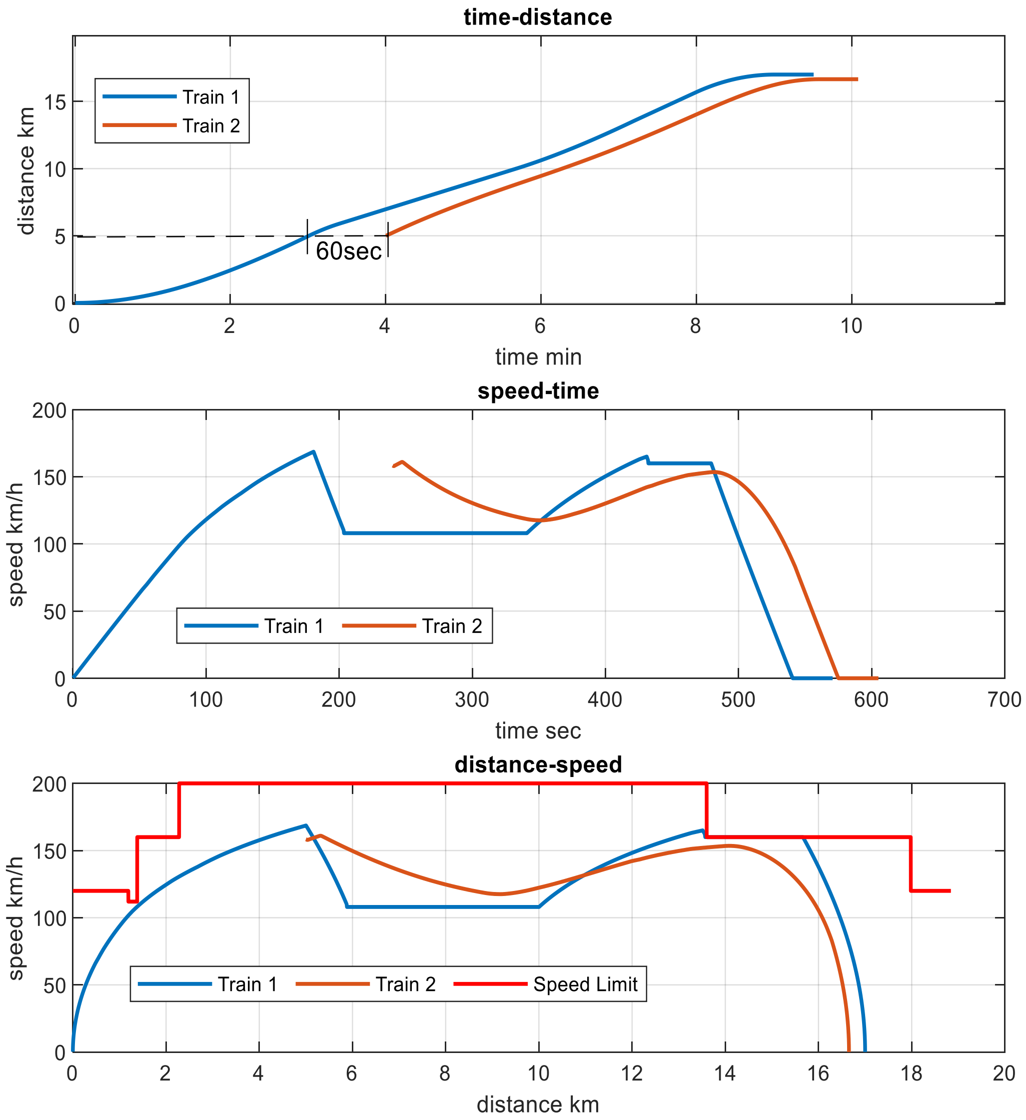


Figure 37: OS3 AB Train Motion Outputs: a) time-distance; b) speed-time; c) distance-speed.

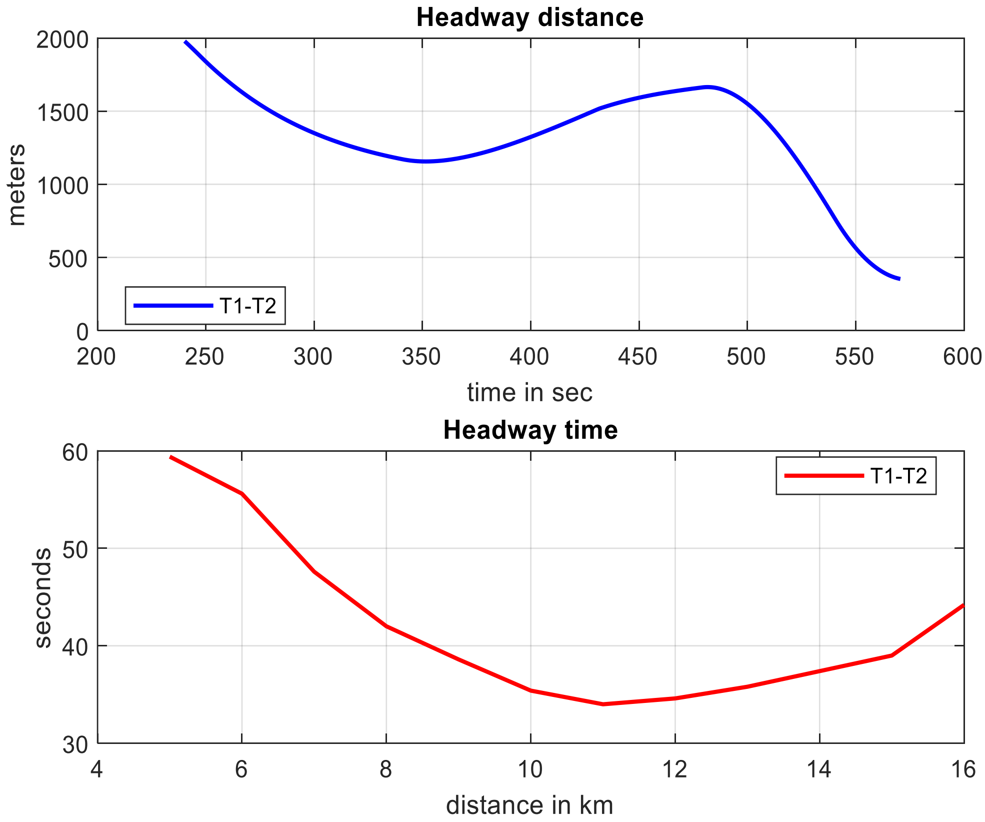


Figure 38: OS3 AB Capacity Outputs: a) Headway distance; b) Headway time; c) Hourly capacity.

Table 19: Performance Outputs for OS3 AB

Metric	**Value**	**Comment**
Capacity	60tph 28,140pphpd	Switch processing limits the capacity.
Number of trains required	17	Turnaround 180sec
Journey Time	T1:541sec T2:335sec	
Energy consumption	T1: 323kWh T2: 99kWh	
Virtual Train Length	min: 573m max: 2220m	
Coupling time location	240 sec – 404 sec (274sec)	

	5km – 11km (6km)	
Train 1 slowdown	5km – 10 km 30m/s	

5.1.3.1.2.4 RESULTS FOR OS4 AB

This scenario is the combination of OS2 and OS3. For the simulation, two turnouts are placed at 5km and 30km. The follower train converges to the plain line through the first turnout. Then later, the follower train diverges from the plain line through the second turnout. A time of 60sec is allocated to the switch processing for safety. In other words, the follower train enters the plain line passing through the turnout one minute later after the moment the leader train passed over it and decouples from the leader train and passes through the turnout one minute later after the moment the leader train passed over it.

Figure 39 indicates the train motions with time-distance, time-velocity, and distance-speed graphs. Figure 40 shows the graphs of headway time over location and headway distance over time. The follower train initiates the coupling process at 240sec and 6.82km and completes it after taking 6km in 274sec. To enable the coupling process, the leader train reduces its speed down to 30m/s from 5^{th} km until 10^{th} km. The slowdown is essential, otherwise the follower one cannot get closer to the lead one since they are homogenous in the tractive effort. Therein lies an assumption that the slowdown is conducted in collaboration with the follower one thanks to the multi-agent VI. The follower train decouples from the lead train at 802sec and in 28^{th} km. The headway time starts to reduce from 60sec, which equals to the safety time allocated to the switch processing, around the junction area down to approximately 15sec and increases towards the junction area until reaching 60sec. Virtual train length varies between 1567m and 2648m.

Table 20 shows the performance outputs. The line capacity is limited by the weakest section that is apparently the junction areas. As per results, VC OS4 AB has a line capacity of 60tph with more than 25,000pphpd. The capacity reduces by 15% as compared to the outcome produced by OS1 AB but is the same with all scenarios with the junction e.g., OS2 RB, OS3 AB. The number of trains required for the fleet is 17, which is the same with that required for OS2 RB and OS3 RB.

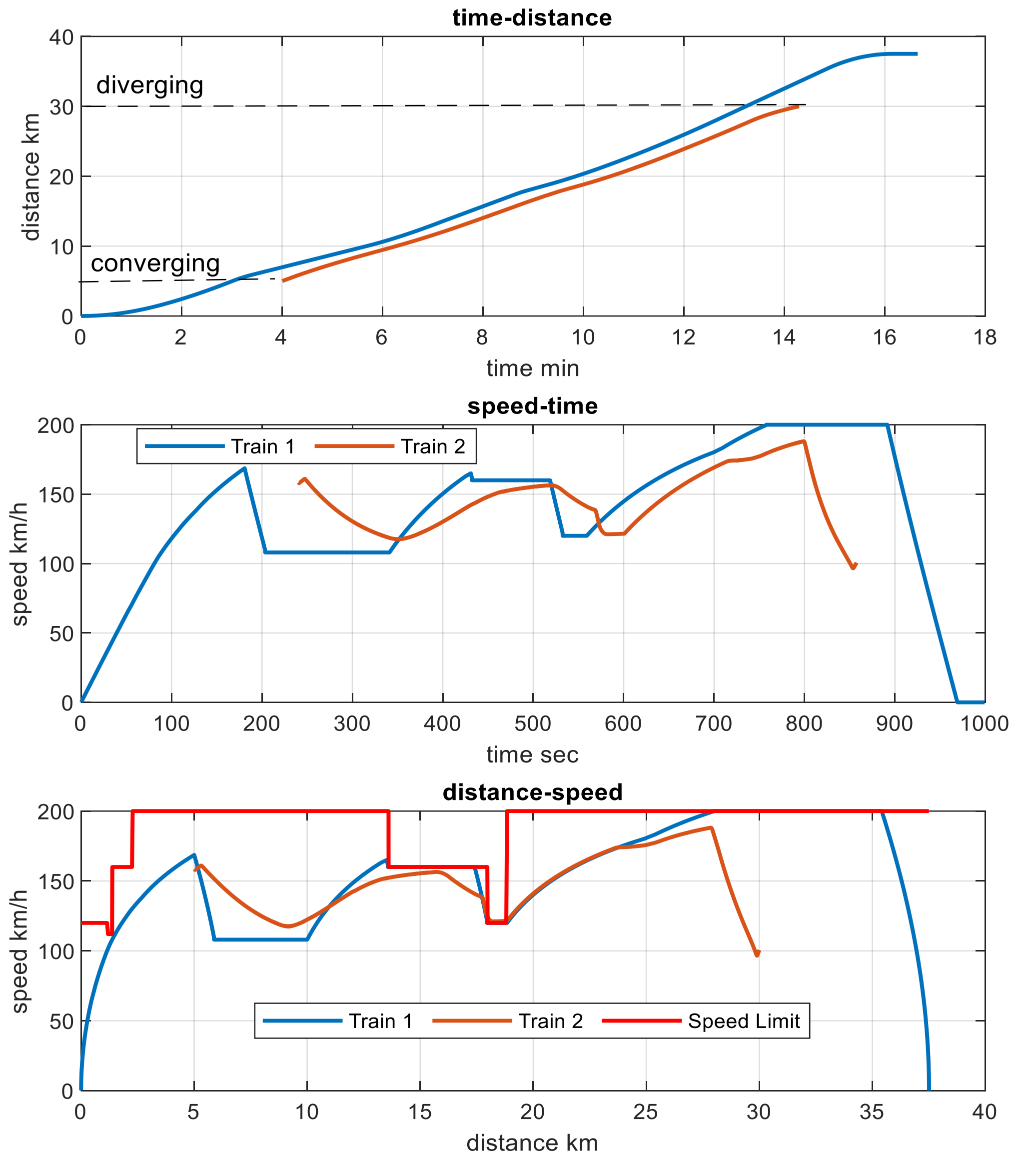


Figure 39: OS4 AB Train Motion Outputs: a) time-distance; b) speed-time; c) distance-speed.

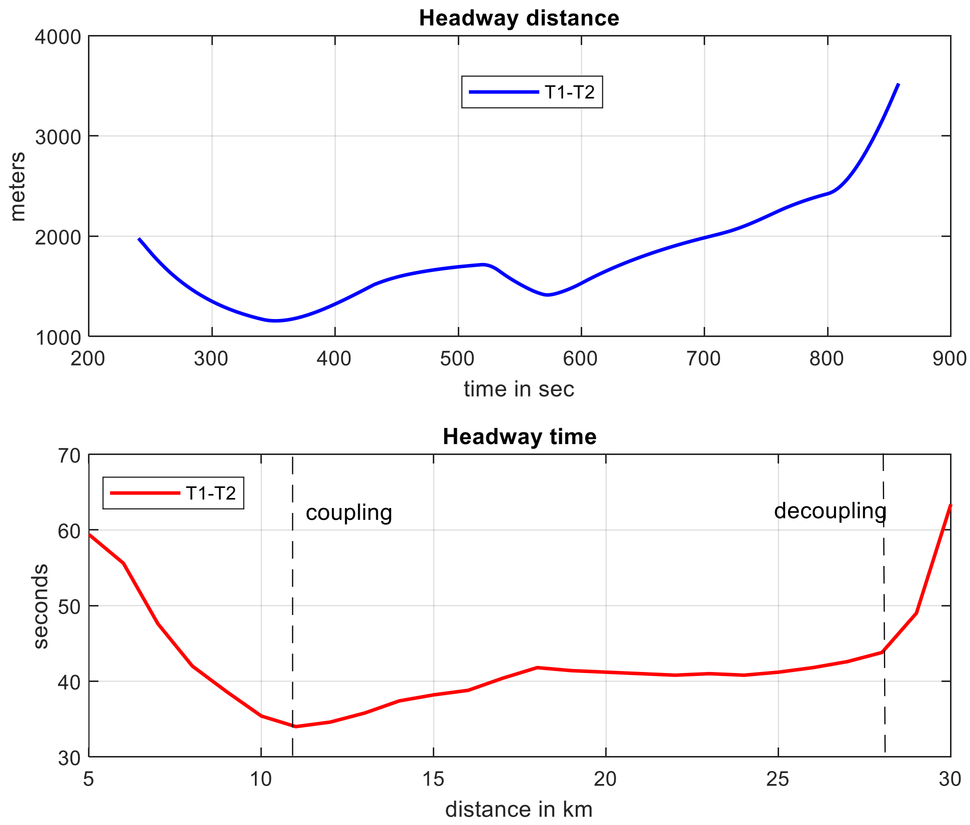


Figure 40: OS4 AB Capacity Outputs: a) Headway distance; b) Headway time.

Table 20: Performance Outputs for OS4 AB

Metric	**Value**	**Comment**
Capacity	60tph 28,140pphpd	Switch processing limits the capacity.
Number of trains required	17	Turnaround 180sec
Journey Time	T1:969sec T2:617sec	
Energy consumption	T1: 692kWh T2: 348Wh	

Virtual Train Length	min: 1567m max: 2648m	
Coupling time location	240 sec – 404 sec (274sec) 5km – 11km (6km)	
Train 1 slowdown	5km – 10 km 30m/s	
Decoupling time location	802sec 28km	

5.1.3.2 Intra-consist VC Operation

The intra-consist operation scenario is one where one train is split into sub-trains and run under the VC-mode. A Pendolino train (see Section 5.1 for details) has 9 cars that can be split into sub-trains in many formations such as 1+8, 1+4+4, 2+5+2 etc. In practice, this form results in two virtually coupled trains from a train with nine cars that physically coupled to each other. This enables an express service that has few planned intermediate stops to leave some carriages at specific stations without stopping itself. In other words, more destinations are offered without having to add extra stops.

An intermediate station is placed at 8.5km. In this simulation, it is assumed that the train is split into sub-trains with the form of one small sub-train having two cars with one sub-train of seven cars: 2+7. The sub-train with two cars as a follower stops at the intermediate station whereas the sub-train with 7cars as a leader finishes its journey at the final station. Figure 41 shows the graphs of headway time over location and headway distance over time. Figure 42 shows the graphs of headway time over location and headway distance over time. The follower sub-train decouples from the lead sub-train at 223sec in 6.7km. The headway time and distance increases after the decoupling until the follower stops at the intermediate station. Table 21 shows the performance outputs. The results hint that the intra-consist operations has a potential to reduce the energy consumption thanks to that the sub-trains have lower masses and shorter journeys: this results in a 32% reduction in journey time and 33% in energy consumption as compared with that the train with 9 cars 6 has a journey time 618sec and energy consumption of 412kWh.

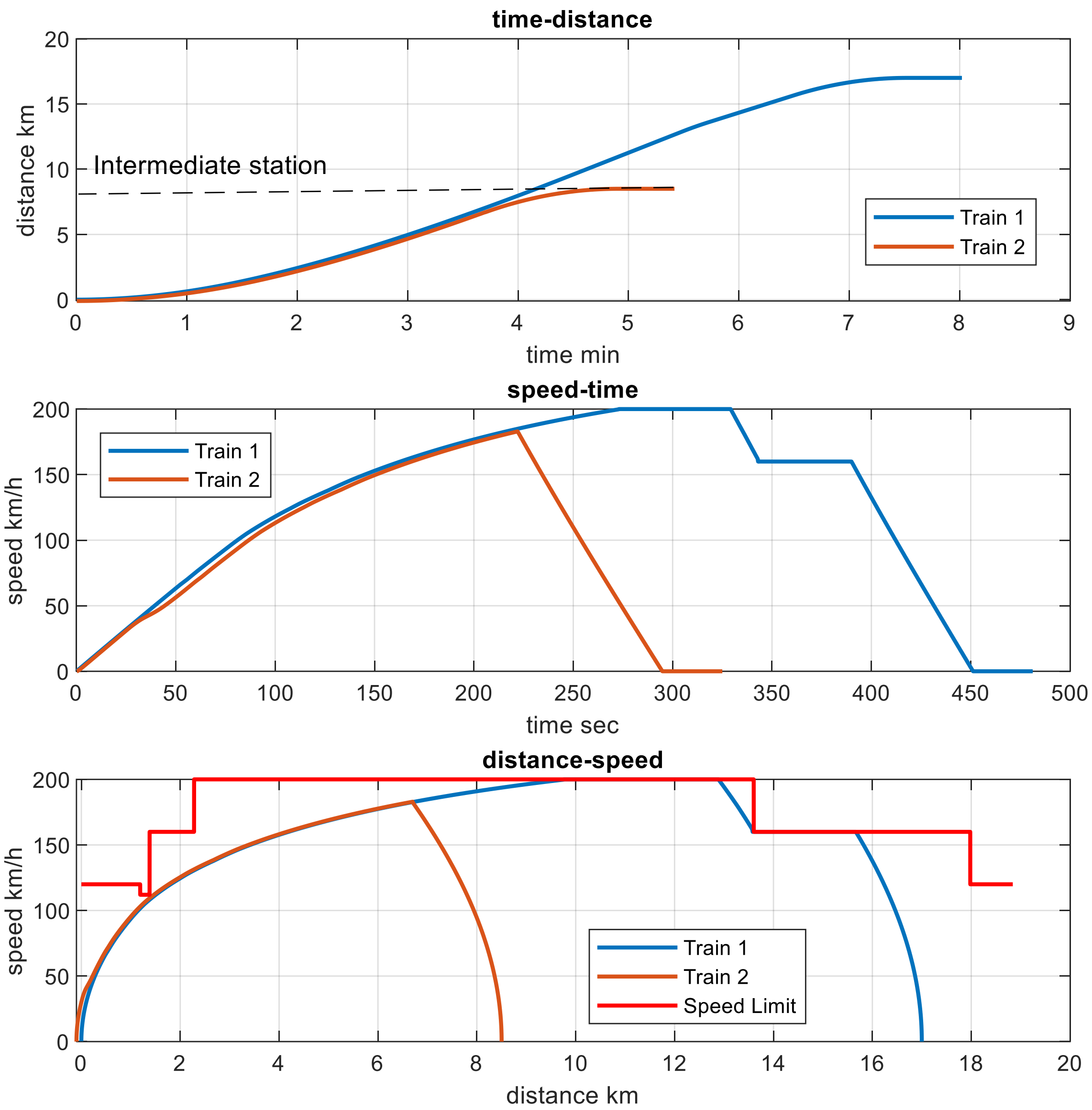


Figure 41: Intra-consist Operation Train Motion Outputs: a) time-distance; b) speed-time; c) distance-speed.

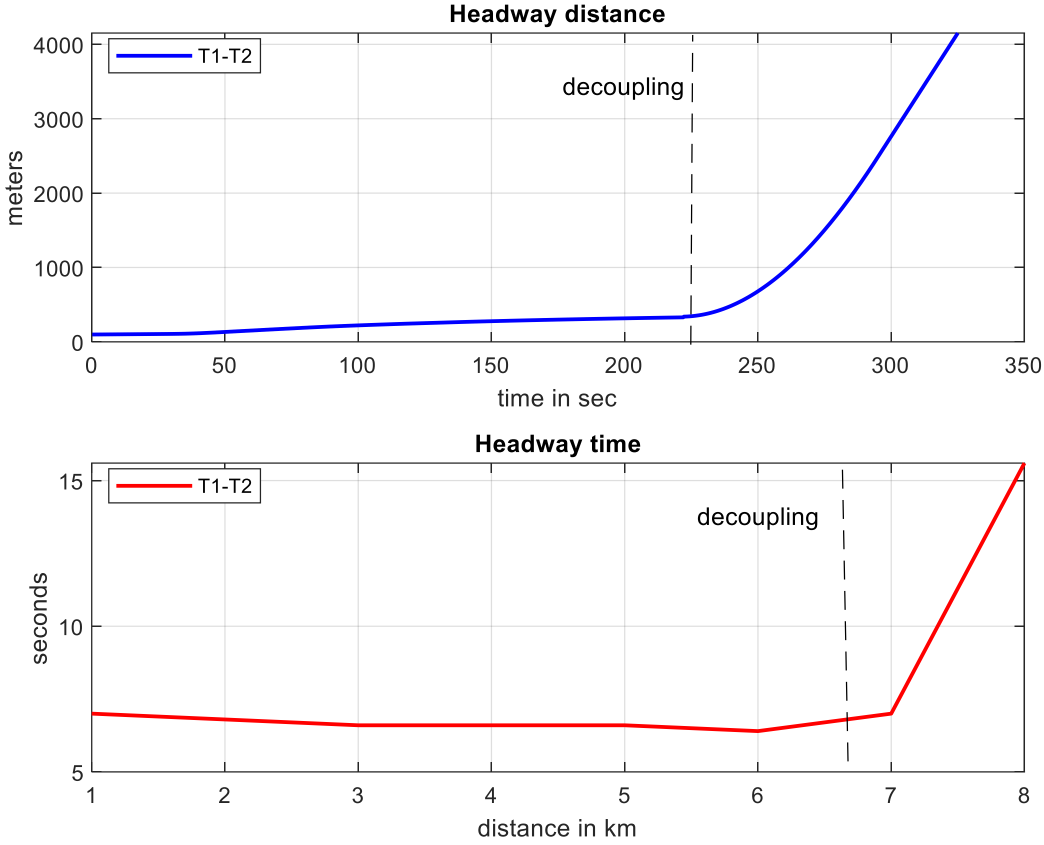


Figure 42: Intra-consist Capacity Outputs: a) Headway distance; b) Headway time.

Table 21: Performance Outputs for Intra-consist Operation

Metric	Value	Commentary
Capacity	225tph	
Journey Time	T1:451sec T2:295sec	For comparison with that the train with 9 cars 6 has a journey time 618sec and energy consumption of 412kWh.
Energy consumption	T1: 276kWh T2: 48kWh	
Virtual Train Length	min: 490m max: 700m	

Decoupled time location	223sec 6.7km	

5.1.4 Analysis of Simulation Results

The results showed that the VC operations on RB can provide a technical capacity of 240tph and a headway time of 15sec over the plain line under the ideal circumstances. The scenarios including junctions can provide a capacity of 60tph and headway time of 60sec. The capacity of these scenarios is limited by the switch processing time and safety principle. The VC operations on AB can provide a technical capacity between 60-70 tph including all kind of operational scenarios. Additionally, the intra-consist operation is a very special VC operation that enables trains to split into sub-trains or smaller trains, which helps reduce energy consumption and journey time especially for express high-speed train services that do not have many commercial stops.

Section 5.2 identifies the capacity influencing factors by changing relevant parameters and running simulations with different parameter values.

5.2 VC Performance Influencers: Railway Operation Components

A railway operation as a *whole* has a complex and complicated nature since it consists of many *part*s like systems, subsystems, and components. These parts affect overall system performance. So, this section aims to explore which factors impact the VC operational performance. Theeg et al. (2009) articulated three major components—infrastructure, vehicle, signalling & interlocking rules—that make up the railway operation as a whole as shown in Figure 43. The following subsections analyse impacts of the factors to be classified under these major components. For the simulations in this section, the same track and rolling stock data were used.

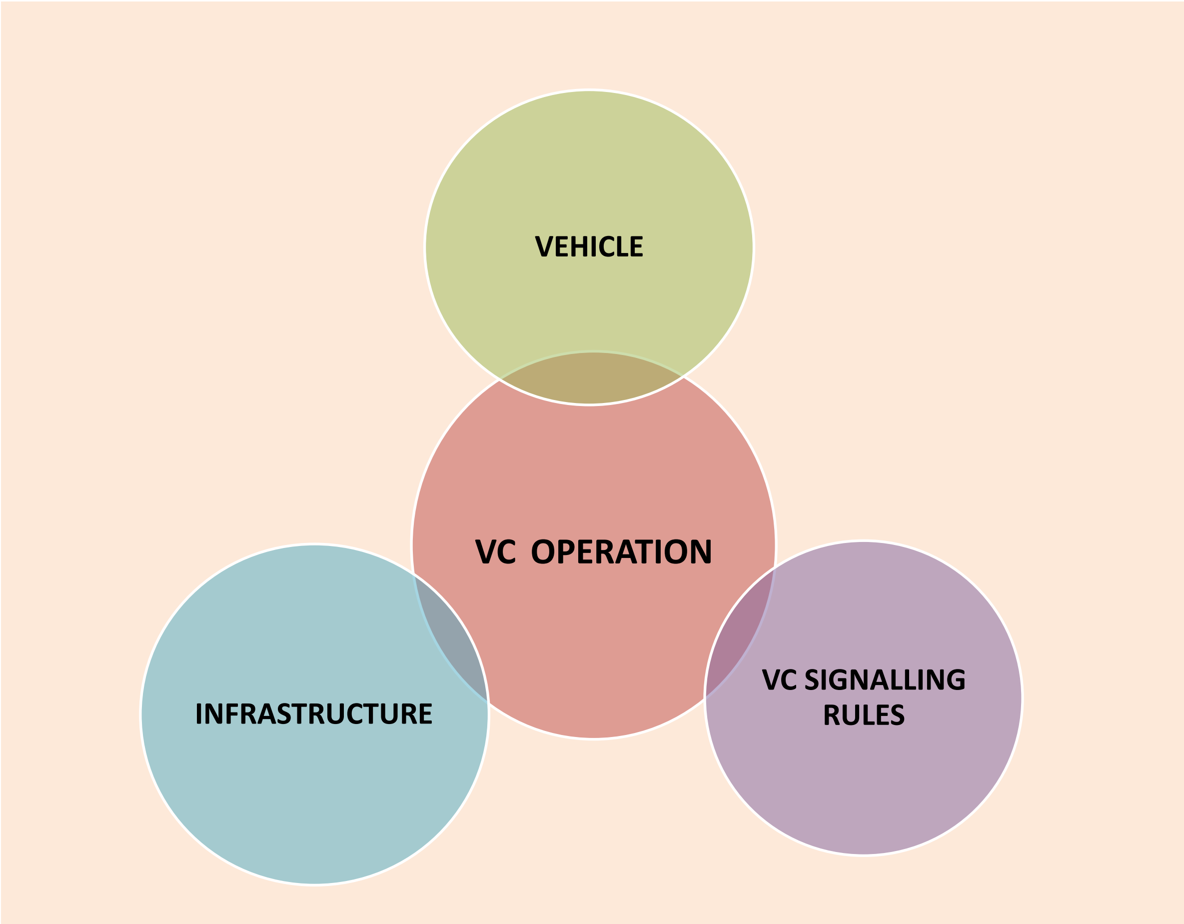


Figure 43: VC Operation Components, adapted from Theeg et al. (2020)

5.2.1 Vehicle or Rolling Stock

The vehicle or rolling stock features can affect the VC performance. These features include tractive and braking rate, train length, fleet heterogeneity, maximum speed, driving strategy. Their parameters will be changed to conduct sensitivity analysis by running simulations for each value and observing their impact on the outputs.

5.2.1.1 Tractive and braking effort

Since tractive effort has two regions: constant force and constant power as explained in Section 5.1, train acceleration capability varies with its velocity. However, for the simplicity, a constant value is assumed for the acceleration and braking rate in this section. To observe the effect of changing acceleration and braking rate on the VC performance, the simulations are separately run with the values as given in Table 22 for acceleration and Table 23 for braking.

Table 22 shows that change in the acceleration rate does not have impact on the capacity performance of VC AB and RB. However, increasing the braking rate has a positive effect on the capacity performance as shown in Table 23. This is because the minimum distance between trains is mostly determined by braking capability.

Table 22: Impact of acceleration rate on headway time and capacity

Acceleration (m/s2)	**Relative braking**		**Absolute Braking**	
	Headway time (sec)	Capacity (tph)	Headway time (sec)	Capacity (tph)
0.3	13.60	264	51.60	69
0.4	13.40	268	51.60	69
0.5	13.40	268	51.60	69
0.6	13.60	264	51.80	69
0.7	13.60	264	51.80	69
0.8	13.40	268	51.60	69
0.9	13.40	268	51.80	69
1.0	13.40	268	51.60	69
1.1	13.40	268	51.60	69
1.2	13.40	200	51.60	69

Table 23: Impact of braking rates on headway time and capacity

Braking	**Relative braking**	**Absolute Braking**

(m/s2)	Headway time (sec)	Capacity (tph)	Headway time (sec)	Capacity (tph)
0.5	16.60	216	63.80	56
0.6	15.40	233	55.60	64
0.7	14.40	250	49.40	72
0.8	13.60	264	44.60	80
0.9	13.20	272	40.60	88
1.0	13.20	272	37.40	96
1.1	13.20	272	35.00	102
1.2	13.20	272	32.80	109
1.3	13.20	272	30.80	116

5.2.1.2 Train length

The longer train length increases headway distance and time but also increases seating spaces in trains. Table 24 shows the simulation results for the impact of changing train length on headway time and capacity. As per the results, the longer trains have longer headway times and lower capacity in tph, however, carry more passenger on board since they can accommodate more people when the length is increased.

Table 24: Impact of train length on headway time and capacity

Train length (m)	**Relative braking**			**Absolute Braking**		
	Headway time (sec)	Capacity (tph)	Accommodation (ppdph)	Headway time (sec)	Capacity (tph)	Accommodation (ppdph)
150	13.40	268	101920	61.20	58	18531
250	18.00	200	106500	64.80	55	29287

350	23.00	156	116298	68.80	52	38766
450	28.20	127	121729	73.20	49	46966
550	34.00	105	123007	78.00	46	53889
650	40.20	89	123220	83.40	43	59533

5.2.1.3 Fleet heterogeneity

The previous simulations have assumed that the trains which are virtually coupled to each other have the same characteristics i.e., they are homogenous. However, the fleet homogeneity is mostly the case for urban rapid transport. Mainline or regional lines have different rolling stock types running on them. To explore whether the fleet heterogeneity affects the capacity performance of the VC operations, the follower train's tractive and braking performance are differentiated in a range of percentage from -40 to +40. The positive values indicate the follower train is stronger in braking and acceleration i.e., higher rates. The negative values indicate the other way around.

Table 25: Impact of fleet heterogeneity on headway time and capacity

Differentiation rate (%)	**Relative braking**		**Absolute Braking**	
	Headway time (sec)	Capacity (tph)	Headway time (sec)	Capacity (tph)
-40	42.96	83	83.80	42
-30	55.80	64	56.40	63
-20	34.80	103	51.60	69
-10	20.60	174	50.80	70
0	14.80	243	50.80	70
+10	13.40	268	50.80	70
+20	13.40	268	50.80	70

+30	13.40	268	50.80	70
+40	13.40	268	50.80	70

As given the simulation results in Table 25, if the follower train has lower tractive and braking performance the line capacity is negatively affected. In contrast, the more powerful follower train in the tractive and braking does not bring about any change. This is because the minimum safe distance cannot be overridden by the stronger train tractive and braking performance.

5.2.1.4 Driving strategy

The driving strategy enables a reduction in energy consumption with cost of higher journey time. The optimisation is conducted with an allowable increase of 100 sec in journey time applying the genetic algorithm, as explained in Chapter 4. The optimised driving of the first train as shown in Figure 44. The results for comparison are tabulated with Table 26. The results indicate that the driving style does not impact the capacity and the second train follows the first train's driving strategy properly, which can be an energy control strategy for the VC operations.

Table 26: Driving style comparison.

Driving Style	Headway Time Capacity	Energy Consumption	Journey Time
Fastest	14.80sec 243tph	T1: 355kwh T2: 346kwh	T1: 451sec T2: 459sec
Optimised	13.20 Sec 272tph	T1:181.77kwh T2: 202kwh	T1: 551sec T2: 556sec

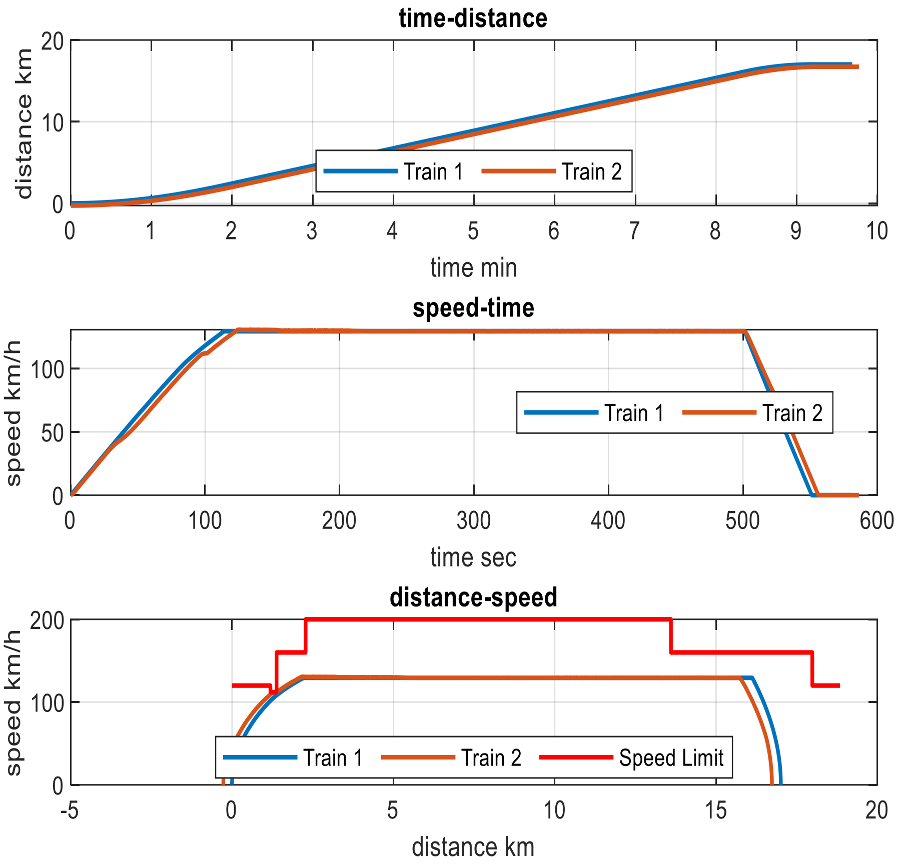


Figure 44: Optimised driving outputs Optimised maximum speed =35.93

5.2.2 Infrastructure

In this section, impacts of infrastructure factors are analysed. The factors include platform, number of stations, junctions, adhesion and gradient.

5.2.2.1 Station layout – Platform

Since trains are dispatched from stations and stops at there, the station layout directly affects the train operations. In case of the VC operations, two aspects deserve to be taken into consideration: platform length and number of platforms. Once we assumed the platform length is unlimited, we could form a VC convoy including infinite number of trains. The ideal length of platform that allows unlimited number of trains in a convoy is shown in Figure 45.

As seen, the ideal platform length for five trains in the convoy is around 1km, for 10 trains is around 2km, and for 20 trains around 4,5km. Obviously, it is not practicable to have such long platforms in the station areas. In a more real scenario, to compensate the shortness of the platform, the station can have multiple platforms in parallel. In this case, the layout with multiple platforms will need a converging point that requires to consider the switch processing time.

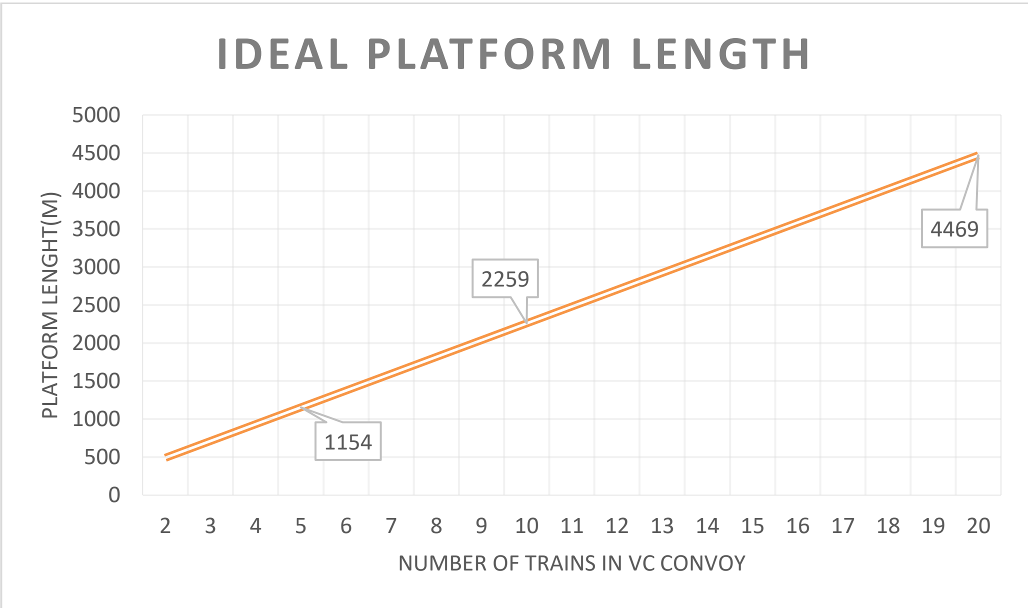


Figure 45: Ideal platform length

Considering two trains in a convoy, if platform length is not long enough to accommodate both trains at the same time, two scenarios can be possible:

i) The follower train approaches and stops at the platform after the lead one leaves the platform. In this case, the follower starts dwelling for passenger boarding after the first train start the motion. This scenario will cause a longer journey time since the first train needs to slow down to enable the follower to catch it. This simulation is shown in Figure 46 and Figure 47.

ii) The follower can start the motion off another platform at the same time with the first train. The follower train joins the first train's line through a converging point. This scenario will increase the journey time depending on the switch processing time. This simulation is shown in Figure 48 and Figure 49.

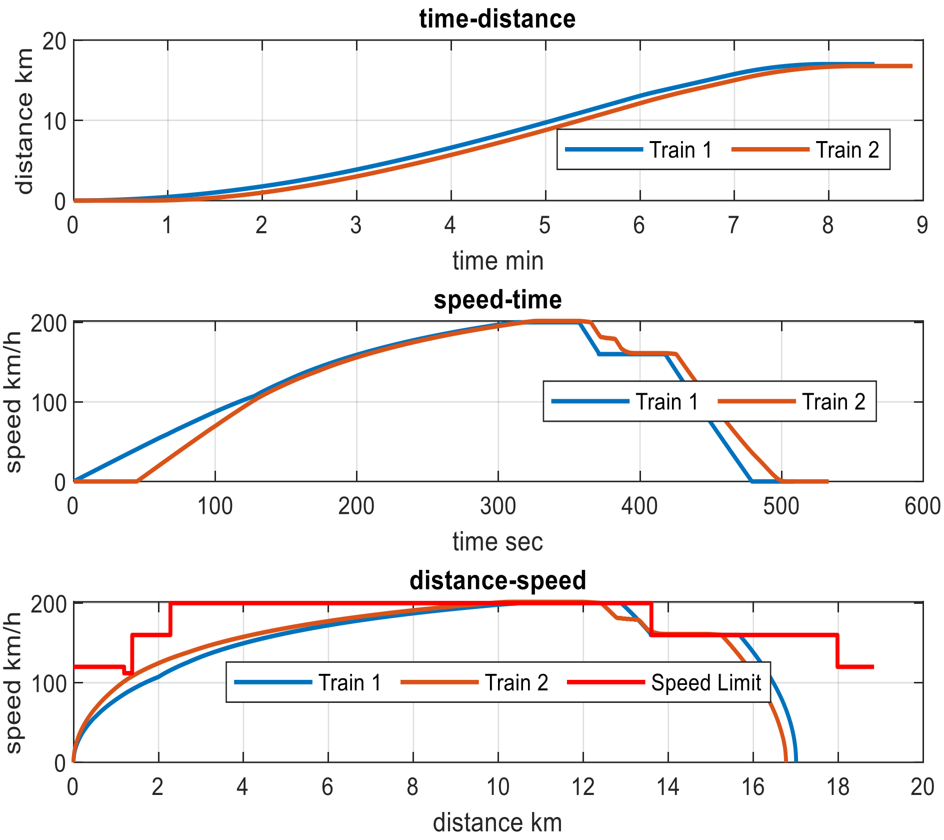


Figure 46: Station layout Scenario 1 – Train 1 reduces tractive performance down to -30 until 2nd km

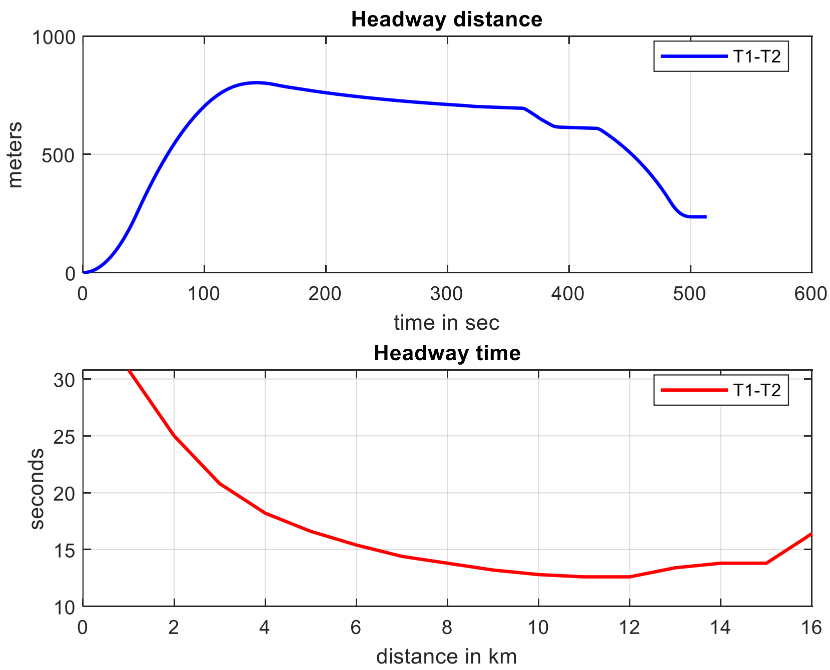


Figure 47: Station layout - Scenario 1 headway time and distance

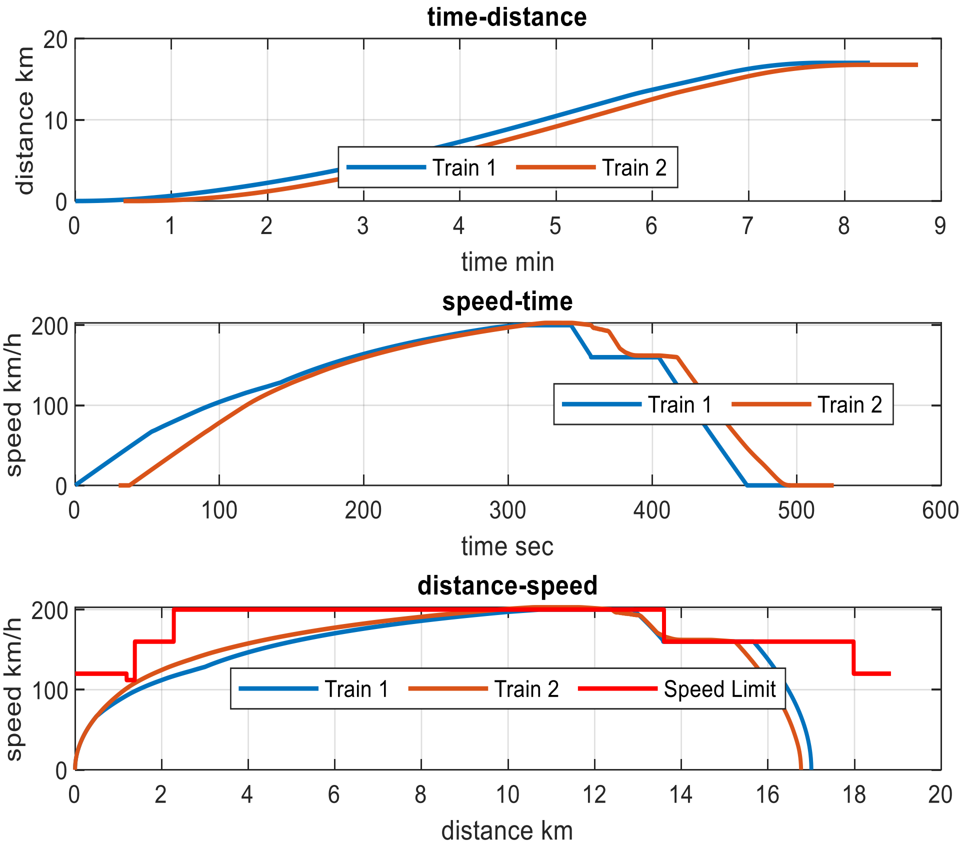


Figure 48: Multiple platform scenario(Train 1 reduces tractive performance to -30 from 300m till 2nd km)

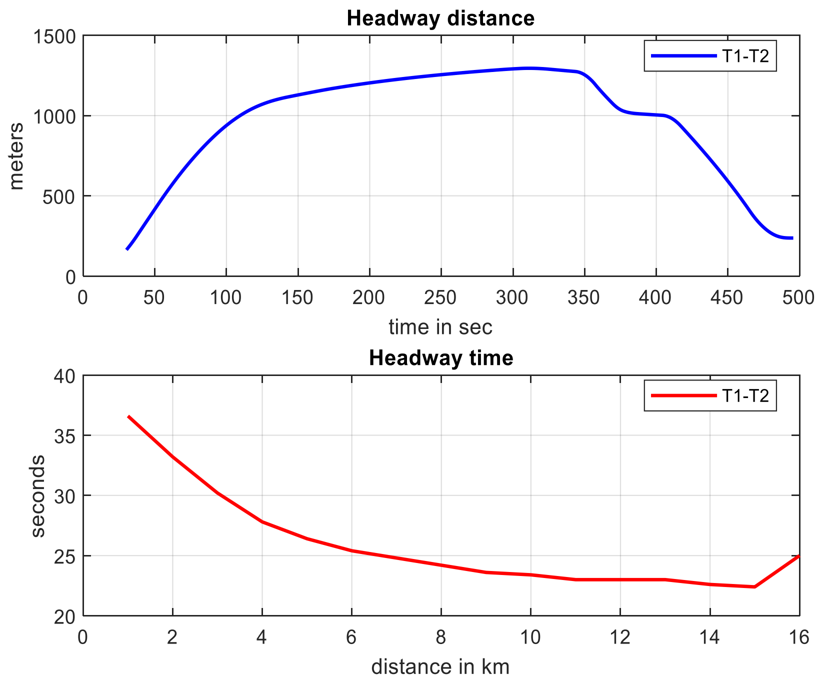


Figure 49: Multiple platform scenario headway distance and time

Table 27: Comparison of station layout scenarios

Station Layout	Headway Time Capacity	Journey Time	Assumption
Scenario 1 - Single Platform	30.8sec 116tph	T1: 479sec T2: 503sec	Train 1 awaits Train2 during dwell time (herein 30sec).
Scenario 2 - Multiple Platforms	36.6sec 98tph	T1: 466sec T2: 495sec	Train 2 joins Train 1's route via a converging point (processing time 30sec).
Scenario 3 - Ideal Platform	15sec 240tph	T1: 451sec T2: 460sec	

Table 27 shows the comparison of three scenarios. The scenarios of single platform and multiple platforms have similar results but worse than the ideal scenario. Additionally, if the number of trains and stations increased, the results would be much worse than the ideal.

5.2.2.2 Station number

The impact of changing station numbers is analysed over several scenarios. The simulation results are shown between Figure 50 - Figure 59. Table 28 shows the comparison of outcomes for different station numbers. Once the station numbers increase, the capacity decreases. This is because Train 2 arrives at each station later than Train 1. The delays lead the trains to have higher spacing than the minimum allowable distance due to the master-slave VI. Additional discussions are made in Section 5.2.3.4 with the multi-agent VI.

Table 28: Comparison of outcomes for different station numbers.

Station Number	Headway Time Capacity	Journey time

2	18.20sec 197tph	T1: 611 T2: 622
3	22.80sec 157tph	T1: 737 T2: 750
4	24.60sec 146tph	T1: 879 T2: 896
5	36.60sec 135tph	T1:999 T2:10182
6	30.40sec 118tph	T1:1108 T2:1131

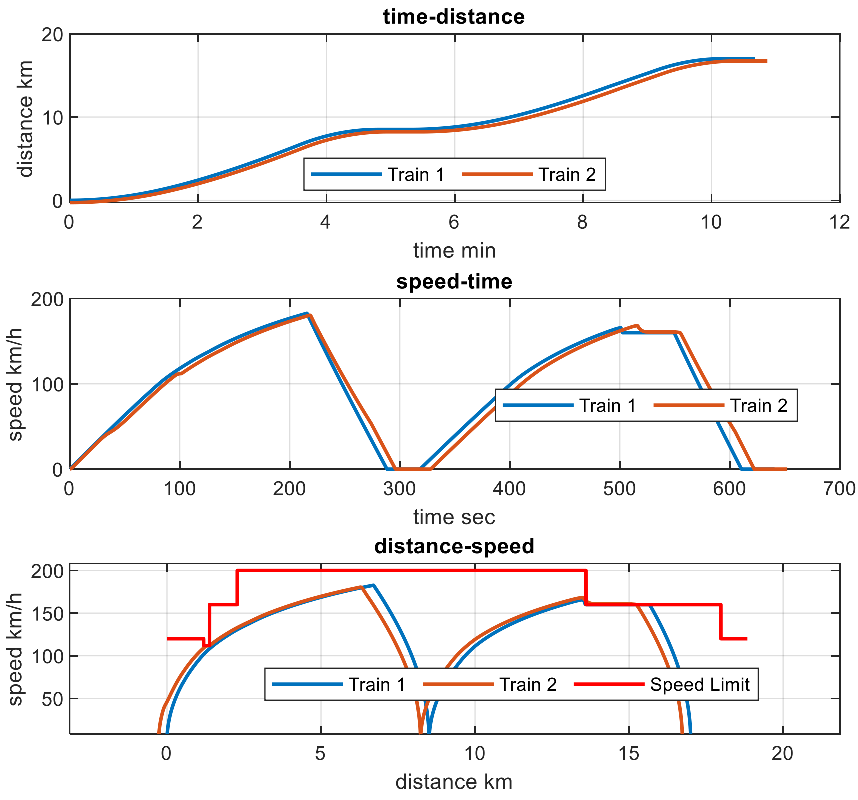


Figure 50: Train motion outputs as the number of stations is set to two.

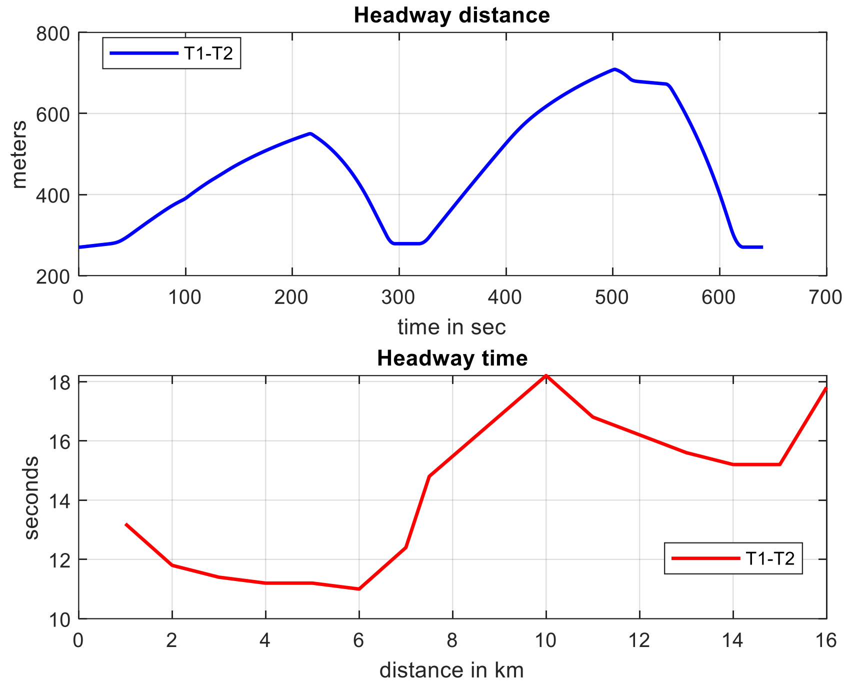


Figure 51: Capacity outputs as the number of stations is set to two.

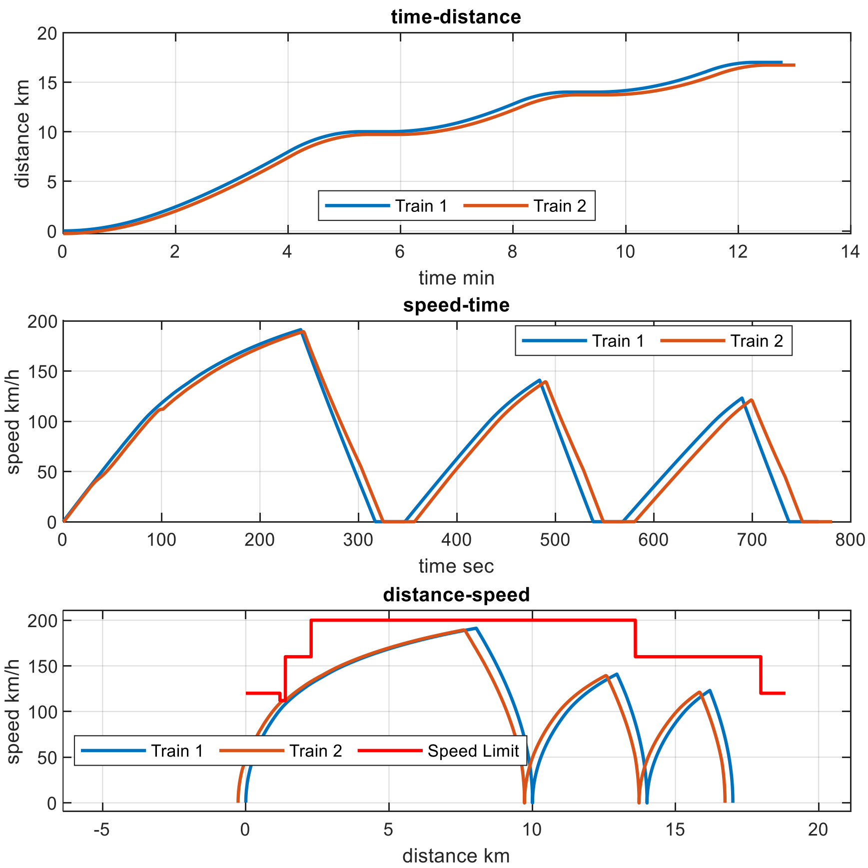


Figure 52: Train motion outputs as the number of stations is set to three.

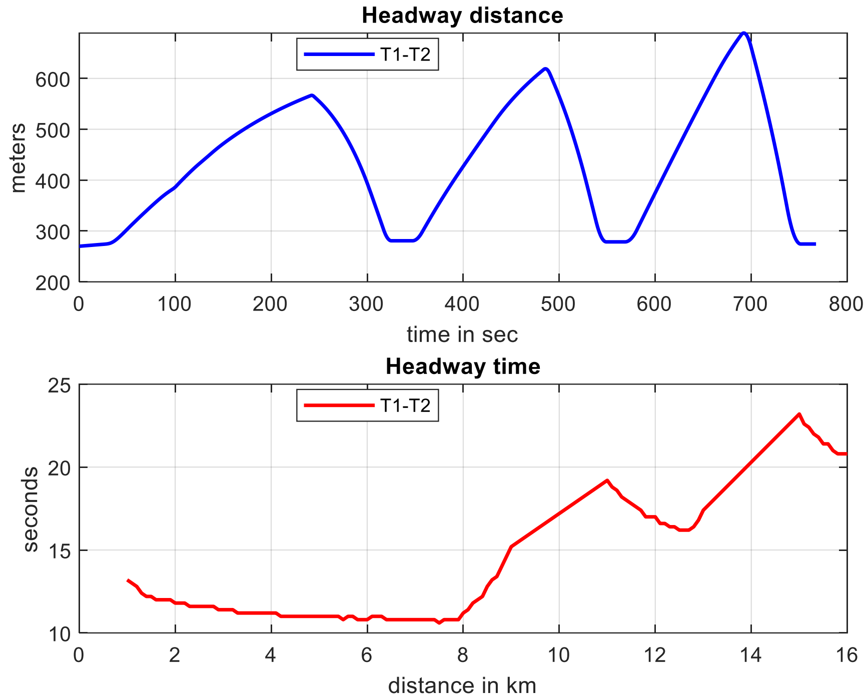


Figure 53: Capacity outputs as the number of stations is set to three.

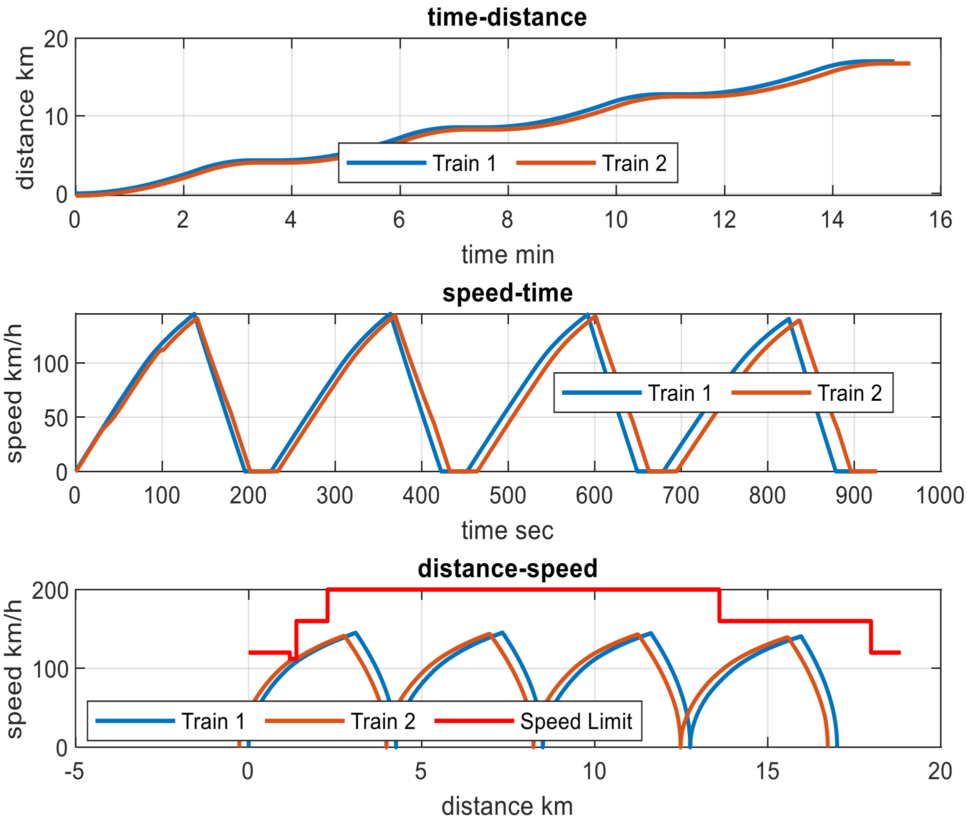


Figure 54: Train motion outputs as the number of stations is set to four.

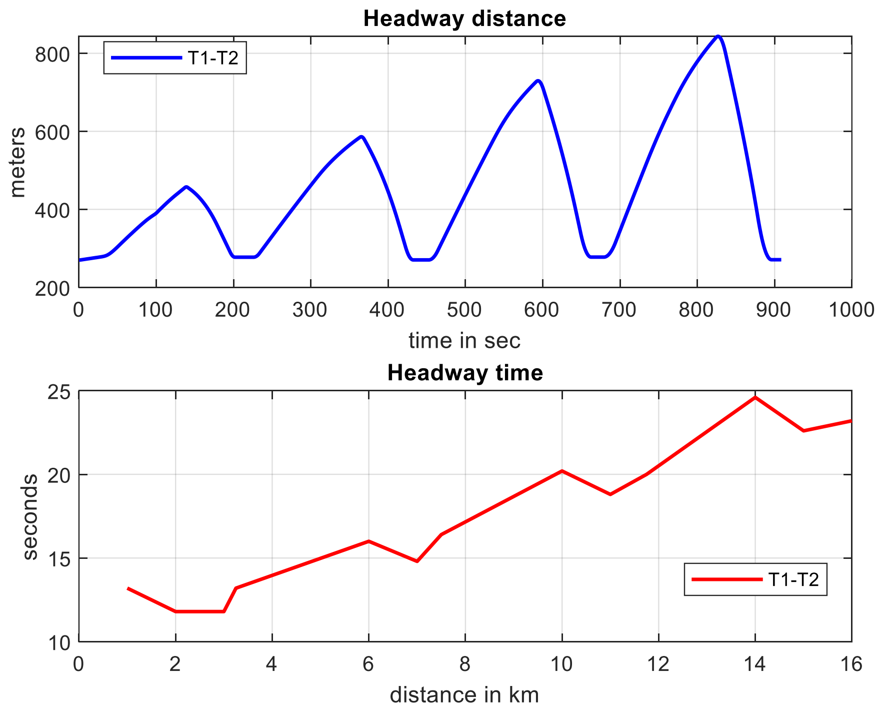


Figure 55: Capacity outputs as the number of stations is set to four.

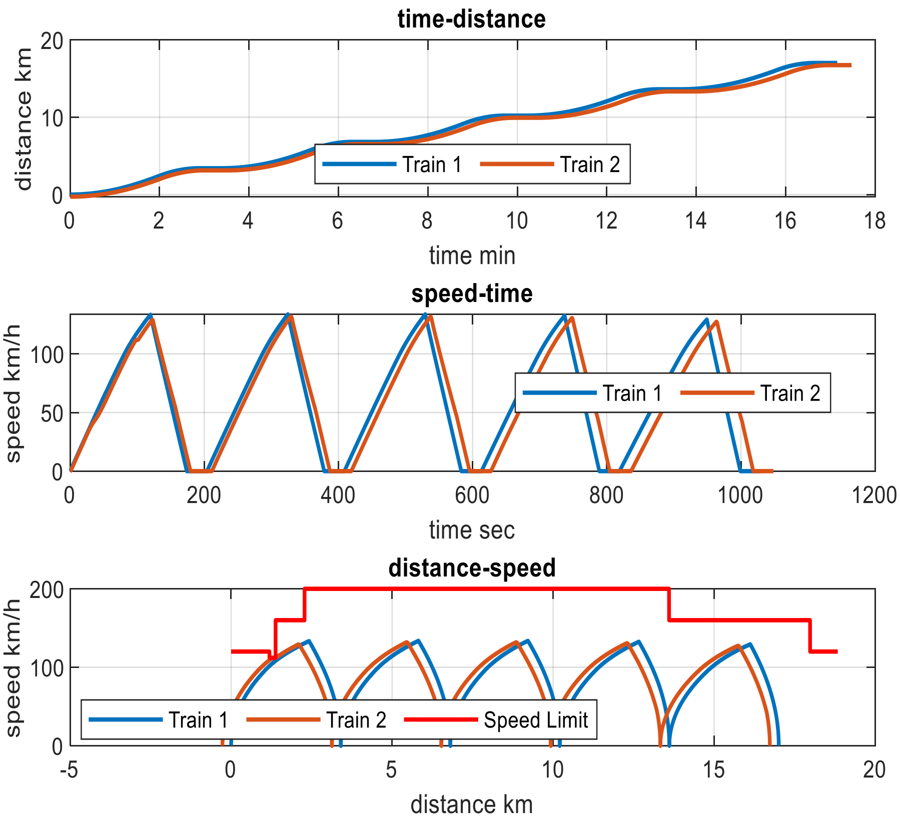


Figure 56: Train motion outputs as the number of stations is set to five.

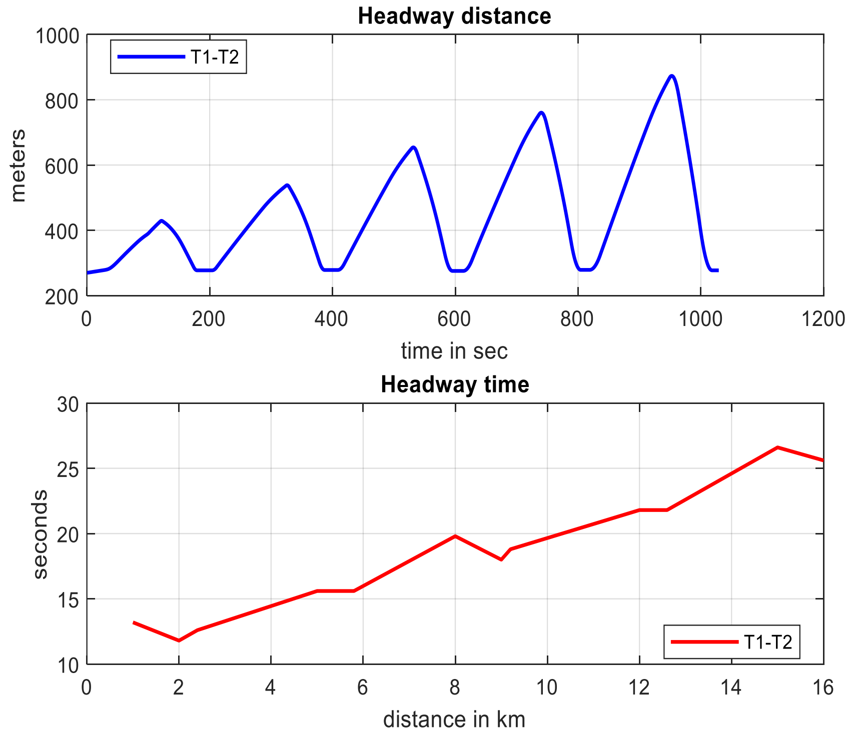


Figure 57: Capacity outputs as the number of stations is set to five.

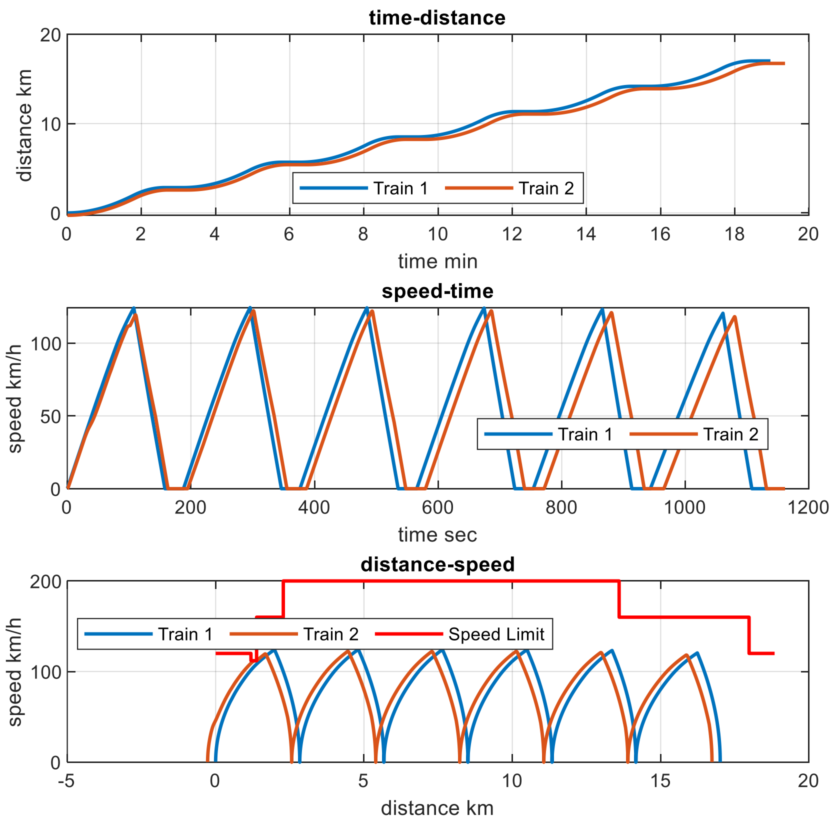


Figure 58: Train motion outputs as the number of stations is set to six.

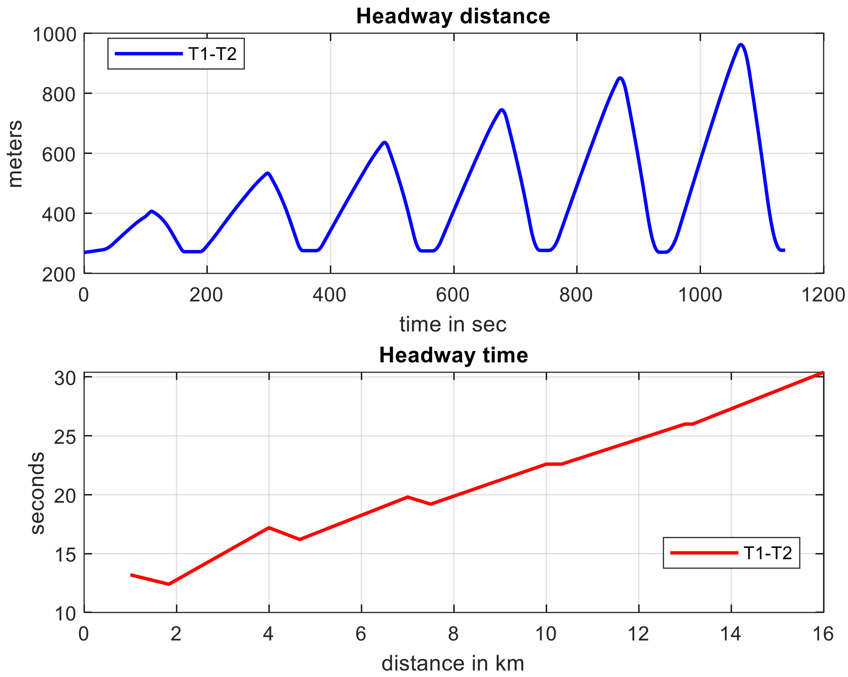


Figure 59: Capacity outputs as the number of stations is set to six.

5.2.2.3 Junctions

The turnout system plays an important role for diverging and converging routes by limited the line capacity due to the switch processing time. As seen in Section 5.1.3, the simulation results showed that the junction zone is the weakest part of the line because of the switch processing time that confines the capacity performance. The switch processing time is around 8-13 seconds (Atamuradov *et al.*, 2009; McNaughton, 2011; Connor, no date) which is small enough to accommodate the reduced headway time enabled by the RB principle. However, if a stricter safety principle, ensuring the follower must be able to stop completely before junction, is taken into action, the capacity enhancement descends onto the level enabled by the AB principle. These two different safety approaches can be summarised as follows:

i) The follower train must keep a distance that allows to stop completely before the junction, if needed, whilst the lead train is passing over the turnout.

ii) The follower train can traverse the junction in a specific time after the first train passes over the turnout.

Approach (i) limits the heady time to large extent because of longer service braking time after the train speed is over 100km/h as seen in Table 29. The approach mostly reduces the performance of the VC operation based on RB that can have around 20sec headway time over the plain line as seen in Section 5.1.3.1.1.1 . This is a different case for the VC operation based on AB of which the safe distance calculation includes full/absolute braking distance. So, only the switch processing time of 8-12 seconds is a supplement to the headway time over the plain line.

Table 29: Braking time depending on the approach speed

Approaching speed (km/h)	**Service braking time (sec) @0.5 m/s^2**	**Emergency braking time (sec) @1.2 m/s^2**
50	27.78	11.57
75	41.67	17.36
100	55.55	23.15
150	83.33	34.72
200	111.11	46.30
250	138.88	57.87
300	166.67	69.44

Approach (ii) takes only the turnout mechanism and its performance into account regardless of the train full braking time/distance. This can be an additional safety problem with RB if the junction zone has a higher possibility of derailment. However, considering that the emergency braking has shorter time and distance than the service braking (as seen in Table 29) thanks to additional systems such as sanding or eddy current brake, a specific time of 30 - 60 sec can be sensible enough depending on the train actual approaching speed.

5.2.2.4 Adhesion and gradient

Adhesion is another important factor that impacts the train's tractive and braking capability. The adhesion changes the maximum traction and braking rate i.e., constant force region in the tractive effort curve as shown in Figure 24. In Section 1.3 of Chapter 4, the equation shows the relationship between adhesion and tractive effort. A similar equation applies to braking. In normal operations, a typical adhesion level varies from 9% to 15% for braking and from 18% to 22% for acceleration (Connor, Harris and Schmid, 2015). Some external factors such as leaf fall in the autumn can reduce adhesion level dramatically down to 1% (Grassie, 2009). Table 30 shows braking rates for different levels of adhesion with the 50% motored axles. To understand how these braking rates affect the capacity, Section 5.2.1.1 can be appealed to.

Table 30: Adhesion - braking rate

Adhesion	Braking rate (m/s^2)	Commentary
0.01	0.05	Autumn leaves effect (Grassie, 2009)
0.09	0.41	
0.10	0.49	
0.15	0.74	
0.20	0.98	

In addition to adhesion, line gradient is another factor that affects the train braking and tractive capability. The steeper route is the more energy consumption and journey time. In the UK, gradients are identified as "1 in N" in which N is the number depending on the line section. If N decreases, the line segment becomes steeper. The N value is mostly higher than 100 as per the Network Rail's data (2005). Even if N equals to 100, it has the impact on braking/acceleration around $0.01m/s^2$, which is not huge enough to make a change in the capacity performance. Thus, although gradient affects energy consumption and journey time, it does not have a considerable impact on the line capacity.

5.2.3 VC Signalling and Control System

In this section, impacts of VC system factors are analysed. The factors include safety margin, braking principle, convoy length, and VI.

5.2.3.1 Safety Margin

In defining SM, there are two approaches as discussed in Section 1.4.3 of Chapter 4:

i) Defining SM as a constant value over the maximum operational speed.
ii) Defining SM as a dynamic value over the actual speed of the train.

Two approaches are simulated over the plain line scenario—OS1. The results are tabulated with Table 31. Dynamic SM brings a considerable additional capacity to the case with RB whereas does not to the case with AB. In Table 32, the result of changing total system delays is shown. The system delays impact the capacity negatively.

Table 31: Impact of SM types on capacity and headway time

SM type	**Relative Braking**	**Absolute braking**
Constant	26.60sec 135tph	53sec 67tph
Dynamic	14.80sec 243tph	50.80sec 70tph

Table 32: Impact of total system delays on capacity and headway time

Total delays	**Uncertainty**	**RB Dynamic SM**
10sec	%2.5 speed %5 location	14.80sec 243tph

20sec	%5 speed	23.20
	%10 location	155tph

5.2.3.2 Braking principle

In the literature, the braking principle is being discussed in a binary form: absolute or relative one. However, the mixed level of both principles could be implemented as a migration strategy to total relative braking. The relative braking equation in Section 1.4.2 of Chapter 4 is manipulated to include the migration approach as follows:

$$d_{min} = \frac{V_2^2}{2b_2} - k_r \frac{V_1^2}{2b_1} + SM,$$

$$k_r \in [0, 1].$$

k_r is a constant showing the relativity index in the braking principal: if $k_r = 1$, it is relative braking; if $k_r = 0$, it is absolute braking.

Table 33: Impact of relativity index on headway time and capacity

Relativity value	**Headway time (sec)**	**Capacity (tph)**
$\boldsymbol{k_r = 0}$	50.80	70
$\boldsymbol{k_r = 0.25}$	42.80	84
$\boldsymbol{k_r = 0.50}$	34.00	105
$\boldsymbol{k_r = 0.75}$	23.60	152
$\boldsymbol{k_r = 1}$	12.20	295

Four different levels of the relativity index are simulated separately, and the results are tabulated with Table 33. It is found that there is a positive correlation between the relativity index and the capacity.

5.2.3.3 Convoy length – number of trains in a convoy

The number of trains in the VC convoy is important factor that impacts the operational performance. The infrastructure cannot accommodate more than its real capability due to the factors such as station track layout, station passenger capacity, turnout, turnaround process, depot, number of tracks, the number of trains in the fleet and so on.

Five different scenarios are created changing the number of trains in the VC convoy from two to 10 incrementally. The scenarios are simulated, and time-distance graphs are shown from Figure 60 to Figure 64. In the scenarios, the signalling system between two convoys is based on ETCS Level 3.

Table 34 indicates operational results with the different number of trains in the VC convoy. As per the results, if the number of trains in the VC convoy increases, the capacity increases directly.

Table 34: Comparison of varying number trains in VC convoys

Train number in a convoy	**Convoy headway time (sec)**	**Capacity (tph)**
2 in 1	112sec	64
3 in 1	126sec	85
4 in 1	144sec	100
8 in 1	210sec	137
10 in 1	240sec	150

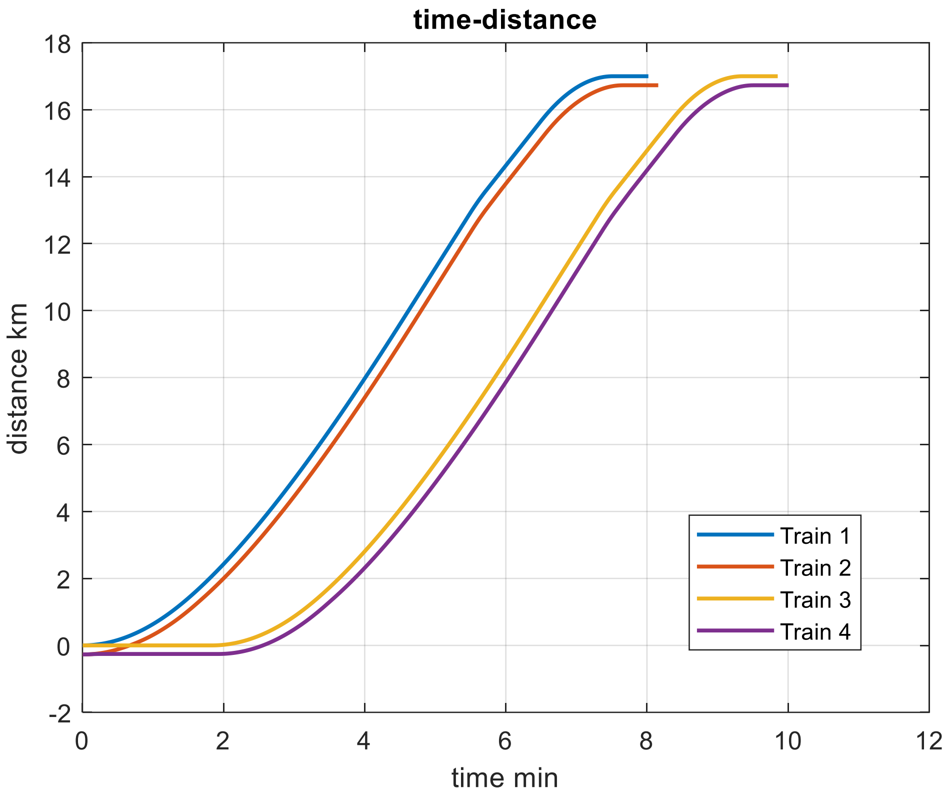


Figure 60:Time-distance graph of the simulation for 2 trains in each VC convoy

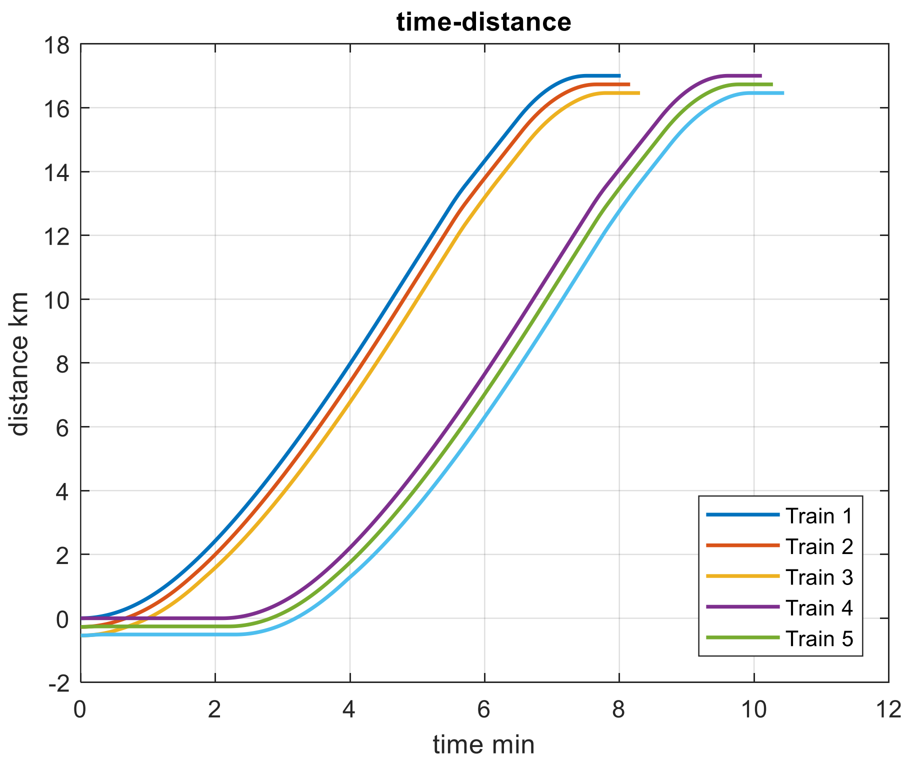


Figure 61: Time-distance graph of the simulation for 3 trains in each VC convoy

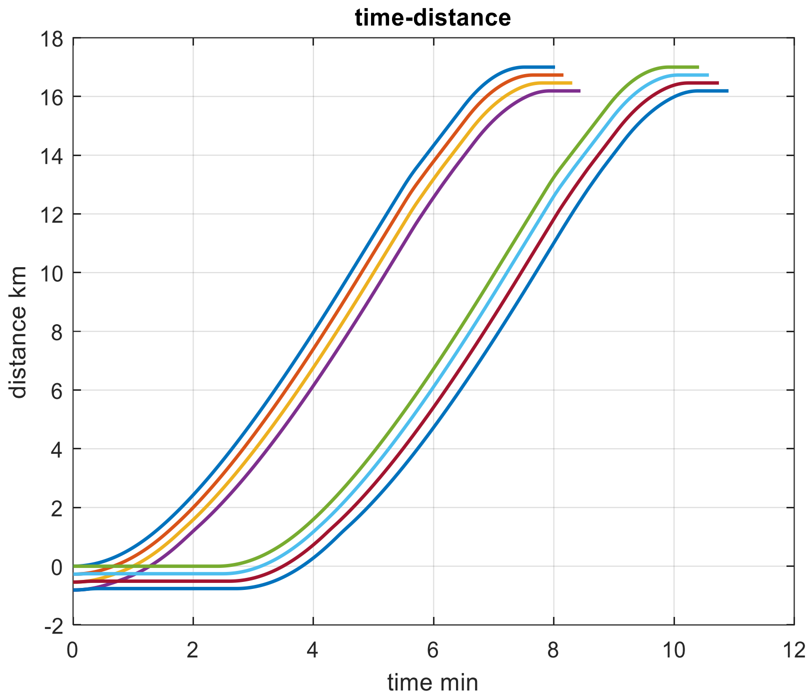


Figure 62: Time-distance graph of the simulation for 4 trains in each VC convoy

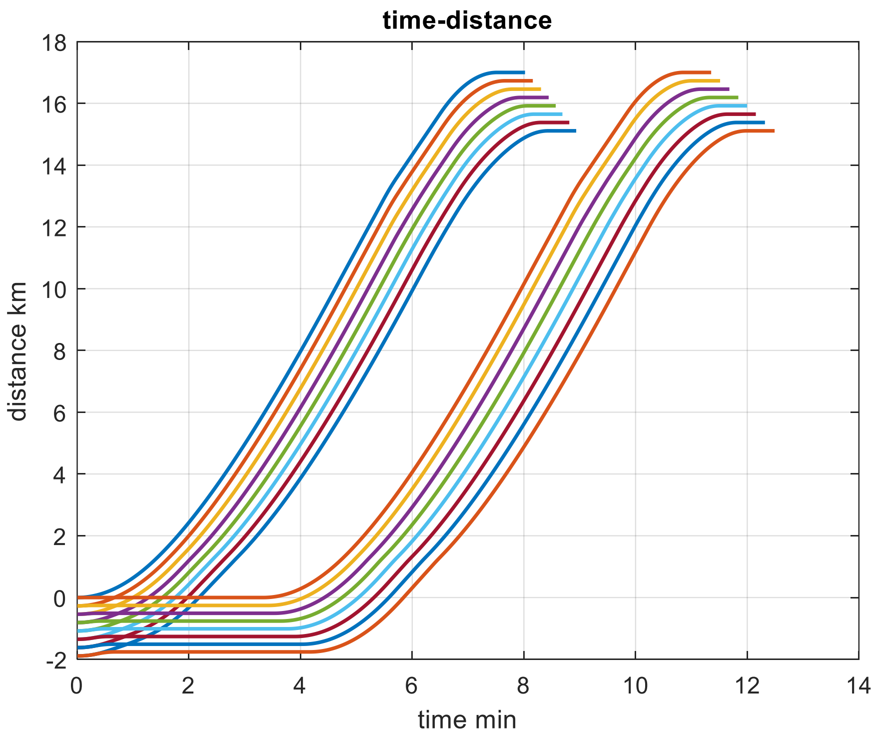


Figure 63: Time-distance graph of the simulation for 8 trains in each VC convoy

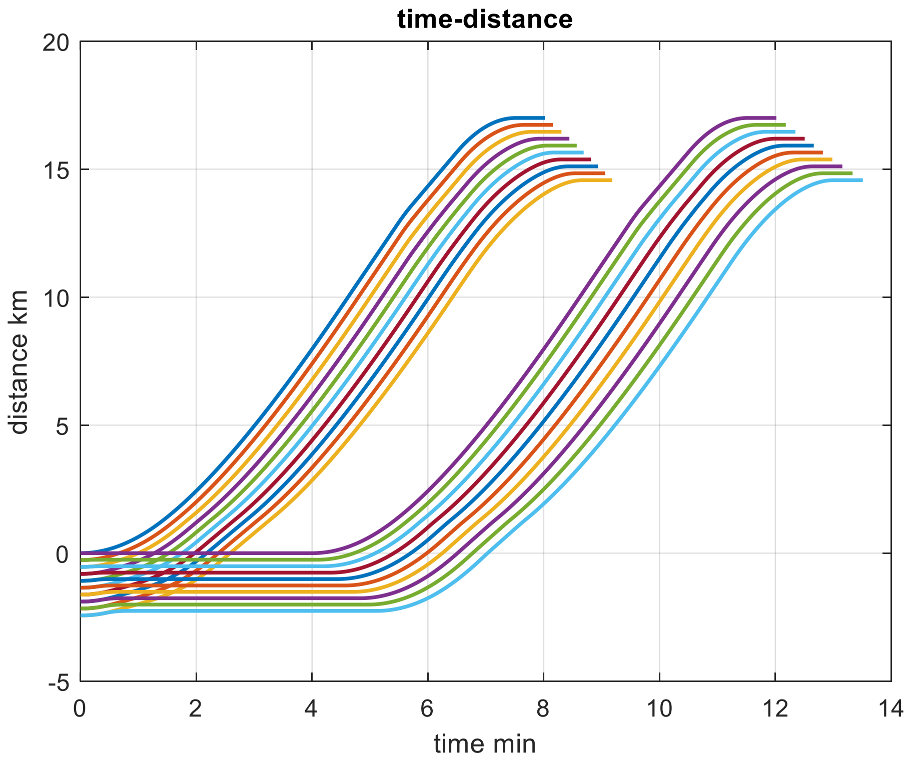


Figure 64:Time-distance graph of the simulation for 10 trains in each VC convoy

5.2.3.4 VI: Primary-secondary vs Multi-agent

The VI has two types as identified in Chapter 3. Recalling their definitions in this context, the following comparison can be made:

i) In the primary-secondary one, the lead train keeps motion regardless of that whether the follower train follows it at minimum distance or larger than. Until now, the simulations in this chapter have been based on this relationship.

ii) In the multi-agent one, however, the lead train keeps motion considering the follower train motion, i.e., if necessary, it adjusts the motion by slowing down to allow the follower one to get closer until reach the achievable minimum distance. This is important for keeping convoy stable especially once the follower train arrives at stations later than the lead train. Otherwise, the VC performance might become a problematic if the route has many stations.

The multi-agent VI is not developed through genuine mathematical modelling as it is beyond the scope of this study. However, to observe its effect on the results, a simple method is followed: The simulation of six multiple stations in Section 5.2.2.2 is repeated as if the lead train slows down in collaboration around the station areas in order that the follower train reduces the actual separation to the minimum one. The slow-down strategy is defined as that the lead train moves on a 12% lowered tractive performance in the 1st km after leaving the stations. The simulation results are illustrated in Figure 65 and Figure 66. The comparison of two scenarios is represented in

Table 35. The scenario of six stoppings has similar performance with the scenario of single stopping at final station. As per the results, it is found out that the impact of increasing station numbers is eliminated thanks to MA VI. Without MA VI, the trains start to have gradually longer headway times along the journey due to stopping at stations.

Table 35: Comparison of VI types over simulation for six stations

VI type	**Station Number**	**Headway Time Capacity**	**Journey time**
Primary-secondary	6	30.40sec 118tph	T1:1108sec T2:1131sec
Multi-agent	6	14sec 257tph	T1:1141sec T2:1143sec

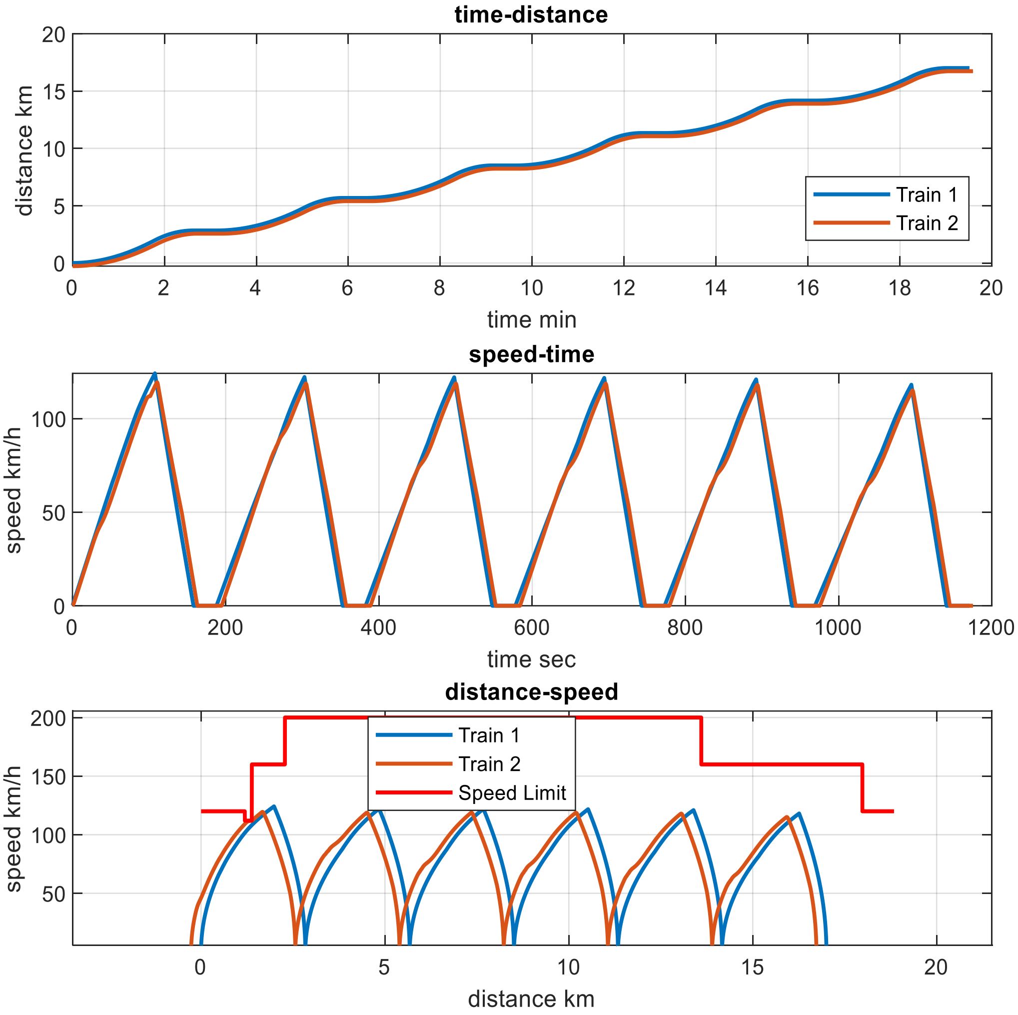


Figure 65: Train motion results of the multi-agent simulation

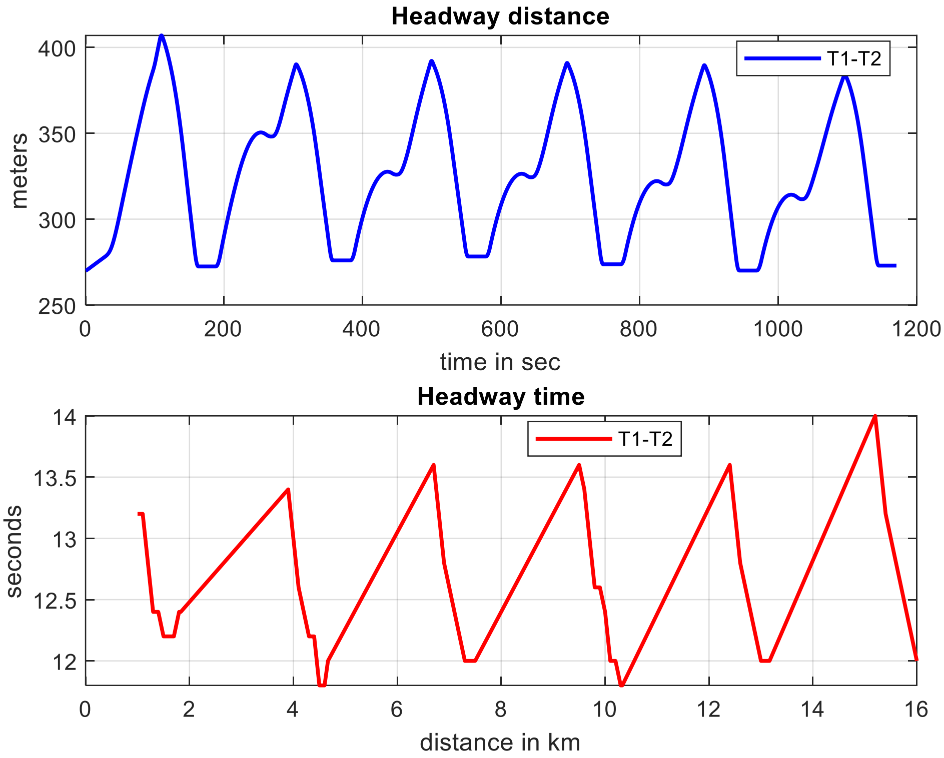


Figure 66: Headway time and distance of the multi-agent simulation

5.2.4 Discussion on the influencers

Section 2 has analysed impact of influencers upon capacity and headway. As per the results, the key points that need to be considered for creating the VC operational plan can be summarised as follows:

- Of the vehicle parameters, braking capability is one of the most important influencers since it directly affects the minimum distance calculation. The more powerful braking trains have, the higher capacity is. But adhesion can limit the braking capability because of external factors such as leaf fall in autumn. Similarly, the fleet heterogeneity can limit line capacity especially when the follower train has lower braking capability than the leader one.
- Station layout and platform can have a considerable impact on the VC operational performance. If the platform length were long enough to accommodate many trains in convoy, the VC capacity could bring about a major increase in capacity. But the capacity benefit might not be always useful depending on the station layout.

- The number of trains in convoy are very effective on capacity and headway. The convoy length is limited by station layout or platform number/ length as well as signalling and control system capability.
- Different safety principles change the capacity benefit of the VC operations. In braking principle, a spectrum approach from absolute braking to relative one is useful to see their impact and make a migration plan. Additionally, different safety approaches around junctions on diverging or converging line affect the capacity as well. The switch processing time is technically small enough, but a strict safety principle may confine the VC potential.
- The interaction type among the virtually coupled trains is also critical. The primary-secondary one does not provide a stable performance for the operational scenarios including converging point or high number of stations. The multi-agent one enables the trains to have a collaborative motion that helps keep capacity high always.

5.3 Summary

This chapter has conducted the evaluation of the VC operations with two sections. Section 1 simulated the VC operational scenarios including inter-consist and intra-consist ones. The results are provided with train motion and headway time and distance graphs. The results showed that the VC operations on RB can provide a theoretical capacity of 240tph and a headway time of 15sec over the plain line under the ideal circumstances. The scenarios including junctions can provide a capacity of 60tph and headway time of 60sec, which is limited by the switch processing time and safety principles. The VC operations on AB can provide a technical capacity between 60-70 tph including all kind of operational scenarios. Intra-consist operation is a very special VC operation that enables trains to split into sub-trains or smaller train, which helps reduce energy consumption and journey time especially for the express high-train services that does not have many commercial stops.

Section 2 explored the factors that influence the VC capacity performance, which is needed for creating the operational plan for a rail line from three aspects: From the vehicle aspect, the braking capability impacts the capacity performance. Similarly, the fleet heterogeneity affects the benefit of the VC operations negatively once the follower train has lower performance than the leader one. On the side of infrastructure, platform, junctions and adhesion are critical for the capacity performance. On side of the signalling and control system, the braking principle with a varying relativity index, the multi-agent VI and the convoy length, number of trains in the convoy are important pints in creating an operational plan for running VC scenarios.

Chapter 6 Framework For Evaluation Steps

This chapter suggests a framework that contains systematic ways for evaluating the VC operations for a specific rail line. The findings in the previous chapters underpin the framework. The framework was created utilising a modelling language, Integration Definition for Function Modelling (IDEF0). Section 1 gives introductory information on IDEF0 such as semantics and syntax. Section 2 illustrates the evaluation process using the IDEF0 model language in a three-level hierarchy.

6.1 Preliminaries for IDEF0 Diagram

In the 1970s, the US Air Force Program for Integrated Computer Aided Manufacturing (ICAM) developed a series of modelling languages named the ICAM Definition (IDEF) methods (ISO/IEC/IEEE, 2012). IDEF0 was built to produce a function model whereas IDEF1 was for an information model and IDEF2 was for a dynamics model. IDEF0 is an effective method that can be used to represent the decisions, actions and activities of an organisation or system.

Figure 67 indicates a generic IDEF0 model. The IDEF0 diagram consists of a function box with four arrows, namely, input, control, mechanism and output (Waissi *et al.*, 2015). The semantics of these terms are explained in Table 36.

Table 36: IDEF0 model terms

Model term	Definition
Function	An activity or process that transforms an input into an output. Identified by a verb or verb phrase.
Input arrow	Data or objects that are transformed by the function into outputs. Enters the function box from the left-hand side.

Output arrow	Data or objects produced by the function. Leaves the box from the right-hand side.
Control arrow	Represents the conditions such as rules, regulations, guidance, etc. that must be fulfilled to produce the correct output. Enters the box from the top.
Mechanism arrow	Represents the means such as material, resources, etc. used to perform the function. Enters the box from the bottom.

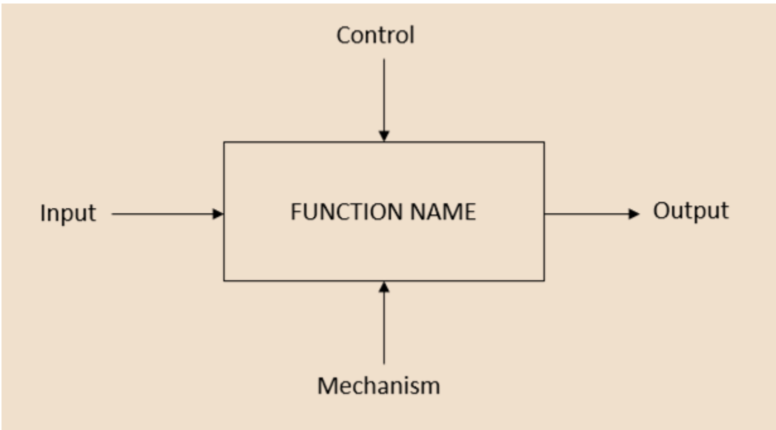


Figure 67: A generic IDEF0 model

The IDEF0 model can have a hierarchical structure that enables the decomposition of a function into a set of low-level functions that hold more details. Figure 68 shows the decomposition of the IDEF0 model in which the top model, A0 diagram, is called the context diagram that shows the highest-level representation with only one box. The lower-level diagrams include more details from the higher-level ones. The number of levels depends on the needs of the model creator.

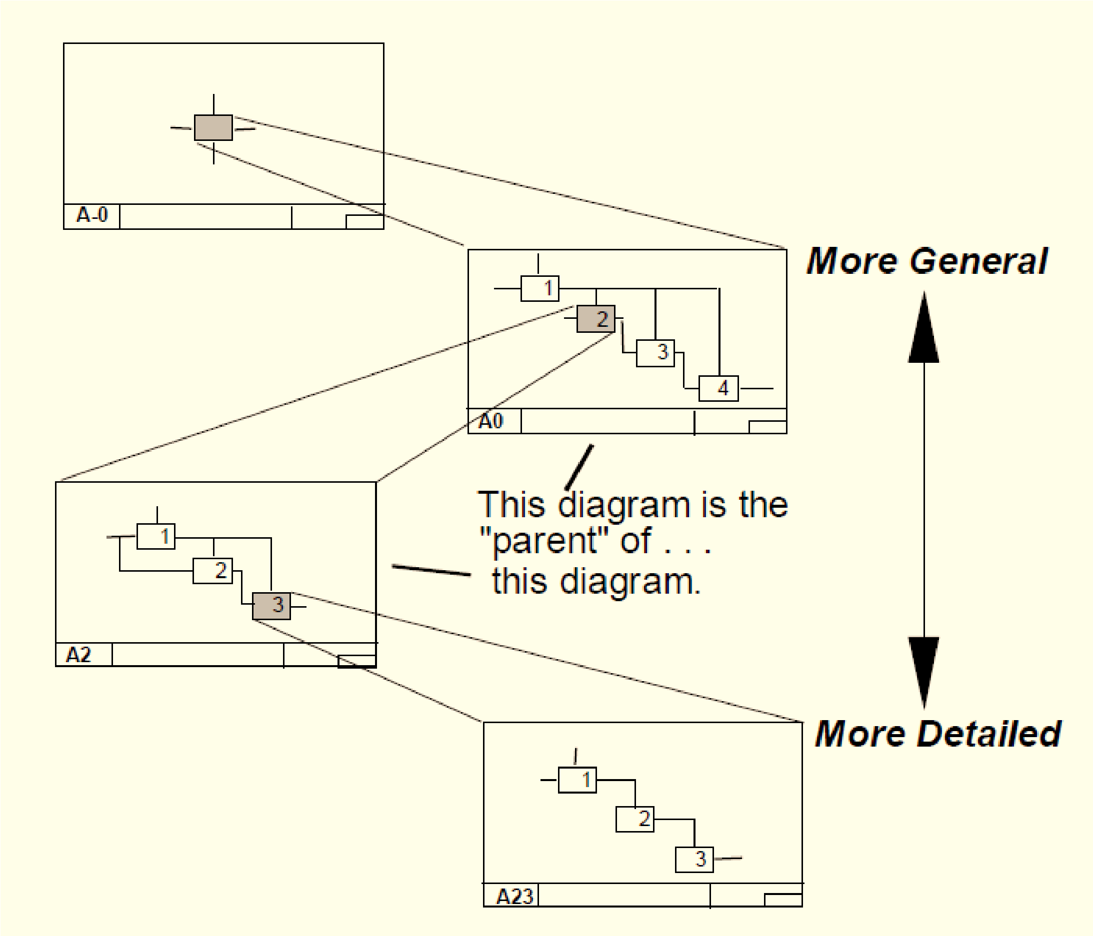


Figure 68: IDEF0 decomposition, adapted from (Fedorova, Shcheglov and Kobylyackiy, 2020)

Evaluating VC operational performance is a process that can be graphically represented as a function model. The key reasons that make the IDEF0 model preferable are as follows:

- This model provides ease of communication with a great variety of stakeholders. Therefore, the steps required for the process of evaluating VC operations can be understandable and followed by technical and non-technical people based on the collaborative consensus.
- IDEF0 enables one to conduct decomposition of functions. The activities can be explained at lower levels in detail. This feature enables traceability among a

hierarchical series of diagrams whose lower levels include more details. The details can be structured in a traceable way and extended to any level of depth.

- IDEF0 is a Systems Engineering(SE) technique that can be applied to VC as a technology at conceptual level in order to perform and manage the SE processes such as system design, requirement definition, functional analysis, and so on. In the scope of this study, it is used only for analysing operational performance.
- IDEF0 is a model, thereby representing a generic process in a formulised way that is not confined to a specific case study. The same model can be applied to any kind of rail line on which the performance outcomes of VC operations are needed.

6.2 IDEF0 Model for Evaluating VC Operations

The IDEF0 model was developed to evaluate the VC operational performance on a rail line.

6.2.1 Top-Level A0 Context Diagram

Figure 69 illustrates the A0 context diagram. The top-level function box is identified by the aim of the evaluation. The function transforms strategic demand for enhanced rail capacity of a line as the input into VC Operations Performance Report as the output. That demand would emerge, for instance, due to the line's signalling system limitation against estimated or current passenger demand for the rail line. The diagram could be a useful part of the course of decision-making of increasing line capacity through VC Operations. The process could be specifically related to upgrading the train control system of the rail line or of conducting feasibility analysis for VC operations on the rail line.

As explained in Section 5.2, a railway operation can be actualised on a rail line by the means including rolling stock, infrastructure, and signalling and control systems. These are the main components of which data is necessary to evaluate VC operations and are fed into the function box as the mechanism. Rolling stock includes all trains in the fleet. For simulating rail operations, rolling stock modelling is a must. Train dynamics were mathematically modelled with point-mass representation in Chapter 4 that explains what sort of information such as power, train length, Davis parameters etc. is required for simulation. Additionally, Section 5.2.1 figured out the important factors of rolling stock that affect VC capacity performance and need to be taken into consideration in creating the operational plan of VC scenarios. Infrastructure includes static data about rail line such as line track layout, gradient data, station position, platform length etc. which are necessary information for railway simulation. How to use data for simulation was explained in Chapter 4 through mathematical modelling. Also, impact of the factors related to infrastructure that can change VC operational performance was investigated in Section 5.2.2. Train Control and Signalling Systems is the third major component of railway operation that directly affect headway time between two rail services. Section 2.2 of Chapter 2 covered details of different train control and signalling systems. Each line has its own specific system that must be modelled in the simulation process and verified and calibrated with the line's baseline capacity. Additionally, the existing system must be compared with the other alternative systems that includes VC one, too. In this study, MTS has been utilised to do benchmarking as explained in Section 4.2. MTS has many systems such as fixed block, ETCS L2 and L3. This study developed a controller for VC operations as the details can be found in Section 4.4. Thus, the mechanism of train control and signalling systems contain information both for the existing system implemented on the line and for the alternative systems that are not implemented currently but necessary to benchmark the VC performance against.

The function has three control arrows that regulate or control an operational plan created for applying VC scenarios: VC Operational Concepts is an important control input that directly impacts how to understand VC operations and to plan operational scenarios. In this the study, Section 3.2 of Chapter 3 provided the details of VC operational definitions, classification, and scenarios. Line Baseline Capacity as another control input represents the current capacity performance of the line that can be accessible through data from the infrastructure manager which is Network Rail in the UK. In Section 5.1, VC operations were evaluated without considering timetable. However, it is necessary to benchmark them over a line's existing capacity performance which is represented by a line's timetable. Safety Principles as third control input regulates VC operational scenarios and, as a result, affects operational performance. As discussed before, this study did not define VC only with relative braking principle because its application carries a lot of barriers. So, Safety Principles feeds the information into the function about the braking principle as well as safety margin along and interlocking processing time. These factors involved in Safety Principles were simulated in Section 5.2.3 and a discussion on the findings can be found in Section 5.2.4.

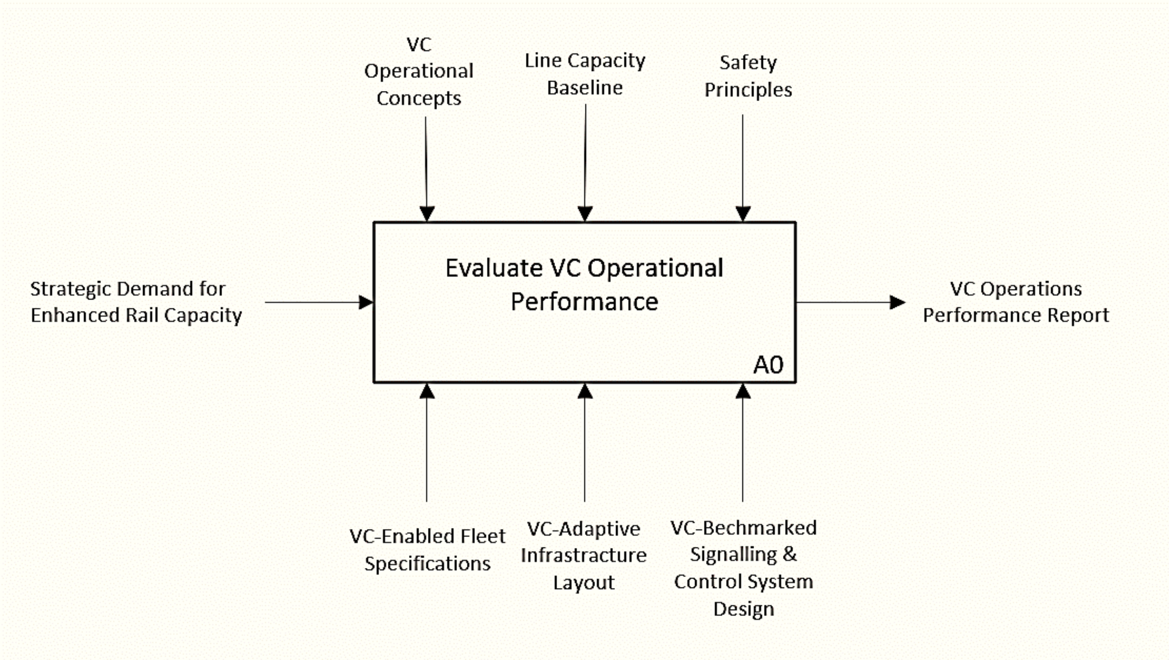


Figure 69: IDEF0 context diagram showing top-level A0 function.

6.2.2 Decomposition of A0 Diagram

The top-level function is decomposed into the child functions which explain the details of the evaluation process represented by the top-level diagram as illustrated in Figure 70. The function, 'Evaluate VC Operational Performance' is decomposed into four child functions: 'Line Capability Assessment', 'VC Baseline Performance Modelling', 'VC Operational Scenario Planning' and 'VC Operational Performance Analysis'.

The A1 function 'Capability Assessment' has as inputs 'Real Timetable Data', 'Fleet Specifications' and 'Infrastructure Layout'. The function output has as output 'Line Capability Report' which includes the analysed information of relevant factors on the existing operational performance. The information delivered as output can be described as an 'operational' inventory of the line.

The A2 function, 'VC Baseline Performance Modelling', sets the existing operational performance as the baseline. This process is necessary to be able to evaluate VC operational performance. The baselining requires the creation of a simulation structure in order to simulate the line traffic. The function input comes from the function A1 output. The process contains the validation of simulation outputs with the real timetable, which is connected to the box as a control. As the real timetable includes additional time margins upon theoretical one, A2 has the second control 'Timetable Validation Rule', which is required for knowing how to use timetable for baselining. It was discussed in Section 7.2 through a case study line's timetable. The baselining produces two outputs: 'VC-specific Simulation Structure' and 'Baseline Performance Metrics', which includes simulated timetable, too. The simulated timetable must be of a designated confidence level to validate the simulation structure and outputs.

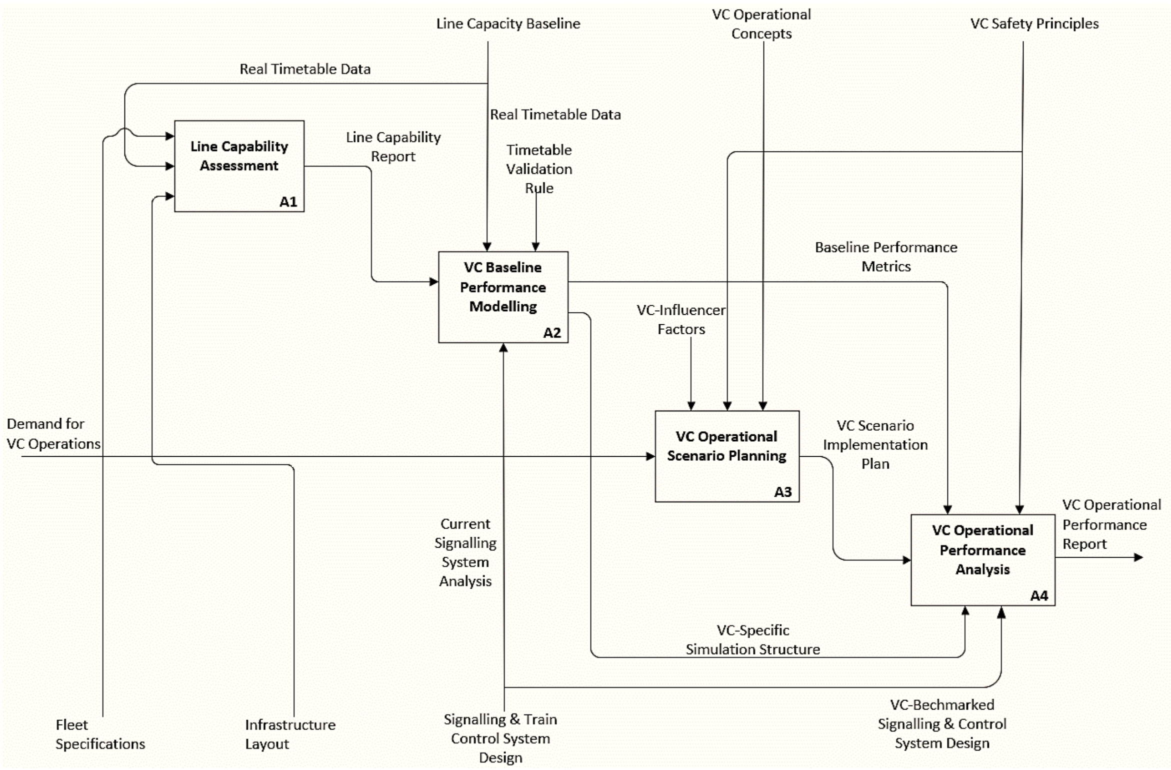


Figure 70: Decomposition of the top-level A0 function in the context diagram.

In the next step, function A3, 'VC Operational Scenario Planning', produces the plan of operational scenarios for running VC operations on the line. The function has as input 'demand for VC operations' which gives information on the stakeholder's expectation from running the VC operations—capacity enhancement, operational flexibility, reduction in energy consumption, etc. ‘VC Scenario Implementation Plan’ as the function output includes the details of how to run the VC operations on the line following ‘VC Operational Concepts’ that are connected to the box as a control and are defined in Chapter 5. ‘VC-Influencer Factors’ and ‘VC Safety Principles’ are other controls of the function. The former one was explained in Section 5.2 of Chapter 5. The latter one is also about influencing factors but only including safety-related ones i.e., braking principles and interlocking processing times. As these parameters have major influences, they are fed into function as a separate control.

Function A4, ‘VC Operational Performance Analysis’, produces the operational performance results for the VC operational scenarios. The function has as input ‘VC Scenario Implementation Plan’ that explains how to run the VC operations on the line. The function has as controls ‘Baseline Performance Metrics’ and ‘VC Safety Principles’. The function has as output ‘VC Operational Performance Report’. The output includes the results against pre-decided KPIs and benchmarking of the VC operations against the other signalling systems.

6.3 Summary

In this chapter, the evaluative steps for VC operations have been structured with a framework. The framework is grounded on the IDEF0 model language which represents any activity or process with a function box and arrows connected to it. The developed framework carries a two-level hierarchy. The first level, the A0 diagram, shows the top-level context diagram for the evaluation that shows the function of transforming stakeholders’ need for VC operations to conducting performance analysis of their scenarios. The second level, A0 diagram, covers the steps required for performing the main function at top-level that includes capability assessment, baselining, operational plan, and performance analysis.

The next chapter aims to demonstrate the framework’s usability through a case study.

Chapter 7 Demonstration of Framework through Case study

This chapter aims to apply the framework developed in the previous chapter to a case study in order to exemplify the process details to evaluate VC Ops on a specific line. The case study is based on the line section extending from London Waterloo until Surbiton.

The chapter has five sections that are named with the A0 level functions illustrated in Figure 70 of the previous chapter. Section 1 assesses the line capability in terms of the current operational performance and the assets that enable that performance. Section 2 discusses the steps required to conduct baselining that builds the ground against which the simulation results are justified. Section 3 describes the operational plan to implement VC Ops including type of scenarios, rules and assumptions. Section 4 analyses the operational performance for VC Ops benchmarking against the current line performance and alternative signalling/ train control systems through measures of the defined KPIs.

7.1 Line Capability Assessment

Line capability is analysed from four aspects as illustrated in Figure 71:

- Infrastructure: Included track layout, line speed limitation, gradient, station and junction positions, and dwell times.
- Rolling stock: Included train tractive and braking performance, train length, passenger accommodation.
- Signalling system: The existing the signalling system that impacts the minimum service interval.
- Timetable: Illustrates train services' arrival time and departure times at each station.

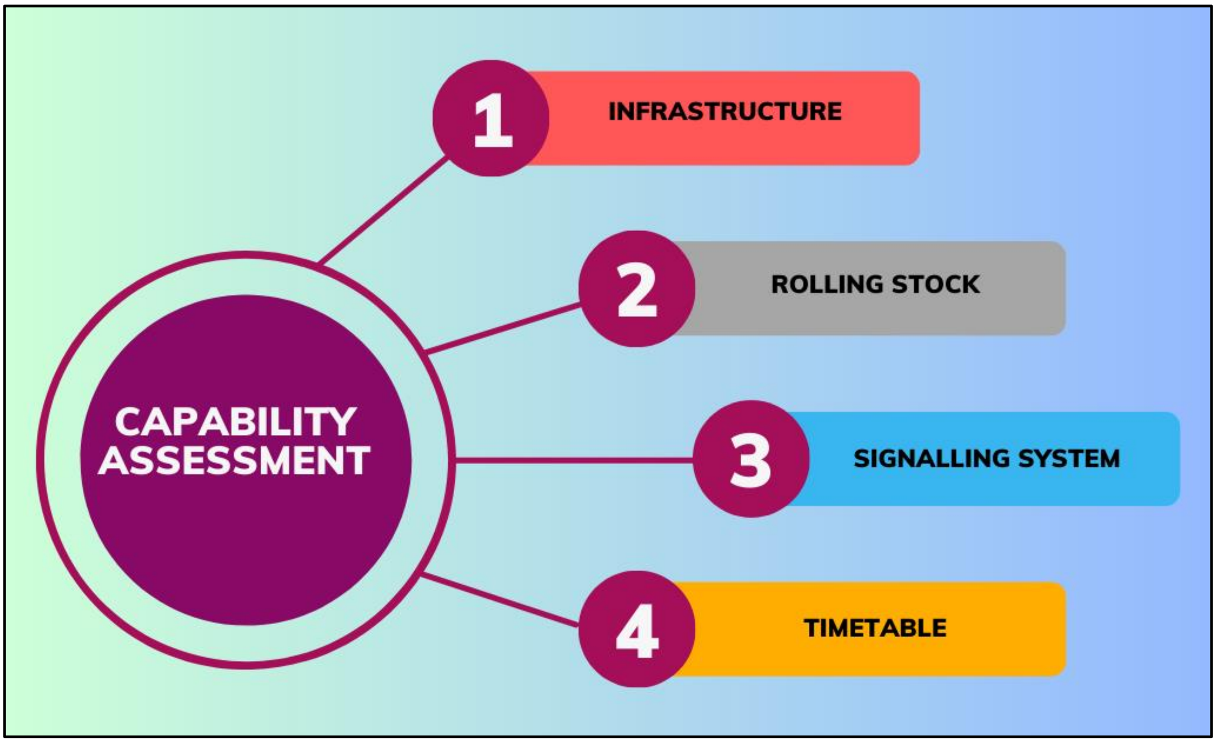


Figure 71: Capability assessment covers four components of the rail line.

Figure 72 shows the track layout that the line section of SWR starts from London Waterloo and ends at Surbiton, in which two junction points exist at Raynes Park and New Malden. The diverging trains leave the section before the station around Raynes Park and after the station at New Malden. Table 37 gives the target positions and existing dwell times. Figure 73 indicates the gradient and speed limit profiles.

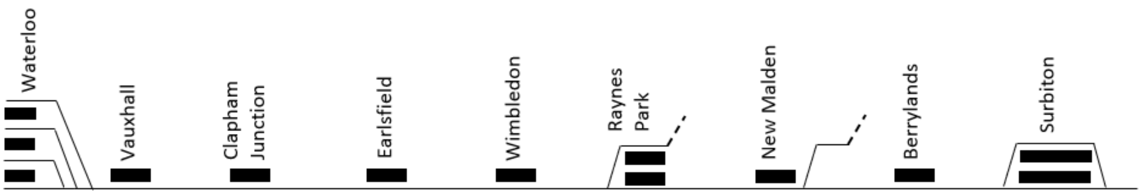


Figure 72: Track layout.

Table 37: Target names, positions, and dwell times

Station/Junction	Position (meters)	Dwell time (seconds)

London Waterloo	0	-
Vauxhall	2012	60
Clapham Junction	6437	60
Earlshield	8851	30
Wimbledon	11668	60
Junction 1	13981	-
Raynes Park	14082	30
New Malden	15691	30
Junction 2	15791	-
Berrylands	17703	30
Surbiton	19312	60

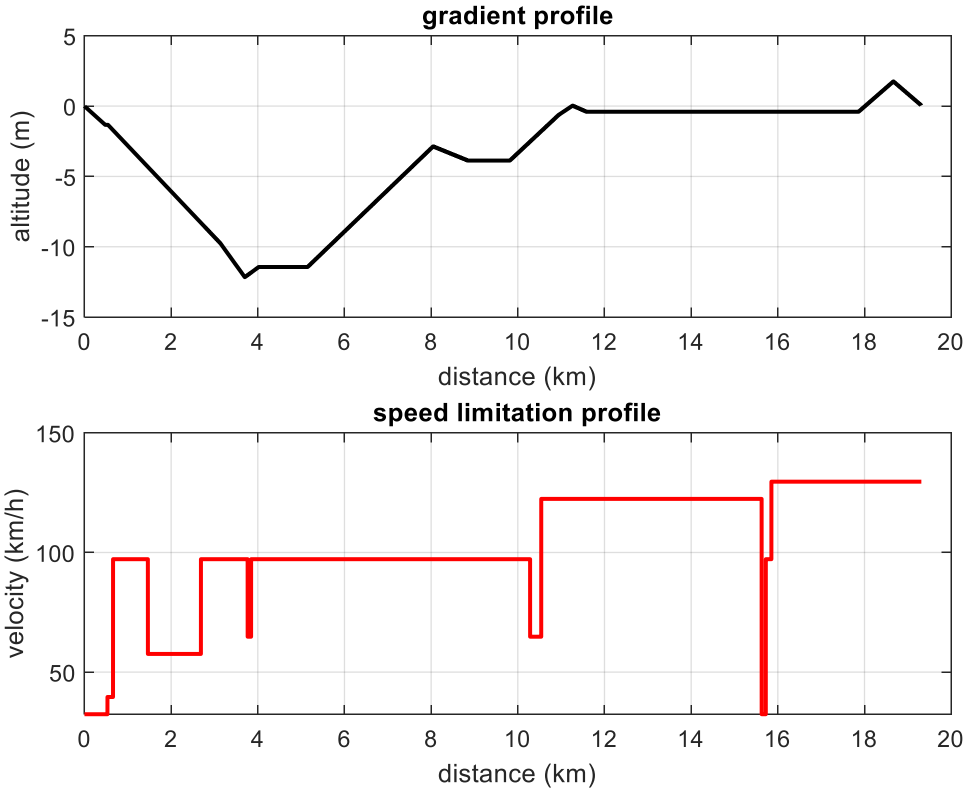


Figure 73: Gradient and speed limit profiles.

On the line section, there are three types of rolling stocks: British Class 450, 455, and 707. Their vehicle parameters are given in Table 38. The tractive effort and acceleration curves are shown with Figure 75, Figure 76, and Figure 77.

Table 38: The vehicle parameters

Parameter	**BC 450**	**BC 455**	**BC 707**
Maximum speed (km/h)	160	121	160
Maximum acceleration (m/s^2)	1.00	0.58	0.85
Tractive system efficiency	85%	85%	85%
Train length (m)	82	82	102
Maximum power at wheel (kW)	1500	1000	1200
Train Mass (tonne)	176	132	165
Proportion of powered axles	50%	25%	40%
Seating capacity	285	244	275
Number of carriages per train	4	4	5

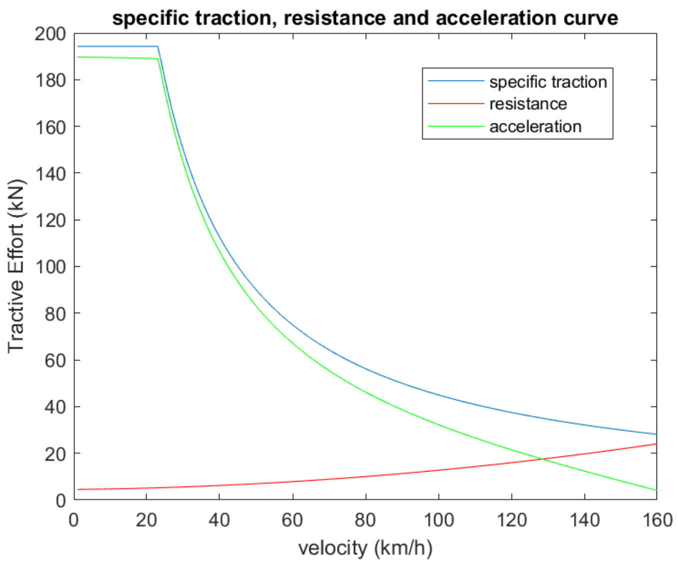


Figure 74: BC 450 tractive effort and acceleration curve.

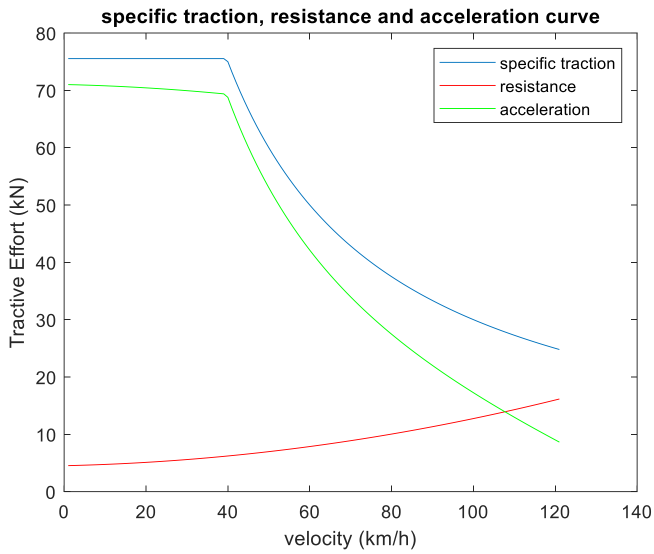


Figure 75: BC 455 tractive effort and acceleration curve.

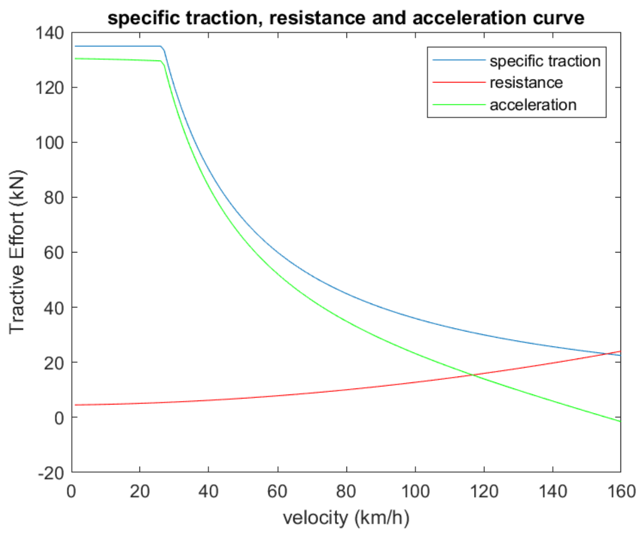


Figure 76: BC 707 tractive effort and acceleration curve.

Figure 77 indicates the timetable of line section between London Waterloo and Surbiton. The timetable is illustrated utilising the data published by Network Rail that includes the departing trains on 14th June 2022 on the direction from Waterloo to Woking between 8am and 9am. Table 39 shows the train services' departure times from Waterloo with their classes. As shown in the timetable, Train 3, 6, 9 and 12 diverge through the junction around New Malden and Train 5, and 10 diverge through the junction around New Malden.

The line is operated with the 4-aspect fixed block signalling system. As per the timetable, the line capacity is 12tph for one hour time window from 8am to 9am as tabulated in Table 39. The minimum service interval between two services is 3min.

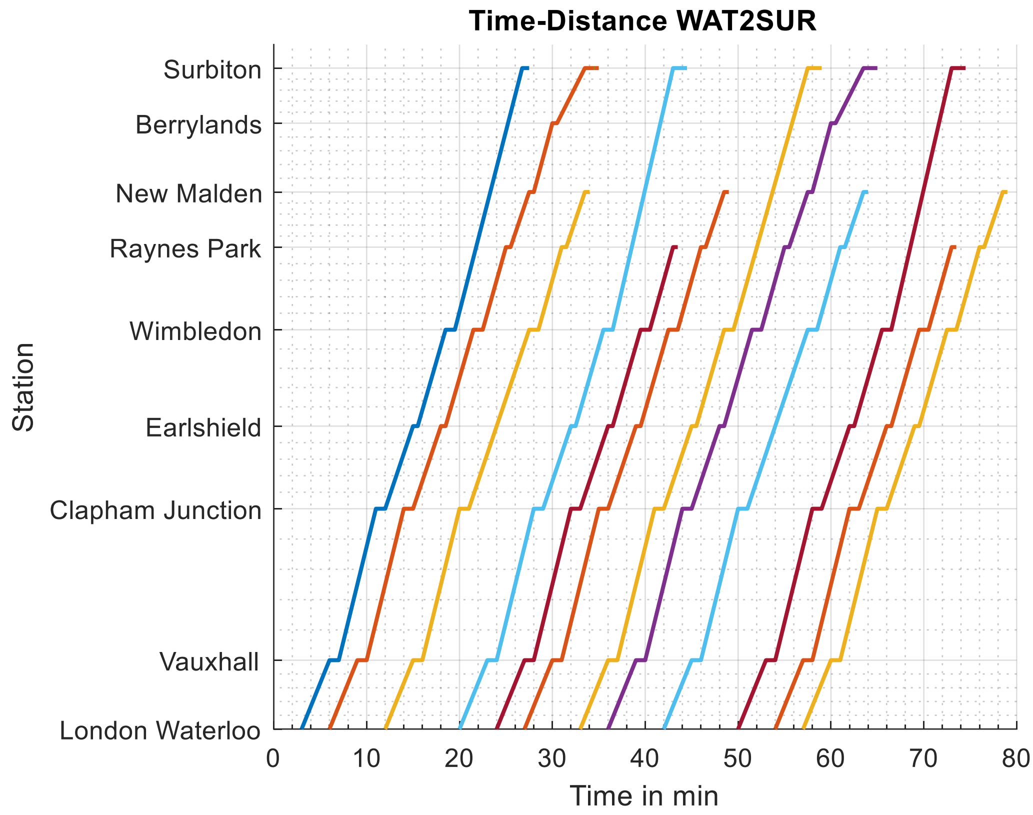


Figure 77: Timetable of line section between London Waterloo and Surbiton

Table 39: Train services vehicle class, and departure time

Service	ROCS Class	Departure Time
Train 1	450	08:03
Train 2	455	08:06
Train 3	707	08:12
Train 4	455	08:20
Train 5	455	08:24
Train 6	455	08:27
Train 7	455	08:33
Train 8	455	08:36

Train 9	707	08:42
Train 10	455	08:50
Train 11	455	08:54
Train 12	455	08:57

7.2 VC Baseline Performance Modelling

Baselining starts with the validation of simulation against the real data. This includes two steps:

i) Validating the train motion with time-distance graph
ii) Validating the minimum headway time/service interval

Step (i): BC 450 departing at 08:03, BC 455 departing at 08:06, and BC 707 departing at 08:12 are simulated to calibrate the simulator. In calibration, maximum speed between two stations is varied and adjusted to set station arrivals times exact to the real TT. The results are given in Table 40 and Figure 78. It is ensured that the simulation results have an acceptable level of confidence.

Table 40: Comparison of simulation results for train position over time to real TT. The numbers are in min.

ROCS Class		Waterloo	Vauxhall	Clapham Junction	Earlsfield	Wimbledon	Raynes Park	New Malden	Berrylands	Surbiton
BC 450	Real TT	3	6	11	15	18.5	-	-	-	26.5
	Simulation Result	3	5.85	11	14.75	18.73	-	-	-	26.71
BC 455	Real TT	6	9	14	18	21.5	25	27.50	30	33.5
	Simulation Result	6	9.12	14.45	17.92	21.63	25.18	27.58	30.32	33.38

BC 707	Real TT	12	15	20	-	27.5	31	33.5	-	-
	Simulation Result	12	15.07	20.35	-	27.52	31.42	33.98	-	-

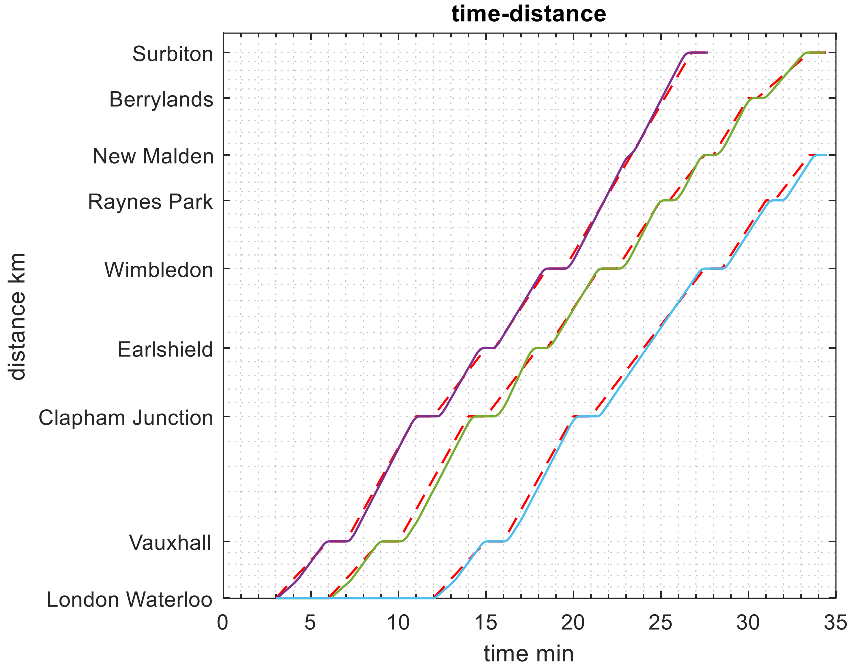


Figure 78: Comparison of the simulation results for train positions over time to the real TT. The red dash lines represent the real TT entries, the colourful lines represent the simulation results for BC 450, 455, and 707 in order.

Step (ii): Validating the service interval of real TT is more challenging. The more realistic results need to run a detailed microscopic simulation that requires to have more information on infrastructure e.g., each block's length throughout the line section, which is out of this study's scope. Furthermore, the real TT has higher headway and lower capacity than technical ones since it includes additional times between the services such as operating margins, and buffer times in order to keep reliability at acceptable level (Abril *et al.*, 2008).

In this analysis, it is assumed the train services in the real TT are arranged applying the UIC 406 compression rule that the operational capacity is 75% of the technical one (2013). Following the UIC principle, MTS is calibrated to have a capacity of 16tph and an average service interval of 223sec. In calibration, the fixed block length is set to a value that does not cause an interference between two trains. If there is any interference, the follower train faces an unnecessary braking implying that the trains are closer than the minimum distance permitted by the signalling and control system. Figure 79 shows the compressed and calibrated TT.

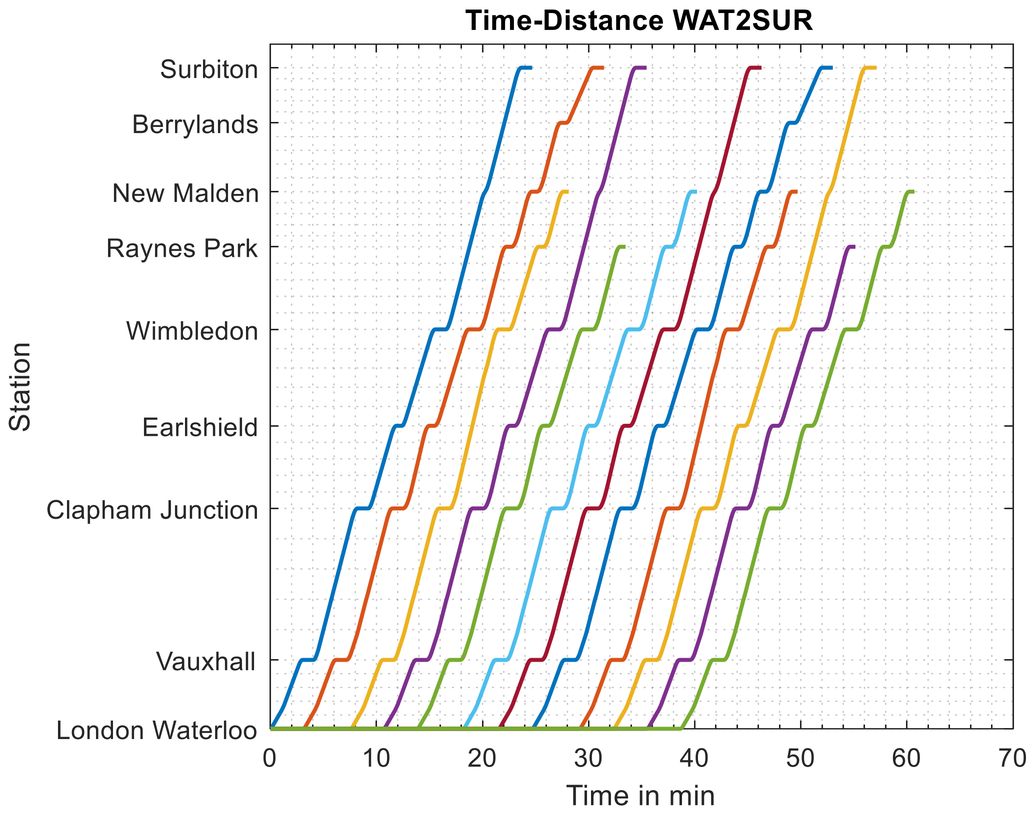


Figure 79: The compressed and calibrated TT that has an average service interval of 210sec.

7.3 VC Operational Scenario Planning

In developing operational plan, some important factors related to the line and VC operations should be taken into consideration as analysed in Chapter 5. Stopping pattern impacts the VC operations. Specifically, the mixed pattern put some difficulties to implementing VC Ops. Coupling and decoupling trains frequently limits the potential unleashed by VC Ops. Thus, it is assumed that each train stops at each station whereas the real TT has mixed stopping pattern. Braking principle is important to arrange the minimum distance between trains in the same convoy. The relativity index is set to three different values to observe the simulations over pure absolute braking, half relative braking, and pure relative braking distance. In addition, the number of trains in the convoy is one of the key factors affecting the VC operational performance directly. The number of trains in the convoy is set to two, three, and four for different scenarios. Also, the junctions have limitation on the VC performance due to the interlocking processing time (IPT). This plan analyses the VC performance with the IPT value of 60seconds. The fleet heterogeneity is another important factor for this line since there are three types of rolling stock. The trains are homogenised in terms of braking and acceleration effort based on the assumption that VI is formed by the multi-agent architecture.

Table 41 indicates the scenarios planned for the case study line. The safety approach determines the relativity index: the low level has the highest relativity, the high level has the lowest relativity, and the medium level is average of both levels. In each safety level, VC convoys are formed with two, three, or four trains, which makes 12 scenarios in total.

Table 41: Operational scenarios applied to the case study line.

Safety Level	Relativity index	Number of trains in convoys
Low	Kr=1	2 in 1, 3 in 1, and 4 in 1
Medium	Kr=0.5	2 in 1, 3 in 1, and 4 in 1
High	Kr=0	2 in 1, 3 in 1, and 4 in 1

The assumptions the scenarios based on are summarised as follows:

- Stopping pattern is changed to a simple TT in order to make decoupling and coupling easier.
- Platform length is assumed sufficiently long to accommodate a *virtual convoy* comprising up to four trains.
- Virtual interlocking is formed by multi-agent architecture by applying the techniques in Chapter 5.
- The timetables produced by the simulations represent the theoretical capacity. The sustainable capacity is set by operation managers considering many factors—which is out of this study's scope.

- The inter-convoy signalling system is based on ETCS Level 3.

In addition to the assumptions, it is necessary as part of the process to decide on which measures are used to assess performance of the operational scenarios defined above. In this study, the KPIs are selected following the quality of service framework developed by (2013):

- Line capacity: Measured by calculating service frequency in terms of train per hour.
- Passenger accommodation: Determined by the rolling stock's capacity to carry passengers. Several rates can be used to measure it such as passenger space kilometre or passenger per direction per hour etc.
- Journey time: The total consumed time for trains to complete their journeys.
- Energy consumption: The total energy consumed by running a rolling stock or all services over a period.
- Resilience: The ability of rail services to balance the impact of unpredicted circumstances that lead to delays in the operating environment. Several rates are suggested to measure it. The maximum total delay in seconds is used in this study.

7.4 VC Operational Performance Analysis

The simulation results of the operational plan are presented in this section with timetabling and the KPIs. The subsections give the results, successively, of the low, medium, and high safety levels.

7.4.1 Safety Level Low

The results are given for three scenarios of the convoy formation i.e., 2 in 1, 3 in 1, and 4 in 1, at low safety level in the following subsections.

7.4.1.1 VC 2 in 1

The simulated timetable of VC on the basis of the 2 in 1 formation at low safety level is given in Figure 80. The zoomed version of TT showing the junction areas closer is shown in Figure 81. In timetabling the operation plan, the train services are compressed as much as the VC system allows it theoretically. The earliest time the 13rd train can start journey is in the 844th second. Then, the average headway time between two trains is 70seconds. As a result, the capacity is 51tph. Table 42 includes these values along with other ones including passenger accommodation, rolling stock usage, journey time, energy consumption.

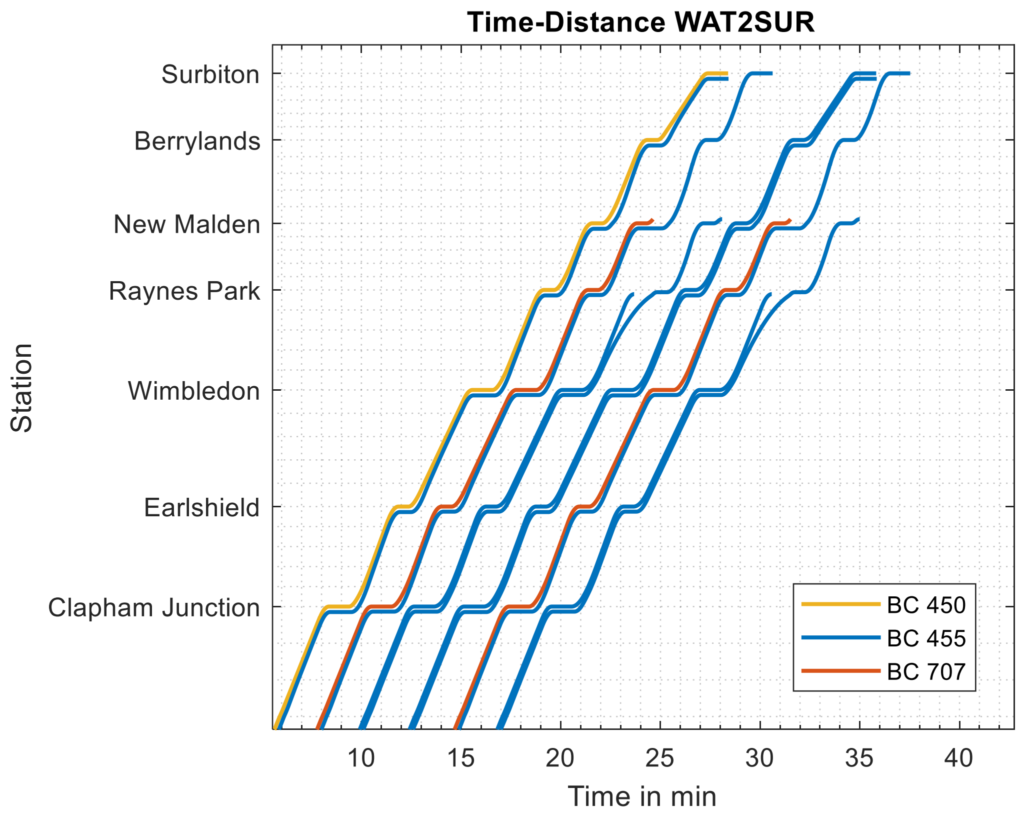


Figure 80: Timetabling for VC 2 in 1 at low safety level

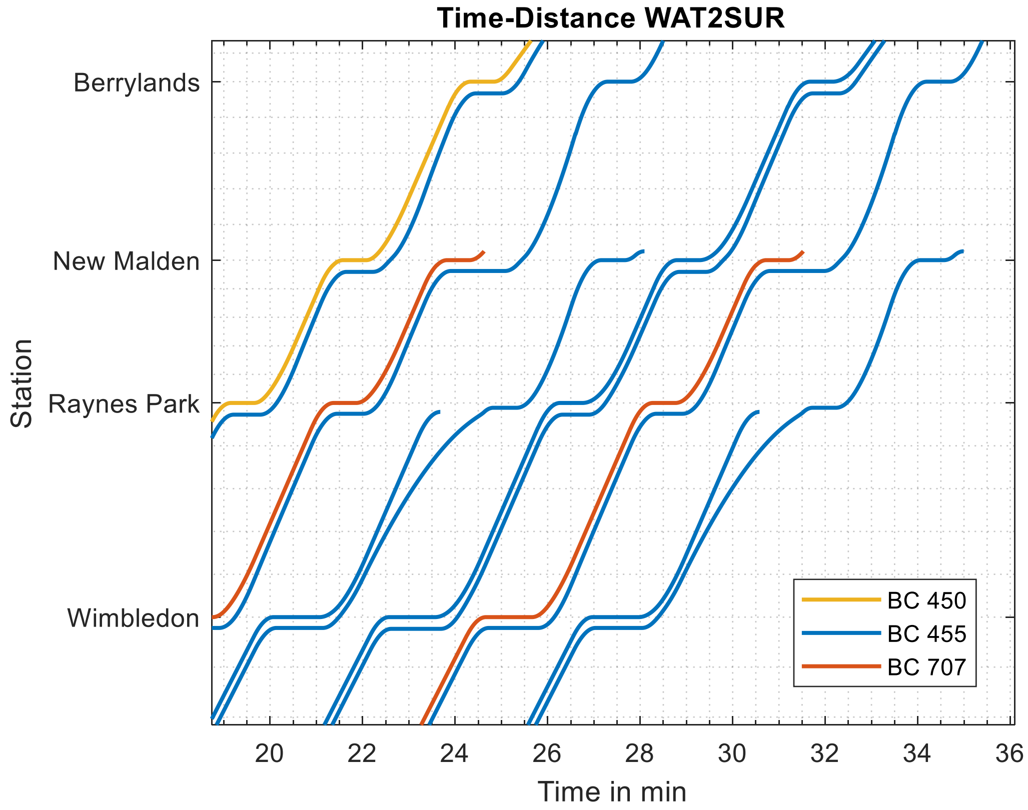


Figure 81: Zoomed view for junction sections

Table 42: Operational KPIs of VC 2 in 1

KPI	**Value**
Line capacity	51tph
Passenger accommodation	25,764ppdph
Rolling stock usage	65 (15min turnaround)
Total journey Time	17,900sec (see Figure 82 for individual values)
Total energy consumption	2715kWh (see Figure 83for individual values)
Resilience – Total delays	778sec (see Figure 84 for individual values)

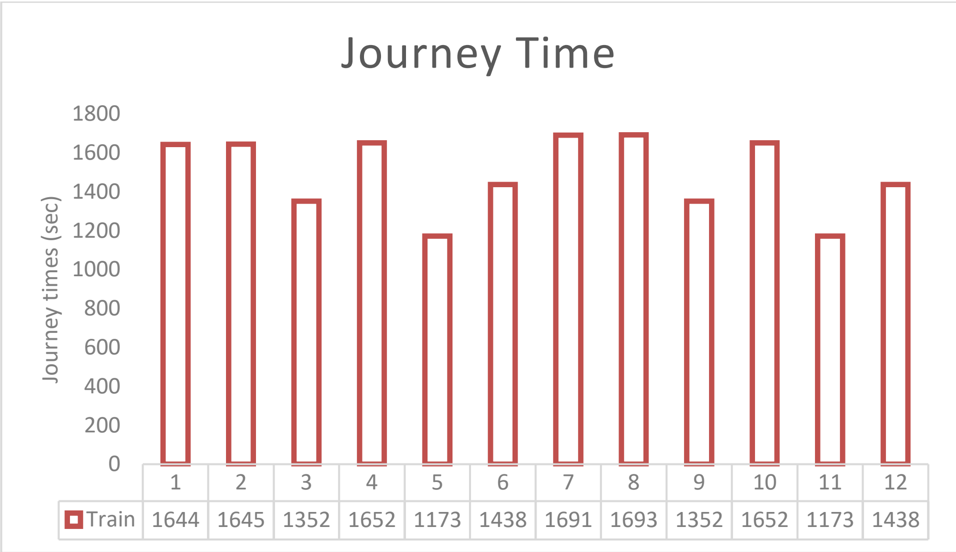


Figure 82: Journey times of VC 2 in1 operation at low safety level

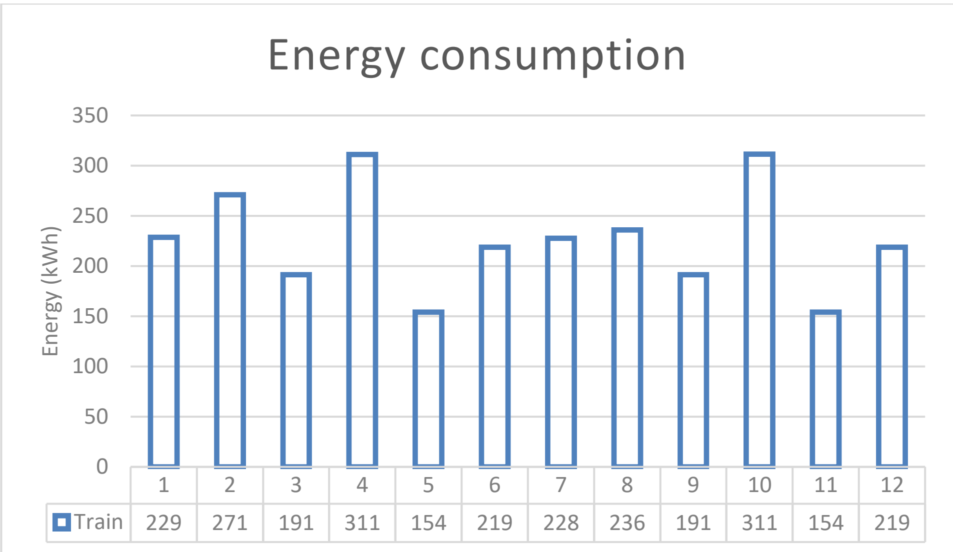


Figure 83: Energy consumption of VC 2 in 1 at low safety level

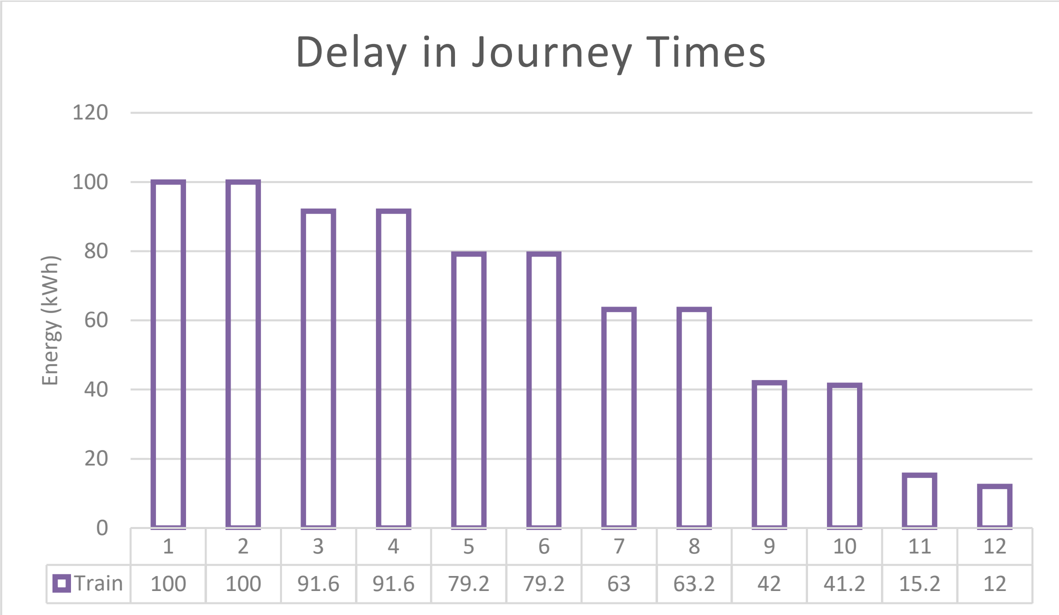


Figure 84: The resultant delays caused by the perturbation operation for VC 2 in 1 at low safety level

7.4.1.2 VC 3 in 1

The simulated timetable of VC on the basis of the 3 in 1 formation at low safety level is given in Figure 85. The zoomed version of TT showing the junction areas closer is shown in Figure 86. In timetabling the operation plan, the train services are compressed as much as the VC system allows it theoretically. The earliest time the 13rd train can start journey is in the 792nd second. Then, the average headway time between two trains is 66seconds. As a result, the capacity is 54tph. Table 43 includes these values along with other ones including passenger accommodation, rolling stock usage, journey time, energy consumption.

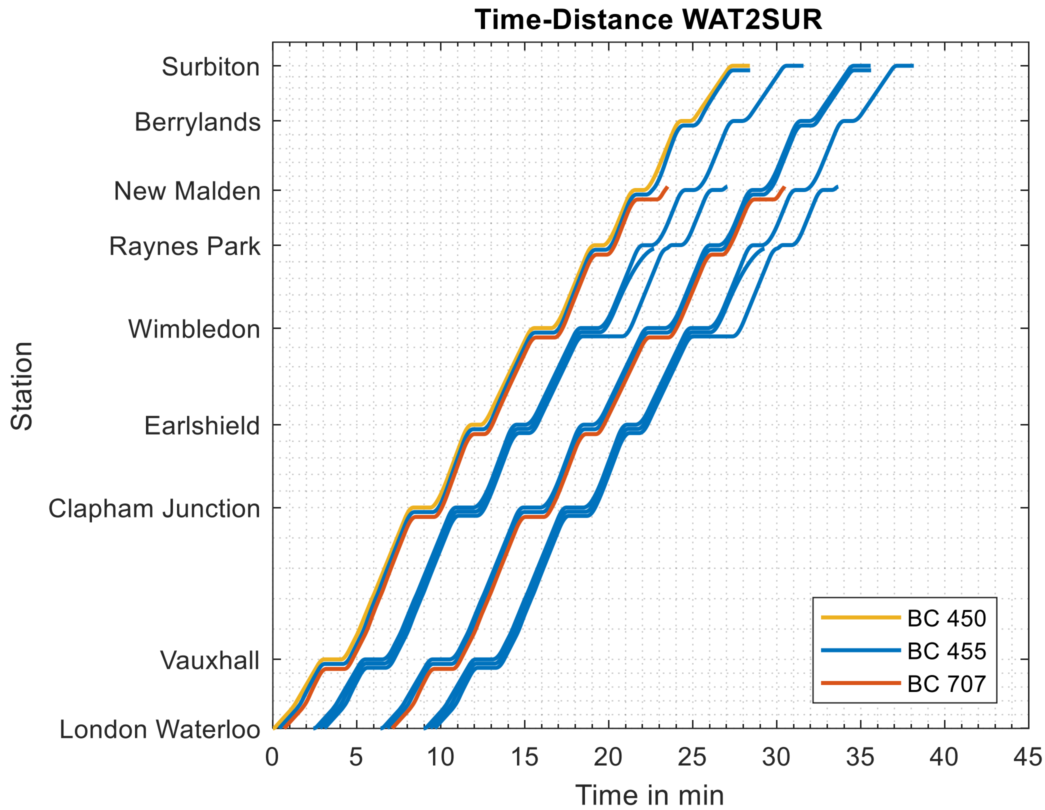


Figure 85: Timetabling for VC 3 in 1 at low safety level

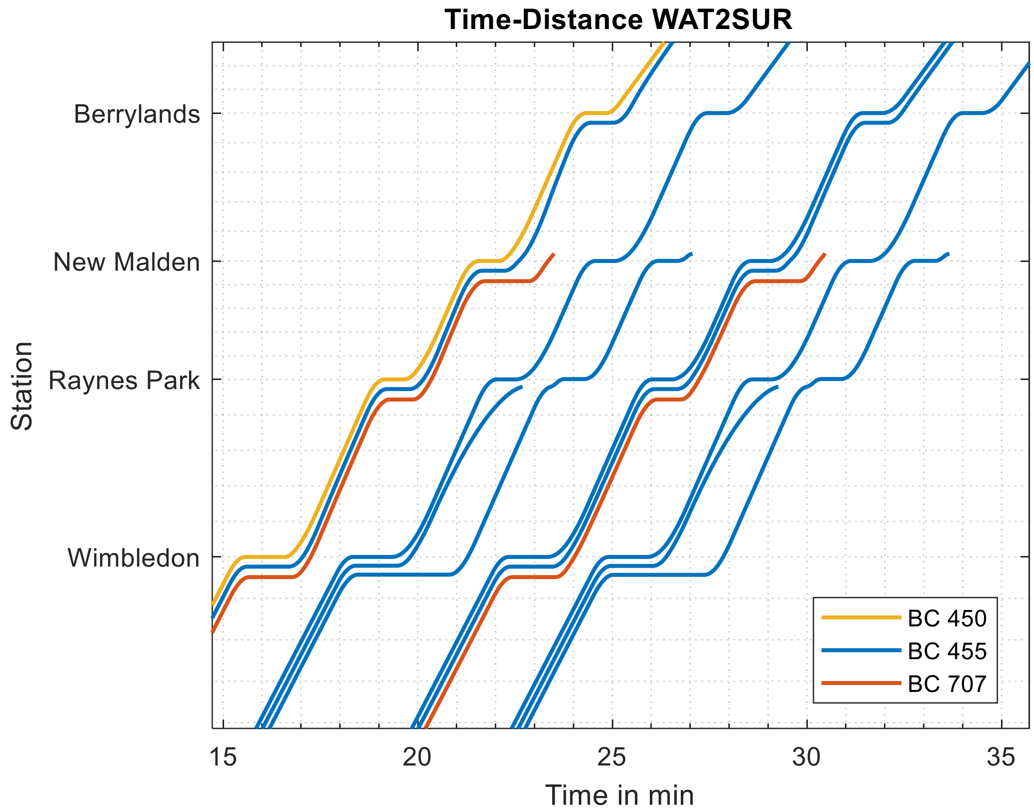


Figure 86: Zoomed view for junction sections

Table 43: Operational KPIs of VC 3 in 1

KPI	**Value**
Line capacity	54tph
Passenger accommodation	27,219ppdph
Rolling stock usage	86 (15min turnaround)
Total journey Time	18,306sec (see Figure 82 for individual values)
Total energy consumption	2606kWh (see Figure 83 for individual values)
Resilience – Total delays	939sec (see Figure 89 for individual values)

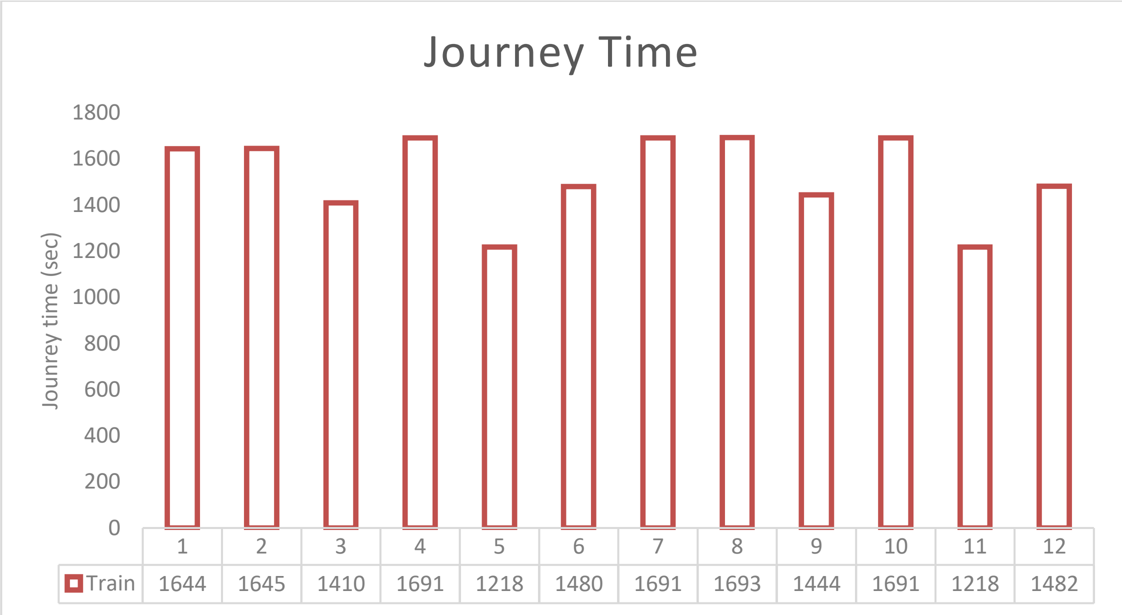


Figure 87: Journey times of VC 3 in 1 operation at low safety level

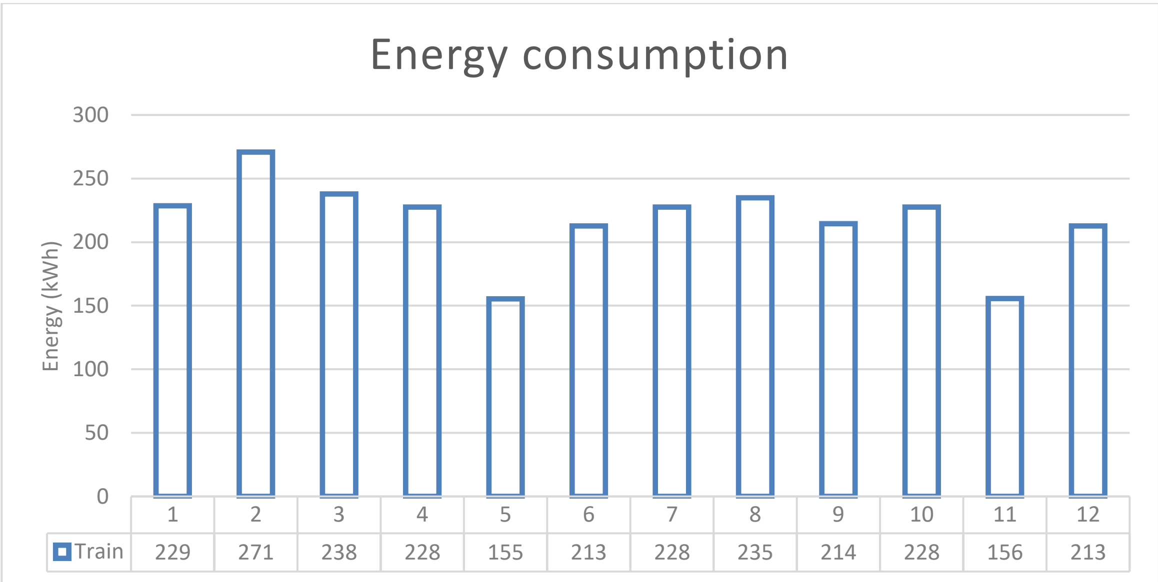


Figure 88: Energy consumption of VC 3 in 1 at low safety level

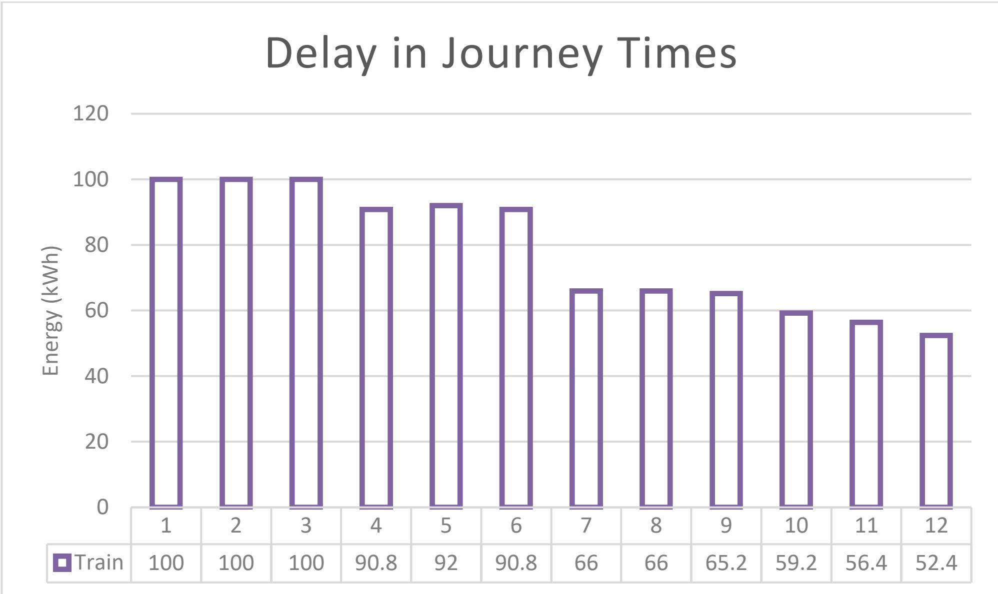


Figure 89: The resultant delays caused by the perturbation operation for VC 3 in 1 at low safety level.

7.4.1.3 VC 4 in 1

The simulated timetable of VC on the basis of the 4 in 1 formation at low safety level is given in Figure 90. The zoomed version of TT showing the junction areas closer is shown in Figure 91. In timetabling the operation plan, the train services are compressed as much as the VC system allows it theoretically. The earliest time the 13rd train can start journey is in the 678th second. Then, the average headway time between two trains is 57seconds. As a result, the capacity is 63tph. Table 44 includes these values along with other ones including passenger accommodation, rolling stock usage, journey time, energy consumption.

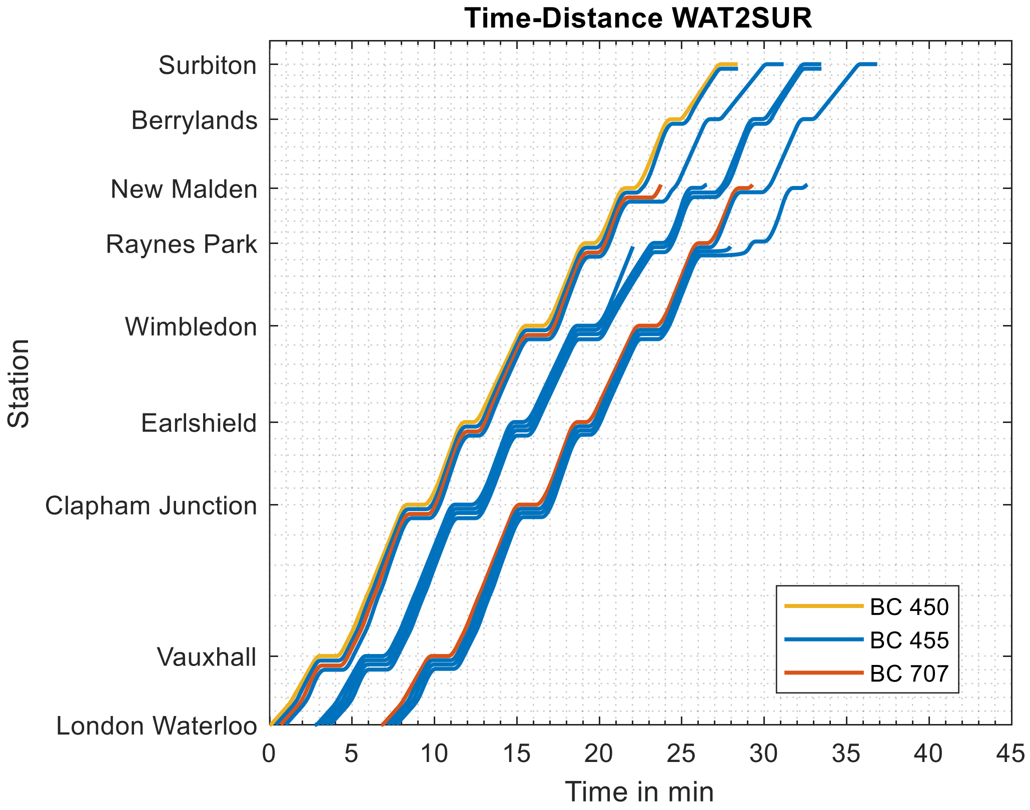


Figure 90: Timetabling for VC 4 in 1 at low safety level

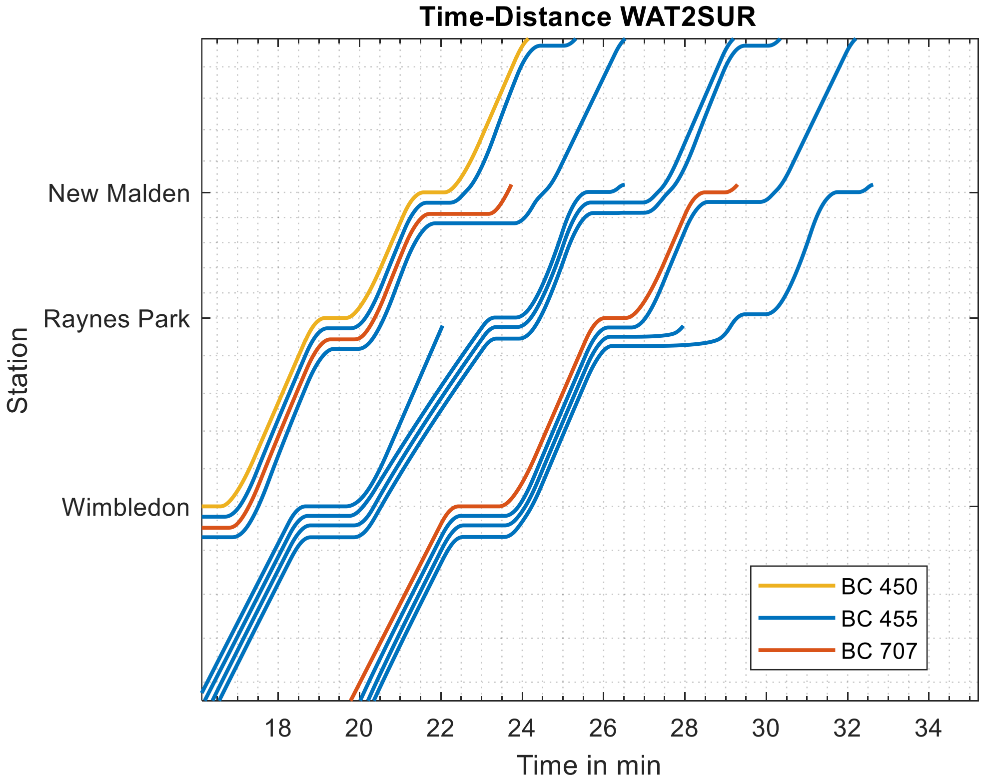


Figure 91: Zoomed view for junction sections

Table 44: Operational KPIs of VC 4 in 1

KPI	**Value**
Line capacity	63tph
Passenger accommodation	31,826ppdph
Rolling stock usage	87 (15min turnaround)
Total journey Time	18598sec (see Figure 82 for individual values)
Total energy consumption	2995kWh (see Figure 83for individual values)
Resilience – Total delays	903sec (see Figure 94 for individual values)

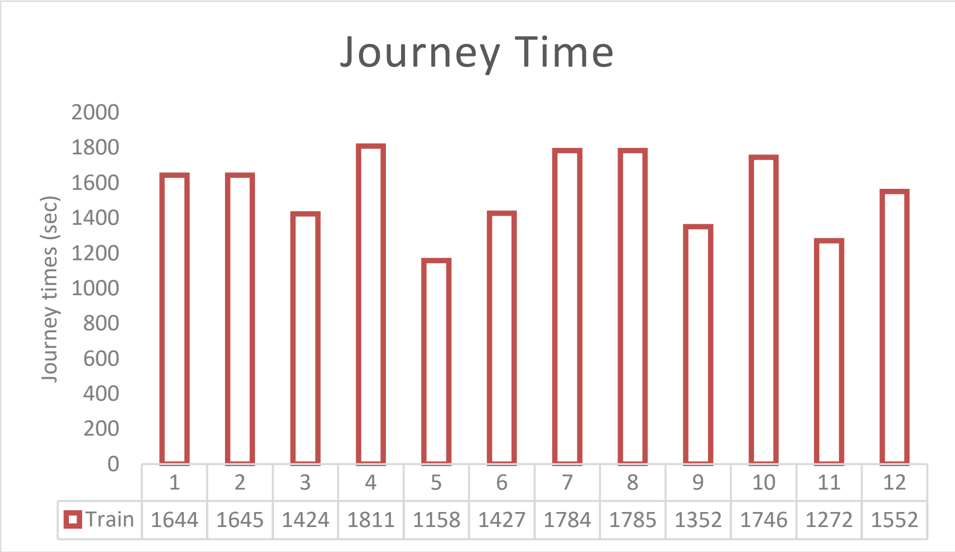


Figure 92: Journey times of VC 4 in 1 operation at low safety level

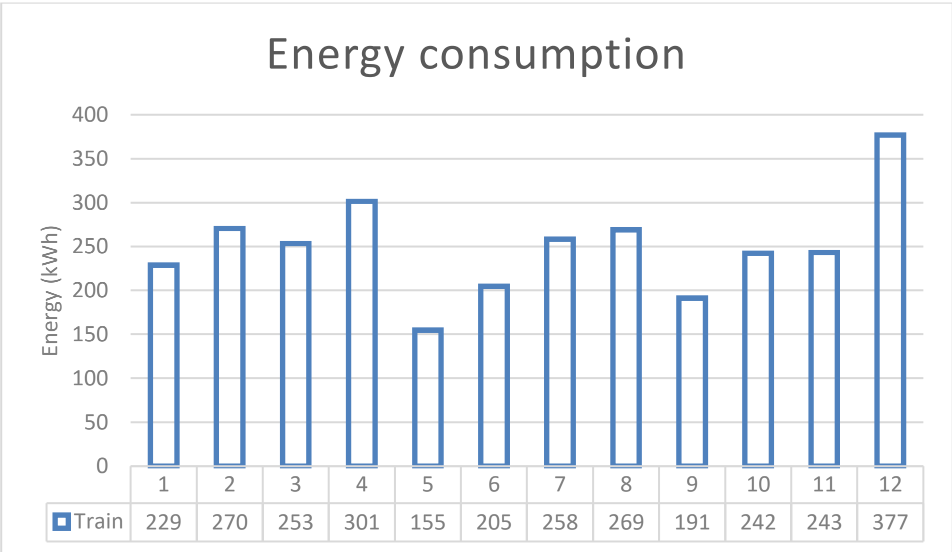


Figure 93: Energy consumption of VC 4 in 1 at low safety level

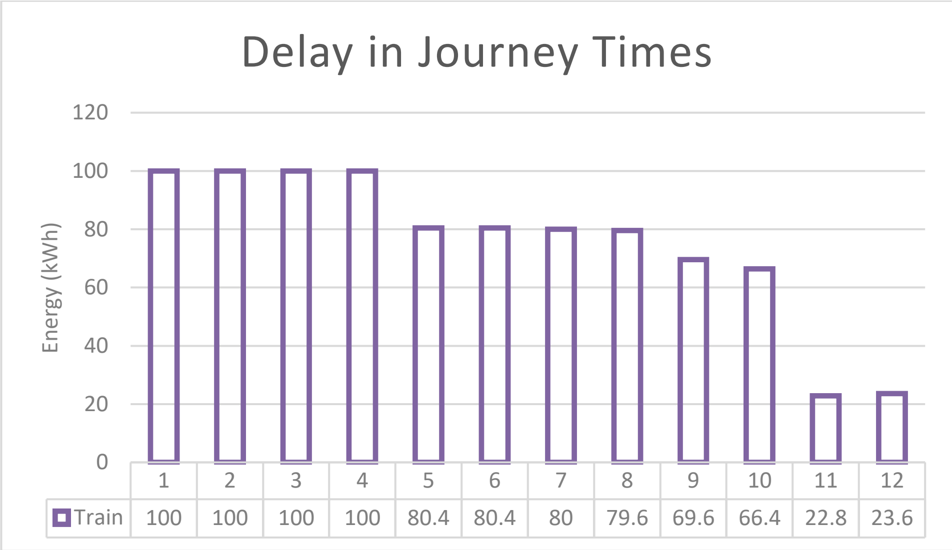


Figure 94: The resultant delays caused by the perturbation operation for VC 4 in 1 at low safety level.

7.4.2 Safety Level Medium

The results are given for three scenarios of the convoy formation i.e., 2 in 1, 3 in 1, and 4 in 1, at medium safety level in the following subsections.

7.4.2.1 VC 2 in 1

The simulated timetable of VC on the basis of the 2 in 1 formation at medium safety level is given in Figure 95. The zoomed version of TT showing the junction areas closer is shown in Figure 96. In timetabling the operation plan, the train services are compressed as much as the VC system allows it theoretically. The earliest time the 13rd train can start journey is in the 890th second. Then, the average headway time between two trains is 74.17seconds. As a result, the capacity is 48tph. Table 45 includes these values along with other ones including passenger accommodation, rolling stock usage, journey time, energy consumption.

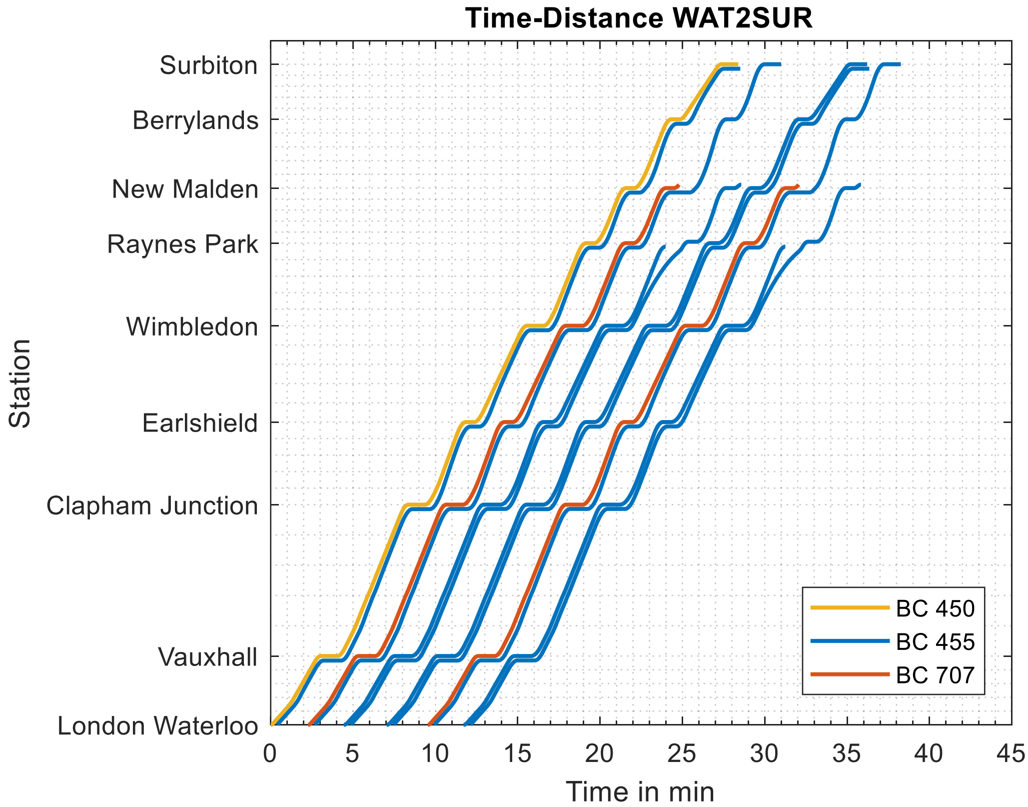


Figure 95: Timetabling for VC 2 in 1 at medium safety level

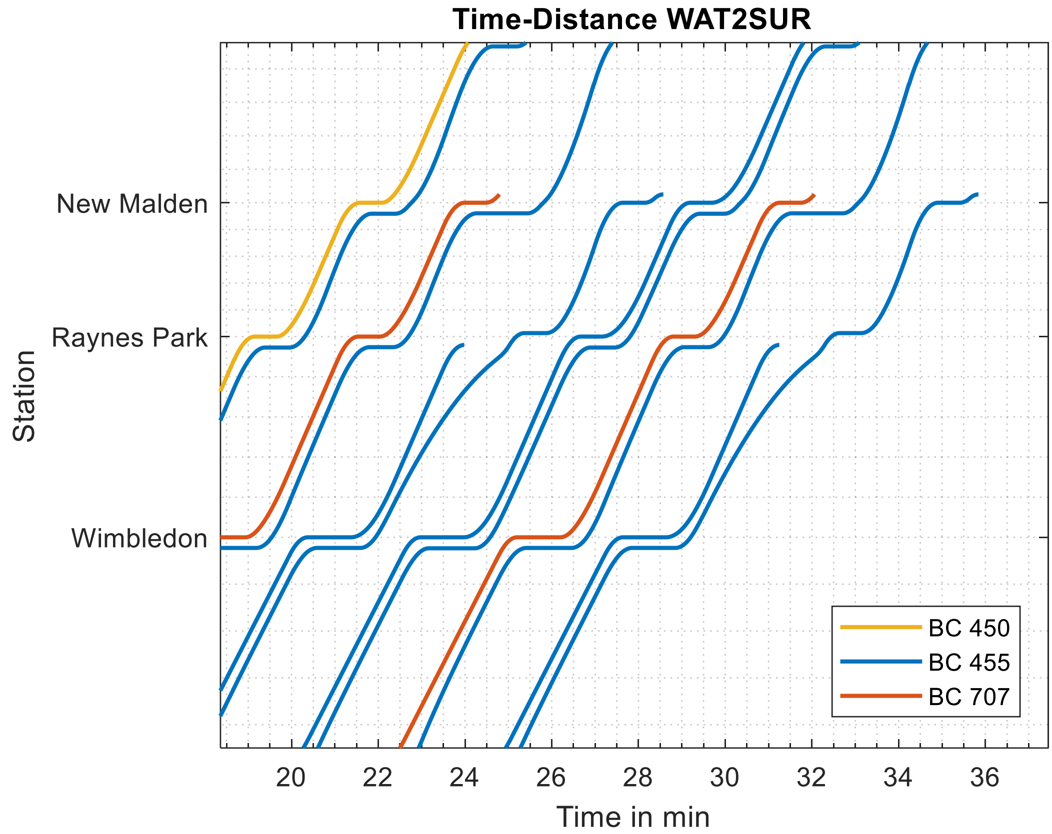


Figure 96: Zoomed view for junction sections

Table 45: Operational KPIs of VC 2 in 1

KPI	**Value**
Line capacity	48tph
Passenger accommodation	24,248ppdph
Rolling stock usage	65 (15min turnaround)
Total journey Time	18,230sec (see Figure 82 for individual values)
Total energy consumption	2,704kWh (see Figure 83 for individual values)
Resilience – Total delays	746sec (see Figure 99 for individual values)

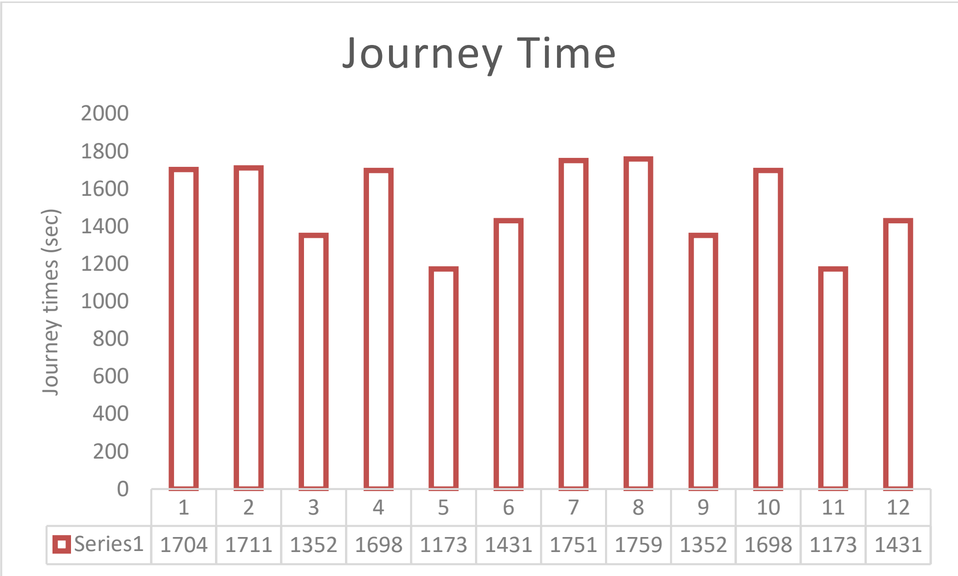


Figure 97: Journey times of VC 2 in1 operation at medium safety level

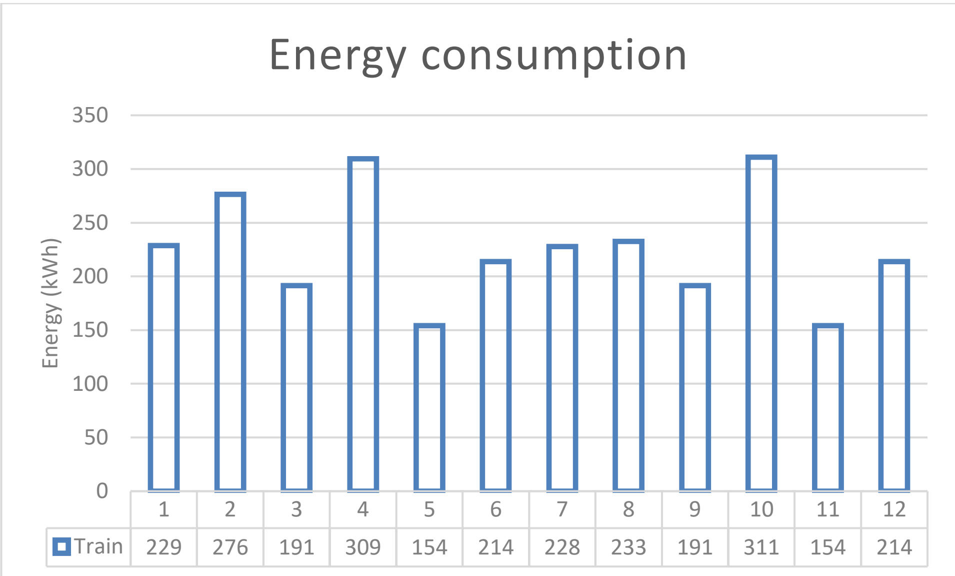
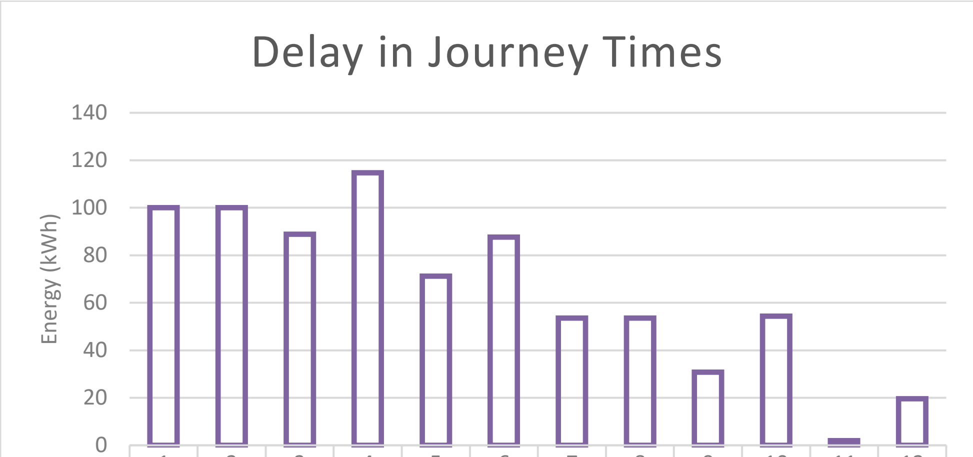


Figure 98: Energy consumption of VC 2 in 1 at medium safety level



	1	2	3	4	5	6	7	8	9	10	11	12
Train	100	100	88.8	114.8	71.2	87.6	53.6	53.6	30.8	54.4	2	19.6

Figure 99: The resultant delays caused by the perturbation operation for VC 2 in 1 at medium safety level.

7.4.2.2 VC 3 in 1

The simulated timetable of VC on the basis of the 3 in 1 formation at medium safety level is given in Figure 100. The zoomed version of TT showing the junction areas closer is shown in Figure 101. In timetabling the operation plan, the train services are compressed as much as the VC system allows it theoretically. The earliest time the 13rd train can start journey is in the 820th second. Then, the average headway time between two trains is 68seconds. As a result, the capacity is 52tph. Table 46 includes these values along with other ones including passenger accommodation, rolling stock usage, journey time, energy consumption.

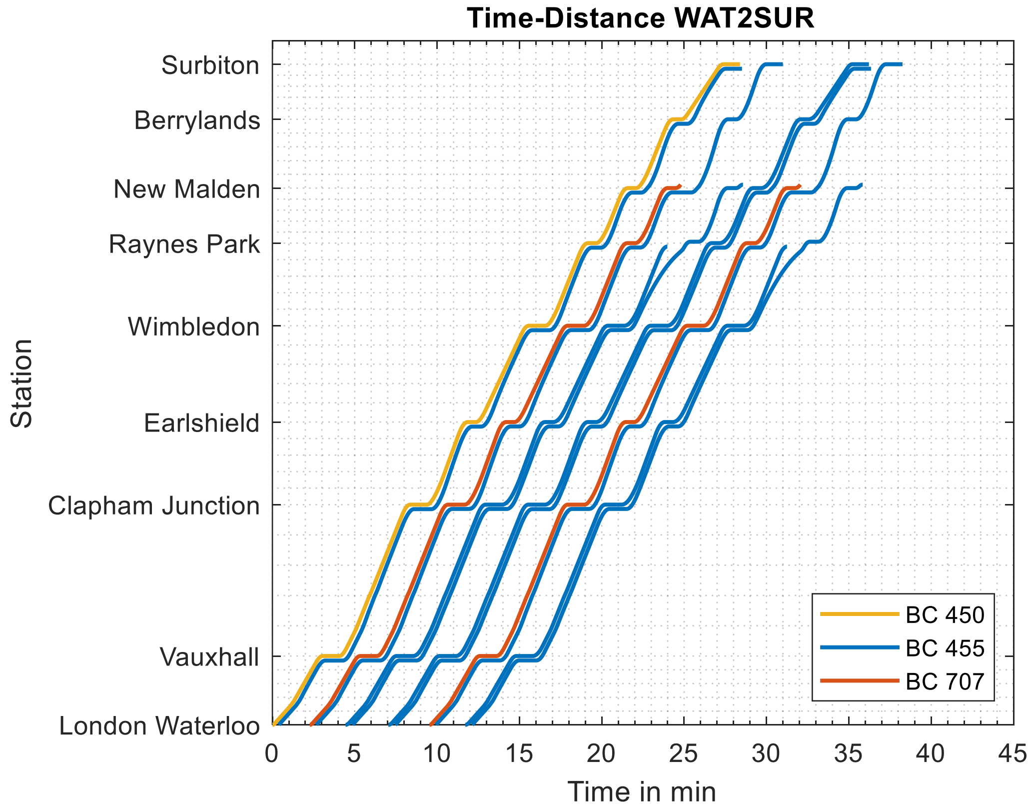


Figure 100: Timetabling for VC 3 in 1 at medium safety level

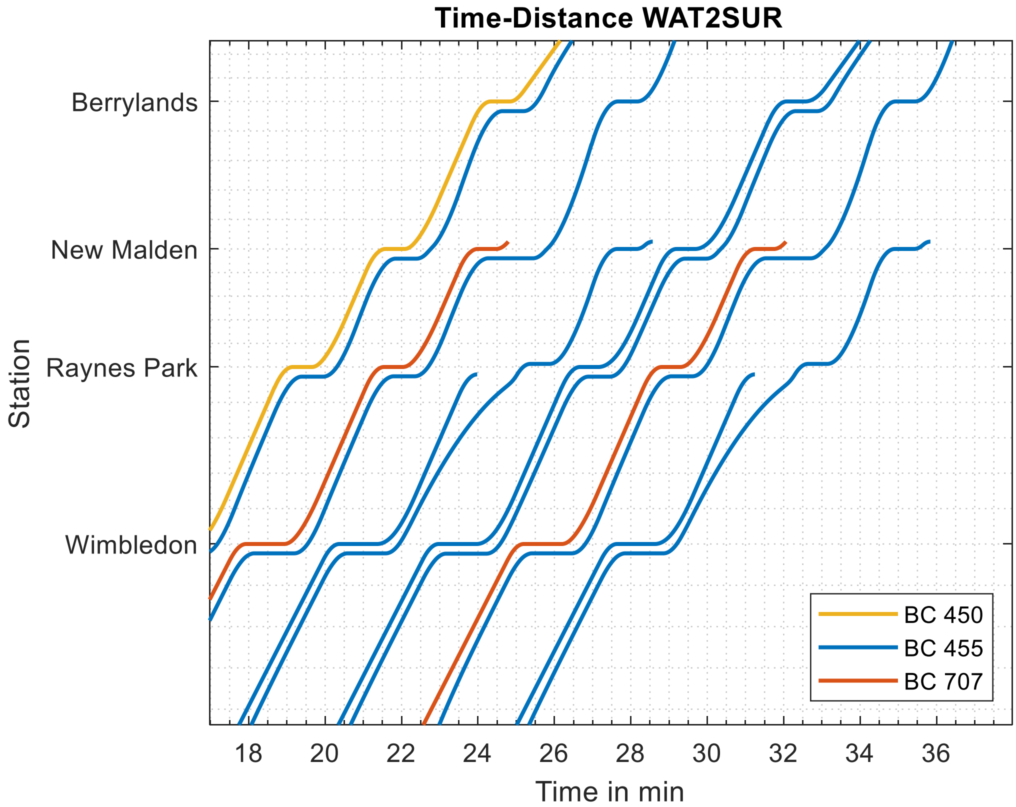


Figure 101: Zoomed view for junction sections

Table 46: Operational KPIs of VC 3 in 1

KPI	**Value**
Line capacity	52tph
Passenger accommodation	26,269ppdph
Rolling stock usage	73 (15min turnaround)
Total journey Time	18,958sec (see Figure 82 for individual values)
Total energy consumption	2546kWh (see Figure 83for individual values)
Resilience – Total delays	1,062sec (see Figure 84 for individual values)

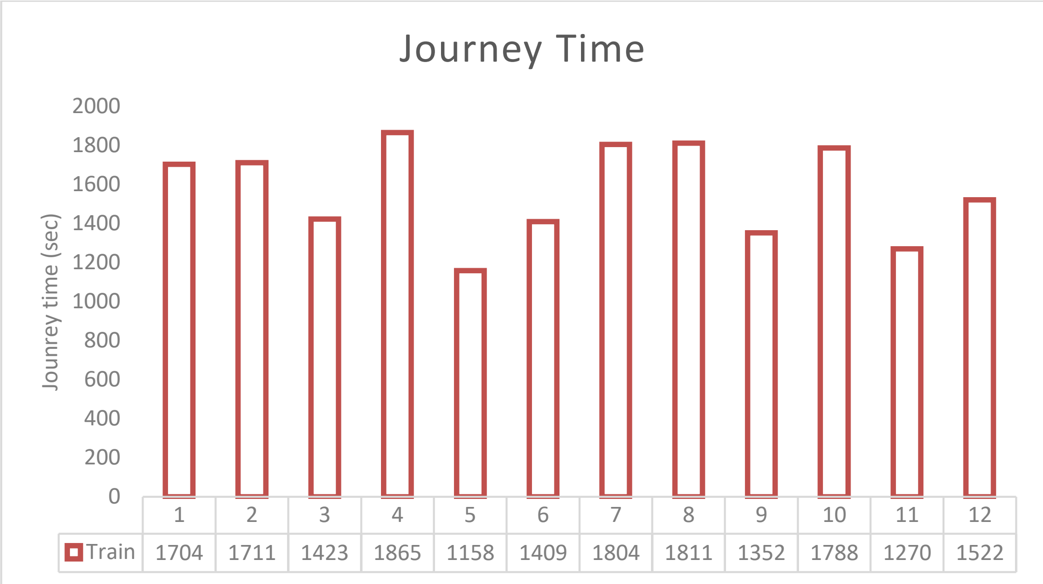


Figure 102: Journey times of VC 3 in1 operation at medium safety level

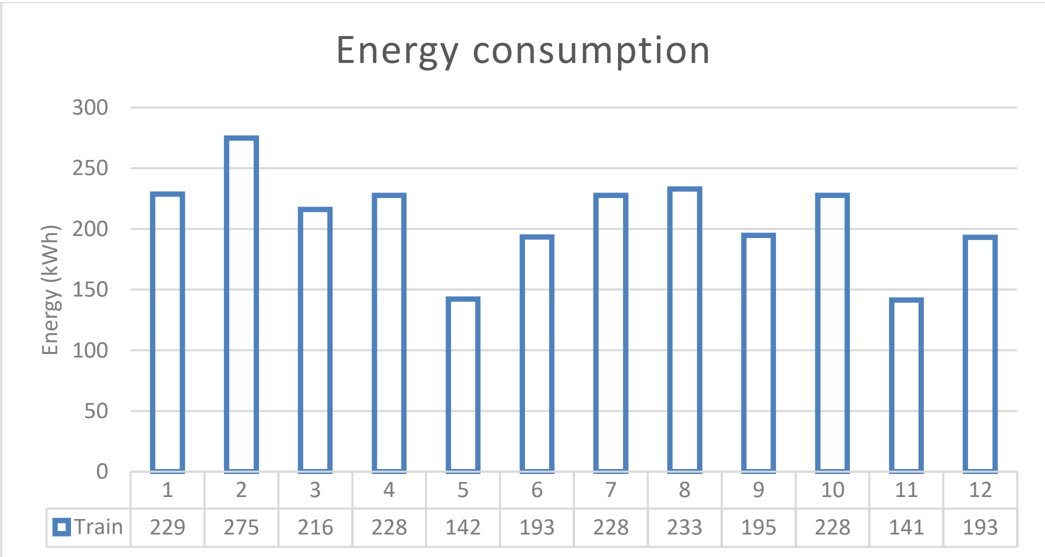


Figure 103: Energy consumption of VC 3 in 1 at medium safety level

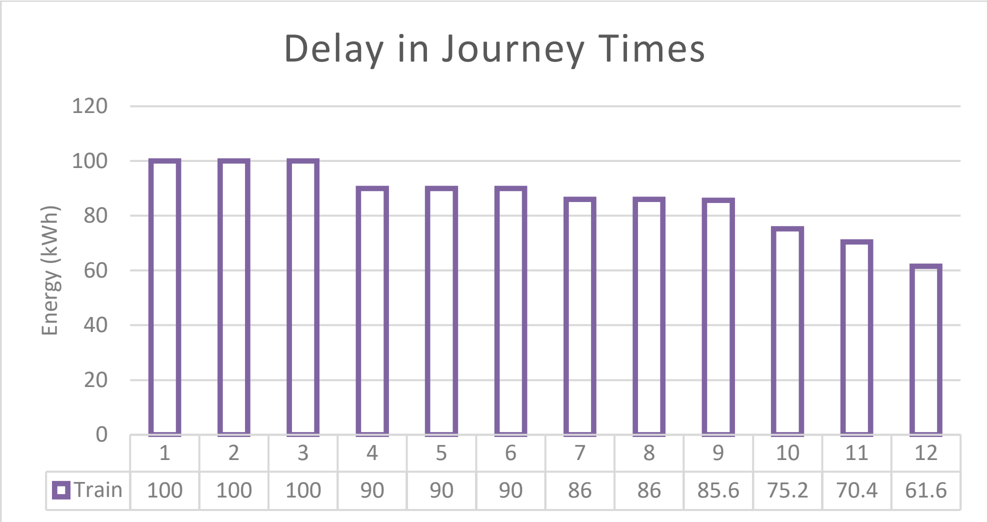


Figure 104: The resultant delays caused by the perturbation operation for VC 3 in 1 at medium safety level.

7.4.2.3 VC 4 in 1

The simulated timetable of VC on the basis of the 4 in 1 formation at medium safety level is given in Figure 105. The zoomed version of TT showing the junction areas closer is shown in Figure 106. In timetabling the operation plan, the train services are compressed as much as the VC system allows it theoretically. The earliest time the 13rd train can start journey is in the 688th second. Then, the average headway time between two trains is 57seconds. As a result, the capacity is 62tph. Table 47 includes these values along with other ones including passenger accommodation, rolling stock usage, journey time, energy consumption.

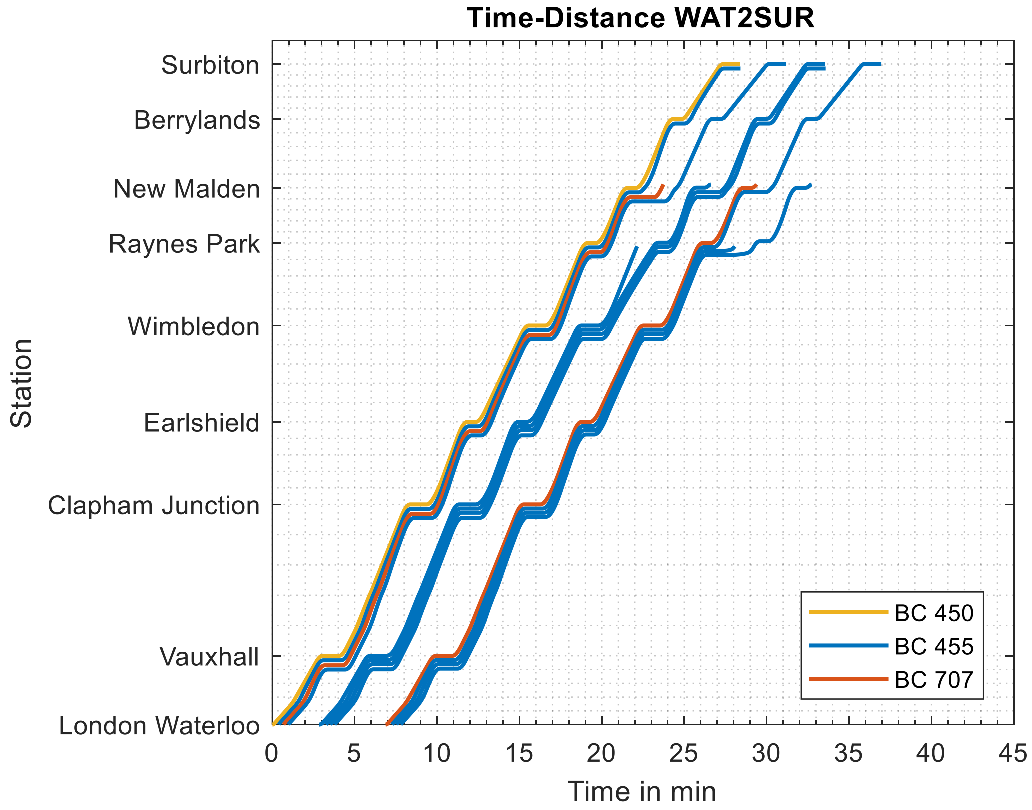


Figure 105: Timetabling for VC 4 in 1 at medium safety level

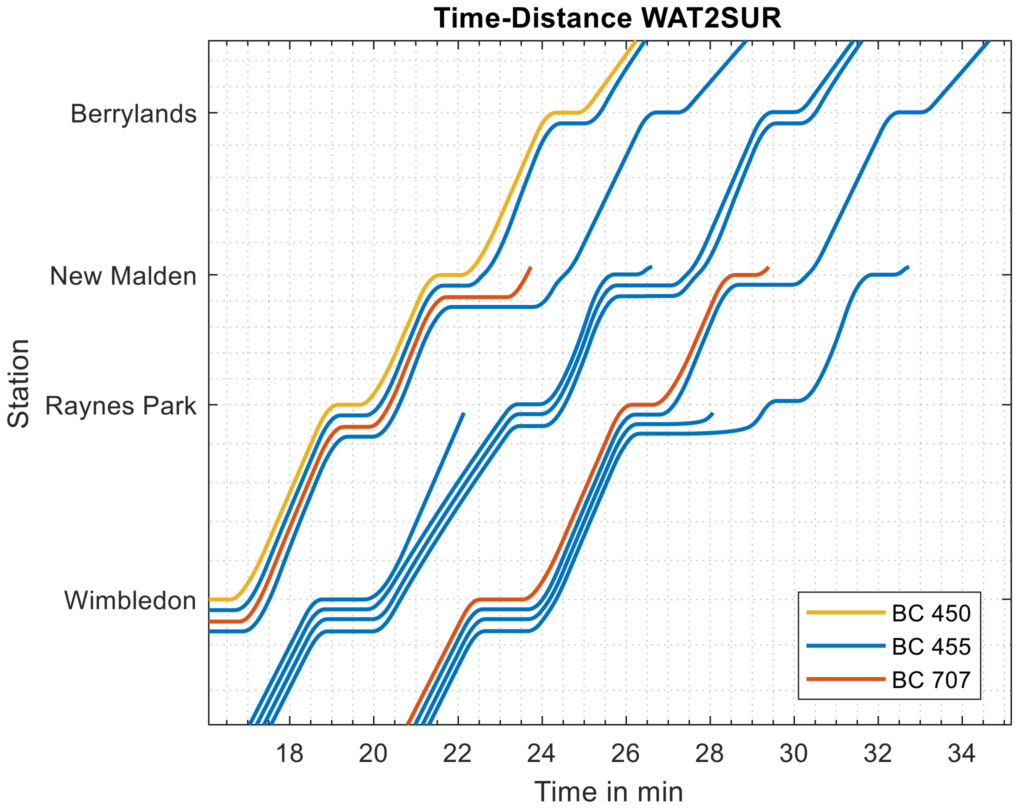


Figure 106: Zoomed view for junction sections

Table 47: Operational KPIs of VC 4 in 1

KPI	**Value**
Line capacity	62tph
Passenger accommodation	31,320ppdph
Rolling stock usage	87 (15min turnaround)
Total journey Time	18,958sec (see Figure 82 for individual values)
Total energy consumption	2,995kWh (see Figure 83 for individual values)
Resilience – Total delays	903sec (see Figure 109 for individual values)

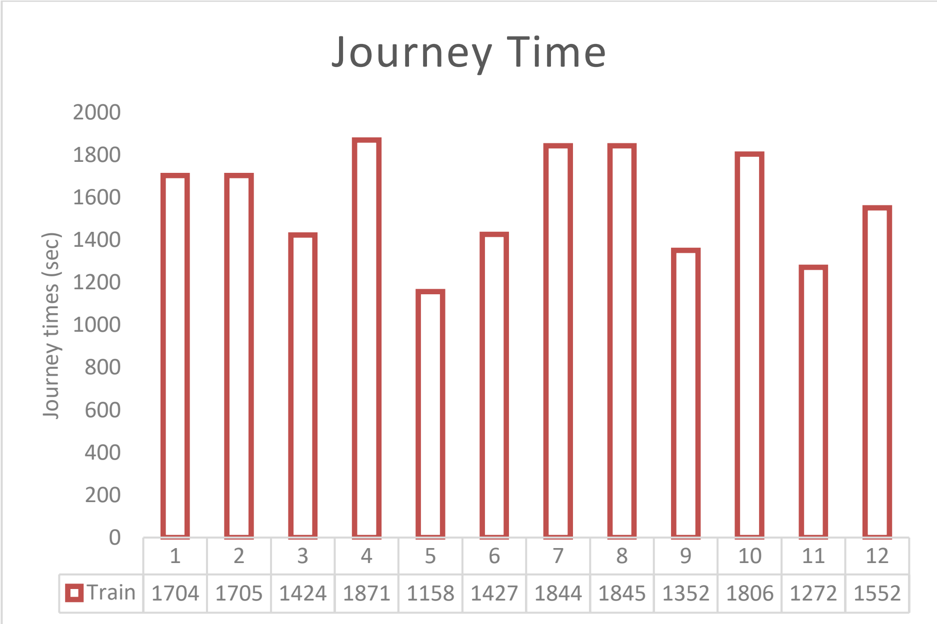


Figure 107: Journey times of VC 4 in1 operation at medium safety level

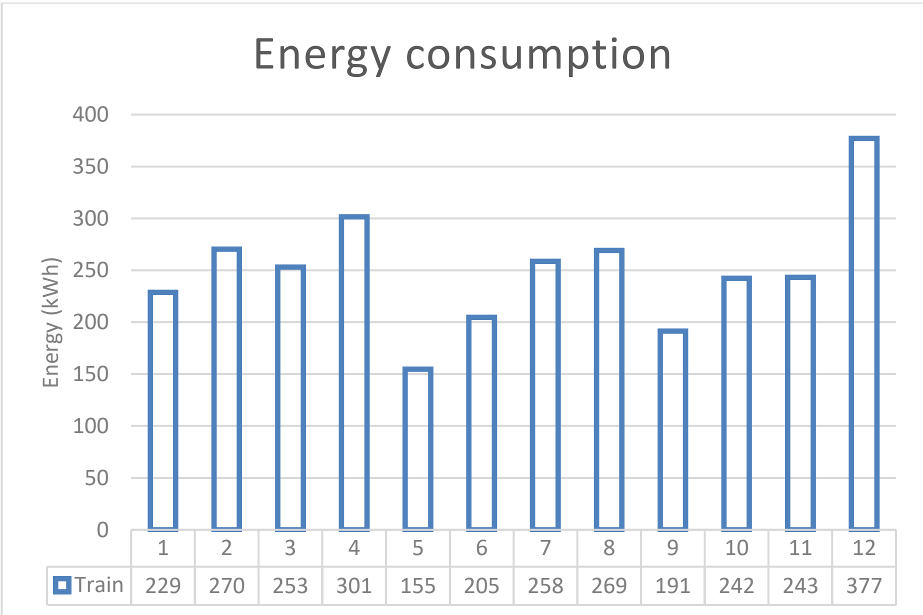


Figure 108: Energy consumption of VC 4 in 1 at medium safety level

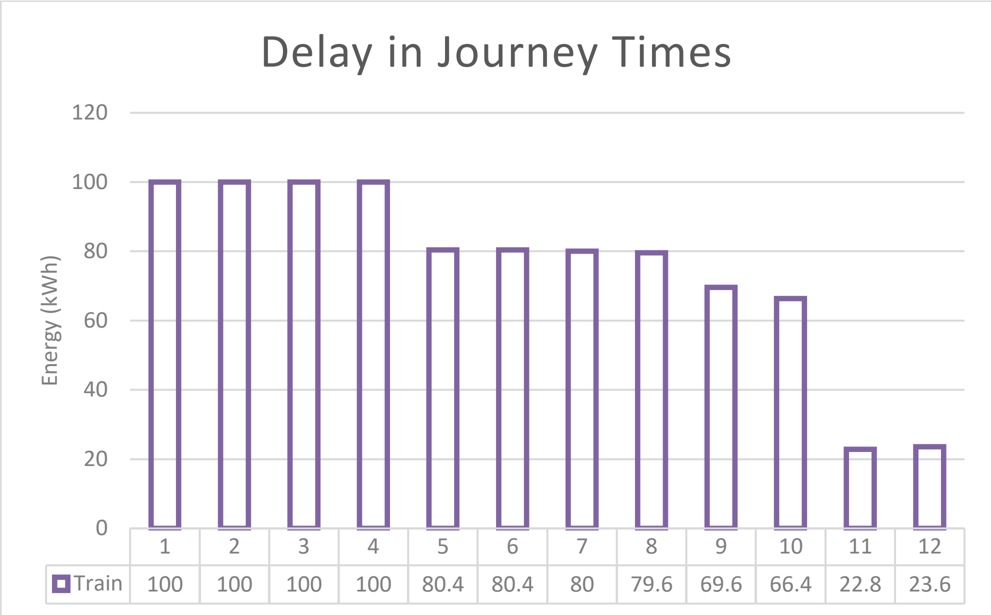


Figure 109: The resultant delays caused by the perturbation operation for VC 4 in 1 at medium safety level.

7.4.3 Safety Level High

The results are given for three scenarios of the convoy formation i.e., 2 in 1, 3 in 1, and 4 in 1, at high safety level in the following subsections.

7.4.3.1 VC 2 in 1

The simulated timetable of VC on the basis of the 2 in 1 formation at medium safety level is given in Figure 110. The zoomed version of TT showing the junction areas closer is shown in Figure 111. In timetabling the operation plan, the train services are compressed as much as the VC system allows it theoretically. The earliest time the 13rd train can start journey is in the 932nd second. Then, the average headway time between two trains is 77.67seconds. As a result, the capacity is 46tph. Table 48 includes these values along with other ones including passenger accommodation, rolling stock usage, journey time, energy consumption.

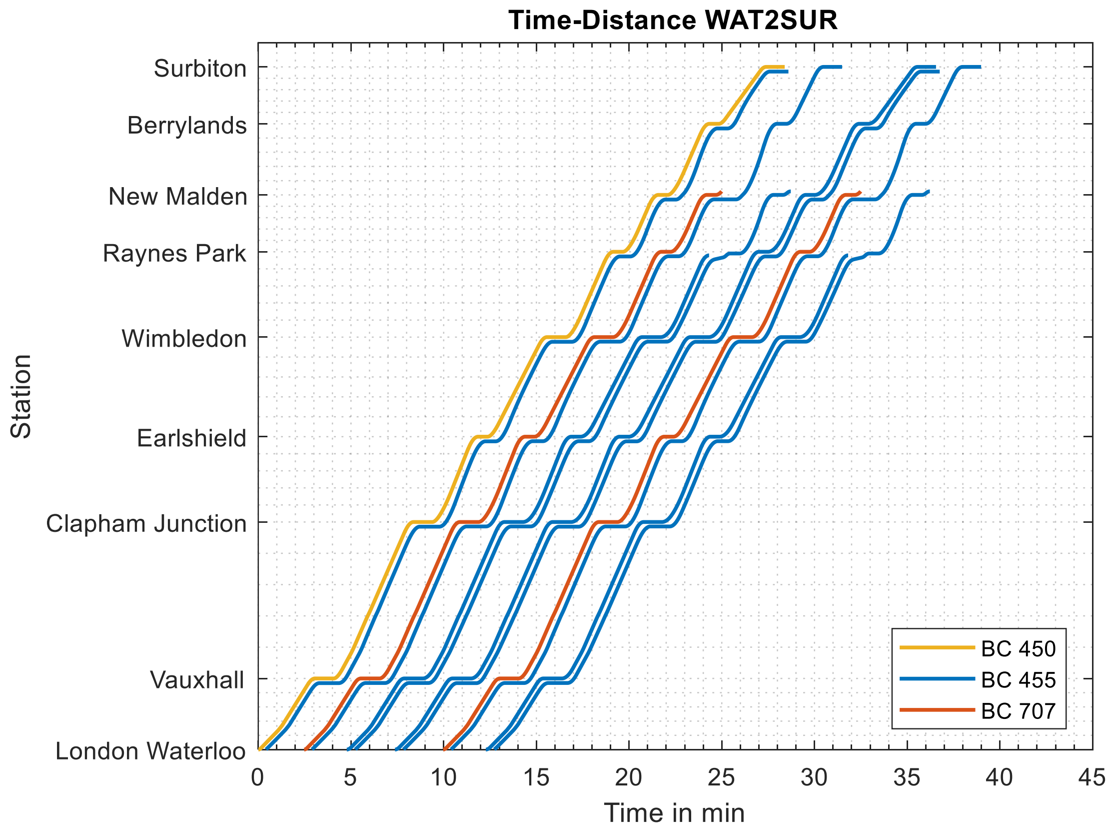


Figure 110: Timetabling for VC 2 in 1 at high safety level

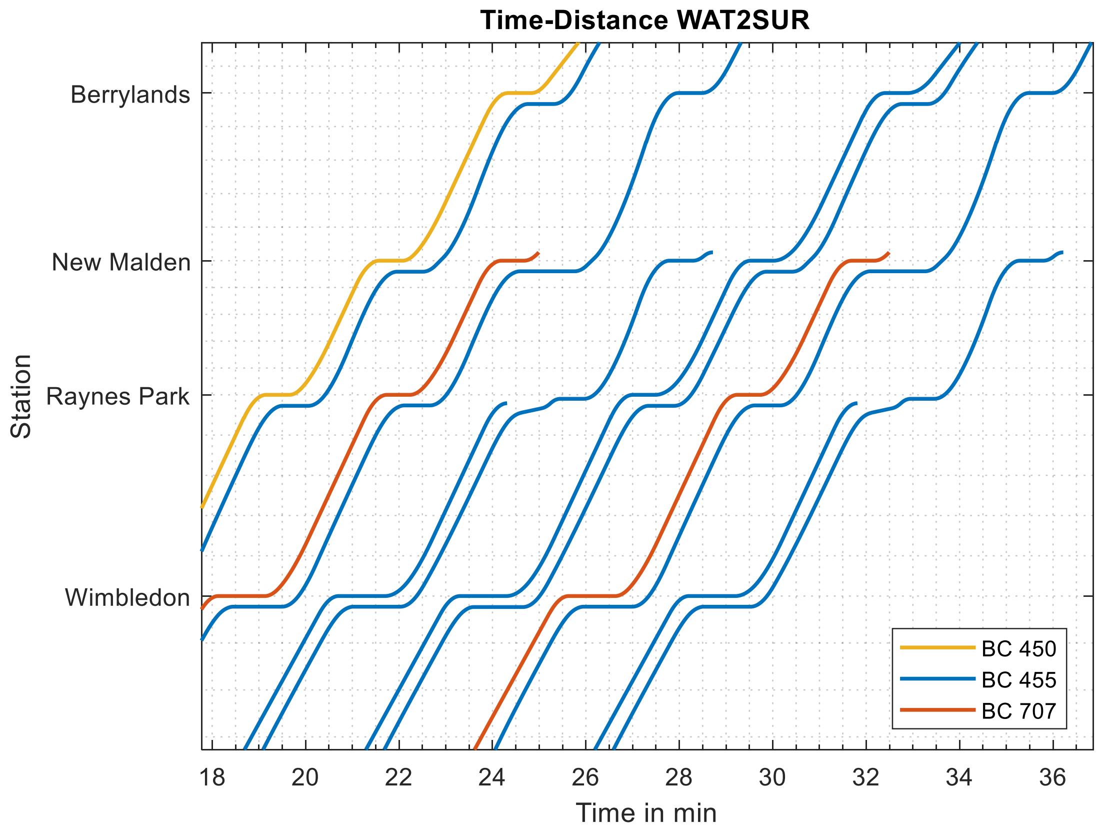


Figure 111: Zoomed view for junction sections

Table 48: Operational KPIs of VC 2 in 1

KPI	**Value**
Line capacity	46tph
Passenger accommodation	23,238ppdph
Rolling stock usage	62(15min turnaround)
Total journey Time	23,238sec (see Figure 82 for individual values)
Total energy consumption	2,669kWh (see Figure 83 for individual values)
Resilience – Total delays	644sec (see Figure 114 for individual values)

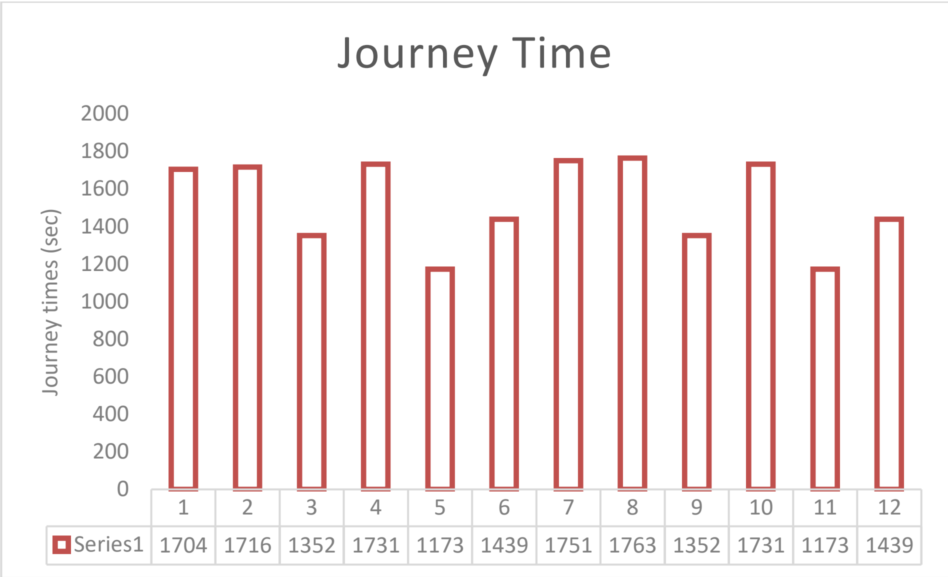


Figure 112: Journey times of VC 2 in1 operation at high safety level

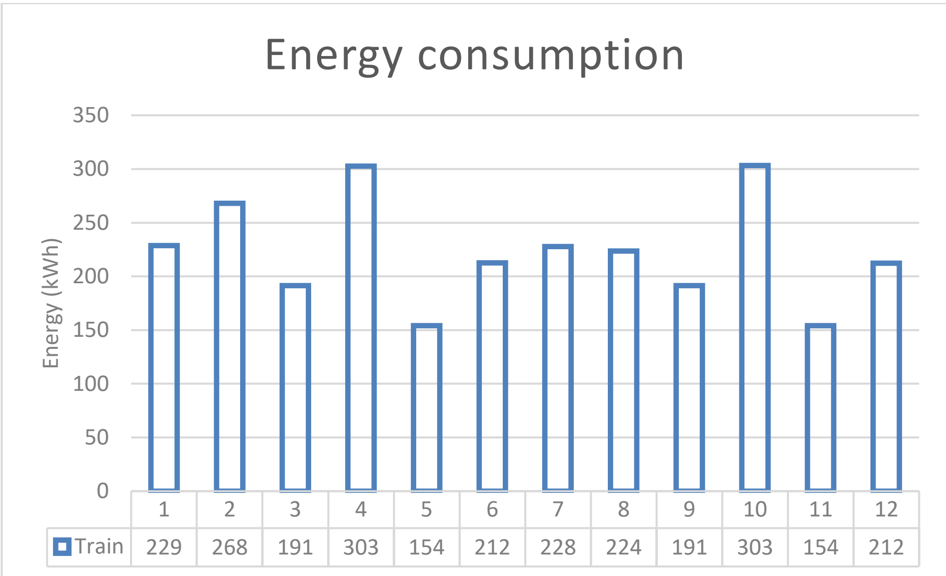


Figure 113: Energy consumption of VC 2 in 1 at high safety level

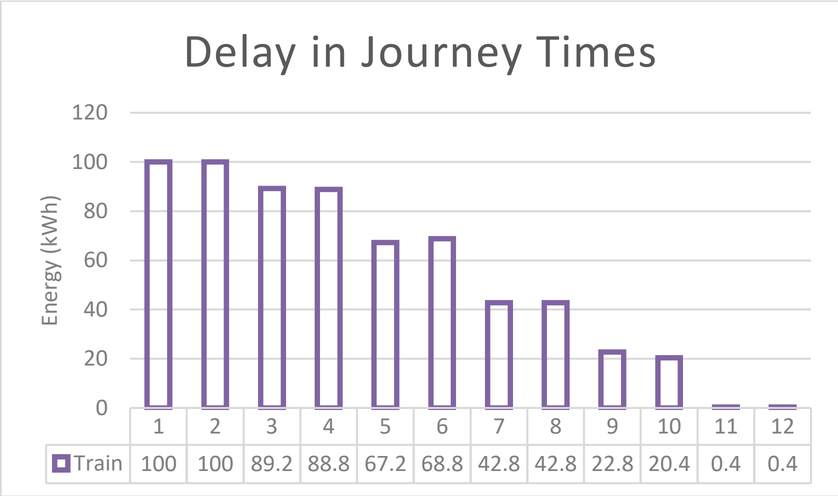


Figure 114: The resultant delays caused by the perturbation operation for VC 2 in 1 at high safety level.

7.4.3.2 VC 3 in 1

The simulated timetable of VC on the basis of the 3 in 1 formation at medium safety level is given in Figure 115. The zoomed version of TT showing the junction areas closer is shown in Figure 116. In timetabling the operation plan, the train services are compressed as much as the VC system allows it theoretically. The earliest time the 13rd train can start journey is in the 880th second. Then, the average headway time between two trains is 73seconds. As a result, the capacity is 49tph. Table 49 includes these values along with other ones including passenger accommodation, rolling stock usage, journey time, energy consumption.

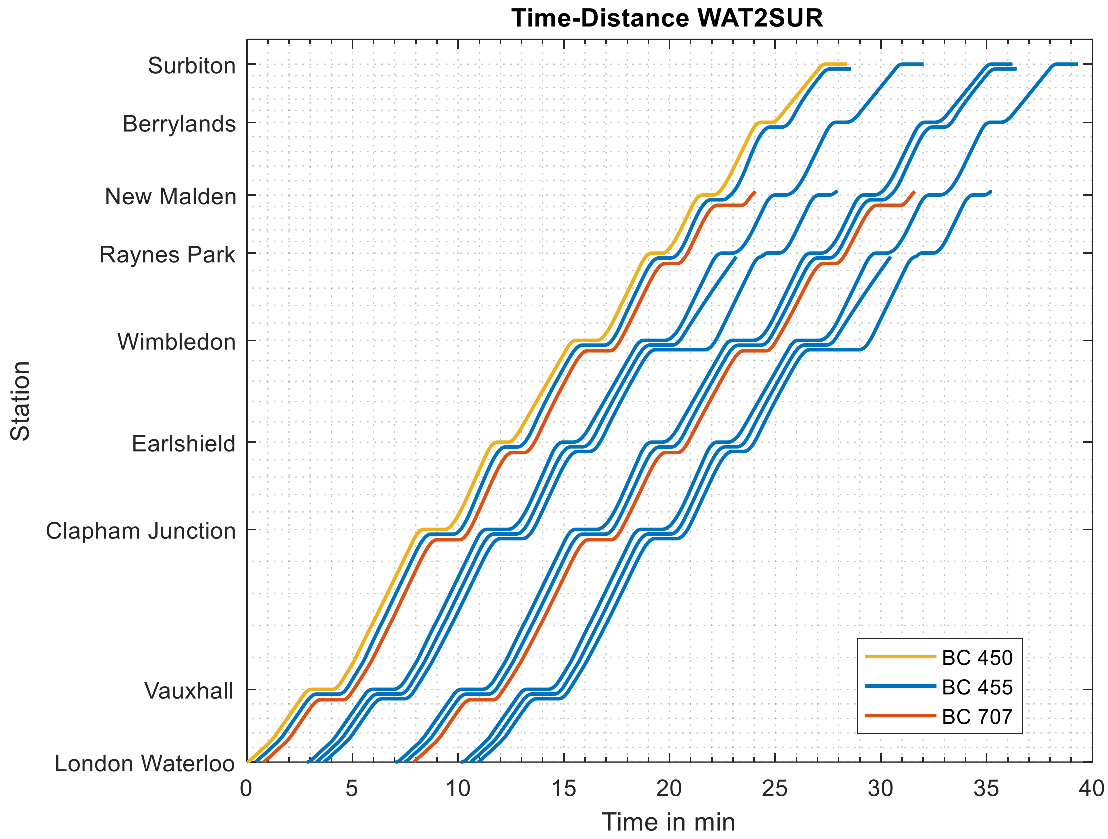


Figure 115: Timetabling for VC 3 in 1 at high safety level.

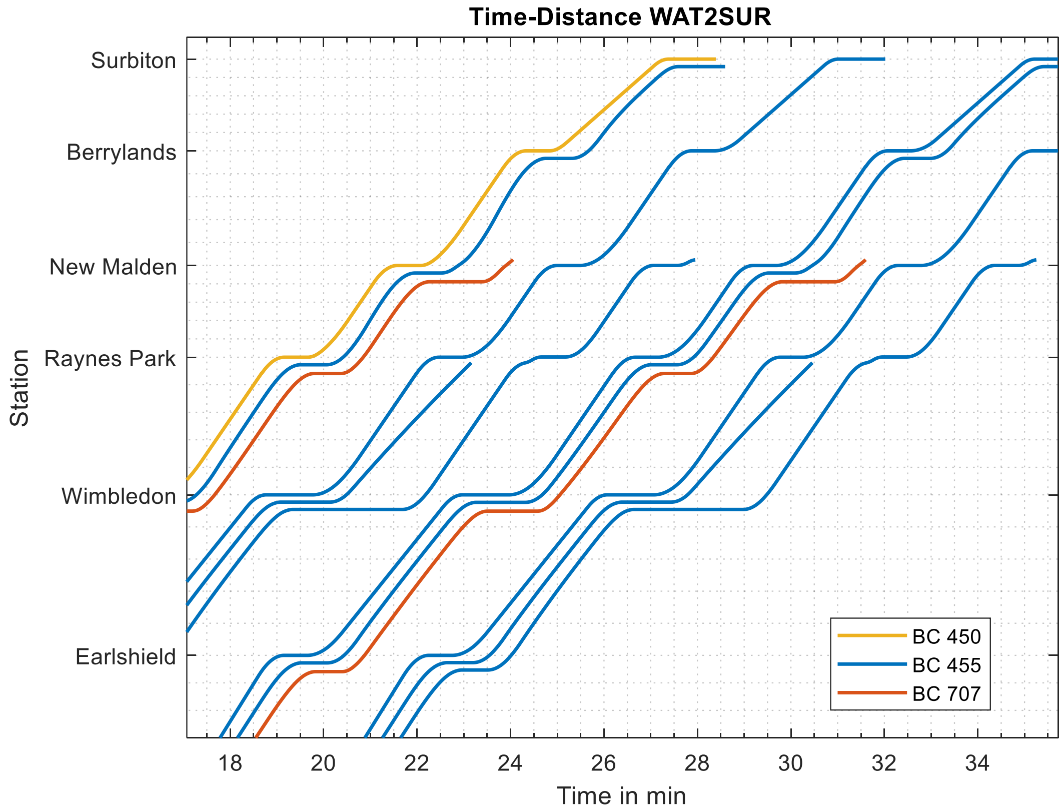


Figure 116: Zoomed view for junction sections

Table 49: Operational KPIs of VC 3 in 1

KPI	**Value**
Line capacity	49tph
Passenger accommodation	24,753ppdph
Rolling stock usage	67 (15min turnaround)
Total journey Time	18,807sec (see Figure 82 for individual values)
Total energy consumption	2469Wh (see Figure 83for individual values)
Resilience – Total delays	1,007sec (see Figure 119 for individual values)

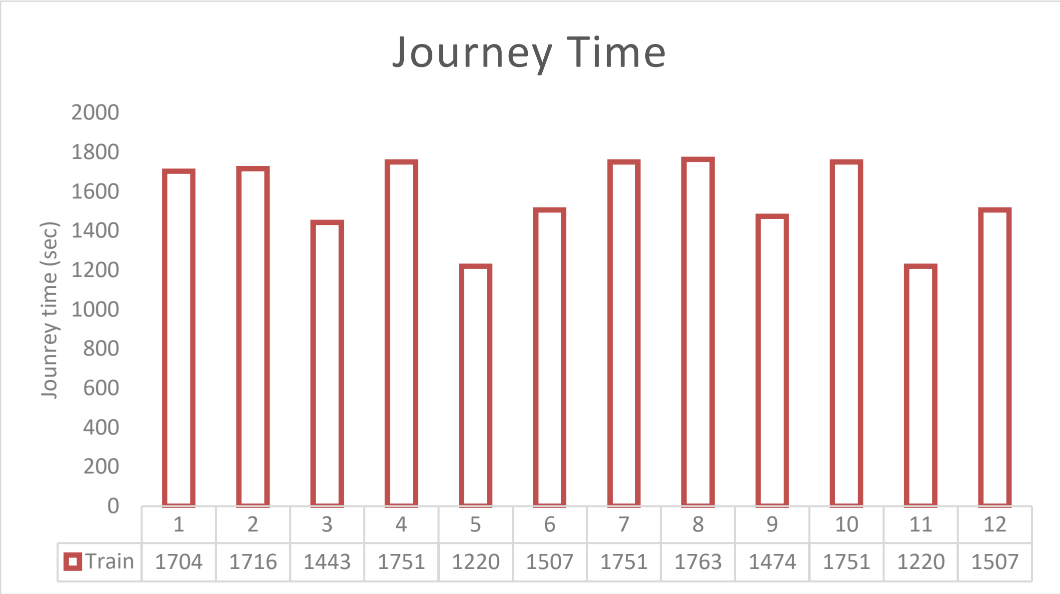


Figure 117: Journey times of VC 3 in1 operation at high safety level

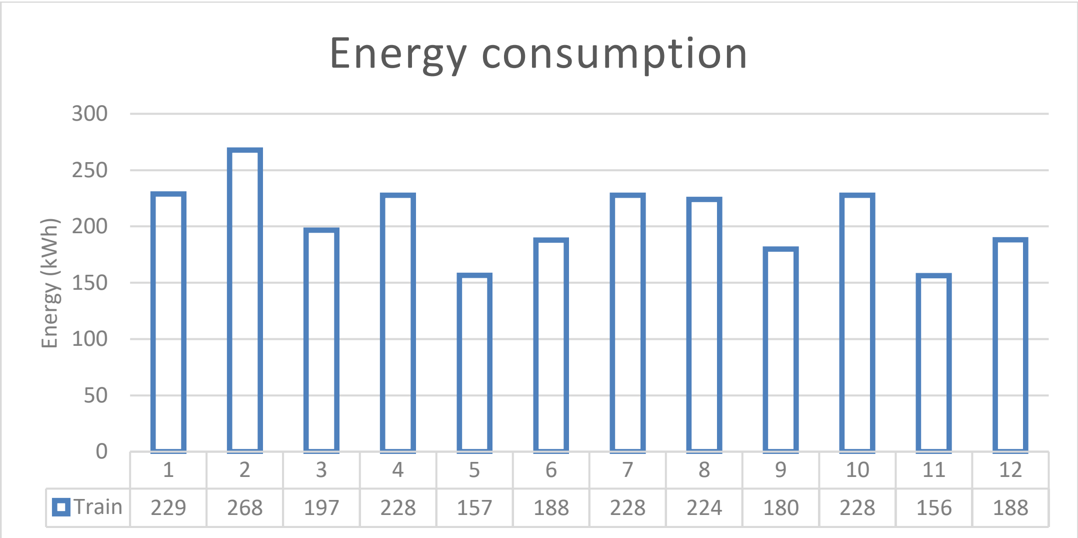


Figure 118: Energy consumption of VC 3 in 1 at high safety level

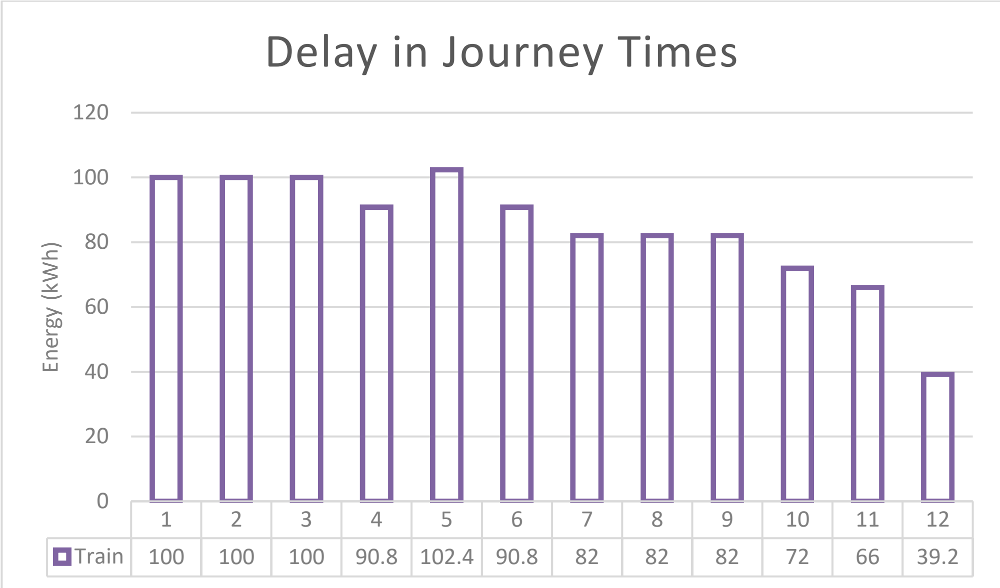


Figure 119: The resultant delays caused by the perturbation operation for VC 3 in 1 at high safety level.

7.4.3.3 VC 4 in 1

The simulated timetable of VC on the basis of the 4 in 1 formation at high safety level is given in Figure 120. The zoomed version of TT showing the junction areas closer is shown in Figure 121. In timetabling the operation plan, the train services are compressed as much as the VC system allows it theoretically. The earliest time the 13rd train can start journey is in the 746th second. Then, the average headway time between two trains is 62seconds. As a result, the capacity is 57tph. Table 50 includes these values along with other ones including passenger accommodation, rolling stock usage, journey time, energy consumption.

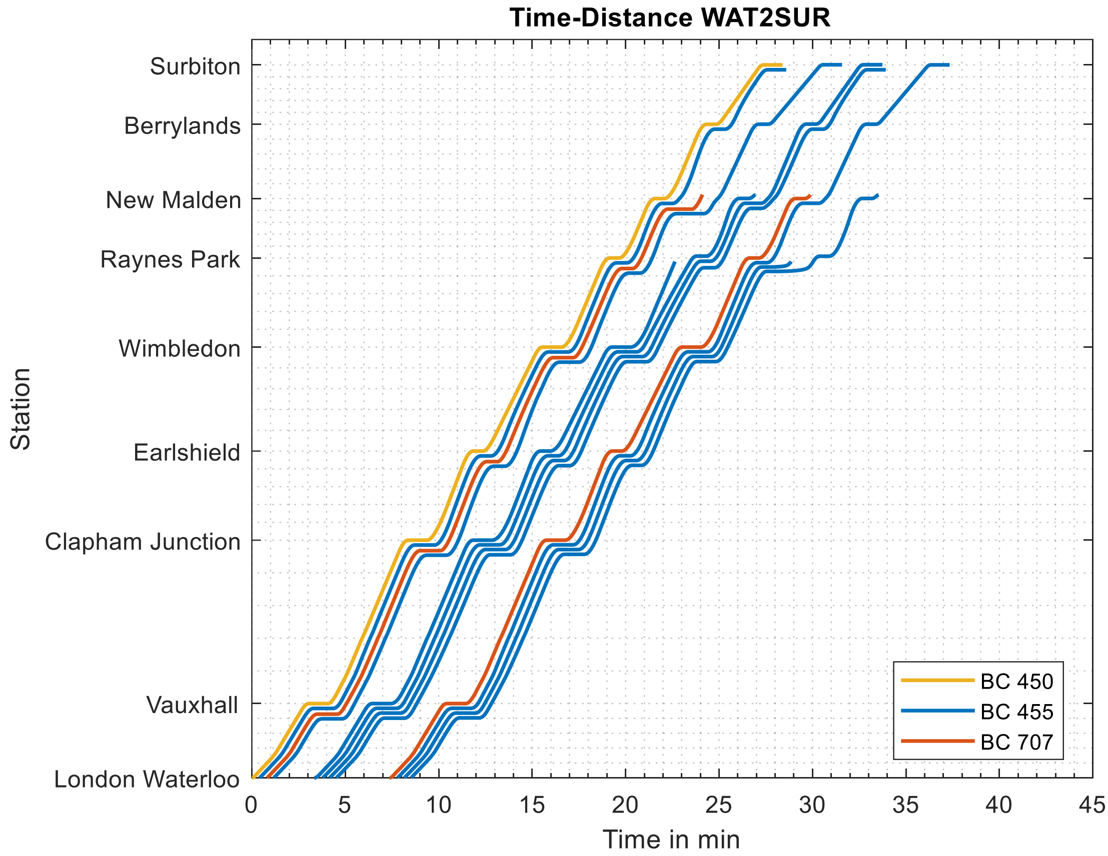


Figure 120: Timetabling for VC 4 in 1 at high safety level

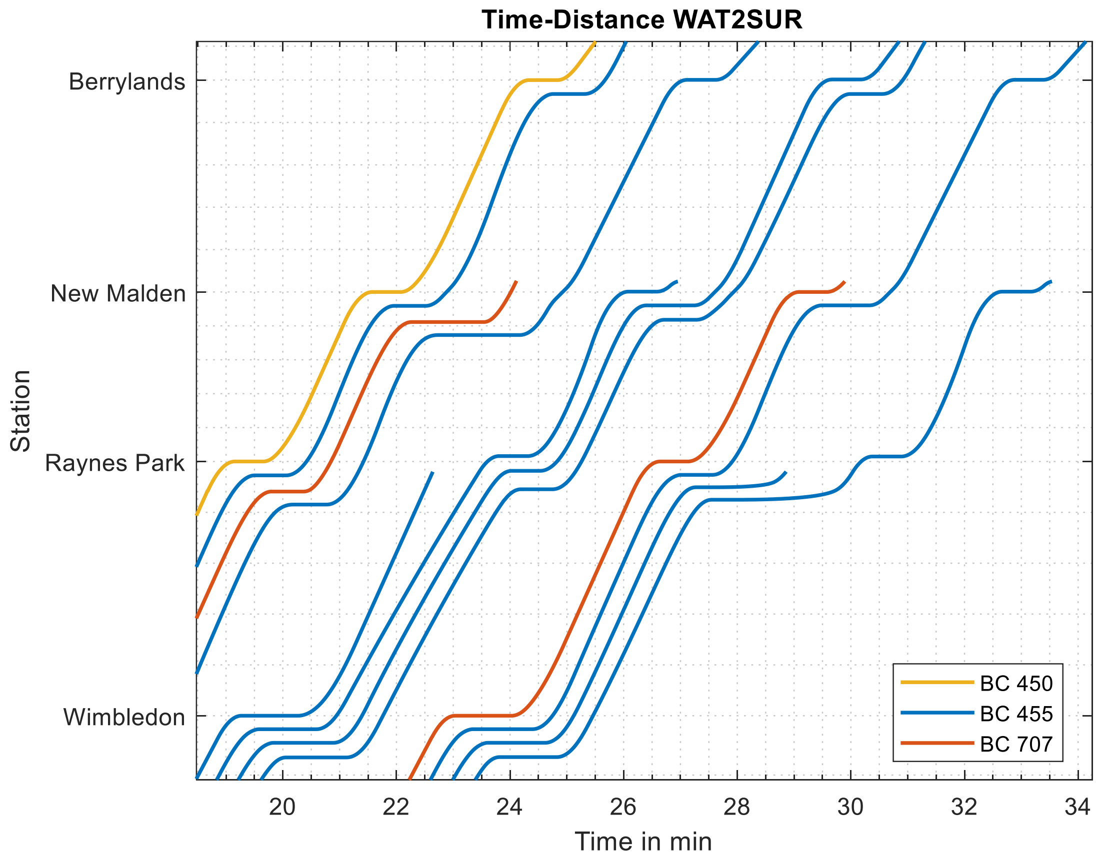


Figure 121: Zoomed view for junction sections

Table 50: Operational KPIs of VC 4 in 1

KPI	**Value**
Line capacity	57tph
Passenger accommodation	19,006ppdph
Rolling stock usage	80 (15min turnaround)
Total journey Time	28,795sec (see Figure 82 for individual values)
Total energy consumption	27,10kWh (see Figure 83for individual values)
Resilience – Total delays	1,000sec (see Figure 124 for individual values)

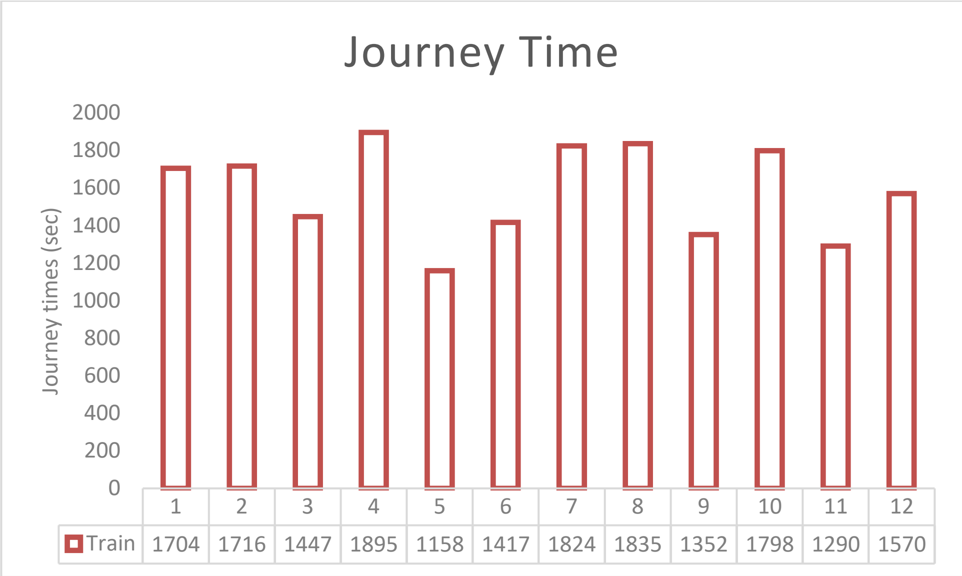


Figure 122: Journey times of VC 4 in1 operation at high safety level

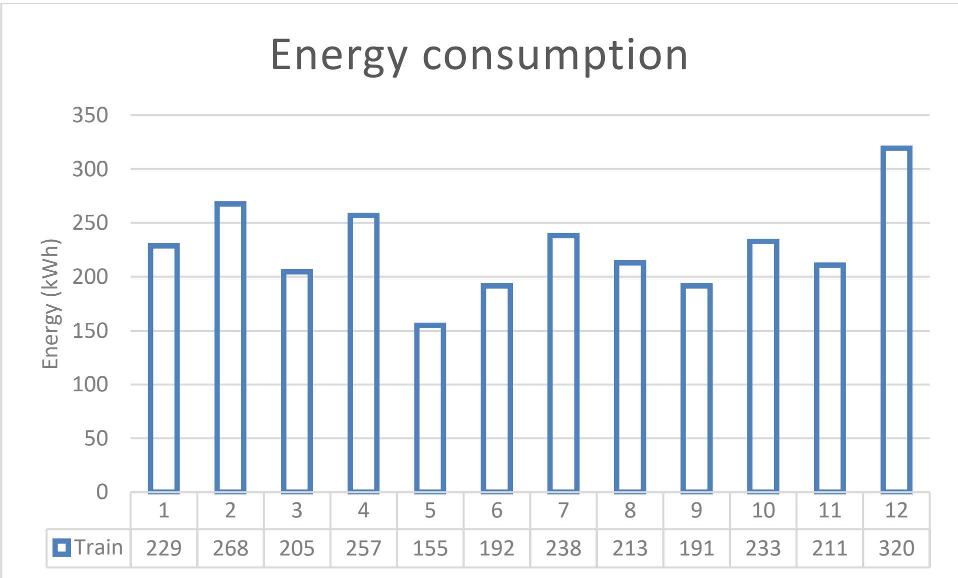


Figure 123: Energy consumption of VC 4 in 1 at low safety level

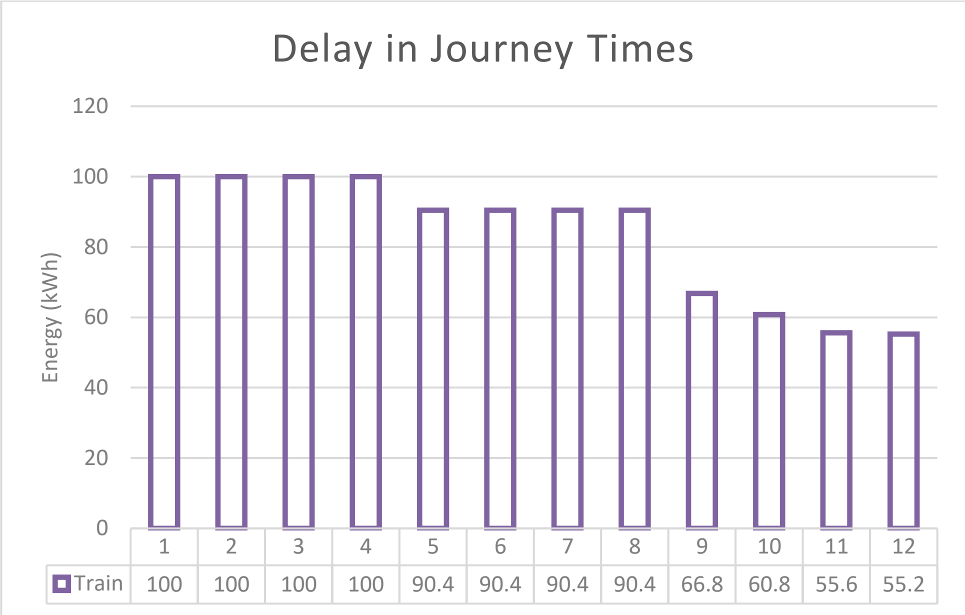


Figure 124: The resultant delays caused by the perturbation operation for VC 4 in 1 at high safety level.

7.4.4 Benchmarking

The VC Operations has a potential of increasing the line capacity between three times and twice as compared to the current operation performance based on the fixed block signalling as indicated in Figure 124. The VC potential varies with changing the convoy formation and the safety level. Important to highlight that the VC potential can be achieved together with ETCS L3 which is needed as the inter-convoy signalling and control system. The number of trains in a convoy has a positive impact on the capacity performance as seen in Figure 126. The 4-in-1 operations have better performance than the 3-in-1 and 2-in-1 ones for the same safety level. A reverse correlation can be seen in Figure 127 for the relationship between safety level and capacity performance. The high safety level has lower capacity performance than the medium and low safety level. More specifically, the operation of 4-in-1 at low safety level increases the capacity by 294% as the highest VC performance whereas the operation of 2-in-1 at high safety level raises it by 188% as the lowest VC performance. As the medium performance, the operation of 3-in-1 at medium safety level enhances the capacity by 225%. The conventional systems have more limited potential increase in capacity as compared to FB: ETCS L3 increases it by 75%, L2 does by 25%.

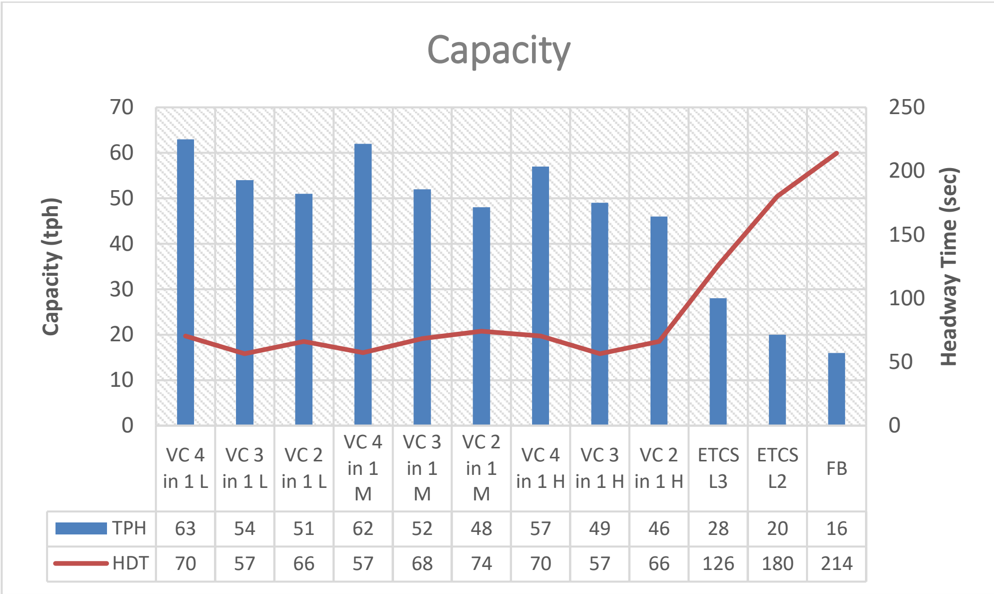


Figure 125: Capacity and headway time performance of the VC operations compared with other train control/signalling systems.

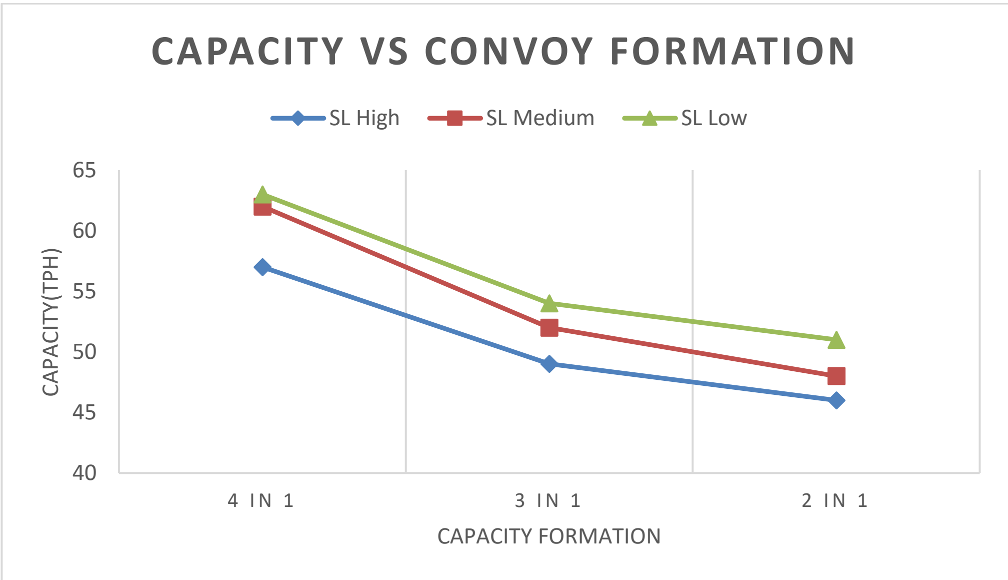


Figure 126: Impact of convoy formation upon capacity performance

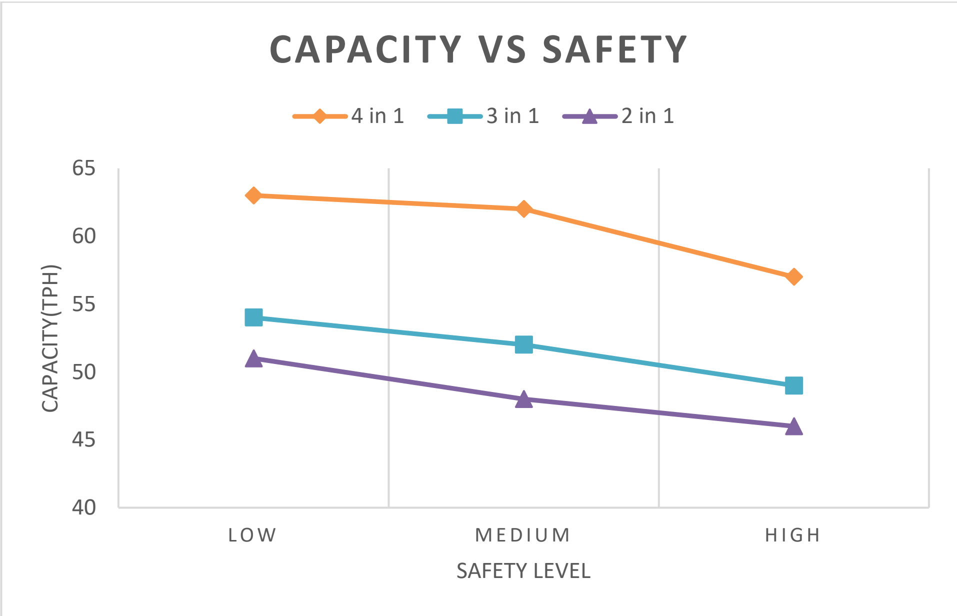


Figure 127: Impact of safety level upon capacity performance

In a similar pattern, the number of passengers accommodated increases along with the increase in capacity as seen in Figure 128. With the current capacity performance under fixed block signalling, 8,000 passengers can be carried per hour per direction. The VC operations raises that up to 32,000 depending on the convoy formation and safety level implemented but 23,000 passengers at the lowest performance. These numbers of passenger accommodation are higher than that enabled by the conventional systems: 14,000 for ETCS L3 and 10,000 for ETCS L2.

The potential capacity increases bring about higher need for resources. Figure 129 shows the minimum ROCS use required to enable the operations at their performance. The train services can run with 22 ROCS at the current capacity performance enabled by FB. For the performance enabled by the VC operations, the number of trains required changes from 62-87. This is potentially a great expansion in the fleet varying from four times to twice. The expansion level is lower with the conventional systems: 37 for ETCS L3 and 26 for ETCS L2.

The journey times taken by the operations can be seen in Figure 130. The operations enabled by the conventional systems including ETCS L3, ETCS L2, and FB are represented all as 'non-VC'. The non-VC operations have the same journey times because the trains with these systems do not have any interaction between each other. The VC operations have 5-7% longer journey times than the non-VC ones.

Figure 128: Passenger accommodation of VC operations along with other train control/signalling systems.

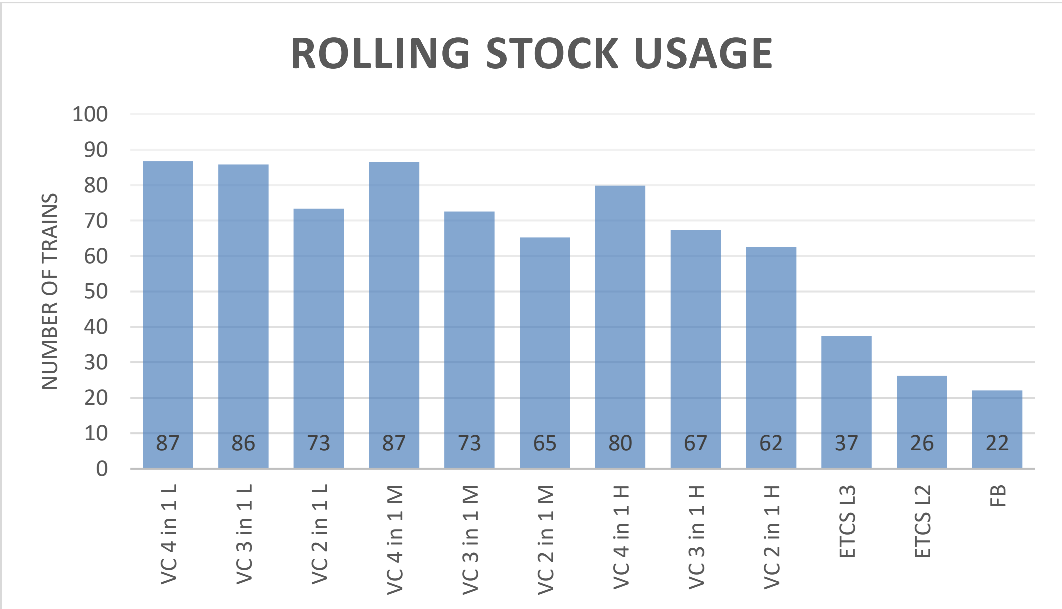


Figure 129: Rolling stock use of VC operations along with other train control/signalling systems.

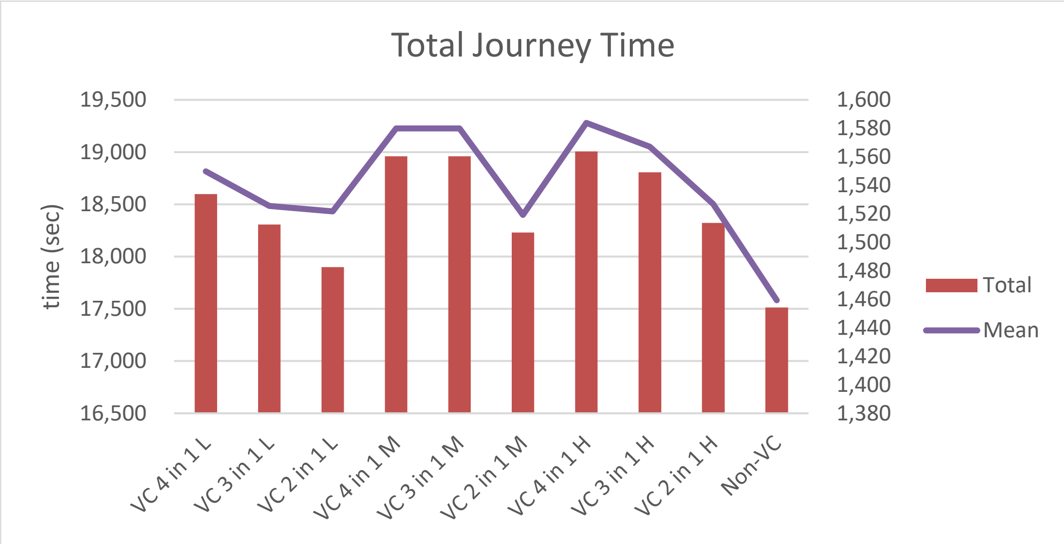


Figure 130: Journey time of the operations

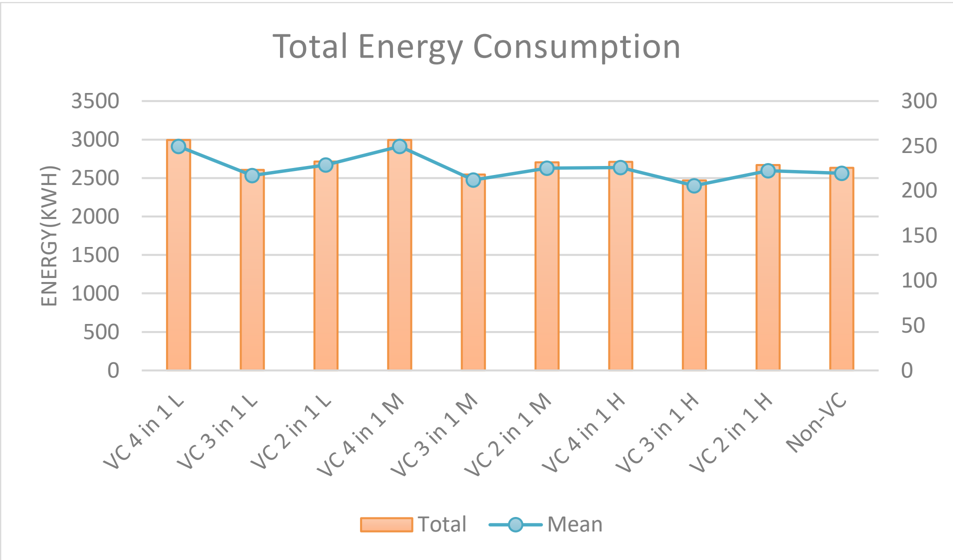


Figure 131: Energy consumption of the operations

The energy consumption has a similar pattern for the conventional operations represented with non-VC as illustrated in Figure 131. The energy consumption of the VC operations is higher than the non-VC operations. The energy consumption is the highest during the 4-in-1 operations at the same safety level. The energy consumption is directly affected by the train speed profiles. The highest energy consumptions are observed through the 4-in-1 and 3-in-1 at low safety level operations: The former is 14%, the latter is 11% higher than the non-VC operation. In the VC operations, the follower trains increase up their speed a little higher than the leader one, which raises the total energy consumption as seen in the previous sections.

The perturbation of that the first train has 100sec delays at the first station has different impact on the VC and non-VC operations. The total delays of the VC operations are bigger than the non-VC operations. In the VC operations, the total delays of the 4-in1 and 3-in-1 operations are bigger than the 2-in-1 operations. The trains in the same convoy has the same delays with the leader one as seen in the previous sections. To reduce the delay propagation, the service intervals between the convoys could be increased. In the non-VC operations, the minimum value is observed through the FB operation with 211 seconds. ETCS Level 3 and Level 2 has similar delays with 413 and 366 seconds in turn.

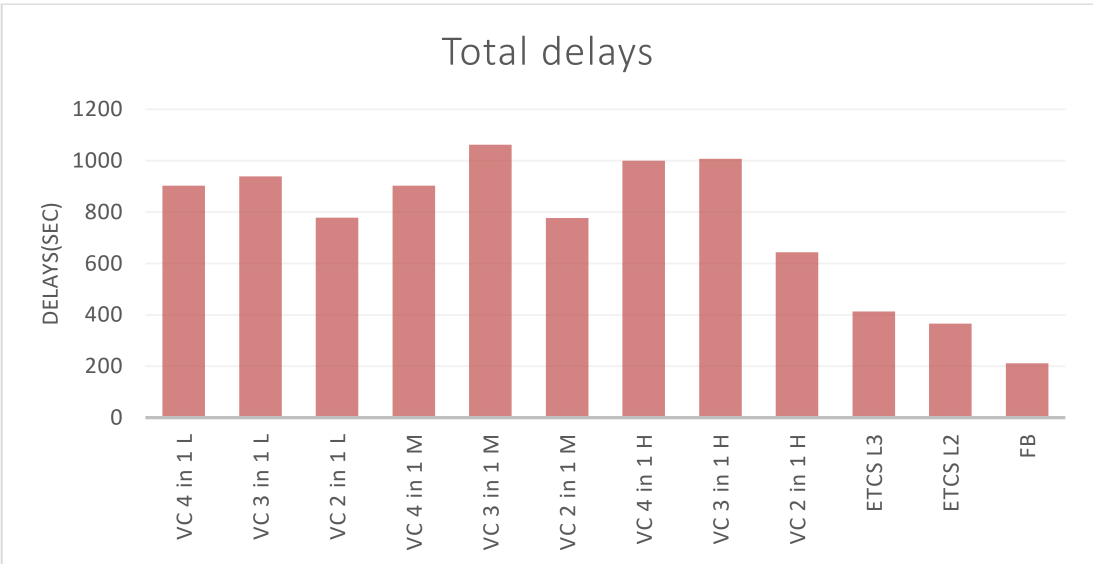


Figure 132: Total delays caused by the perturbated operation.

In order to achieve the greatest capacity, some technical capabilities would be considered as requirements. Reducing safe braking principle is an extraordinary change to railway safety understanding. Thus, there is a trade-off between safety and capacity gain. The capacity gain could be unleashed depending on how much safety risks could be reduced following the principle of "as low as reasonably practicable". Convincing technologies are necessary to change this understanding. Depending on reliability of these novel technologies, an optimum point on the line of trade-off between safety and capacity gain would be found. For instance, more robust communication systems such as V2V to have low latency and advanced sensing technologies to measure inter-train distances and train location much more accurate and precise. and smart braking systems to predict changes in adhesion levels to reduce minimum safe distance, and on-board interlocking systems to be independent of trackside systems could be some of technical capabilities.

7.5 Summary

In this chapter, the framework has been applied to the line from London Waterloo to Surbiton to prove the evaluation steps to analyse the operational performance of VC comparing to that of the conventional train control and signalling systems. The evaluation started with assessing the line from four aspects including infrastructure, rolling stock, signalling system, and timetable. In the next step, baselining was carried out through two steps. Firstly, the simulator was calibrated to make the train motions have the same arrival and departure times with the real TT. Secondly, the minimum allowable service interval was set in the simulator to the theoretical capacity enabled by the existing signalling system. In the third step, the operational plan was prepared to simulate the VC operational concepts with the scenarios specified to the line. In total, nine scenarios were identified from two perspectives each of which has three arrangements: three levels of safety and three types of convoy formation. In the fourth step, the operational plan was simulated, and the performance of the scenarios were analysed benchmarking with the defined KPIs. The VC operations can achieve its capacity gain together with deploying a non-VC system for inter-convoy signalling and control system e.g., ETCS L3 is chosen in this study.

As per the results, the VC operations has a potential of increasing the capacity from twice to four times depending on the convoy formation and the safety level. Even with high safety level, based on absolute braking, the VC operations has an important potential. To balance the increase in capacity, the fleet must be expanded to include more ROCS with additional trains ranging from 40 to 80 depending on the selected scenario. The results indicate that resilience can be problematic for the VC operations. The delays propagate through the same convoy that increases the total delays in case of perturbation. The total delays can be reduced by decreasing number of trains in a convoy and setting enough time margins for service intervals between two convoys. In terms of journey times and energy consumption, the VC operations have slightly higher values than the non-VC operations, which is not at unacceptable level.

Chapter 8 Conclusions

8.1 Findings

This study has approached to VC research analysing feasibility of its operations. VC is defined from an operations perspective in Section 2 of Chapter 3 along with its terminology, types, and operational scenarios. The definition has provided a formal understanding prior to the simulation process. VC is classified into four types from two viewpoints. As per the viewpoint of convoy formation, two different trains build an inter-consist one whereas or one train can be split into two or more sub-trains. As per the viewpoint of safe distance between rail vehicles, virtually coupled train can follow each other at relative braking or absolute braking distance. The simulation architecture required to assess the operational scenarios is explained and a controller that enables trains to follow each other as per the VC operational definition is designed in Chapter 4.

In Chapter 5, the findings have demonstrated that under ideal conditions, VC operations on RB can deliver a technical capacity of 240tph and a headway time of 15sec over the plain line. The scenarios that involve junctions can offer 60 tph capacity and 60 second headway time. The switch processing time and safety principle set a cap on the capacity of these scenarios. Theoretical capacity for the VC operations on AB can range from 60 to 70 tph, taking into account all possible operational scenarios. Additionally, a unique VC operation defined as the *intra-consist operation* allows trains to split into smaller trains or sub-trains, which helps to cut down on energy use and travel time, especially for express high-speed train services that do not have a lot of commercial stops.

The impact of different factors on capacity performance has been investigated in Section 2 of Chapter 5, which is important to creating a VC operational plan onto a line. Braking capability is one of them since it directly affects the safe minimum distance. The more powerful braking rates can contribute more to the VC potential. However, adhesion can reduce braking rates due to external factors such as autumn leaf fall, rainy weather. The cases of unforeseeable reductions in adhesion can deteriorate safety. VC capacity performance is negatively affected by fleet heterogeneity, particularly if the follower train has less braking and tractive effort than the leader train. This is a common circumstance for main line operations in which rolling stock types have a diversity. Also, station layouts and platform length can have a limitation on VC performance. If the platform length is not sufficient to accommodate all trains in a VC convoy, trains cannot initiate the virtually coupled form at the standstill, which leads to additional difficulties for coupling after departing from the station. Different safety principles in determining minimum braking distance have a direct impact on capacity performance. It has been suggested in this study that a migration approach from ABD to RBD can be followed to see their impact with changing relativity index that represents the proximity to pure relative braking. Following a decided safety approach, a specific value can be chosen to benefit from relative braking without taking over all safety burdens of pure relative braking. In forming convoy, the number of trains is critical as a limitation on VC capability. A VC convoy cannot include infinite number of trains. The convoy length is confined by station layout or platform number/length or VC control system capability. The interaction type among the virtually coupled trains has an important effect on convoy stability performance. The primary-secondary one does not have a stable performance in following the leading train at minimum distance for the operational scenarios including more than several stops. The multi-agent one is better in following performance but requires a more complicated control design. Thanks to the multi-agent one, the number of stopping locations does not impact VC capacity performance.

A framework that systemises the evaluative steps has been developed using IDEF0 notation in Chapter 6. The developed framework holds a two-level hierarchy. The top-level is the context diagram of the evaluation goal demonstrates how to convert stakeholders' demands to analysis of VC operational performance. The steps necessary to carry out the primary function at top-level are covered in the second level including capability assessment, baselining, operational planning, and performance analysis. In Chapter 7, the framework is applied to the line section from London Waterloo to Surbiton to prove the framework's usability. The line capability has been assessed from four aspects including infrastructure, rolling stock, signalling system, and timetable. In the process baselining, the simulator is calibrated against the real timetable in terms of train motions. Additionally, the minimum service interval is set to have the same theoretical capacity in the simulator as the one succeeded by the existing signalling system. In the process of operational plan, nine operational scenarios have been defined from two viewpoints including three levels of safety and three types of convoy formation. In the last process, the operational plan is simulated, and performance analysis has been conducted against the defined KPIs. The results have showed that the VC operations can enhance capacity from twice to four times—even at the highest safety level, which is based on full braking. However, to unleash that potential, the fleet expansion is inevitable: additional trains of 40-80 must be added to the inventory of existing ROCs. On the negative side, delay propagation can degrade the potential carried by VC operations. In the deterministic perturbation scenarios, the delay led by the first train in the convoy is propagated as the same through the same convoy, which increases, in effect, the total delays. However, as a resilience strategy, this result can be alleviated by decreasing number of trains in a convoy and setting enough time margins for service intervals between two convoys.

8.2 Further Research and Recommendations

To further the simulation results, a more comprehensive simulation plan can explore the capacity benefits of VC operations with more convincing evidence. This study has a limitation in terms of simulation granularity. The infrastructure was not modelled in all details such as station layout, platform numbers. Additionally, the simulation was run over for a section rather than all the line network. SWR has different routes over the branched lines that converge into or diverge from the spinal line from Waterloo to Weymouth in Southampton, which makes a focused line section analysis in timetabling not sufficiently robust. The network effect deserves to be analysed considering converging and diverging lines covering all the network.

In this study, the simulation was conducted in a deterministic way. As a further work, it is required to conduct a stochastic analysis that helps understand the VC capability better for robustness or resilience of timetabling. The analysis should include the delays occurred in existing train operations such as delays at station area due to high passenger intensity, or all platforms being occupied. Similarly, passenger circulation should be simulated to observe the sufficiency of station and platform capacity for accommodating the increased demand at peak hours.

The study has defined the safety relativity index to develop an incremental approach to migrate from absolute braking principle to pure relative braking. Safety relativity index is a blended principle of absolute and relative braking at an assigned value. It is suggested as a further research topic to develop a safety method that finds the most suitable index value for each line considering safety related factors. This is an important step to change the existing strict perception about safe distance principle between two consecutive train services. In addition to the index, adhesion is critical in safety context. Unforeseeable changes in adhesion directly affect braking capability, thereby increasing the likelihood of head-to-tail collision between trains in a VC convoy. Some works should focus on to which extent the external factors such as weather conditions, leaf fall etc. can alter adhesion, and in effect, braking capability and which solutions can be developed to mitigate the reduction in adhesion and braking capability. This research must cover the hypothetical worst-case scenarios that lead to collisions due to low adhesion rate.

Intra-consist VC operations can bring new functionality to rail transport services by modernising old-fashioned slip-coach application which was abandoned in the early 1990s. A new concept, so-called ‘rail-taxi’, should be a research topic that has a potential of increasing flexibility in rail operations. Rail-taxi can provide unique and fast services for passengers with a personalised route selection that skips stations if anyone on board does not plan to get off. Rail-taxi should be integrated with mobile applications to arrange instant travel demands. This research can be applied to a pilot line to observe pros and cons. In addition to flexibility, intra-consist operations can reduce energy consumption, especially for train services with a low number of stoppings. This can be achieved by cutting VI between sub-trains or single units to leave them at oncoming stations without halting all units.

The research on capacity benefit would be furthered to analyse trade-off between capacity gain and cost of safety. In the UK context, FWI is a preferred indicator that measures fatalities and injuries in terms of monetary values by assigning specific weights for incidents against the value of a statistical life. Through FWI measures, a cost-benefit analysis could be conducted for VC operations. This analysis could include demand analysis, operational revenue with an increase in number of passengers versus technical upgrade costs and safety costs. That would offer an economic evaluation to complements this study’s feasibility analysis of VC Operations that has focused on capacity benefit excluding the economic aspect.

Furthermore, the required technical capabilities for VC operation to gain capacity benefit would be an important part of further research. Acquiring these technical capabilities could be potentially challenging due to the complex and complicated nature of railway systems. Thus, deciding on where a technical capability is more effective and achievable could be a research focus. In later stages of realising VC operations, designing experimental trials is critical, especially for a system design that replaces the physical connection between two carriages with a virtual connection. The physical connection balances continuous mechanical push-pull forces along the consist. The virtual connection and controller should be demonstrated through experiments on a small scale at the outset. For instance, every year IMechE Railway Challenges are run on a line with miniature track gauge—that's suitable for testing processes. In addition, interlocking technologies are critical to process switch blades fast and keep lines safe as the simulation results have indicated. The current technologies are based on a trackside controller architecture such as Computer-based Interlocking. Different architectures including on-board interlocking should be developed and tested. In addition, novel sensor technologies should be a research topic especially for sensing inter-vehicle distances that would be important once VC operations potentially shorten the existing distances between trains. The sensing technologies enabled Autonomous Cars can make contribution to the rail domain.

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