UNIVERSITY OF BIRMINGHAM

PhD in Civil Engineering

# A Risk-Informed Approach to setting Economically-Justifiable Maintenance Strategies for Railway Tracks

By

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## Abstract

The global railway infrastructure is carrying ever increasing amounts of railway and freight traffic which in turn is causing accelerated rates of infrastructure deterioration. Given the pressure to increase track utilization, the ageing infrastructure on which much of the railway transport systems are founded, and the constrained budgets under which the infrastructure is managed, appropriate maintenance needs to be predicted, prioritized, planned and carried out efficiently and economically. This doctoral research aims to develop a means of appraising railway track maintenance strategies economically while taking into account the associated risks and uncertainties. To this end, this research proposes, a Whole Life Cycle Cost Analysis (WLCCA) under uncertainty, while considering the direct and indirect costs of track maintenance, and the benefits to train operation, users, safety and the environment. The developed risk-informed approach is demonstrated via case studies on three different route types within the UK mainline railway network.

# Dedication

To my father, mother and family,

I thank you for your constant support, reassurance, and love over the years.

Without whose support, the road would not have been built.

To my friends,

Without whom the journey would not have been enjoyable, nor as fulfilling as it has been.

To my mentors,

For the never-failing support, humour and encouragement.

Without whom the path would not have been travelled on.

*"Two roads diverged in a wood, and I-*

*I took the one less travelled by,*

*And that has made all the difference."*

*- Robert Frost,*

*The Road Not Taken*

# Acknowledgement

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I am thankful to my parents Sasidharan P A and Meena Sasidharan, for being by my side and without whom, I would not have the courage to embark on any journey. My father, who through a telephone conversation at a crucial time, helped me find the strength to carry on. My mother, who constantly reminds me the purpose of one's life - to be content at heart.

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*'Un pour tous, tous pour un'*

*'All for one, one for all'*

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# Chapter 1

# Introduction

## 1.1. Background and Scope of Research

Transportation systems not only provide mobility, but also drive economic development, influence land use, urban planning, impact the environment and enhance the liveability of both cities and rural communities (Castillo et al., 2010). With global population increase, rapid urbanisation and economic development, the transportation industry is being tasked to provide more rapid, frequent, reliable, less congested and safer services which carry ever increasing numbers of goods and passengers. However, transport is one of the major contributors to greenhouse gas emissions and therefore climate change. In light of these conflicting drivers there is a need for transportation in all of its forms to become sustainable and at the same time ensure that mobility is available for all (SUM4ALL, 2017). Indeed, sustainable transport has become a fundamental goal of transport planning and policy worldwide (Castillo et al., 2010). Although not one of the United Nation's (UN's) 17 Sustainable Development Goals (SDGs), transport could be considered to contribute to at least 8 of these, especially those related to climate change, sustainable infrastructure, cities and human settlements, health, energy and food security (UNECE, 2017). Furthermore one of the goals within SDG 11 - Sustainable Infrastructure and Cities (i.e. SDG 11.2) mentions directly, the wish to provide access to safe, affordable, accessible and sustainable transport systems for all by 2030.

Sustainability associated with transport can be considered in terms of equity, economy and ecology (Burrow et al., 2016). Maintaining the balance between these three objectives can only be usually achieved only when there is a trade-off between economic development and its impacts on the environment and human life (May et al., 2007). This requires decision makers to consider the *'impacts including depletion of non-renewable fuels, climate change, air pollution, fatalities and injuries, congestion, noise pollution, low mobility, biological damage, and lack of equity'* when deciding on transport policy and appraising investment in transportation (Gilbert, 2006).

Railways are a major component of a sustainable transport policy in many countries as they are green, efficient and safe (Sasidharan, 2019). Furthermore, they are a key mode for the transportation of passenger and freight traffic in urban, suburban, regional and national levels. Railways are therefore an important part of many countries economic and social development (Sasidharan, 2017). Consequently, many such countries have experienced significant economic, environmental, social and political pressures to increase railway operation and safety.

Since 1975, the global passenger and freight railway usage have grown by approximately 130% and 76% respectively (UIC, 2017). Consequently, there is an increasing demand for the railway industry to expand capacity, availability and to transport goods and people at higher speeds. However, in many countries investment in the expansion of infrastructure has not kept up with the demand for increased usage. There is therefore an increasing pressure for railway infrastructure maintainers to make the best use of the available resources. In the United Kingdom for example, although there has been significant investment in several high-profile schemes, the size of the railway network has not changed significantly in the last 20 years and the network is now the second most intensively used in Europe (Sasidharan et al., 2017). In 2016-17, £548 million was spent on track maintenance in the UK; 10% more than forecast (ORR, 2017). The UK is also projected to spend £18.5bn on operation and maintenance during 2019-24, an increase of 25% from the previous five years.

Railway track maintenance directly affects the condition of the railway track and therefore, the likelihood of accidents, the fuel and maintenance costs of running trains, travel time costs of freight and passengers and fuel emissions. Indeed, the maintenance and renewal activities of railway infrastructure form a major component of investment in most developing and developed countries (Sasidharan, 2019). Since the railway can be regarded as a public good, paid for from public money, investment strategies should be such that the chosen maintenance strategy should provide the greatest return of investment to all stakeholders.

However, maintenance decisions are largely based on short-term, subjective criteria (due to a lack of data or the uncertainty of its accuracy), which not only ignores a whole-system perspective, but also fail to consider the costs and benefits of operation and maintenance (Sasidharan et al., 2017). This is being exacerbated in many countries where the ownership of the infrastructure and the operation of rolling stock are formally separated. For example, this can result in a lack of consideration of the damage that infrastructure may cause to rolling stock and vice versa, resulting in higher total transport costs (Sasidharan et al., 2019).

Safety is also a paramount consideration in the sustainable operation of the railway, but intensive usage increases the likelihood of accidents (Sasidharan et al, 2017). In many accidents, such as derailments, preventive maintenance is a key factor to mitigate risks before they impact operations, revenue or safety. In the UK, there were 687 train accidents in 2016-17, with 25 of them classified as Potentially Higher Risk Train Accident (PHRTA) resulting in at least one death, considerable delay costs, track downtime and damage to property (ORR, 2017). For many accidents maintenance is a key factor in prevention. The UK's Railway Safety Standard Board (RSSB) suggested that the UK railway industry needs to consider the costs and benefits associated with reducing risks within its decision making process (RSSB, 2016a). Integrating risk management and asset management would facilitate this and tackle other asset management challenges faced by the railway industry, namely restricted maintenance budgets, increasing track usage and uncertain and limited data for decision making.

To facilitate the effective management of the railway transport system under these constraints, this doctoral research project develops a railway maintenance investment appraisal approach, to enable economically justifiable maintenance standards to be determined for traditional ballasted railway tracks. The approach incorporates asset management and risk management concepts and considers the needs of railway stakeholders over the whole life-cycle of a railway.

## 1.2. Aims and Objectives

The aim of this research is to develop a means of appraising railway track maintenance strategies economically taking into account risks and uncertainties.

To achieve this aim the research has the following objectives:

1. To scrutinise, by means of a literature review, the factors that contribute to the deterioration of ballasted railway track and how railway track deterioration may be modelled.
2. To identify how railway track deterioration is assessed and measured in practice, the maintenance techniques available to address deterioration and the effectiveness of these techniques.

3. To explore how railway track condition impacts the operation of the railway and affects stakeholder benefits and costs.
4. To explore approaches to assess the economic costs and benefits of different types of railway track maintenance.
5. To review the literature to determine, if and how, risk management concepts can be used to model railway accident risks and data uncertainty within the approaches identified in objective 4.
6. To validate and demonstrate the proposed risk-informed approach through a variety of suitable case studies.

## 1.3. Novelty of the Research

In terms of methodological advancements, this research makes two contributions to the body of knowledge.

Firstly, the approach developed in this research can be used to compare different track maintenance strategies on a whole-transport-system basis, to identify the most economically beneficial strategy.

Secondly, the Whole Life Cycle Cost Analysis (WLCCA) approach developed by this research, takes into account accident risk and the uncertainty of data.

Hence the risk-informed asset management approach proposed within this research for the first time, provides railway policy and decision makers with a means to appraise maintenance investment strategies by considering environmental, safety, social and economic costs and benefits.

## 1.4. Overall Structure of the Thesis

The remainder of this thesis consists of seven chapters.

Chapter Two critically reviews different railway asset management techniques. The chapter also investigates the possibility of integrating risk and asset management concepts for setting periodic maintenance strategies for the railway tracks.

Chapter Three provides a review of risk management practices and risk assessment techniques, with a focus of those used within the railway industry.

While Chapter Four presents the methodology adopted to carrying out this research, Chapter Five describes the components and techniques that make up the proposed theoretical framework for the risk-informed asset management approach

Chapter Six demonstrates the usability of the risk-informed approach through case studies of three different route types on the UK mainline railway network.

Chapter Seven, the discussion chapter, critically overviews the approach developed.

Chapter Eight presents the conclusions of the research and recommends areas for future development.

The findings from this research have been published within two conference proceedings (i.e. The 14th Railway Engineering Conference, Edinburgh, United Kingdom and the 15th World Conference of Transport Research Society, Mumbai, India). One journal paper has been submitted to the Journal of American Society of Civil Engineers. All the three publications can be found in Appendix A.

# Chapter 2

# Asset Management

The purpose of this research is to investigate the possibility of using asset and risk management concepts to develop a tool which can be used to compare railway track maintenance standards on an equitable basis. To this end, this chapter explores the concepts of asset management and its application to railway track assets. A review of literature and theoretical background for the current railway asset management approaches are also presented.

## 2.1 Concepts

Assets are items with a value and could be either tangible (such as buildings, equipment) or intangible (such as human capital, royalty). ISO 55000 (2014) defines asset management as *'the coordinated activity of an organisation to realise value from assets'*. A simple objective of asset management, according to Mitchell (2007), is to *'increase the value and return delivered by the physical assets'*. Hence, asset management policies cover social, economic and technical attributes of the asset, and is a process of continuous improvement (Van der Westhuizen et al., 2013).

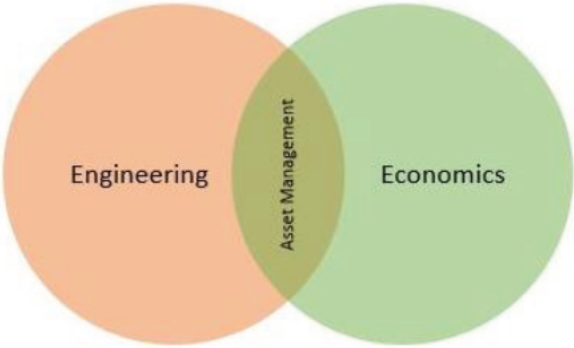



Figure 2.1 Conceptual components of infrastructure asset management (Robinson, 2008)

It can therefore be seen that, asset management requires consideration of the long term health of the physical asset and how the asset can be utilized to maximize their benefit to stakeholders at least cost over their lifetime. This requires consideration of engineering, the social sciences and economics.

When it comes to asset centric industries like transportation, asset management is focused on the infrastructure involved. Hooper et al. (2009) describes infrastructure asset management as *'the combination of management, financial, economic, engineering and other practices applied to physical assets with the objective of providing the required level of service in the most cost-effective manner'*. Van der Westhuizen et al. (2013) describes infrastructure asset management as a *'rational decision making process'* which aims to satisfy service and quality demands of assets while *'minimising costs and maximising effects'*. In principle, infrastructure asset management can be viewed as an overlap of engineering and economics as shown in Figure 2.1.

## 2.2 Transport Asset Management

Transport is an important part of many countries' economic and social development, with linear transport infrastructure (roads and railways) often considered to be the largest public owned asset in terms of size and investment (FHWA, 2012). Globally, the transportation industry is being relied upon heavily to find solutions to reduce congestion and, environmental impact and at the same time to increase capacity, to support economic growth, urbanisation and increased human mobility needs.

However, transport is one of the major contributors to greenhouse gas emissions and therefore climate change. The transportation sector as a whole consumed 28.8% of the global energy, while contributing to 24.7% of global CO2 emissions in 2017 (UIC, 2017). The damaging environmental impacts of transportation is a worsening global problem that needs to be tackled with local solutions, such as maintaining the infrastructure sustainably. Although railways contributed to only 4.2% of the global $CO_2$ emissions, many countries are setting ambitious environmental targets for their railway industry (UIC, 2017) (refer to Table 2.1 in page 29). In light of these conflicting drivers there is a need for transportation in all of its forms to become more sustainable and at the same time ensure that mobility is available for all.

Policy makers are often faced with two basic decisions: to expand the infrastructure networks and to maintain existing networks (Berg et al., 2016). Transport infrastructure is often the largest public-owned asset in both developed and developing countries, and the need to maintain or manage them is often greater than the decision to construct new ones (ITF, 2013).

The condition of linear transport assets deteriorate over time due to the combined effect of traffic and the environment. This in turn impacts their capacity, safety, user costs and the environment. Therefore transport assets need to be maintained. Maintenance activities involve direct costs in the form of labour, machinery and planning, while the activity itself can result in capacity loss (e.g. delays, speed restrictions, road closures and cancellations of train services), social and environmental costs. Furthermore, the condition of a transport asset also impacts the costs of the use of the asset. Typically, as the condition improves the economic, environmental and social costs associated with using the asset reduce (de Jong et al., 2012; Pradhan et al., 2013; Al-Douri et al., 2016).

Typical maintenance strategies are corrective and preventive. Corrective maintenance is usually carried out when the system fails or a hazard happens (such as derailments, rail breaks, slope failures etc.). Preventive maintenance includes routine-based and condition-based maintenance and is, generally carried out to before the asset fails and to maintain appropriate quality (Heggie et al., 1998; Stenstrom et al., 2016). For a given section of road or railway, choices need to be made between alternative maintenance strategies. This situation is exacerbated when there are limited maintenance budgets and competition between different sectors in terms of their maintenance needs. While deferring maintenance intervention for a short term is an easy solution, it can be expensive in the long term as it increases maintenance and vehicle operation costs, safety risks and environmental impacts (Al-Douri et al., 2016).

## 2.3 Railway Asset Management

Railways serve as a key mode of transportation of passenger and freight traffic in urban, suburban, regional and national levels. With the rise in road traffic, which is seen as a less green form of transport and associated congestion, there is an increasing demand for railways to expand their capacity, availability and carry goods and passengers at higher speeds. By 2025, railways are expected to carry 11,912 billion tonne-kilometres of freight and 5,149 billion passenger-kilometres worldwide. This is an increase of 14.75% and 37.2% respectively from 2015 (SCI, 2017). In many countries, investment in the expansion of infrastructure has not kept up with the demand for increased usage. In the United Kingdom for example, passenger journeys have increased by approximately 137% between 2018-19 and 1993-94 without any significant increase in the amount of railway infrastructure, making the UK railways Europe's second highest congested railway network (ORR, 2019). Similarly, during the same period passenger numbers in the United States have risen by 63.5% with a 9% increase in railway track length (BTS, 2019; APTA, 2017) and in India the corresponding figures are 236% and 7% respectively (World Bank, 2019; MoIR, 2017).

By 2025, the UK aims to reduce the journey time for long distance passenger operations by up to 6% by increasing current operational speeds and introducing high speed lines. For example, the speed of the majority of passenger trains in the East Midlands will increase by 13% in the next 10 years (NR, 2011). India too aims to increase the speed of all the long-distance passenger trains on its network by 25km/h by 2022 (MoIR, 2017). Such increasing trends of usage results in a faster degradation of railway assets, higher associated maintenance costs, a rise in safety risks and Green House Gas (GHG) emissions. For example, the amount spent on maintaining the railway track infrastructure in the USA (FRA Class 1 rail roads), UK and India during 2016-17 was $9.8 million, $775 million and $2.08 billion respectively, which was 1.2%, 3.8% and 24% higher than in the previous year (APTA, 2017; ORR, 2017; MoIR, 2017). Also in 2016-17, UK spent 10% more on maintenance and renewals than forecasted. There is therefore an increasing pressure for railway infrastructure maintainers to make the best use of their available resources.

For traditional ballasted railway track in particular, railway track maintenance directly affects the condition of the railway track and therefore, the likelihood of accidents, rolling stock fuel and maintenance costs, travel time costs and emissions. Safety is a paramount consideration in the sustainable operation of the railway, but the intensive usage increases the likelihood of accidents. In many accidents, such as derailments, preventive maintenance is a key factor to mitigating risks before they impact operations, revenue or safety. For example, a lack of track inspection and maintenance were major contributing factors for several passenger train derailments in the UK during 2000-2010 (RAIB, 2010). While in India, timely maintenance and renewal of the track infrastructure led to a 30% reduction in the accidents during 2010-2016 (MoiR, 2017).

Due to cost constraints associated with  the availability of machinery, human resources and the availability of the railway, railway maintenance and renewal activities need to be planned at least one year in advance (Quiroga et al., 2011). Railway track maintenance (See Section 2.3.1) is further complicated by the ever-increasing utilisation of the railway networks and the pressure to make the railway continuously available.

Network Rail, the owner, operator and asset manager of the majority of the UK's railway network defines railway asset management as *'a group of systematic and wide coordinated activities in an institution which manages optimally their assets as well as their performance,* *risk and costs during their life cycle according with the strategic plan'* (NR, 2011). OECD (2001) observes that the railway asset management should consider the following to make cost-effective decisions:

(i) the economic value of assets,

(ii) cost optimisation through their life cycle,

(iii) a clear understanding of the organisation's role as the manager of the assets

The goal of a railway track asset management from the track owner/operator perspective is to determine the best strategy that can maintain track quality at an acceptable level, in terms of passenger comfort, safety and cost-efficiency (Prescott et al., 2013). Accordingly, the track use costs (other than safety) are often overlooked. Determining an ideal strategy is a complex problem that requires consideration of the interrelated processes of track utilisation, track use costs, deterioration, inspection, maintenance and renewal (See section 2.3.2).

Given that the life cycle of the railway track is 25+ years and preventive maintenance decisions are planned several years in advance, there is a need to consider future costs and benefit uncertainties. The problem is exacerbated as the ownership and operation of rolling stock and infrastructure is often separated in many countries, such as in the UK (Sasidharan et al., 2019). As mentioned above, this can result in infrastructure owners/managers having little concern for track use costs, including rolling stock operation costs. It is in the interests of both track infrastructure managers and rolling stock operators to maintain the infrastructure and rolling stock appropriate, since poor infrastructure condition leads to high dynamic train loads which damage the track and result in higher train operation costs and greater derailment potential. Similarly poor vehicle wheel condition leads to high dynamic loads, resulting in infrastructure damage and higher train operation costs.

Further, railways not only provide mobility, but also influence economic development, land use, urban planning, and environment and enhance the liveability of cities. Therefore, since the railway can be regarded as a public good, paid for from public money, investment strategies should be such that the chosen design and maintenance strategies should provide the greatest return to all stakeholders. Maintenance strategies for the railway track should not only consider the direct costs of track maintenance, but also the direct and indirect impact to rolling stock, users, safety and the environment. A well-maintained track not only provides a suitable level of ride comfort and safety but also increases the life of the track as well as track availability. Maximizing the benefit of maintenance investment can only be achieved by determining optimal and sustainable maintenance strategies, while considering a whole system perspective. To this end, this research explores the possibility of using a Whole Life Cycle Cost (WLCC) analysis approach informed by the prediction of track behaviour to different maintenance strategies (see Sections 2.3.2-2.3.4).

### 2.3.1 Railway Track Maintenance

Railway track infrastructure maintenance is *'the complete process of maintenance and renewal necessary to satisfy the availability, safety and quality requirements'* of the track structure (Famurewa, 2015). The maintenance process is concerned with the effective use of resources and technique to enable an asset to extend its operational life. As mentioned earlier, maintenance and renewal activities are costly. Hence, it is important to plan maintenance activities in advance and to make best use of the costs involved.

#### *2.3.1.1 Railway Track Deterioration*

Over time, railway track settle due to permanent deformations of the ballast and subgrade, arising from repeated traffic loading and the effect of the environment (Dahlberg, 2001). This causes railway track geometry to worsen. Due to their direct contact with the wheels during the repeated traffic loading, the track is subjected to the highest levels of stress (dynamic load) causing the ballast to settle, resulting in track deterioration (Dahlberg, 2001; Oberg et al., 2007). Deterioration increase as a function of the weight of the train, speed and track condition (Burrow et al., 2017). The worse the track condition the higher the dynamic loads imposed on the track and therefore the greater the rate of deterioration. Environmental factors such as temperature variations, rainfall, land-slides, flooding, falling rock and snow also contribute towards the deterioration of the track (Guler, 2011; RSSB, 2016). Figure 2.2 presents a cause and effect diagram or fishbone diagram categorising the different causes that lead to track geometry deterioration.

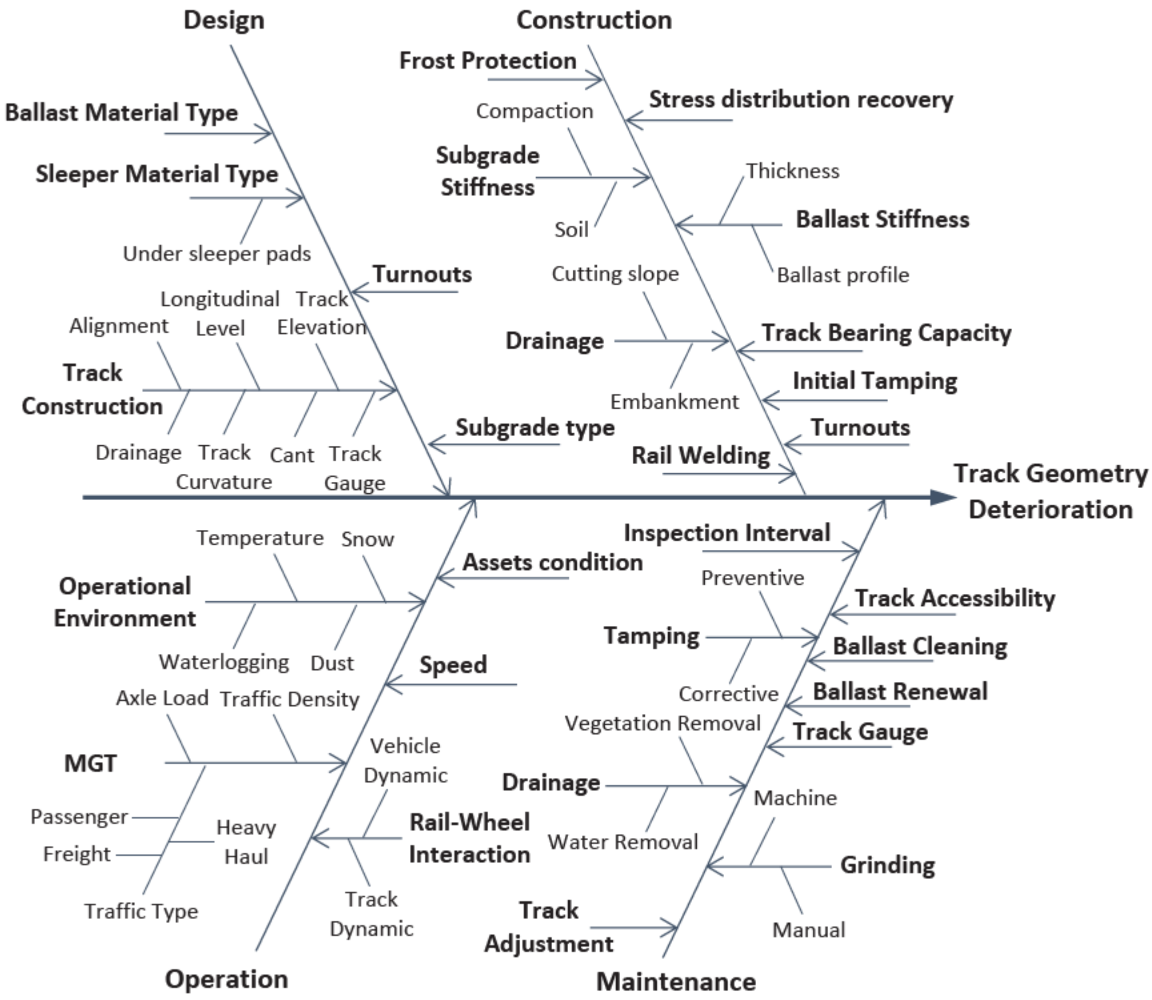



Figure 2.2 Fishbone diagram of the factors influencing railway track geometry deterioration
Source: adapted from Arasteh khouy et al. (2014)

Track geometry deterioration results in poor ride quality, vehicle and track component damage, reduced safety and higher train operating costs. Consequently, the track needs to be maintained periodically (Thom et al., 2006; Guler, 2013; Jovanovic et al., 2015; Burrow et al., 2017). Initially track deterioration manifests itself in a loss of track geometry, i.e. the functional performance of the track decreases. However, overtime track deterioration affects the structural performance of the track i.e. long-term health of the track sub-structure (Burrow et al., 2009).

#### *2.3.1.2 Measures of track condition*

Functional and structural track condition issues manifest themselves in different ways, are measured using different strategies and require different types of maintenance. These aspects are discussed below. While the functional condition directly relates to track operation (i.e. serving the rail users), the structural condition deals with its capability to carry load and protect subgrade (Burrow et al., 2009).

##### *2.3.1.2.1 Track geometry*

Track inspections are carried out to measure the quality or condition of the railway track at pre-determined intervals. Inspection could be visual or non-destructive testing such as ultra-sonic inspection, track geometry inspections and laser inspections. Specially-instrumented recording vehicles are used at intervals, based on the traffic volume and the line speed, to measure the track geometry (Prescott et al., 2013). The track geometry data thus collected aids the planning of track maintenance and informs the track deterioration process (Guler, 2013).

For traditional ballasted railways, the track geometry is used as a measure of the functional integrity of the track and the safety of train travel and is often used by railway asset maintainers to trigger track maintenance and renewal (M&R) activities (Guler, 2014). It is usually described in terms of vertical and horizontal track geometry, and associated tolerances are usually specified in track design and maintenance standards such as BS EN 13848 - Track Geometry Quality (BSI, 2017). Vertical track geometry is mostly used as an indication of maintenance needs, while horizontal alignment is usually indicative of safety requirements (Guler, 2013). The standard Deviation (SD) of the railway track geometry, both vertical and horizontal, are measured at a pre-defined interval (e.g. every metre).

As the track quality deteriorates over time, increases occur in operating costs through a rise in fuel consumption, environmental emissions and train maintenance requirements, while passenger comfort reduces. Track geometry deterioration poses safety issue due to potential derailments, and imposing speed restrictions to avoid this risk results in delays within the network (Quiroga et al., 2011). Consequently, it is used in the railway industry as the primary indicator for railway track maintenance and it also drives track use costs.

##### *2.3.1.2.2 Track stiffness*

Track stiffness is a measure of the structural condition of the track and is taken to be the load required to produce a unit deflection of the rail (Burrow et al., 2009). This deflection is measured using variety of methods namely, accelerometers, multi-depth-delfectomters and falling weight deflectometers (Powrie et al., 2016). Maintaining the track stiffness is important as it affects the extent to which load from the wheels are distributed along the length of the railway track. Lower track stiffness can result in wider deflection or bending of the rail.

#### *2.3.1.3 Railway track maintenance activities*

In order to remedy track deterioration a variety of maintenance techniques are used. Some of the frequently employed maintenance techniques are presented in the following sub sections. Ballast is renewed when the maintenance activities cannot achieve the required track quality as per the safety limits (Guler, 2013).

*Track realignment*

The most commonly used methods to correct vertical track geometry faults (i.e. functional issues) are tamping and stone blowing (Prescott et al., 2013). These techniques are henceforth referred to as track realignment. It restores the track geometry by compacting the ballast under the sleepers, allowing the repositioning of the rails and sleepers (Cellmer et al., 2016). This usually involves packing the ballasts underneath the sleepers to correct the alignment, which in turn improves the track quality.

### *Ballast cleaning*

The occurrence of fines within the ballast can be caused by ballast attrition resulting from loads imposed on the ballast by rolling stock, the upward migration of fines from the sub-ballast or subgrade, or the destructive effects of tamping on ballast particles during maintenance (Selig et al., 1994). Ballast attrition and the migration of fines are exacerbated by excessive dynamic train loads which can result from poor track or rolling stock condition (Burrow et al., 2017). The presence of fines within the ballast reduces interlocking between ballast particles and permeability, and therefore the ability of the ballast to carry train loads, subsequently affecting track geometry (Mundrey, 2010). Ballast cleaning machines are often used for this purpose.

### *Routine maintenance*

Routine maintenance activities such as shoulder cleaning, weed spraying, vegetation removal and clearing of leaves on track are also carried out at regular intervals (Guler, 2013). Multi-Purpose Vehicles (MPV) spray herbicides to control the weed/plant growth on the tracks. Vegetation growth on the line side poses safety risks to the railway operation by blocking access and line of sight. NR's maintenance teams routinely cut back plants and trees that grow close to the railway track to prevent the falling of leaves on tracks. Drainage system components such as pipes and culverts are often cleaned to enable smooth exit of water from the track infrastructure.

Track maintainers are therefore tasked with devising maintenance strategies which need to consider track deterioration rates, acceptable track geometry levels, and costs, track down time and train schedules (Quiroga et al., 2011). Figure 5.1 shows how different maintenance strategies can affect track geometry deterioration and produce different average track geometry values over time.  Higher (poor) average track geometry values overtime result in higher railway track use costs as discussed above. A challenge therefore when devising economic track maintenance strategies is to weigh the railway track inspection and maintenance costs required to keep the track to a given average value over time, against the associated railway track use costs (Andrade, 2016; Asplund et al., 2016; Kirkwood et al., 2016; Skinner et al., 2011). Appropriate means of achieving this are through the adoption of Whole Life Cycle Cost (WLCC) approaches as discussed below.

### 2.3.2 Whole Life Cycle Costs

The concept of life cycle costing is associated with the belief that an increase in initial investment decreases long-term expenditure (Kirkwood et. al., 2016). Life cycle cost analysis (LCCA) is concerned with accounting for future direct and indirect costs over the duration of an asset's economic life (Kirkwood et. al., 2016). The whole Life Cycle Cost Analysis (WLCCA) includes the renewal and disposal costs (Boussabaine et. al., 2004), see Figure 2.4.

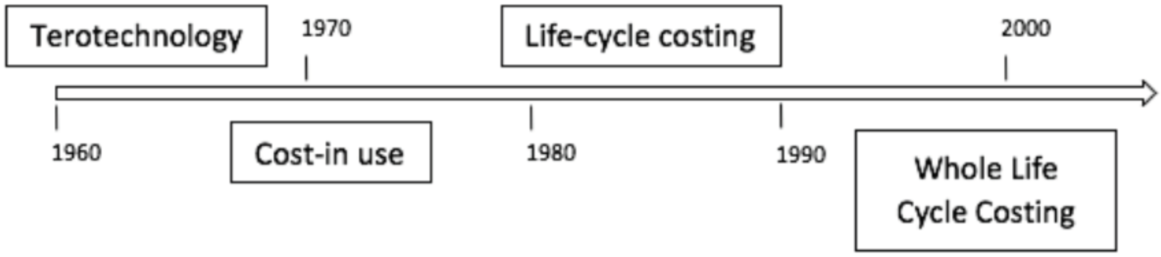



Figure 2.3 Evolution of Whole Life Cycle Costing (Boussabaine et al., 2004)

ISO (2011) Standard 15686 defines Whole Life Cycle Cost Analysis (WLCCA) as *'a methodology for the systematic economic consideration of all whole life costs and benefits over a period of analysis, as defined in the agreed scope'*. It helps asset managers to appraise and prioritise investments. Responsible decision making is possible, only when costs and performance are considered on a long-term, life-cycle basis. The objective of WLCCA is to *'determine the total cost of ownership of an asset'* by identifying the direct and indirect costs that are incurred during an asset's lifecycle (Atkins, 2011).

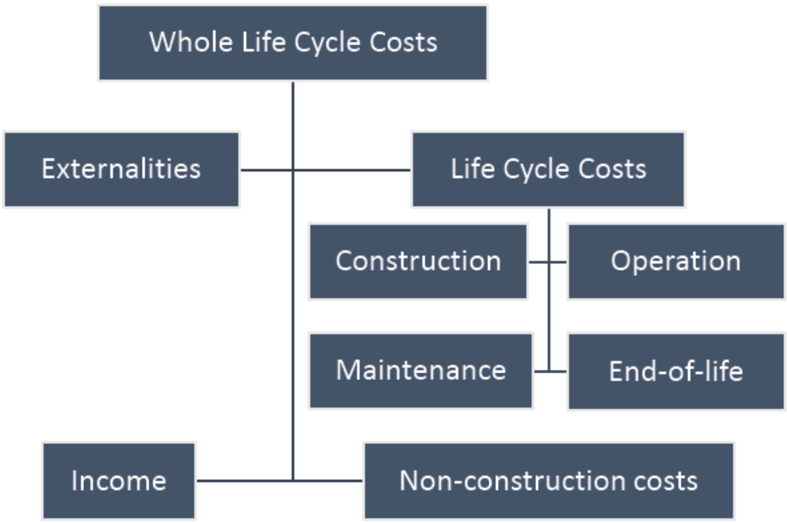



Figure 2.4 Whole Life Cycle Costs adapted from ISO 15686-5 (2011)

#### 2.3.2.1 WLCC components

An effective asset management systems can be put in place, only when the different components within its life cycle are identified (Wenz, 2018). For this research, these components are informed by ISO (2011) (see Figure 2.4) and are identified from the literature of the current approaches reviewed in Section 2.3.3. The WLCCA approach proposed by this research for ballasted railway track maintenance (See Section 5.1.1), considers the direct and indirect costs associated with ballasted track construction, maintenance, de-commissioning and railway track use costs. Railway track use costs include rolling stock operation costs (i.e. fuel consumption and maintenance costs), travel time costs and socio economic costs. Figure

5.2 conceptualises the different cost elements, as a function of the average track condition to aid the decision maker in arriving at economically justifiable or cost-effective track maintenance strategies.

##### *2.3.2.1.1 Construction*

With respect to normal ballasted railway tracks, the ballast layer contributes significantly to the track quality (See Section 2.3.1). The initial geometry of a railway track continuously degrades over its life-cycle, with consequences for maintenance and availability of the railway track (Paixao, et al., 2013). Hence the investments and design principles during the construction phase has long lasting impacts. The costs involved in the construction of the railway track include surveying, procuring the land, staff, machinery and materials.

##### *2.3.2.1.2 Maintenance*

Maintenance costs associated with a ballasted railway track are those to do with direct costs to inspect and maintain the railway track and the indirect costs associated with track maintenance such as delays, accidents and emissions (ITF, 2013).

- When the track quality is worse than the acceptable limit, speed restrictions are imposed until maintenance activities are carried out, to ensure safety. This in turn results in loss of capacity of the railway line as well as delay costs to passengers and freight.
- For track sections that run freight trains, spillage is a major issue that not only results in additional clean up charges and delays, but also causes service life reduction to the track as well (ORR, 2013).

##### 2.3.2.1.3 Track use costs

From an engineering perspective, the main role of the railway track is to support and guide the railway vehicle. To enable an effective and economic track maintenance strategy, it is important to understand how train operation, safety and environment, are related to track quality (Furkawa et al., 2005). Also, consideration needs to be given to the socio-economic costs incurred by railway users when there is a shift in the mode of travel.

###### 2.3.2.1.3.1 Train Operation

The train operating costs associated with the track quality are related to fuel and rolling stock maintenance. The track quality deterioration, particularly the vertical track geometry, results in higher wheel-rail dynamic forces (Kumar et al., 2008). This in turn affects the condition of wheelsets and dampers of the rolling stock (Smith et al., 2017) and results in an increased fuel consumption (Zarembski et al. 2010).

###### 2.3.2.1.3.2 Accident costs

Train accidents cause damage to infrastructure and rolling stock, service disruptions, casualties and harm the environment. In many of the accidents, such as derailments, preventive maintenance is a key factor to mitigating risks before they impact operations, revenue or safety.

Although safety is of critical importance to railway operators, the intensive use of the railways increases the likelihood of accidents. In 2016-17, UK mainline railways witnessed 687 train accidents, with 22 of them classified as Potentially Higher Risk Train Accident (PHRTA) resulting in at least one death, considerable delay costs, track downtime and damage to property (see Figure 2.5 ). Six out of the 22 PHRTA were derailments (ORR, 2017).

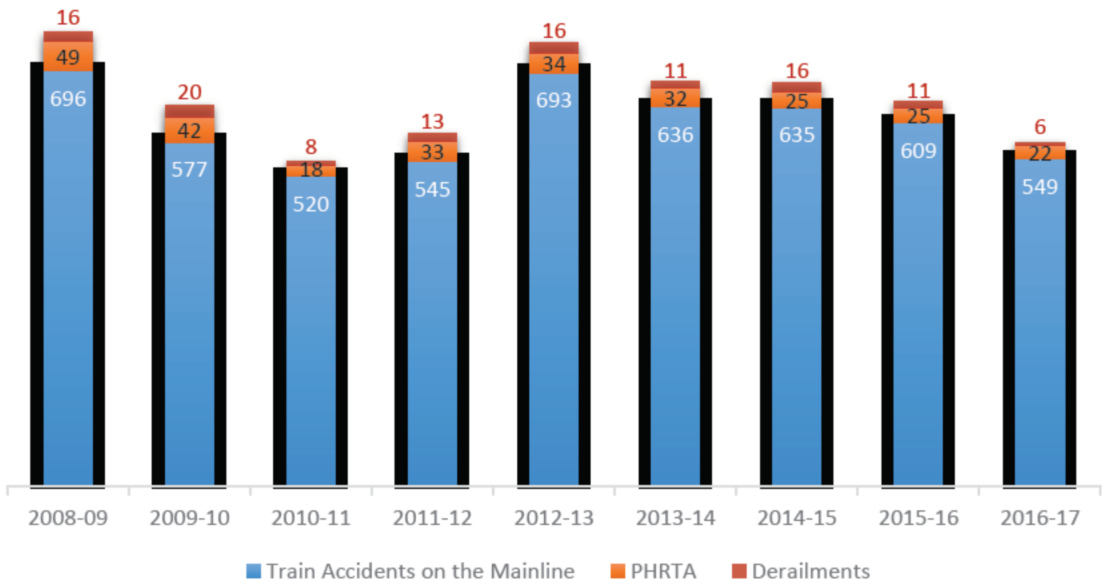



Figure 2.6 Trend in Train Accidents on UK Mainline (Source: ORR, 2017)

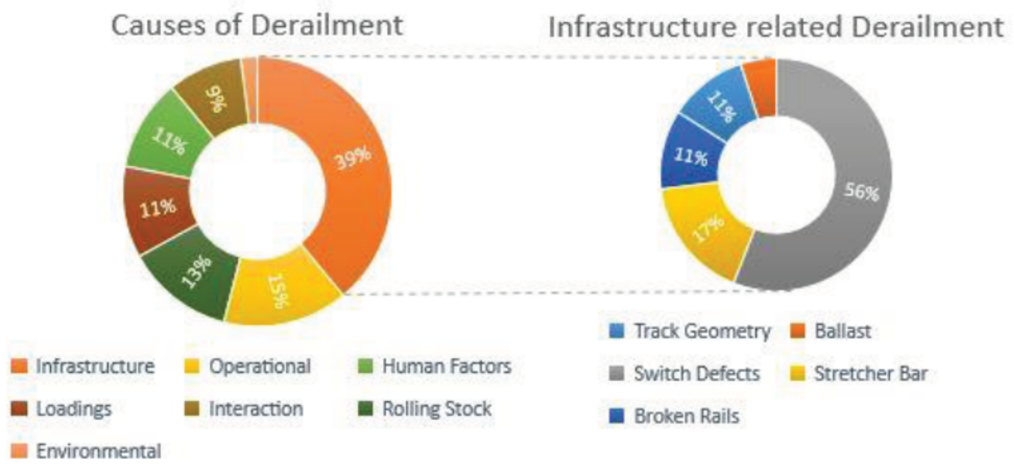



Figure 2.5 Causes of derailments during 2016-17 in the UK (ORR, 2017)

The causes of derailment are generally classified as infrastructure, rolling stock, and operation failure and environmental associated (ORR, 2017). While the track infrastructure was responsible for 39% of the derailments in 2016-17, more than half of track infrastructure related derailments are due to track geometry defects (See Figure 2.6). The average cost of a major derailment in the UK, caused due to track infrastructure issue is estimated to be £661,073 (RSSB, 2016b).

Generally, the railway industry is safety conscious and accordingly much of risk management in railways focuses on the prevention of accidents resulting from derailments and system failures or degradation, which can result in a derailment (See Section 3.3).Even though the probability of a derailment occurring is quite low, while compared to other accidents, the severity of such incidents is high (RSSB, 2018). The UK's Railway Safety and Standards Board's (RSSB) Safety Risk Model calculated the 7-year national average of derailment risk was 1.24 Fatalities and Weighted Injuries (FWI) per year for passenger trains and 0.67 FWI/year for freight trains (RSSB, 2018). The 7-year average risk of track quality related derailment was calculated as 0.13 FWI/year, from the Train Accident Precursor Indicator Model (RSSB, 2018) (See Figure 2.7). It is estimated that a single derailment can cost up to £6.5 million including infrastructure damage and operational delay costs (RSSB, 2016b).

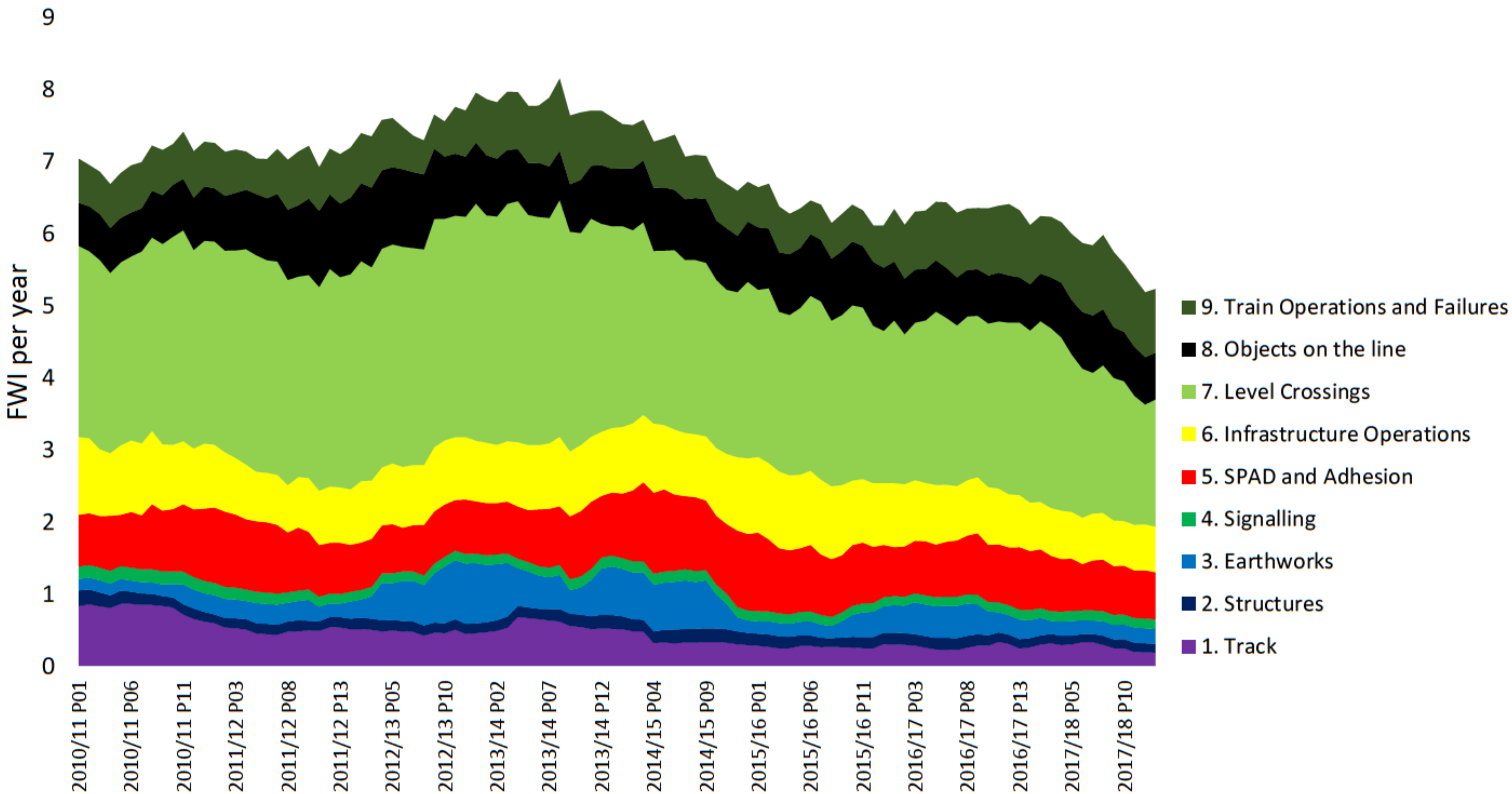



Figure 2.7 Risk of Derailments caused due to different factors (RSSB, 2018)

##### 2.3.2.1.3.3 Environmental costs

In 2016-17 the transportation sector as a whole consumed 28.8% of the global energy, while contributing to 24.7% of global CO2 emissions (UIC, 2017). Electricity constitutes more than one-third of the energy use in railways and a quarter of the world's railway lines are electrified (UNCRD, 2014). Figure 2.8 shows that railway is one of the most environment friendly modes of transport, with many countries setting ambitious environmental targets for their railway industry (see Table 2.1). Since fuel consumption directly impacts environmental emissions, maintaining the track quality at an appropriate level is important in order for the environmental impacts to be acceptable.

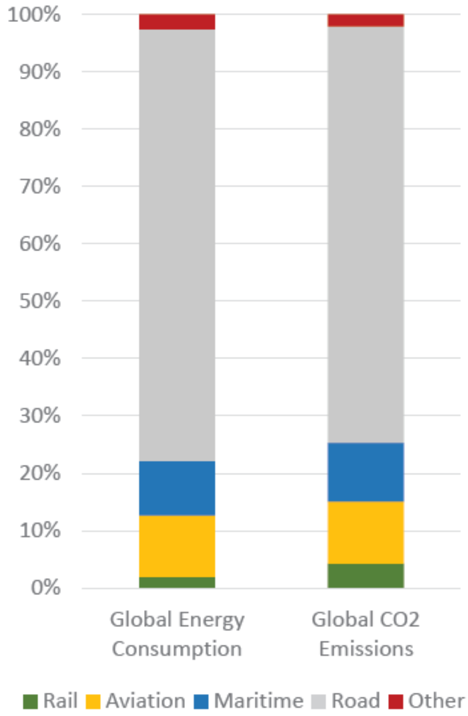



Figure 2.8 Comparison of different modes of Transportation (UIC, 2017)

Table 2.1 Country specific environmental targets for Railways (Sasidharan, 2019)

| Country | Environmental Targets for Railways |
|---|---|
| Germany | By 2020, reduction of specific $CO_2$ emissions from all transportation modes by20% compared to 2006 levels.<br>By 2050, rail transport to be completely $CO_2$-free |
| India | Saving of 3.33 million tonnes of $CO_2$ emissions (approximately 80%) by 2020 |
| France | Cutting GHG emissions by 20% between 2014 and 2025 |
| Japan | Halving of CO2 emissions from its railway business by 2030 compared to 1990. |
| Russia | Reduction of the negative environmental impact due to $CO_2$ emissions by 15% in 2030 compared to 2012 |
| UK | Carbon emission reduction by 34% by 2020 and by 80% by 2050 |

##### *2.3.2.1.3.4 Mode change costs*

The railway transport system provides a wide range of direct and indirect benefits to the economy. Apart from being a significant provider of jobs and tax revenues, they also provide benefits to the rail users (Godden, 2018). Sustainable transport policies in many countries are encouraging a shift of passengers and freight from road to rail that will bring about a reduction in road congestions and accidents, and result in less damage to the environment (Lingaitis, 2014). Railway transport also generates indirect benefits such as stimulating economic development which in turn increases in land value and industrial production (Dolinayova et al., 2016).

##### *2.3.2.1.4 End of Life*

The de-commissioning costs consist of the total costs incurred to dispose of the track assets at the end of their useful life, can be either positive or negative depending on the use to which the infrastructure asset is put.

#### 2.3.2.2 Deterioration modelling

WLCCA requires the prediction of current and future maintenance requirements. The prediction of future maintenance requirements requires the rate of deterioration of track components to be determined. Widely used track DMs in the railway industry (see Table 2.2) considers the prediction of vertical track settlement as the main controlling factor for track geometry and therefore for track maintenance (Dahlberg, 2001; Sadeghi et al., 2010; Milosavijevic et al., 2012). Table 2.2 summarises models available in the literature.

Most of these models predicts the vertical track settlement as a function of number of loading cycles, while some as a function of average train speed and a few as a function of effectiveness of maintenance interventions. The required track condition data can be assessed by measuring the geometry of the railway tracks, while the empirical analysis of the collected data (using models listed in Table 2.2) would aid in informing and predicting the deterioration trend and maintenance effectiveness associated with each track section (Burrow et al., 2009; Sadeghi et al., 2010).

Table 2.2 Track deterioration models

| Country | Model name | Equation | Influencing Factors |
|---|---|---|---|
| UK | Shenton (1985) | $S = K_s \frac{A_e}{20}(0.69 + 0.028L)N^{0.2} + 2.7 \times 10^{-6}N)$ | S - track settlement<br>$K_s$ - structure factor<br>$A_e$ - equivalent axle load<br>N - Total Number of axles<br>L - Lift given by tamping machines |
| Germany | DSM (Milosavljevic et al., 2012) | $S_N = S_1(1 + K_H \ln N)$ | $S_N$ - track settlement after N loading cycles<br>$S_1$ - initial settlement<br>$K_H$ - coefficient* |
| Japan | Hoshino (Milosavljevic et al., 2012) | $\Delta = L_H.J.Z$ | Δ - coefficient of track deterioration<br>$L_H$ - load factor<br>J - structure factor<br>Z - condition factor |
| | Sugiyama (2007) | $S = 2.09 \times 10^{-3}.\ T^{0.31}.V^{0.98}.J^{1.10}.R^{0.21}.K_p^{0.26}$ | S - average growth of track irregularities in section<br>T - passed tonnage<br>V - average running speed<br>J - structure factor<br>R - influence factor for jointed rail<br>$K_p$ - influence factor for subgrade |
| | Satoh (1997) | $S_1 = \begin{cases} a_s(p_b - p_{g.br})^w, p_b > p_{g.br} \\ 0, p_b \le p_{g.br} \end{cases}$<br>$S_2 = \alpha_s.p_b^w$ | S1, S2 - ballast settlement<br>$a_s$, $\alpha_s$ - coefficients*<br>$p_b$ - sleeper-ballast contact pressure<br>$p_{b.gr}$ - threshold limit value of sleeper-ballast contact pressure<br>w - exponent* |
| France | Guérin (1999) | $\frac{dS}{dN} = \alpha_G . y^{\beta_G}$ | S - settlement<br>N - number of loading cycles<br>y - maximum elastic deflection during loading cycle<br>$\alpha_G$, $\beta_G$ - material parameters |
| South Africa | Frohling (1998) | $S_{Ni} = \left[\left[K_{F1} + K_{F2}.\left(\frac{D_{2mi}}{K_{F3}}\right)\right]\frac{Q_{tot}}{Q_{ref}}\right]^w \log N$ | $S_{Ni}$ - track settlement<br>$D_{2mi}$ - measured track stiffness at a particular sleeper i<br>$K_{F1}$, $K_{F2}$, $K_{F3}$ – settlement constants*<br>$Q_{tot}$ - prevailing wheel load<br>$Q_{ref}$ - reference wheel load<br>N - number of loading cycles<br>w - exponent* |
| Exponential (Quiroga et al., 2011) | | $TQ_m = Ae^{B(x-x_o)}$ | *$TQ_m$ - track quality measure*<br>*A, B - exponential coefficients*<br>x, $x_0$ - time or tonnage |
| Linear (Soleimanmeigouni et al., 2018) | | $TQ_m = (a.x) + b$ | $TQ_m$ - track quality measure<br>x - time or tonnage<br>a, b - linear coefficients* |

* - coefficients whose values depend on local conditions and are determined empirically

### 2.3.3 WLCC practice and research

The need for improving the appraisal of maintenance and renewals was first stated by Geyer (1935). Though he suggested the need to analyze alternative maintenance strategies and techniques to identify cost-effective ones, he did not offer any suggestion on the means to do the same. Since the 1980's Lamson et al., (1983) proposed a method for costing the track M&R activities aided by a track deterioration model. Economic appraisal with benefit analysis for railways using a life cycle technique was suggested by Zarembski (1989) and Trask et al., (1991) proposed the use of a degradation models to plan M&R activities. Trask et al., (1991) presented a model which predicts the track deterioration over a 5-year period, based on the current track quality. Later, Stirling et al., (2000) proposed an approach to optimise maintenance costs by comparing costs with track condition.

Despite the above research, in practice, railway infrastructure maintenance decisions are largely based on time, cumulative tonnage or predetermined subjective maintenance standards, which ignore the downstream costs of operation and maintenance and thus they fail to optimise maintenance interventions to deliver maximum benefits (Atkins, 2011). This culture is gradually changing for the reasons described in Sections 2.3 and 2.3.1, and the sector is moving towards condition-based maintenance, where the condition of the asset is monitored to enable preventative maintenance (van Noortwijk et al., 2004) (See section 2.3.1). This philosophy has been encouraged by the publication of asset management standards and guidelines which advocate WLCC approaches, including ISO 15686-5 (2008) and EN 60300-3-3 (2009). These initiatives have been supported by academic research, a summary of which is presented in Table 2.3.

‘ECOTRACK’ was developed in 1997, as a technical and financial rule based expert system to aid infrastructure managers in maintenance planning and renewal (Zaalberg, 1998). Though the aim of ECOTRACK was to minimise life cycle costs, a whole-system view was not considered. The INNOTRACK (2009) project developed a number of LCC tools such as UNIFE, D-LCC, CATLOC, LCCare and Relex to enable cost effective high performance railway lines to be built and operated. But the project failed to consider the socio-economic impacts and risk of accidents associated with maintaining the tracks within the decision making system.

InfraCaLCC v2.0 is a LCC software for standard railway and urban railway networks, which considers direct (personnel, equipment, external services, energy) and indirect (delay, downtime cost, socioeconomic) costs (MAINLINE, 2013). However, it does not consider the impact of different track maintenance strategies on the track quality, the impact of track quality on track operation costs, nor the risk of accidents.

The LCC model under uncertainty proposed by Patra et al., (2009) took into account ballasted track related M&R costs and track downtime costs during maintenance. Guler (2013) advanced the LCC model suggested by Patra et al., (2009) to develop a decision support system to aid infrastructure managers in deciding the ideal time for carrying out M&R interventions. But, the models suggested by both Patra (2009) and Guler (2013) did not include the risk of accidents, user costs and train operation costs within their models.

Rama et al., (2016) introduced a whole-transport-system based life cycle cost analysis for railway infrastructure asset management, informed by a degradation model. Though it was a step towards optimising total transport costs, only delay costs were considered within the train operation, while fuel and rolling stock maintenance costs, and user costs were not considered.

A considerable amount of research has been undertaken to understand the impacts and costs of rolling stocks on track degradation namely, Stewart et al., (1988), Eisenmann (1992), Iwnicki et al., (2000), Dahlberg (2001), Furukawa et al., (2005), Remennikov et al., (2007), Zakeri (2008), Gong (2013), Kaewunruen (2014), Steenbergen et al., (2015), Burrow et al., (2017), Nielsen at al., (2017) and Smith et al., (2017). Despite significant research over the last 40 years, the research does not provide a relationship between the rolling stock maintenance costs and track quality, and hence the total transport costs incurred to the whole railway system (Liden, 2015).

Table 2.3 Overview of Railway Asset Management models

| Author/Project | Description | Features considered within the model | | | | | | | | | | WLCC Approach | Application | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Asset Deterioration | Cost Elements | | | | | | | | | | | | | | |
| | | | Design/Construction | Maintenance | | Operation | | | | | End of Life | | | | | | |
| | | | | Track | Rolling Stock | Capacity Lost | Fuel / Energy | Environment | Risk of Accident | Socio-Economic Impacts | | | Track | Signaling | Electrification | Rolling Stock | Infrastructure |
| Lamson et al., (1983) | Proposed a method for application of decision network analysis to railway track maintenance and replacement optimization. | ✓ | | ✓ | | | | | | | | | ✓ | | | | |
| STAMP (2000) | Network Rail's single asset decision modelling tool to evaluate maintenance and renewal options for structural assets | ✓ | | ✓ | | ✓ | | | | | | ✓ | | | | | ✓ |
| Zoeteman (2001) | A LCC approach to support decision-making system for design and maintenance decisions | ✓ | ✓ | ✓ | | ✓ | | | | | | | ✓ | | | | |
| Zhao et al., (2006) | A LCC model for optimising railway ballast maintenance policies | ✓ | | ✓ | ✓ | ✓ | | | | | | | ✓ | | | | |
| Reddy et al., (2007) | Employs a LCC approach for optimising rail maintenance based on rolling contact fatigue, traffic wear, rail grinding interval and lubrication | ✓ | | ✓ | ✓ | ✓ | | | ✓ | | | | ✓ | | | | |
| Antoni et al., (2008) | Developed statistical model to estimate lifetime and maintenance costs throughout life cycle of railway assets | | | ✓ | | ✓ | | | | | | | ✓ | ✓ | ✓ | | |
| Patra et al., (2009) | Presents a methodology for estimating uncertainty related to LCC within a developed track maintenance cost estimation model | | | ✓ | | ✓ | | | | | | | ✓ | | | | |
| INNOTRACK (2009) | A research project that aimed to develop a cost effective high performance track through reduced LCC and improved RAMS and developed various tools such as D-LCC, CATLOC, LCCWare etc. | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | | | ✓ | | ✓ | | | | |
| InfraCaLCC (2010) | A commercial software that calculates rail infrastructure LCC from the existing databases. | | | ✓ | | ✓ | ✓ | ✓ | | ✓ | ✓ | | ✓ | | | | ✓ |
| De Jong et al., (2012) | An integrated LCC-SEC assessment approach proposed as part of Urban Track project to aid the development and construction of modular track systems for tram, metro and light rail. | | ✓ | ✓ | | ✓ | | ✓ | | ✓ | ✓ | | ✓ | | | | |
| VTISM (2012) | Integrates several models, i.e. VAMPIRE, WLRM, T-SPA, WPDM, and W-SPA to optimise rail and wheel life and maintenance regimes | ✓ | | ✓ | ✓ | | | | | | | ✓ | ✓ | | | ✓ | |
| Zhang et al., (2012) | A genetic algorithm approach for maintenance scheduling at a minimal overall cost | ✓ | | ✓ | | ✓ | | | | ✓ | | | ✓ | | | | |
| Mokrousov et al., (2013) | A LCA method which can be applied to different rail elements | ✓ | | | ✓ | | | | | | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ |

| Author/Project | Description | Features considered within the model | | | | | | | | | | WLCC Approach | Application | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Asset Deterioration | Cost Elements | | | | | | | | | | | | | | |
| | | | Design/Construction | Maintenance | | Operation | | | | | End of Life | | | | | | |
| | | | | Track | Rolling Stock | Capacity Lost | Fuel / Energy | Environment | Risk of Accident | Socio-Economic Impacts | | | Track | Signaling | Electrification | Rolling Stock | Infrastructure |
| LCAT (2013) | Life Cycle Assessment Tool was developed as part of the MAINLINE project to reduce the economic and environmental impacts of maintenance, renewal and improvement of railway infrastructure | ✓ | ✓ | ✓ | | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | | | |
| Arasteh khouy et al., (2014) | Proposes optimization of track geometry inspection interval to minimize total ballast maintenance costs while considering risk of accidents due to poor track quality | ✓ | | ✓ | | | | | ✓ | | | | ✓ | | | | |
| Caetano et al., (2014) | Introduced an optimization model to schedule track renewal operations using a LCC approach | ✓ | | ✓ | | | | | | | | | ✓ | | | | |
| Gattuso et al., (2014) | Proposes a set of cost functions for the estimation of regional railways investment and operating costs | | ✓ | ✓ | ✓ | | | ✓ | | | | | ✓ | ✓ | ✓ | ✓ | |
| Zhang et al., (2014) | An approach involving Bayes linear method to combine expert knowledge and historical data, and cost modelling for maintenance strategy optimisation | ✓ | | ✓ | | | | | | | | | ✓ | | | | ✓ |
| Banar et al., (2015) | LCA and LCC method to assess the environmental and economic impact on transportation systems | | ✓ | ✓ | ✓ | | | ✓ | | ✓ | ✓ | | ✓ | | | ✓ | |
| Fang et al., (2015) | A model to predict LCC of different maintenance strategies for rolling stocks | | ✓ | | ✓ | | | | | | | | | | | ✓ | |
| Zhang et al., (2015) | A LCC model for real-time condition monitoring in railways and metro systems under uncertainty approach | ✓ | | | ✓ | ✓ | | | | | | | | | | ✓ | |
| Fourie et al., (2016) | Developed and tested a LCC framework for mission-critical assets with emphasis on cost of ownership and effective maintenance and renewal strategies | ✓ | | | ✓ | | ✓ | | | | | | | | | ✓ | |
| Rama et al., (2016) | A modelling framework for evaluating multi-asset infrastructure LCC with a whole-system context | ✓ | | ✓ | ✓ | ✓ | | | | | | | ✓ | | | | ✓ |
| Jones et al., (2017) | Uses a LCA approach to study the environmental impact of a high-speed rail in Portugal | | | ✓ | ✓ | | | ✓ | | | | | ✓ | | | ✓ | |
| Smith et al., (2017) | A methodology to estimate the relative marginal cost of railway maintenance | ✓ | | ✓ | ✓ | | | | | | | | ✓ | | | | |
| Vitasek et al., (2017) | A LCC method to optimise design of railroad switches | | | ✓ | | ✓ | | | | | ✓ | | ✓ | | | | |

The Department of Transport initialised a ‘Rail Value for Money Study’ in 2011. One of the key recommendations was ‘a closer alignment between infrastructure managers and the Train Operating Companies (TOCs)’ (DfT, 2011) while noting that neither the TOCs nor Network Rail have any incentive to reduce the total transport costs. Recently, railway infrastructure and rolling stock organisations also have started to develop their own asset management tools which incorporate some WLCC or total transport cost principles. The UK’s Network Rail has developed analytical tools such as Vehicle Track Interface Strategic Model (VTISM) and Overhead System Loading Simulation Package (OSLO) which includes WLCC principles (MAINLINE, 2013). Though VTISM employs different predictive models to determine maintenance costs and track deterioration, it does not consider the socio-economic costs and benefits (e.g. travel time) nor take into account rolling stock operation costs (Arup, 2011). Further, VTISM does not consider risk uncertainties associated with predicting future life cycle costs. STAMP is another asset management tool developed in 2000 by Network Rail, to evaluate maintenance and renewal options for structural assets by employing WLCC concepts (MAINLINE, 2013).

In the USA, the Federal Transit Administration’s Asset Management Guide (FTA, 2012) clearly defines the best practices for managing railway assets throughout its life cycle, with a focus on maintenance and quality monitoring steps. Also, effective life cycle management procedures for rolling stock are provided in FTA (2013). Virgin Trains, a major train operating company in the United Kingdom, as part of its Railcar Lifecycle Management Model, has set a performance-based contract with the fleet manufacturers, which requires them to consider lifecycle costs during procurement and maintenance (FTA, 2013). Similarly, Chicago Transit Authority’s Rail Car Maintenance Plan, provides an effective lifecycle management approach to the maintenance of its railcar assets (FTA, 2013). Maryland Mass Transit Administration, while procuring light rail vehicles considered minimizing life cycle costs of rolling stock, alongside identifying and managing risks (FTA, 2013). But, these models do not consider the track use costs within its decision making process.

Also, several studies have modelled the railway accidents, with a focus on asset deterioration and maintenance strategies. But they have not been included with other direct and indirect costs and benefits for railway track asset management. For example, Arasteh khouy et al., (2016) considered the costs associated with inspection, tamping, speed restrictions (delays) and risk of accidents between two consecutive maintenance events, alongside a track deterioration model to inform cost-effective maintenance strategies. But costs associated with renewals, train operation and track use costs were not considered.

#### 2.3.3.1 Limitations of existing studies

While employing WLCC to aid decision making for railway maintenance, there are some challenges concerning the lack of data associated with maintenance costs and the degradation rates of different infrastructure components; giving rise to uncertainties (Andrade, 2016; Kirkwood et al., 2016; Skinner et al., 2011). It is also possible that the risk data is incomplete or there is a high uncertainty involved in the available risk data (An et al., 2016) (See Section 3.2.2). Since the WLCC analysis approach are based on the predictions of future scenarios, the sources of uncertainty could vary (Asplund et al., 2016). It is under conditions of uncertainty that decision makers must evaluate, compare and select among alternative strategies, the cost-effective one (Dienemann, 1966). Although track quality/condition related uncertainties can be dealt with by further inspections, improved deterioration modelling and expert opinion, they are often costly and not always feasible (El-Cheikh et al, 2015). Risk assessment methodologies such as Monte Carlo simulation, Bayesian, Fuzzy Sets theory and Petri Nets are recommended to solve uncertainties in asset management practices (Zhang et al., 2014; Vogl, 2015; D. Rama et al., 2016) (See Section 3.2.2) These approaches are summarised in Chapter 3.

## 2.4 Summary

Ballasted railway track is maintained periodically to keep the ride quality and safety within acceptable limits. Ride quality, as measured by track geometry is used in the railway industry as the primary indicator for railway track maintenance and it also drives track use costs. In the past, railway maintenance strategies were based on knowledge and experience of the maintainers, and pre-determined standards. Since the main goal was to provide high levels of safety, little consideration was given to economic track maintenance standards. Currently, the railway industry is facing growing pressures to implement sustainable strategies that are cost-effective for the whole transport system, while ensuring a safe and green mode of travel. To this end, there is a need for railway track asset management to consider WLCC approaches to be risk informed, while dealing with uncertainties.

This chapter reviewed such asset management approaches suggested in the research literature and used in the industry. The review found that there are a number of limitations to these approaches. In particular, future railway track infrastructure M&R costs are not taken into account together with railway track use costs. Further, the existing WLCC tools and methodologies for different railway systems rarely take risk costs of accidents, like derailment into consideration. Considering that the principles of asset management is embedded into WLCC concepts, it is a necessity that a risk-informed approach is employed to ensure safety while arriving at suitable maintenance strategies (Boussabaine, 2004).

To address these issues, this research aims to develop a Whole Life Cycle Cost Analysis (WLCCA) approach to determine maintenance strategies for traditional ballasted railway track, while considering both railway track use and future maintenance costs so that the benefits of investment in maintenance can be weighed against the associated costs (see

Section 5.1.1). To effectively manage the railways safely, there is a need to incorporate risk management concepts within asset management procedures so that, periodic maintenance requirements can be predicted in advance of track failure/safety issues and prioritised, and identified risks and uncertainties can be considered within the decision-making processes. Chapter 3 describes risk management, research and tools pertinent to this research and Chapter 5 describes the development of a WLCCA approach under uncertainty for the railway maintenance investment appraisal.

# Chapter 3

# Risk Management

In order to inform the development of a risk-informed railway infrastructure investment appraisal model, this chapter provides a review of the risk assessment literature. Attention is given to recent developments in infrastructure risk assessment research and risk management practices in the railway industry.

## 3.1 Risk Management

The International Standards Organisations (ISO) defines Risk management as *"coordinated activities to direct and control an organisation with regard to risk" (ISO, 2009)*.

In its simplest form the total risk, *R*, to which an entity may be subjected as a result of *i* possible risk, is given by:

$$\mathrm{R} = \sum_{i=1}^{I} N_i \; * p_i \qquad (3.1)$$

Where

$N_i$ is the severity of the consequence of risk, *i*, (e.g., persons killed or injured, damage caused)

$p_i$ is the probability of occurrence of the risk, *i*

The Institute of Risk Management states that *'risk management should be a continuous and developing process'* and should be able to address all the risks of past, present and future (IRM, 2002). Risk management involves the processes of risk identification, risk analysis, risk evaluation, risk response and risk monitoring as shown in Figure 3.1.

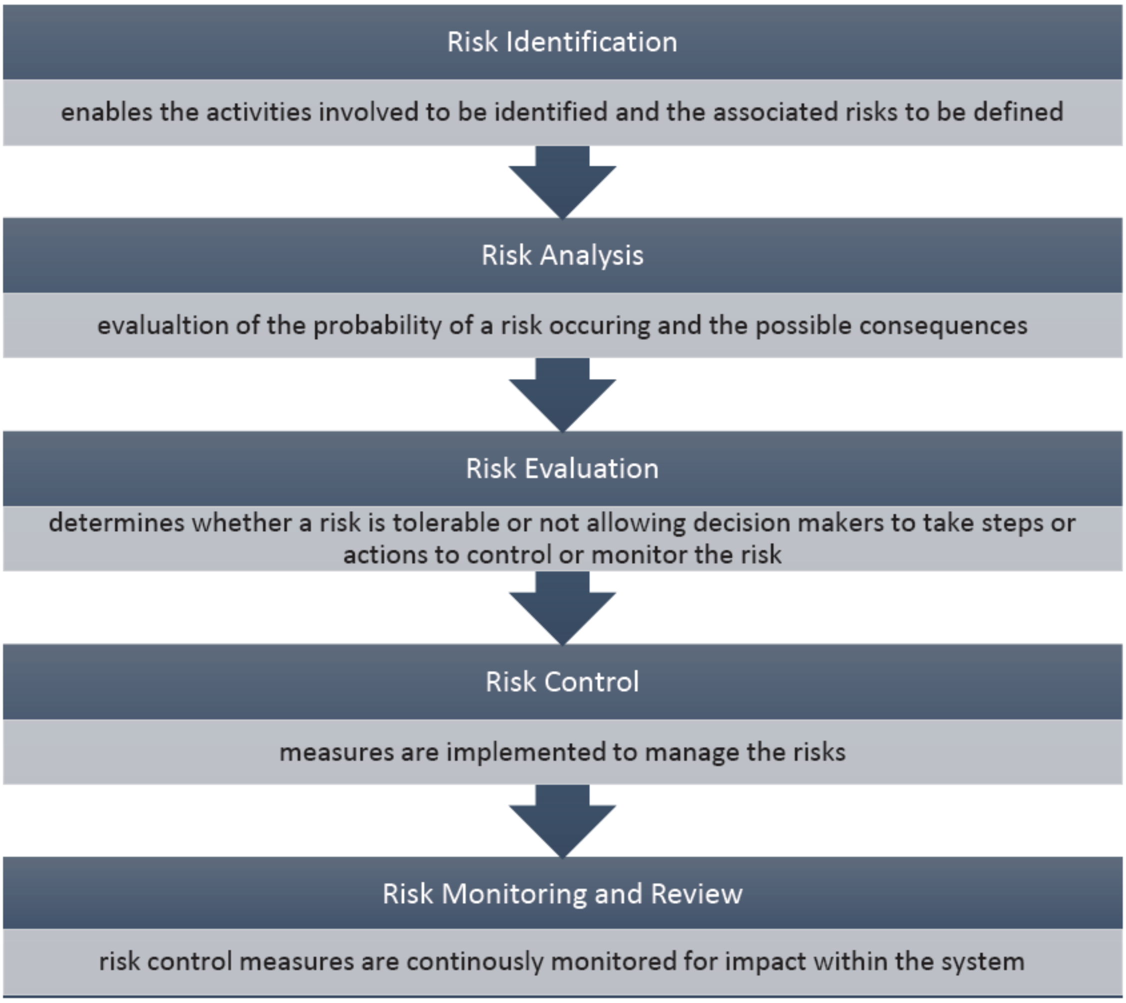



Figure 3.1 Risk management process (ISO, 2009)

The first three stages of the risk management process are collectively termed as risk assessment (ISO, 2009). The objective of risk assessment is to develop a rational foundation for objective decision making by systematically using the available information to estimate the risks involved (Chen, 2003; Sadeghi et al., 2010; Salling, 2011; Grote, 2015; Torbaghan et al., 2015). For risk assessments, the aim is to provide understanding and quantification of the risks and compare these with predefined criteria to enable risk mitigation strategies to be formulised. This allows the decision-maker to foresee the effect of any risk (Salling, 2011).

## 3.2 Risk Assessment

The concept of risk and risk assessment has a long history. Over 2400 years ago, the Athenians are believed to have demonstrated a capacity of assessing risk before making a decision (Bernstein, 1996). Risk management principles were used in the 19$^{th}$ and 20$^{th}$ centuries in various fields including health and sanitation (to decrease the risk of mortality and morbidity); safety engineering (e.g. the development of building and fire codes, and building and operating nuclear power plants) and transportation (Molak, 1997). In the last 30-40 risk assessment has developed significantly by embracing the concepts of probability theory using scientific methods to quantify risks. The academic literature on risk management and assessment therefore is mainly from the past 30-40 years (Aven, 2016).

The nature of a risk assessment depends upon the type of risk involved, the aim of the analysis, and the availability of data and resources (Chen, 2012). The assessment methods could be quantitative, qualitative or a mixture of both. Quantitative methods use numerical values for the analysis of probability and consequences. For e.g. probabilities of adverse effects of natural disasters (e.g. floods, earthquakes) or type of human activities (e.g. transportation accident rates, diseases) or economic risk analysis (e.g. environmental impact costs) can be predicted based on historical data (Molak, 1997). Sensitivity analysis, expected monetary value analysis, decision trees and simulations (e.g. Monte Carlo analysis) are techniques which are often employed to undertake quantitative risk analysis.

It is often the case that risk managers and assessors face situations where there is insufficient or unreliable data that hinders the decision making process. In such scenarios, qualitative methods are employed based on expert judgements and the subject-specific knowledge of the assessor. Qualitative methods tend to use linguistic variables (e.g. low, medium, and high) or ranges of values (e.g. 0-3, 3-5 etc.) in order to describe probability and impact. This often gives rise to uncertainties within the risk assessment process (see section 3.2.2).

Risk assessment can also be carried out by employing a combination of qualitative and quantitative methods. Such a combination are normally used in two ways: the frequency is measured qualitatively, while the severity is measured quantitatively or vice versa. It is also possible that both frequency and severity are measured quantitatively, while the decision making relies on qualitative methods. For example, quantitative risk values maybe augmented by other quantitative or qualitative risk information to arrive at a decision. For example,  the U.S Nuclear Regulatory Commission's 'risk-informed' approach combines risk information with quantitative and qualitative results from available data and engineering judgement to set regulatory decisions and policies (Modarres, 2016).

### 3.2.1 Techniques to support risk assessment

Risk assessment has become an important element within the decision making processes of many industries (Arunraj et al., 2013). Many risk assessment techniques and methodologies have been developed to aid in this process. With the introduction of Fuzzy approaches (see Section 3.2.1.2) in 1960s and Monte Carlo (see Section 3.2.1.1) simulation in 1970s, they have replaced the statistical methods which were initially used to carry out risk assessments (Edwards et al., 1998). Though Monte Carlo and fuzzy approaches are the most popular, other approaches including hybrid ones have also been utilised (see Section 3.2.1.3). The sections below describes these techniques and provides some applications of the same.

#### 3.2.1.1 Monte Carlo

The Monte Carlo method is a statistical method used frequently in probabilistic risk assessment that involves the simulation of uncertain and variable ranges of numerical data. It informs the most probable outcome and their probability of occurrence (Loyd, 2004). The term 'Monte Carlo' was first introduced by von Neumann and Ulam during World War II, when simulation were carried out to study thermonuclear reactions (Salling, 2011).

Since its introduction in the 1970s, Monte Carlo Simulation (MCS) has become one of the most widely used technique in risk assessment, as it can combine multiple probability density functions of risk to quantify uncertainty or variability in terms of probability distributions. The method selects input values at random to simulate the model, where the variables have a definite range of value but an uncertain value for any particular time or event. It has been proved mathematically that through iterations, an accurate result of the entire range of possible scenarios can be provided (BSI, 2010). The outputs of the MCS are probability distributions of the output variables (UNESCO, 2005).

A large amount of sample data has to be collected in order to generate these distributions, since it reduces the uncertainty and helps the better characterization of variability. The simulations can be run once the model is set up and the probability distributions for all the input parameters are defined (see Figure 3.2). Typically, a MCS consists of hundreds or thousands of iterations, generating a distribution of a possible combination of uncertain values that could occur (Molak, 1997).

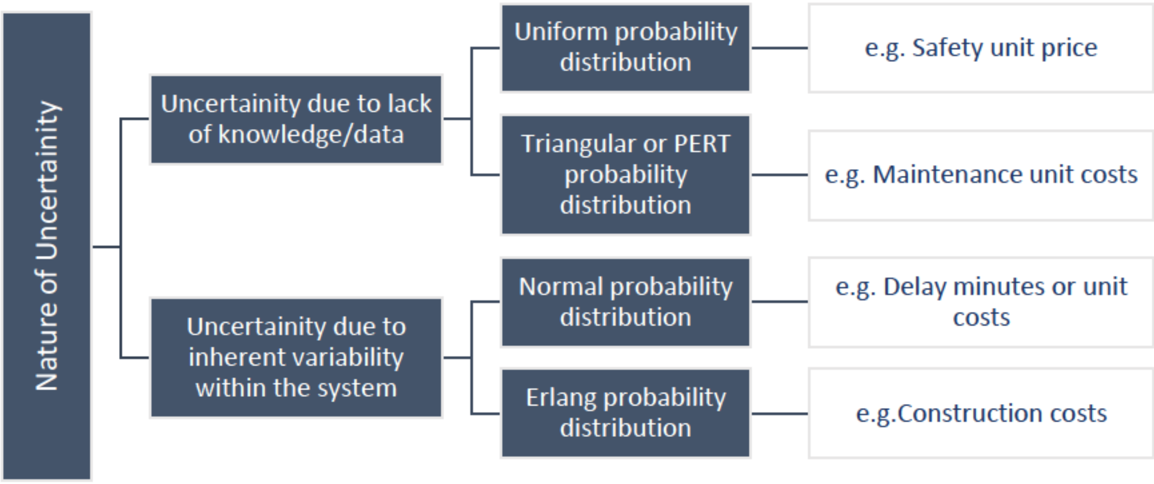



Figure 3.2 Nature of uncertainty and the associated probability distributions for linear transport infrastructure projects (Salling et al., 2011)

Monte Carlo simulation has been proven to be efficient in solving both deterministic and stochastic problems. The deterministic solutions often takes into consideration the quantification of consequences of the identified risks on people, environment, machinery etc. (Tixier et al., 2002). The stochastic methods are based on the probability/occurrence of potential risks and the associated impacts or severity and often used within transport asset management. For e.g. Quiroga et al. (2011) employed a stochastic model using MCS to predict the infrastructure condition. The United States' Environmental Protection Agency also employs Monte Carlo simulation for human health risk assessments associated with hazardous waste management (EPA, 1994). Stroeve et al. (2009) performed a systematic accident risk assessment of air traffic using Monte Carlo simulation. It was also used by Vanorio et al. (2012) for the safety risk analysis of railway tunnels to evaluate the consequence of undesired events. The US Food and Drug Administration developed a tool which utilised Monte Carlo simulation to analyse potential food contamination risks (Risk

Management Monitor, 2015). Monte Carlo method was also used for the environmental risk impact assessment of an energy company in Romania using a model proposed by Olaru et al. (2014).

#### 3.2.1.2 Fuzzy approach

The fuzzy reasoning theory was introduced by Zadeh (1965), to provide concepts and techniques to deal with sources of uncertainty or imprecision of a non-statistical nature. Using the approach impreciseness and vagueness are usually characterised using linguistic terms such as low, medium and high. A fuzzy set is a mathematical tool that can accommodate the use of such linguistic terms based on subjective judgment (An et al., 2006 & 2011).

The fuzzy mathematical operations consider the most likely values to be of the same importance as the extreme values. Therefore, the results so obtained have wide range of possible values of input parameters as compared to Monte Carlo. Moreover, fuzzy approach was proven to yield comparable results to Monte Carlo method within risk assessment processes (Loyd, 2004).

Fuzzy approach is often used within risk assessment processes when the data is incomplete or there is a high level of uncertainty involved (An et al., 2006). Jafarian et al. (2012) employed a fuzzy approach with fault tree analysis to deal with incomplete data while evaluating the root causes of passenger train derailments. A fuzzy risk matrix was proposed by Skorupski (2012) to carry out risk assessment of air traffic accidents while dealing with imprecision within the associated data using fuzzy linguistic variables. Ardeshir et al. (2014) developed a fuzzy approach for the risk assessment of construction projects while employing fuzzy data to calculate the probability and severity of risks identified, based on four criterias of time, cost, quality and safety. Similarly, Behnood et al. (2017) developed a fuzzy decision-support system to measure the efficiency of road safety measures by analysing the incomplete data collected.

Expert opinion is often employed to deal with uncertainty within data (see Section 3.2.2) and Fuzzy approach is often used within the risk assessment process when resorting to expert opinion (Salling, 2011). In this context, Huang et al. (2006) presented a fuzzy approach to assess the likelihood of railway foundation failure, where expert opinion was used to inform the frequency of occurrence, consequence and levels of risks. An et al. (2006) employed fuzzy approach for the risk assessment of rolling stock assets. In their approach expert option was used to understand the severity of risks associated with the failure of different systems within the rolling stock. Fuzzy approach was employed by Idrus et al. (2011) for estimating the cost contingency plans for construction projects while considering contractors' subjective judgement (i.e. expert opinion) within the risk analysis. The application of Fuzzy approach to assess the risk via expert opinion (or subjective data) and thereby inform mitigation measures is formidable.

Fuzzy approach has also been used to deal with uncertainties within infrastructure investment appraisals. For e.g. El-Cheikh et al. (2013) employed fuzzy logic to deal with uncertainties within economic evaluation of infrastructure projects and demonstrated the model using a case study for railway project appraisals. Similarly, Urbina et al. (2017) introduced a fuzzy logic-based framework to deal with uncertainty while evaluating the benefits of investment on safety measures for oil and gas pipelines in Colombia. An integrated Monte Carlo-Fuzzy approach was proposed by Duru et al. (2010) to aid the investment appraisal within the shipping industry, while considering the associated uncertainties.

#### 3.2.1.3 Other approaches

Various other techniques to support risk assessment have been developed. Tixier et al., (2002) provides a useful review of 62 risk assessment methodologies that have been employed in different industries. Such applications include using decision trees, Markov models, survival and hazard functions, fault trees and sensitivity analysis. Examples include for the use of other techniques in transportation, health risk assessment, computer models etc. (Cho et al., 2011; Tom et al., 1997; An et al., 2006, 2011, 2013; Sadeghi et al., 2010; Peng et al., 2014; Trivedi et al., 2015).

Several authors have developed combined approaches for various applications. Karunarathna et al. (2013) developed a Markov-Monte Carlo simulation for bridge deterioration modelling and Faghih-Roohi et al. (2014) used a similar approach for accident risk assessment in marine transportation. A Fuzzy-Analytic hierarchy process was used by Verma et al. (2014) for risk assessment in the mining industry. Gharehdaghi et al. (2015) employed an integrated Fuzzy and Markov for solving a system of linear algebraic equations. A Monte Carlo-Bayesian network was developed by Smid et al. (2010) for food safety industry to assess the risks associated with food hygiene. The risk analysis of high speed and conventional railway lines incorporating human errors was carried out using a Markovian-Bayesian network by Castillo et al. (2015).

### 3.2.2 Uncertainty within risk assessment

Uncertainty is a key concept of risk assessment. Risk can be defined as the effect of uncertainty (BSI, 2011) and is often evaluated through a combination of the probability of an event occurring and its consequence (IRM, 2002). Uncertainty is the chance of an event occurring where the probability distribution is unknown (Smith et al., 2006).

To a large extent, risk assessment techniques use historical data and probability judgements, and conclusions on the acceptability of solutions are often made directly based on derived probabilities. The risk (or uncertainty) associated with the knowledge supporting these probabilities is not addressed or captured by the analyses. In many situations, it might also be extremely difficult to predict the probability and magnitude of risks through probabilistic risk assessment, due to the uncertainty within the data. Patra et al. (2009) observed that uncertainty in complex industries could also exist in costing, reliability and maintainability parameters. The use of expert opinion is often suggested as a means of overcoming such issues (Torbaghan et al., 2015). Important considerations when utilising expert option include (Terje, 2016):

- How can the risk assessment results, which currently are based on expert judgement and historical data, aid effective decision making?
- How can we know that the expert judgement is good enough?
- How can we accurately represent uncertainties, for proper justification of risk management practices?

Aven (2016) also observed that the key point is *'not only to represent the available knowledge but also to use probability to express the beliefs of the experts'*. In other words, if subjective probabilities (from expert opinion) are used to express the uncertainties, we also need to reflect on the knowledge that supports the probabilities. For this purpose, various authors have employed weighting factors to the expert opinion. By applying weighting factors to the expert opinion, the strength of expert knowledge can be quantitatively expressed. For example, Huang et al. (2006) weighted expert opinion to compare the contribution of various types of railway subgrade failures by assessing the risk levels of subgrade failure types.

Similarly, Idrus et al. (2011) used weighted expert opinions within a fuzzy approach to inform contingency plans for cost overruns of constructions projects.

To jointly consider both randomness and uncertainty, a combination of probabilistic and qualitative approaches is often used (Aven, 2016). The possibility of using an integrated Monte Carlo – Fuzzy approach to address this issue is discussed in the next section.

### 3.2.3 Integrated Monte Carlo - Fuzzy approach

While solving real-life problems, both uncertainty and imprecision could be encountered. From previous sections within this chapter it is evident that, Monte Carlo simulations have been employed widely for addressing probabilistic uncertainty, while the Fuzzy approach successfully handles non-probabilistic uncertainties arising from subjective and linguistically expressed data (Sadeghi et al., 2010). Hence, a combination of Monte Carlo Simulation and Fuzzy approach can be used to address both the likelihood and consequences of a failure event that is uncertain in natural and linguistic form.

In Monte Carlo analysis, the samples are more likely to be centred on areas of high probabilities of occurrence in the distribution. The values outside the range of distributions used are not represented in the outputs and hence their impacts on the results are not incorporated. Clustering becomes a major problem when low probability outcomes have a great impact on the results. It is important to include effects of low probability risks in the simulation results, but Monte Carlo iterations may not sample sufficient quantities of these events to accurately represent their impact on the output. A major disadvantage with respect to Monte Carlo analysis is when there is unavailability of sufficient data to establish the accuracy of input parameters (Smid et al., 2010). Furthermore, a fuzzy approach considers extreme events to be of the same importance as the most likely ones.

Unlike Markov models, the structuring of a Monte Carlo simulation employs a clear memory of past events and enables the user to sample from a known or estimated distribution. By combining it with Fuzzy approach, the ambiguous nature of events in the distribution can also be dealt with. Hence, the combination of Monte Carlo with Fuzzy approach will satisfy decision-making support by handling both types of fuzzy and probabilistic inputs. By combining the advantages of both simulation techniques, the decision makers can resort to subjective judgment, as they have access to both fuzziness and probabilistic uncertainties (Sadeghi et al., 2010). Table 3.1 gives an overview of application of an integrated Monte Carlo and Fuzzy approach in various industries. Of particular pertinence to this research were the studies by Sadeghi et al. (2010), Baraldi et al. (2012), Arunraj et al. (2013) and Mitropolulos et al. (2017).

Sadeghi et al. (2010) and Arunraj et al. (2013) proposed an integrated Monte Carlo-Fuzzy approach, to handle both random and fuzzy uncertainties within the risk assessment for construction projects and chemical industry respectively. Sadeghi et al (2010) employed Monte Carlo to choose between fuzzy sets and probability distributions to quantify the uncertainties within the input parameters. Arunraj et al. (2013) employed fuzzy approach to quantify the severity associated with identified risks, probability of their occurrence was modelled using Monte Carlo. Arunraj et al. (2013) suggested to model the severity of risks as a triangular membership function. Similar suggestions were found in the studies by An et al. (2006, 2007) and Jafarian (2010) which was adapted within the risk model employed for this research (see Section 5.1.2.2).

Baraldi et al. (2012) proposed a framework for the condition based maintenance of assets using an integrated Monte Carlo-Fuzzy approach. In this study, expert opinion was employed to deal with uncertainty associated with the degradation and failure rates of assets, when subjected to different maintenance strategies. To this end, fuzzy approach was employed to analyse the expert opinion data, and Monte Carlo was then used as an interface into the fuzzy model for arriving at the most-likely scenarios. The proposed approach was demonstrated using a case study for optimising the maintenance of electrical components. Similarly, Mitropolulos et al. (2017) also combined fuzzy approach with Monte Carlo for assessing the sustainability of vehicles within the urban environment. Concepts proposed by Baradli et al. (2012) was pertinent to the development of the risk-informed approach to railway track asset management proposed within this research (see Chapter 5).

A hybrid approach for solving both fuzzy and random types of uncertainties in a model, without converting one type of uncertainty to another was proposed by Guyonnet et al. (2003). Sadeghi et al. (2010) and Bauderit et al (2005) suggested that the hybrid approach has some shortcomings. Bauderit et al (2005) indicated that a hybrid approach may lead to unrealistic outputs and overestimation and suggested an approach of post processing using the theory of evidence, a mathematical approach for the representation of uncertainty. Sadeghi et al. (2010) argues that this method, does not directly represent the randomness involved. Kentel et al. (2004) proposed the combination of probability density functions of random variables and membership functions of fuzzy variables in calculating the fuzzy risk estimates for individual hazards.

Table 3.1 Applications of Risk Assessment models that combined Monte Carlo and Fuzzy Approach (Sasidharan et al., 2017)

| Industry | Models | Application |
|---|---|---|
| Health | Kental et al. (2005) | Health risk modelling |
| | Sallak et al. (2008) | Health safety instrumented systems |
| Environment | Chen et al. (2003, 2010) | Ground water systems |
| | Baudrit et al. (2005, | Ground water contamination |
| | 2006) | Ground water contamination |
| | Li et al. (2007) | Climate change |
| | Hall et al. (2007) | Health impact from air pollution |
| | Heng et al. (2008) | River water quality management |
| | Rehana et al. (2009) | Pollution control problems |
| | Qin (2012) | Flood damage assessment |
| | Yu et al. (2013) | |
| Construction | Davis et al. (1997) | Slope stability predictions |
| | Sadeghi et al. (2010) | Cost range estimating |
| | Jahani et al. (2014) | Reliability assessment |
| Electricity | Reddy et al. (2008) | Faults on transmission lines |
| | Wenyuan et al. (2008) | Power system risk assessment |
| | Canizes et al. (2011) | Electricity network distribution |
| | Baraldi et al. (2012) | Maintenance of electrical components |
| | Canizes et al. (2012) | Electricity network reconfiguration |
| | Nascimento et al. (2016) | Power optimization |
| Chemical | Arunraj et al. (2013) | Benzene extraction risk analysis |
| Nuclear | Baraldi et al. (2008) | Maintenance modelling |
| Information Technology | Ustundag et al. (2010) | Radio frequency identification |
| Transportation | Zonouz et al. (2006) | Reliability of critical systems |
| | Duru et al. (2010) | Uncertainty in ship investment |
| | Wanke et al. (2016) | Airline industry safety |
| | Mitropolulos et al. (2016) | Sustainable transportation planning |
| Hybrid MC-Fuzzy methodologies | Guyonnet et al. (2003) | Authors developed methodologies for generic applications |
| | Diego et al. (2009) | |
| | Banomyong et al. (2010) | |
| | Innal et al. (2013) | |
| | Gharehdaghi et al. (2015) | |
| | Dreakar (2015) | |

Guyonnet et al. (2003) had suggested that, in simulation of construction projects, the usual problems faced are variables with fuzzy and random nature. Such a scenario applies to the railway industry too; specifically, with respect to derailments where most of the incidents are unique and only limited data is available. For example, human error is a subjective contributing factor and including them in to the risk assessment framework is also necessary. Therefore, for real life scenarios of railway industry, a risk assessment model that can handle both random and fuzzy uncertainties are necessary.

However, as yet the integrated Monte Carlo and Fuzzy approach is in its infancy in the railway industry, albeit there is considerable opportunity for it to be used. The approach could be used successfully in risk management of derailments where most of the incidents are unique and only limited data is available. In a risk management approach, Monte Carlo may be used to model costs involved, whereas Fuzzy approach would be more appropriate while incorporating expert opinion within the risk assessment.

## 3.3 Risk Management in Railways

A goal of a railway transport system is to produce a defined level of railway operation at a given time, with a defined quality of service under tolerable residual risk and within defined cost limits. Railways carry both passenger and freight and therefore risk are associated both in terms of loss of human life and damage/destruction of assets (Fink et al., 2018).

Accordingly, in the railway industry, risk is primarily associated with economic management and safety (Cox et al., 2003). The uncertainties arising from the cost estimation of investments and benefits were discussed in Chapter 2. The railway industry is safety conscious and accordingly much of risk management in railways focuses on the prevention of accidents resulting from derailments and system failures or degradation, which can result in a derailment (Zarembski et al., 2006). Accordingly, Railway safety risk assessment is designed to assess risks arising from hazards/events which could lead to fatalities, minor or major injuries and loss to private and public property. In an idealized railway network, different stakeholders collaborate to effectively deliver their safety responsibilities through safety management systems (SMSs), reporting systems, safety standards and using common safety methods, techniques and tools. As the railway industry encompasses several stages of design, construction, operation and maintenance, there are various safety disciplines and regulations with which to comply. Each stage involved, has associated risks with different magnitudes and nature. Furthermore, the amount of risk is influenced by the probability and severity of the identified events. Considering the variability of parameters governing severity, the range of conditions considered can be extensive.

Although safety is of critical importance to railway operators, the intensive use of the railways increases the likelihood of accidents. For instance, the UK mainline railway had 687 train accidents in 2016-17, with 22 of them classified as Potentially Higher Risk Train Accidents (PHRTA) resulting in at least one death, considerable delay costs, track downtime and damage to property (ORR, 2017).

A variety of approaches to railway risk management have been developed within different railway systems. Pertinent studies identified from the literature are summarised in Table 3.2. Of pertinence to this research are the studies by An et al. (2006, 2007), Huang et al. (2006) and Jafarian et al. (2010). An et al. (2006) proposed fuzzy reasoning in the risk assessment of accidents in railway depots. For such accidents at platform train interface, the probability for minor injury was high and fatality was low. Even though the risk scores were different, employing fuzzy logic ensured that all the possible outcomes were equally considered.

Another study by An et al. (2007) proposed a fuzzy approach integrated with analytical hierarchy process to evaluate both quantitative and qualitative data within railway risk assessment. The proposed approach was applied to a case study for the risk assessment of shunting at a depot in Waterloo. A fuzzy fault tree model was proposed by Jafarian et al. (2010) to evaluate the safety risks on the railway networks and to evaluate the root causes for train derailments. This study employed a weighted average method for gathering expert opinion, which was adapted within this research. A similar approach to weighted expert opinion as earlier proposed by Huang et al. (2006) for modelling the failure of sub-grade layer within railway foundations.

Table 3.2 Risk Assessment methods in the railway industry (Sasidharan et al., 2017)

| Application | Qualitative | Quantitative |
|---|---|---|
| Buildings | Horner et al. (1997) | Dolsek (2012) |
| Lighting | Aberg (1988) | |
| Electricity | | Chattopadhyay et al. (1995) |
| Access ways | | Jafarian et al. (2012) |
| Level crossings | RTA of NSW (2011)<br>Rajayogan et al. (2012) | Cirovic et al. (2013), Liu et al. (2014) |
| Engineering structures | | Stein et al. (1999), Liu et al. (2004), Lounis (2006), Frangopol et al. (2007), Orcesi et al. (2010), O'Connor et al. (2011), Yuan et al. (2013) |
| Ground | Power et al. (2016) | Vanneuville et al. (2005), Huang et al. (2006), Jaedicke et al. (2013), Rathje et al. (2013) |
| Tracks | | Budai et al. (2004), Zio et al. (2007), Zhao et al. (2006, 2007, 2009), Zhang et al. (2013b) |
| Station | | Liu et al. (2015) |
| Network | An et al. (2007) | An et al. (2007) |
| Generic | Haile (1995) | |
| Rolling stock | An et al. (2006) | |

Within the transportation sector, Highways England, the asset manager of UK's road networks has developed a model to aid decision making by prioritising strategies according to different factors such as severity, disruption, climate change and its associated uncertainties (Arup, 2010). Highways England also developed a risk-based framework for improving budgeting decisions of its geotechnical assets (Arup, 2010).

The railway industry has employed a variety of tools or techniques to deal with risks within its daily operations. Network Rail, the owner, operator and asset manager of the majority of the UK's railway network approaches risk management through the application of its Enterprise Risk Management (ERM) process (Sasidharan et al., 2017). ERM employs a framework with a standardised approach to the identification, assessment and recording of risks for analysis and mitigation purposes. The ERM identifies risks on a day to day operational basis feeding the risk management strategies put in place. Australia also has a similar framework which analyses the risk tolerability within its railway system (NTC, 2005). The Swedish Transport Administration employs a risk based model to evaluate the safety risks on its railway infrastructure caused due to rail wear (STRA, 2017).

Following the lead of other industries, the railway industry, because of pressures associated with growing demand on already congested networks, is increasingly focusing on the application of risk management approaches to railway maintenance and management (Elcheikh et al., 2016; Zhao et al., 2014, Cheeseman., 2006). Network Rail recently developed a strategic Decision Support Tool (DST) known as SCAnNeR (Strategic Cost Analysis for Network Rail), which prioritises intervention and budgets for the maintenance of earthworks based on the risk profiles of asset portfolios (Power et al., 2016).

When employing such risk-informed approaches within the railway context, quantifying the risk of the predicted failure will enable preventative maintenance to be carried out and prioritised. To this end, they help to establish and determine suitable maintenance strategies for the infrastructure, while managing the identified risks (Park et al., 2013). The risk-informed approach also acknowledges that human judgment has a relevant role in decisions, and that technical information cannot be the unique basis for decision-making (Zio et al., 2012). In such approaches fault diagnosis methods and failure prediction are key components (Dadashi et al., 2011). The first step towards reducing the probability of failures is by identifying when the interventions should be executed (Martani et al., 2016).

Hence, risk-informed approach for the task in hand in this research, should be based on a predictive identification of the boundaries of safe operation and maintenance (informed by the track deterioration models see Section 2.3.2.2). Ideally, such a mechanism would involve a dynamic function based on expert knowledge and historical data, albeit where uncertainty cannot be avoided.

## 3.4 Summary

Risk assessment techniques are employed to support decision making in a variety of areas. Several such techniques have been described in this chapter. Monte Carlo and Fuzzy approach was found to be most widely used techniques. While the former deals with statistical data, the latter is employed when resorting to subjective or linguistic information within the risk assessment process.

Uncertainty within risk assessment could arise due to incomplete or unavailable data, which hinders effective decision making. To this end, this chapter discusses different sources of uncertainties and the techniques employed to deal with the same. Pertinent to the railway industry, there is a lack of data required for accurate analyses and often expert opinion is used to augment the available data. Whilst a number of risk assessment models may be utilized, the integration of Monte Carlo with Fuzzy approach has been shown to be effective for a number of applications in various industries. It could be especially pertinent to the railway industry as it would enable the uncertainties associated with data and the credibility of expert judgement to be dealt with.

A risk-informed approach would enable risk management officials and the decision makers to get a better understanding of risks, the impacts of risk mitigation decisions and thus enabling efficient asset management. Within the railway context, such an approach would enable preventative maintenance requirements to be identified and prioritised in advance of track failure, while considering the associated risks and uncertainties within the decision-making process.

Such an approach is explored for the research proposed herein in Chapters 4 and 5.

# Chapter 4

# Research Methodology

The literature reviewed in Chapter 2 and 3 identified the need for a risk-informed asset management approach which can compare the cost-effectiveness of different railway track maintenance strategies based on economic criteria. To this end, this chapter presents the research methodology used to conduct this research.

## 4.1 Research Methodology

The purpose of this research is to develop a Whole Life Cycle (WLC) risk informed approach to appraise cost-effective railway track maintenance strategies while utilising appropriate methodologies of asset management and risk management. To achieve this, the research adopted a combination of both exploratory and descriptive research approaches as summarised in Table 4.1

An exploratory research approach was employed initially consisting of a detailed literature review of relevant risk assessment methods (Chapter 3) and asset management approaches (Chapter 2).The descriptive research approach consisted of collecting data pertaining to track quality and maintenance history, WLC costs and risk of derailments. The nature of the input data was both historical and expert opinion based, and were collected from published literature, railway industry reports and data sets, and a workshop.

The data thus collected was used to validate and augment the proposed risk-informed asset management framework via case studies. Utilizing the framework, a prototype tool was thereafter developed, which can be used to compare different track maintenance strategies on a risk-informed whole life cost basis.

The different stages of the research approach undertaken are described below:

### 4.1.1 Literature review

A comprehensive literature review was carried out to:

- Identify different factors that contribute to ballasted railway track quality deterioration and understand track maintenance planning
- Review the current risk assessment methods and asset management approaches
- Identify suitable components and techniques to be used within a risk-informed asset management framework

The literature from international standards, books, journals and conference articles were reviewed. While the international standards and books provide guidance on generic risk and asset management practices, journals and conference articles provide methods and techniques that can be used for the specific purpose of this research. The components of the WLC approach were identified, and appropriate risk assessment techniques were adopted from the literature (see Chapter 2 and 3).

### 4.1.2 Development of theoretical framework

Based on the findings from the literature review, a prototype tool that employs a risk-informed asset management framework (see Chapter 5) was developed using Microsoft Excel™ and the @Risk™ plug-in within Excel to run Monte Carlo simulations.

### 4.1.3 Data collection

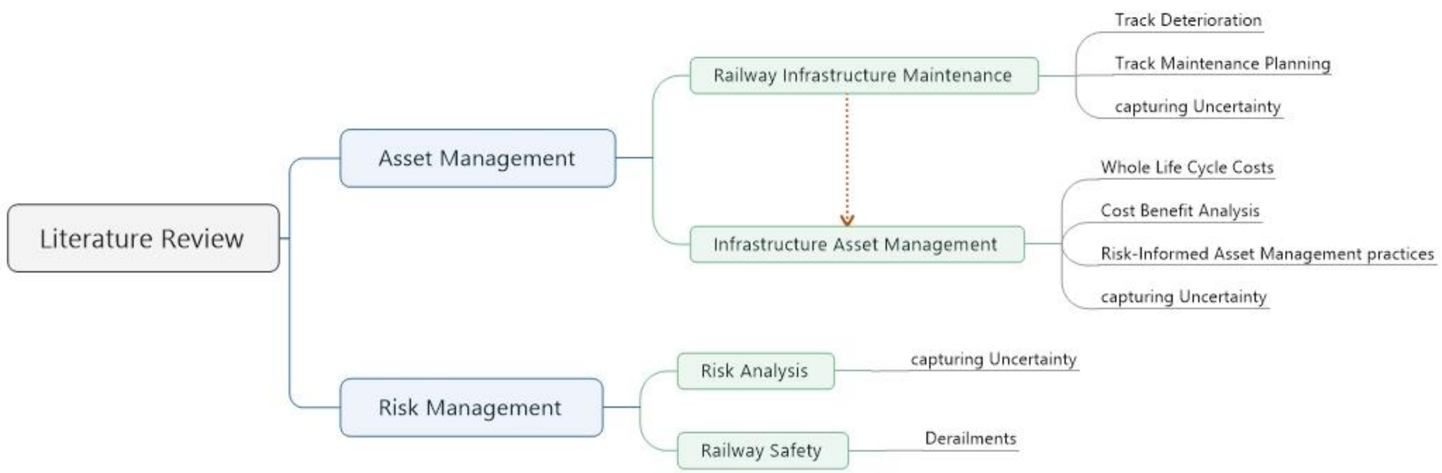
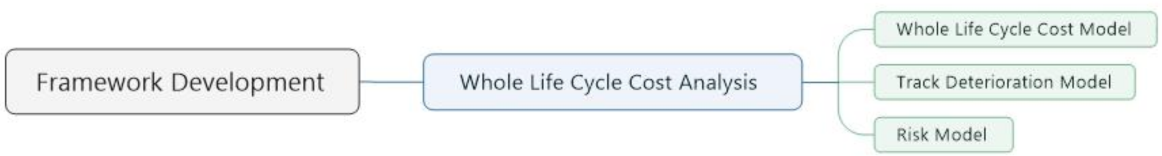
The data required for the case studies were collected from historical datasets and expert opinion. While the former was collected from published datasets and the literature, the latter was pertaining to the derailment risks and was gathered from experts during a workshop.

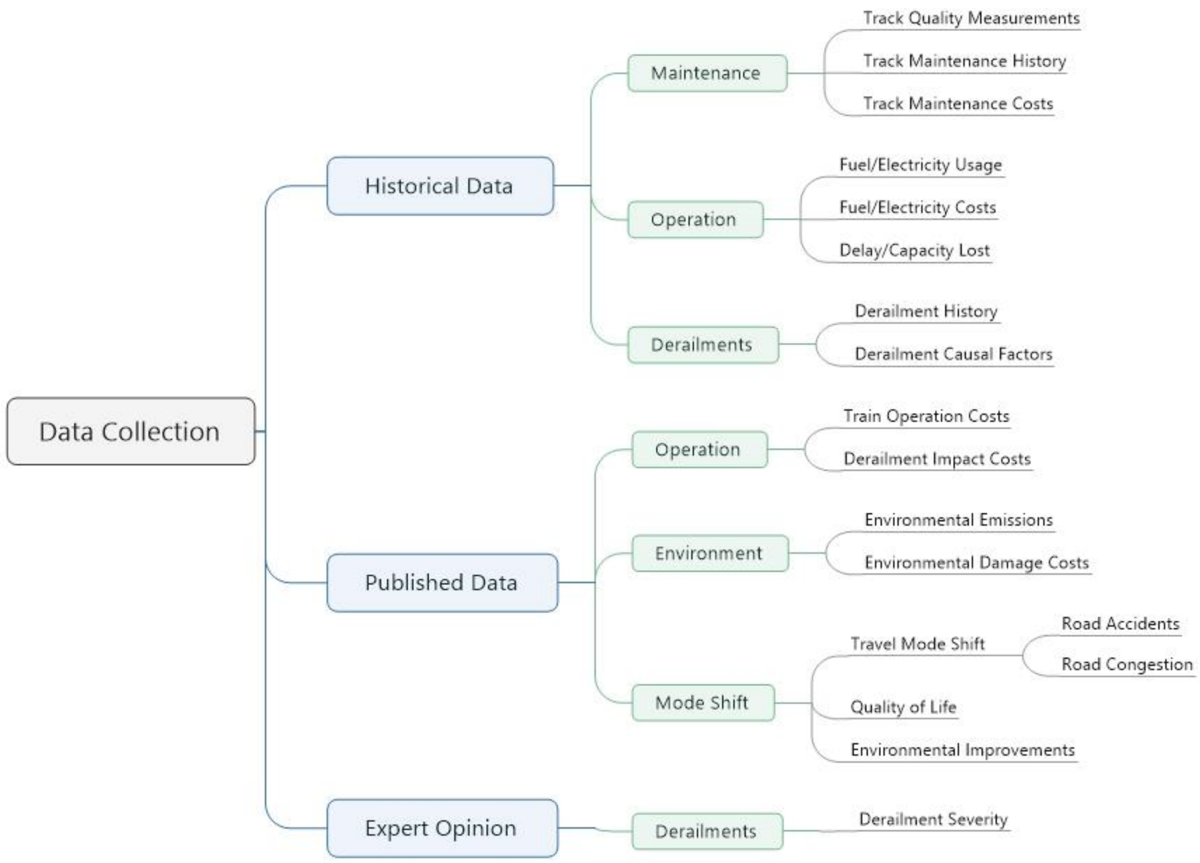
### 4.1.4 Case studies

The developed risk-informed asset management approach was demonstrated via case studies for different operational environments within the UK mainline railways (see Chapter 6).

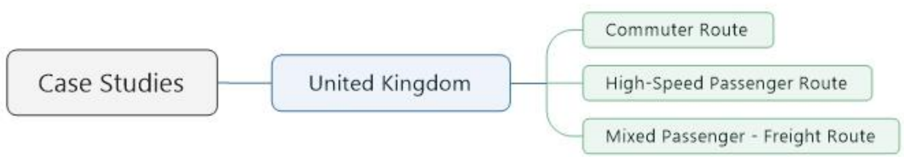
The different stages of the research approach adopted and the corresponding research objectives (see Section 1.2) is illustrated in Table 4.1

Table 4.1 Stages of research

| Stages of Research | Corresponding Research Objectives |
|---|---|
|  | **Objectives 1, 2, 3, 4, 5** |
|  | **Objectives 4, 5** |




**Objectives 2, 3, 4, 5**




**Objective 6**

## 4.2 Summary

This chapter has presented the research methodology adopted to develop a risk-informed method for the appraisal of railway track maintenance strategies. Firstly, the research reviewed the current challenges and problems related to the appraisal of railway track maintenance strategies, while considering the impacts to the whole transport system. This confirmed the need for a risk-informed asset management approach which can compare the cost-effectiveness of different track maintenance strategies based on an economic criteria. The problems and challenges are reflected in the establishment of the research purpose and objectives. Maintenance management practices that consider a whole-transport system view are new concepts to the railway industry. Therefore much of the data required for the proposed model does not exist (e.g. relationships between track quality and derailment risks and train operation costs). This gives rise to uncertainties and requires the consideration of risk analysis approaches. Therefore, the methods and techniques to resolve such a problem were presented and their application method was described in detail. A whole life cycle analysis approach under uncertainty was proposed which considers the costs and benefits to all stakeholders and the environment to enable the most beneficial and timely maintenance solutions to be identified. Given that the life cycle of railway track is 25+ years and preventative maintenance decisions are planned several years in advance, there is also the need to consider the uncertainties associated with future costs and benefits. Finally, this chapter has presented the research process and steps to explore the costs and benefits of track maintenance strategies for given levels of risk. Chapter 5 uses the findings from the research methodology to build the risk analysis framework.

# Chapter 5

# Theoretical Framework

The literature reviewed in Chapter 2 and 3 identified the need for a risk-informed asset management approach to compare the cost-effectiveness of different track maintenance strategies based on economic criteria. This chapter describes the components and techniques that form the theoretical framework of such an approach.

This chapter consists of two parts:

- Whole Life Cycle Cost Analysis (Section 5.1.1), describes the whole-transport system based economic model under uncertainty, and the associated track deterioration model
- Risk model (Section 5.1.2), explains the techniques used for quantifying the risk of derailments

## 5.1. Theoretical framework

The quality of a railway track degrades over time as a function of the environment and the cumulative damaging effects of the repetitions of train loads. Consequently, appropriate track maintenance needs to be applied periodically so that the track condition and its rate of deterioration, and track use costs (including train operation, accident, environmental and delay costs) are kept within acceptable limits (refer to Section 2.3).

Different maintenance strategies can produce different average track qualities over time. Since track use cost is a direct function of track condition, the chosen maintenance strategy will therefore impact track use costs.  Figure 5.1 illustrates this concept and shows three different track maintenance strategies, each resulting in a different average track condition.

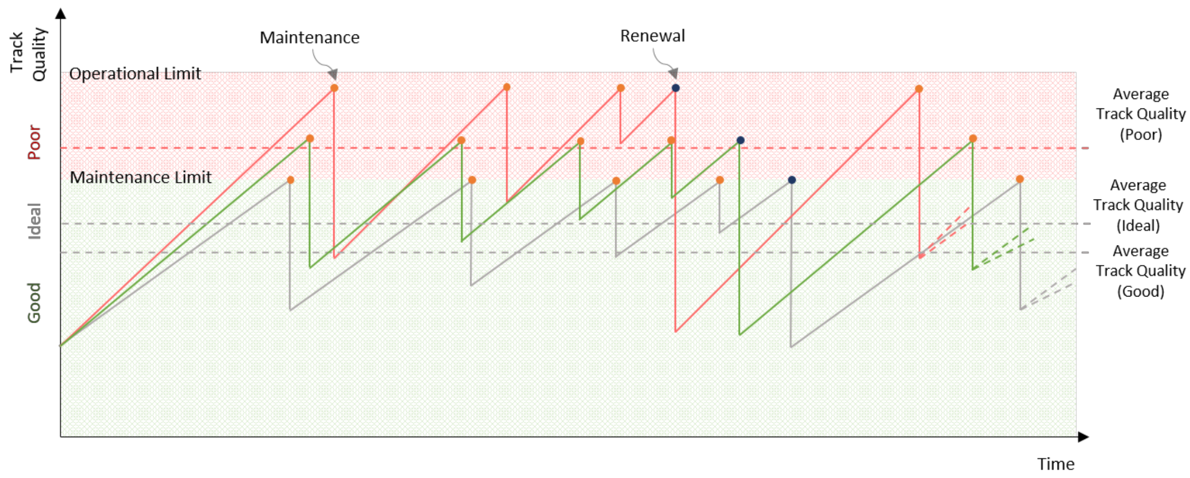



Figure 5.1 Track geometry deterioration

Therefore, maintenance decisions can only be taken responsibly when the costs and benefits of maintenance alternatives (i.e. total transport costs) are compared on a long-term, whole life-cycle cost basis. Further, decisions and strategies for renewing, maintaining and operating the railway infrastructure should also consider any uncertainties within the data (see Section 2.3.3.1 and 3.2.2). The consideration of uncertainty within a whole life cycle cost basis is termed here as whole life cycle cost under uncertainty.

The total transport costs are those associated with track construction, maintenance, de-commissioning and track use (see Section 2.3.2 and Figure 5.2). The track maintenance costs are those to do with direct costs to inspect and maintain ballasted railway track and the indirect costs associated with track maintenance such as delays. Track use costs include train operation costs (i.e. the maintenance of rolling stock, fuel/energy consumption) and impact of derailments, mode change and the environment. These costs are primarily associated with railway track condition. Mode change is associated with perceived change in socio-economic costs incurred by railway users. The de-commissioning costs are to do with disposing of track assets at the end of their useful life.

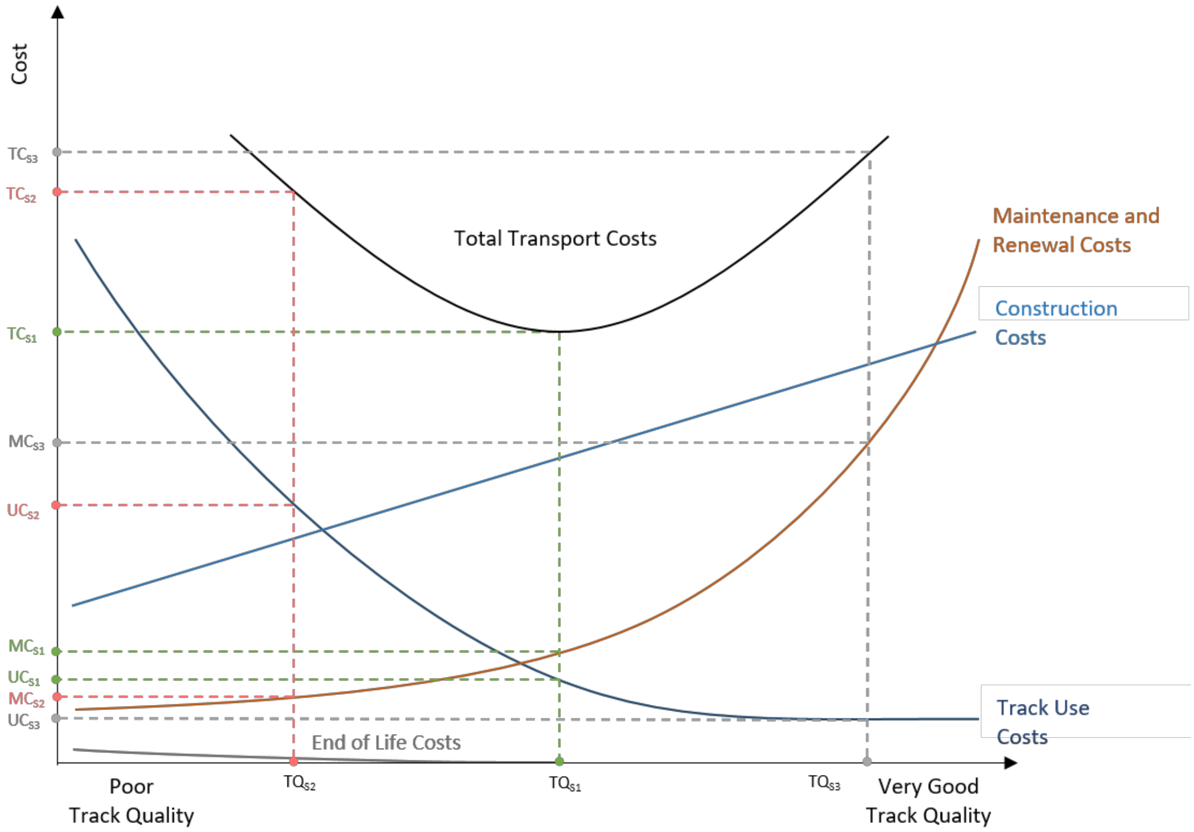



Figure 5.2 Whole Life Cycle Costs of Railway Track

Figure 5.2 conceptualises the different cost elements that might occur within the whole life cycle of a railway track (see Section 2.3.2.1), as a function of the average track condition. Achieving a higher desired average track condition requires either or higher maintenance costs and construction costs (see Figure 5.2). On the other hand, train use costs are also a non-linear function of track condition, except as track condition improves these costs decrease (Zarembski et al., 2010). The ideal average track condition ($TQ_{S1}$) over the life cycle of the track (as shown in Figure 5.2) is that which provides the minimum total transport cost ($TC_{S1}$). Point $MC_{S1}$ shows the maintenance cost of achieving this standard. Achieving a track condition, $TQ_{S2}$, less than the ideal track condition results in an increase of train user costs of $UC_{S2}$, whereas a track condition, $TQ_{S3}$, greater than the ideal condition causes a reduced train use cost of $UC_{S3}$.

Maintenance optimisation procedures could be employed to decide when and what maintenance interventions need to be carried out, while reducing the total cost of operation and maintenance of the railway industry (Liden et al., 2016). However, railway infrastructure asset managers do not have the appropriate computational tools which enable them to look critically at relevant data, assess the quality of the data and acquire an insight into minimising the Whole Life Cycle Cost (WLCC) (see Section 2.3.2). To address this, this research adapts a method in which the (uncertain) costs and benefits of different candidate maintenance strategies are compared on a Whole Life Cycle Cost Analysis (WLCCA) under uncertainty basis, to arrive at the most appropriate maintenance strategy. The ideal strategy is the one with the lowest total transport costs determined on a whole life cycle basis under uncertainty.

Since the timing of track maintenance and track use costs vary over time as a function of track quality it is necessary to incorporate a model of track deterioration model within a WLCCA. Such a model allows the condition of the track to be predicted at any time and thus the required maintenance and associated track use costs. The track deterioration model used for this purpose is presented in Section 5.1.1.2.

The proposed WLCCA approach for ballasted railway tracks considers the direct and indirect costs and benefits to all stakeholders i.e. owners, operators, maintainers and users. The components of the WLCCA approach were selected following the literature review of existing approaches as detailed within Chapter 2 (See Table 2.3 in particular).

Accordingly, the theoretical framework for the proposed risk-informed asset management approach consists of two components as listed below:

Stage 1 - Whole Life Cycle Cost Analysis (Section 5.1.1)

Stage 2 - Risk Modelling (Section 5.1.2

An overview of the proposed theoretical framework is illustrated in Figure 5.3

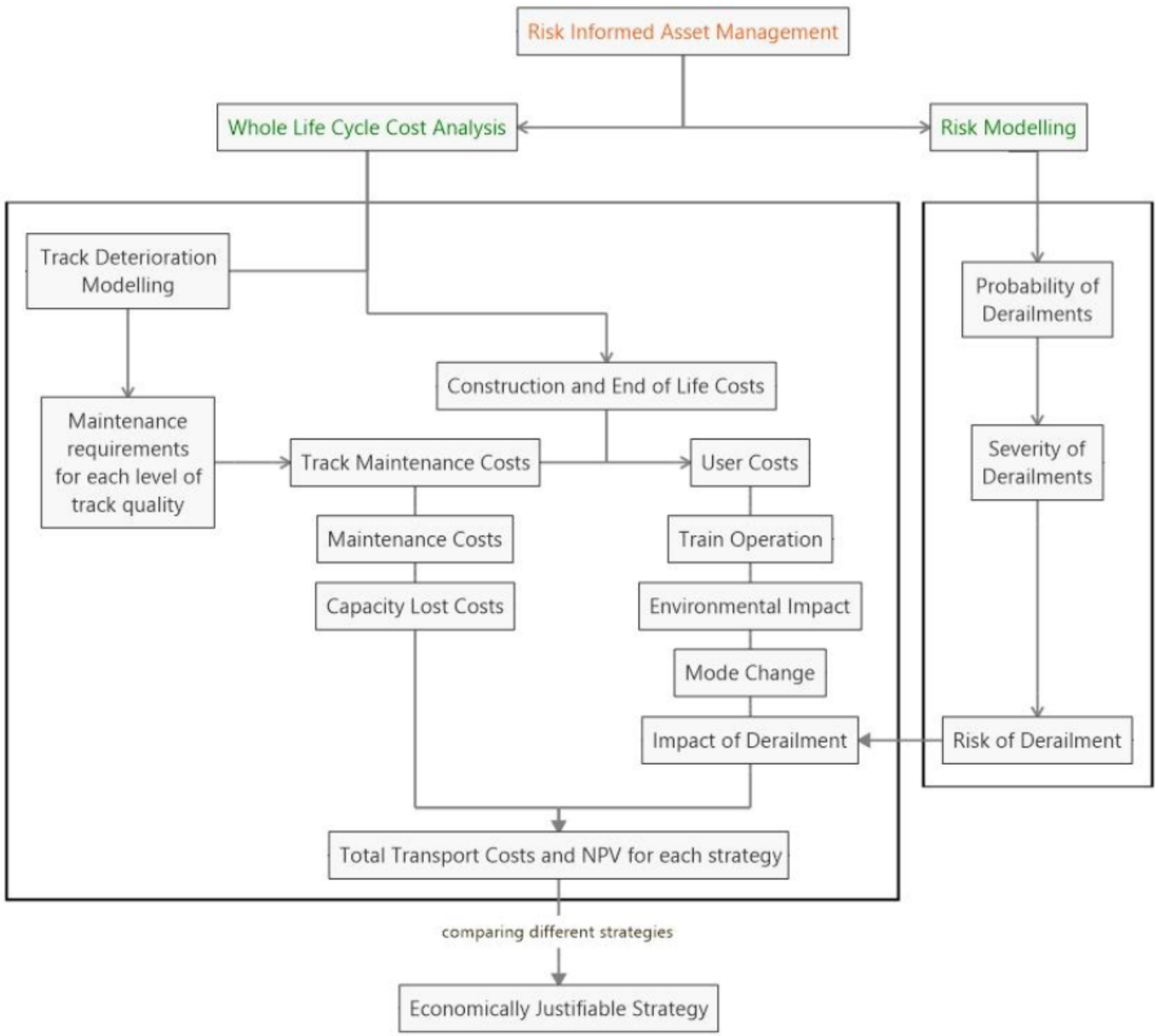



Figure 5.3 Theoretical Framework of a Risk-Informed Approach Used to Compare Alternative Track Maintenance Strategies

### 5.1.1 Stage 1: Whole Life Cycle Cost Analysis

The three most commonly used economic measures to support decision making in transport WLCCA appraisals are the Internal Rate of Return (IRR), the Benefit-Cost Ratio (BCR) and the Net Present Value (NPV) (Bristow et al., 2000). The IRR gives the rate of return on investments, or the discount rate at which the present-day values of benefits and costs are equal (Spiller, 2013). While comparing mutually exclusive investment options, the IRR may rank the options incorrectly if the time profile of benefits and costs differ (World Bank, 1998). The BCR is the ratio of benefits and costs expressed in present day values, with the BCR ratios greater than one indicating economic viability. However, the BCR is often liable to misrepresentation due to its dependency on the degree of aggregation of benefits and costs over the successive time periods (Immers et al., 2004).

The most widely used economic measure used within a WLCCA is the NPV of current and future cost streams discounted to a reference time (Bristow et al., 2005). Accordingly, NPV was chosen for the task at hand (see Section 5.1.1.1) to identify the economically justifiable strategy.

NPV is defined as follows (World Bank, 1998):

$$\widehat{NPV} = \sum_{\mathrm{n}=0}^{\mathrm{N}-1} \frac{(\widehat{\mathrm{B}_n} - \widehat{C_n})}{(1+\hat{r})^n} \tag{5.1}$$

Where

$\widehat{B_n}$ are the benefits in the $n^{th}$ year

$\widehat{C_n}$ are the costs accruing in the $n^{th}$ year

$n$ is the specific year in the WLCCA period

*N* is the length of analysis period in years

$\hat{r}$ is the discount rate

Note ˆ is used to signify that the values are uncertain. Uncertainty with respect to the WLCCA is discussed in Section 2.3.3.1. Chapter 6 describes the case studies used to demonstrate the WLCCA approach and shows how uncertainty has been modelled.

##### 5.1.1.1. Total transport cost

From Equation 5.1, the total transport cost, $\hat{C}_n$ over the whole life cycle of a railway track section to achieve an average track quality, *Q*, during the year, *n*, may be calculated using Equation 5.2 as follows:

$$\hat{C}_n = \hat{C}_{\text{Construction}(Q)_n} + \hat{C}_{\text{Maintenance}(Q)_n} + \hat{C}_{\text{Use}(Q)_n} + \hat{C}_{\text{EndofLife}(Q)_n} \qquad (5.2)$$

Where $\hat{C}_{\text{Construction}(Q)_n}$, $\hat{C}_{\text{Maintenance}(Q)_n}$, $\hat{C}_{\text{Use}(Q)_n}$, $\hat{C}_{\text{EndofLife}(Q)_n}$ terms are the costs for year, *n*, and average track quality, *Q*, with respect to the track construction, maintenance, use and end of life respectively. Some of the cost components have positive or negative values depending if they are a benefit (positive value) or a cost (negative value). The terms are described in more detail in the sections below

###### 5.1.1.1.1. Construction cost

The cost of construction is made up of costs associated with acquiring land and employment of staff, procurement of materials and deployment of machinery type, *m*, for building the railway track.

$\hat{C}_{\text{Construction}(Q)_n}$ given by Equation 5.3, is the cost to construct the railway track of length, *L*.

$$\hat{\mathrm{C}}_{\mathrm{Construction}(Q)_n} = \left(\hat{C}_{Prop} * L\right) + \sum_{m=1}^{M} \left[\left(\hat{C}_{Emn} * \hat{E}_{mn}\right) + \left(\hat{C}_{Cmn} * L\right)\right] \quad (5.3)$$

Where

$\hat{C}_{Emn}$ is the average employee cost of operating a piece of equipment, *m*, in year, *n* (since the construction takes place during the first year, n = 0 in this case).

$\hat{C}_{Cmn}$ is the cost per metre, of using a piece of equipment, m, for track construction in year, *n*

$\hat{C}_{Prop}$ is the cost of land procured per metre to construct the track

$\hat{E}_{mn}$ is the average number of employees for operating a piece of equipment, *m*, in year, *n*

*L* is the length of the track section in metres

##### 5.1.1.1.2. Maintenance cost

The direct and indirect discounted costs associated with the ballasted railway track maintenance to achieve an average track quality, *Q*, during year, *n*, are calculated using as Equation 5.4.

$$\hat{\mathrm{C}}_{\mathrm{Maintenance}(Q)_n} = \hat{\mathrm{C}}_{\mathrm{INS}_n} + \hat{\mathrm{C}}_{\mathrm{TRA}_n} + \hat{\mathrm{C}}_{\mathrm{BC}_n} + \hat{\mathrm{C}}_{\mathrm{BR}_n} + \hat{\mathrm{C}}_{\mathrm{RM}_n} + \hat{\mathrm{C}}_{\mathrm{CL}_n} + \hat{\mathrm{C}}_{\mathrm{SPL}_n} \quad (5.4)$$

Where ($\hat{\mathrm{C}}_{\mathrm{INS}_n}$), are the costs of inspection, track realignment ($\hat{\mathrm{C}}_{\mathrm{TRA}_n}$), ballast cleaning ($\hat{\mathrm{C}}_{\mathrm{BC}_n}$), ballast renewal ($\hat{\mathrm{C}}_{\mathrm{BR}_n}$), routine maintenance ($\hat{\mathrm{C}}_{\mathrm{RM}_n}$), delays ($\hat{\mathrm{C}}_{\mathrm{CL}_n}$) and spillage ($\hat{\mathrm{C}}_{\mathrm{SPL}_n}$),

The different cost elements that contribute to the maintenance costs of the ballasted track are calculated using Equations 5.5-5.11.

#### 5.1.1.1.2.1. Track Inspection Cost

Track inspection is carried out periodically to assess the condition of the infrastructure. Track inspection costs depend upon the frequency of the inspections, *u*, in a year and deployment of different types of equipment of type, *m*. The costs are calculated via Equation 5.5.

$$\hat{C}_{\mathrm{INS}_n} = \sum_{u=1}^{U} \sum_{m=1}^{M} (\hat{C}_{Emn} * \hat{E}_{mn} + \hat{C}_{TImn}) * L \quad (5.5)$$

Where

$\hat{C}_{TImn}$ is the cost of using a piece of equipment, *m*, per metre for a track inspection in year, *n*

*u* is the number of times a piece of equipment, *m*, is used in year, *n*

#### 5.1.1.1.2.2. Track Realignment Costs

Track realignment costs are a function of the number of times, *u*, the maintenance activity is carried out in a given year and on the deployment of the required machinery of type, *m*. Realignment costs are determined using Equation 5.6.

$$\hat{C}_{\mathrm{TRA}_n} = \sum_{u=1}^{U} \sum_{m=1}^{M} (\hat{C}_{Emn} * \hat{E}_{mn} + \hat{C}_{TRAmn}) * L \quad (5.6)$$

Where

$\hat{C}_{TRAmn}$ is the cost of using equipment, *m*, per metre for track realignment in year, *n*

#### 5.1.1.1.2.3. Ballast Cleaning Cost

Ballast cleaning is carried out to remove the fine-grained ballast material caused due to the friction between ballasts during loading and environmental influences. The cost of ballast cleaning is a function of the number of times ballast cleaning takes place in a year, *u*, and the deployment of the required machinery of type, *m*. The costs are calculated using Equation 5.7

$$\hat{C}_{\mathrm{BC}_n} = \sum_{u=1}^{U} \sum_{m=1}^{M} (\hat{C}_{Emn} * \hat{E}_{mn} + \hat{C}_{BCmn} + \hat{C}_{B}) * L \quad (5.7)$$

Where

$\hat{C}_{BCmn}$ is the cost of equipment, *m*, for ballast cleaning per metre in year, *n*

###### 5.1.1.1.2.4. Ballast Renewal Cost

Ballast renewal is carried out when the ballast is at the end of its useful life. The costs incurred due to ballast renewal are a function of the number of ballast renewals, *u*, carried out in year *n*, and the deployment of machinery of type, m. The costs are calculated using Equation 5.8.

$$\hat{C}_{BR_n} = \sum_{u=1}^{U}\sum_{m=1}^{M} (\hat{C}_B + \hat{C}_{Emn} * \hat{E}_{mn} + \hat{C}_{BRmn}) * L \qquad (5.8)$$

Where

$\hat{C}_{Bn}$ is the cost per metre of ballast material in year, *n*

$\hat{C}_{BRmn}$ is the cost per metre of using equipment, *m*, for ballast renewal in year, *n*

###### 5.1.1.1.2.5. Routine Maintenance Costs

Activities such as weed spraying, vegetation removal and drainage cleaning are considered as routine maintenance activities. Routine maintenance costs are calculated using Equation 5.9 as a function of the number of such activities in a year u, and the deployment of machinery type, *m*.

$$\hat{C}_{RM_n} = \sum_{u=1}^{U}\sum_{m=1}^{M}(\hat{C}_{Emn} * \hat{E}_{mn} + \hat{C}_{RMmn}) * L \qquad (5.9)$$

Where

$\hat{C}_{RMmn}$ is the cost per metre of equipment, *m*, used for routine maintenance in year, *n*

###### 5.1.1.1.2.6. Capacity Cost

The capacity costs are those associated with speed restrictions, disruptions and unplanned maintenance activities. Speed restrictions on the railway are required when the track quality exceeds safety values specified in maintenance standards and results in travel time delays. Unplanned or maintenance which over runs, can cause disruptions and or cancellations to services. Assuming that the number of train services remain the same during year, *n*, capacity cost is calculated using Equation 5.10.

$$\hat{C}_{\mathrm{CL}_n} = \left[\hat{C}_{PDn} * \left(\frac{L}{S_{RP}} - \frac{L}{S_L}\right) * \hat{N}_{PTSRn}\right] + \left[\hat{C}_{FDn} * \left(\frac{L}{S_{RF}} - \frac{L}{S_L}\right) * \hat{N}_{FTSRn}\right] + \left(\hat{C}_{PDn} * \hat{N}_{PTDn} * \hat{T}_{APDMn}\right) + \left(\hat{C}_{FDn} * \hat{N}_{FTDn} * \hat{T}_{AFDMn}\right) \quad (5.10)$$

Where

$\hat{C}_{PDn}$ is the average delay cost for a passenger train in year, *n*

$\hat{C}_{FDn}$ is the average delay cost for a freight train in year, *n*

$S_{RP}$ is average restricted speed for passenger trains along the track section

$S_{RF}$ is average restricted speed for freight trains along the track section

$S_L$ is the operational speed for trains along the track section

$\hat{N}_{PTSRn}$ is average number of delayed passenger trains in year, *n*, due to speed restrictions

$\hat{N}_{FTSRn}$ is average number of delayed freight trains in year, *n*, due to speed restrictions

$\hat{N}_{PTDn}$ *is* the number of delayed passenger trains in year, *n*, due to track possession for maintenance

$\hat{N}_{FTDn}$ is average number of delayed freight trains in year, *n*, due to track possession for maintenance

$\hat{T}_{APDMn}$ is average passenger train delay in minutes in year, *n*, due to track possession for maintenance

$\hat{T}_{AFDMn}$ is average freight train delay in minutes in year, *n*, due to track possession for maintenance

##### 5.1.1.1.2.7. Spillage Cost

These costs are to do with the clean-up using machinery type, *m*, train delays and reduced service life of a track section on the plain line, due to the spillage of materials such as fuel, coal and chemicals. The spillage cost is determined using Equation 5.11.

$$\hat{\mathrm{C}}_{\mathrm{SPL}_n} = \left[\sum_{m=1}^{M}\left(\hat{C}_{Emn} * \hat{E}_{mn} * L\right) + (\hat{C}_{CSmn} * L)\right] + (\hat{C}_{PDn} * \hat{N}_{PTDn} * \hat{T}_{APDMn}) + (\hat{C}_{FDn} * \hat{N}_{FTDn} * \hat{T}_{AFDMn}) + (\hat{T}_{RSLn} * \hat{C}_{RSLn}) \quad (5.11)$$

Where

$\hat{C}_{CSmn}$ is the machinery cost per metre for cleaning up the spillage of materials using equipment, *m*

$\hat{C}_{RSLn}$ the cost of reduced service life of the track per year during year, *n*

$\hat{T}_{RSLn}$ is the mean reduced service life of the track in years, n

#### 5.1.1.1.3. Track use costs

The discounted railway track use costs, $\hat{\mathrm{C}}_{\mathrm{Use}(Q)_n}$, for the year, *n*, for an average track quality, *Q*, are associated with train operation ($\hat{\mathrm{C}}_{\mathrm{TO}_n}$), derailments ($\hat{\mathrm{C}}_{\mathrm{DR}_n}$), environmental impacts ($\hat{\mathrm{C}}_{\mathrm{ENV}_n}$) and modal change costs ($\hat{\mathrm{C}}_{\mathrm{MCC}_n}$). Track use costs are calculated using Equation 5.12.

The track use costs in any year are assumed to be a function of the average track quality in that year.

$$\hat{\mathrm{C}}_{\mathrm{Use}(Q)_n} = \hat{\mathrm{C}}_{\mathrm{TO}_n} + \hat{\mathrm{C}}_{\mathrm{DR}_n} + \hat{\mathrm{C}}_{\mathrm{ENV}_n} - \hat{\mathrm{C}}_{\mathrm{MCC}_n} \quad (5.12)$$

##### 5.1.1.1.3.1. Train Operating Cost

The train operating costs considered within this model are the costs associated with rolling stock fuel consumption, maintenance and replacement of spare parts of vehicle type, *v*, as expressed in Equation 5.13.

$$\hat{C}_{TO_n} = \sum_{v=1}^{V}(((\hat{F}_{CPnV(Q)} * \hat{C}_{FPnV} * L) + (\hat{N}_{TSPnV(Q)} * \hat{C}_{TSPnV(Q)}) + \hat{C}_{TMPnV(Q)}) * \hat{N}_{PnV}) + ((\hat{F}_{CFnV(Q)} * \hat{C}_{FFnV} * L) + (\hat{N}_{TSFnV(Q)} * \hat{C}_{TSFnV(Q)}) + \hat{C}_{TMFnV(Q)}) * \hat{N}_{FnV}) \quad (5.13)$$

Where

$\hat{C}_{FPnV}$ is the unit cost of fuel during year, *n*, for passenger train of type, *V*
$\hat{C}_{FFnV}$ is the unit cost of fuel during year, *n*, for freight train of type, *V*
$\hat{C}_{TSPnV(Q)}$ is the unit cost of spare parts during year, *n*, for the components of passenger train of type, *V*, for the average track quality, $Q_A$, achieved in year n.
$\hat{C}_{TSFnV(Q)}$ is the unit cost of spare parts during year, *n*, for the components of freight train of type, *V*, for the average track quality, $Q_A$, achieved in year n
$\hat{C}_{TMPnV(Q)}$ is the average train maintenance cost during year, *n*, for a passenger train of type, *V*, for an average track quality, $Q_A$, achieved in year n
$\hat{C}_{TMFnV(Q)}$ is the average train maintenance cost during year, *n*, for a freight train of type, *V*, for an average track quality, $Q_A$, achieved in year n
$\hat{F}_{CPnV(Q)}$ is the total fuel consumed during year, *n*, by passenger train of type, *V*, for an average track quality, $Q_A$, achieved in year n
$\hat{F}_{CFnV(Q)}$ is the total fuel consumed during year, *n*, by freight train of type, *V*, for an average track quality, $Q_A$, achieved in year n
$\hat{N}_{TSPnV(Q)}$ is the average number of components renewed during year, *n*, per passenger train type, *V,* for an average track quality, $Q_A$, achieved in year n
$\hat{N}_{TSFnV(Q)}$ is the average number of components renewed during year, *n*, per freight train type, *V,* for an average track quality, $Q_A$, achieved in year n
$\hat{N}_{PnV}$ is the number of journeys on passenger train type, *V*, through the track section during year, *n*
$\hat{N}_{FnV}$ is the number of journeys on freight train type, *V*, through the track section during year, *n*

##### 5.1.1.1.3.2. Risk of Derailment Cost

The cost of derailments in a year is estimated by multiplying the average cost of a derailment ($C_{DQ}$) with the probability of derailments ($P_{DQ}$) during the analysis period, calculated using Equation 5.14. The cost components of a derailment include damage to third party property and passenger's health, loss of life, damage to goods and costs involved in rescue, delays and investigation and repair and renewal of track and rolling stock (see Section 5.1.2).

$$\hat{C}_{\mathrm{DR}_n} = \hat{P}_{DQ} * \hat{C}_{DQ} \tag{5.14}$$

Where

$\hat{C}_{DQ}$ is the average cost of a derailment on the track section during year, *n*

$\hat{P}_{DQ}$ is the probability of derailments occurring during year, *n*, on the track section of an average track quality, *Q*

##### 5.1.1.1.3.3. Environmental Cost

The costs incurred due to pollutant type, *p*, during construction ($\hat{E}_{pCn}$), maintenance ($\hat{E}_{pMn}$) and renewal ($\hat{E}_{pRn}$), operation ($\hat{E}_{pOn}$) and disposal ($\hat{E}_{pDn}$) during year, *n*, are determined using Equation 5.15 as follows:

$$\hat{C}_{\mathrm{ENV}_n} = \sum_{p=1}^{P}(\hat{E}_{pCn} + \hat{E}_{pMn} + \hat{E}_{pRn} + \hat{E}_{pOn} + \hat{E}_{pDn}) * \hat{C}_{pIn} \tag{5.15}$$

Where

$\hat{C}_{pIn}$ is the impact cost of pollutant type, *p*, on the environment during year, *n*

##### 5.1.1.1.3.4. Mode Change Benefit

Improved track condition enhances the journey quality and safety, which in turn encourages users to shift from other modes of transportation to railways (Lingaitis, 2014). In this work, the benefits considered from such a shift are changes in travel times, reduced road congestion and road accidents and associated environmental costs. The mode change benefit is determined using Equation 5.16.

$$\hat{C}_{MCC_n} = (\hat{N}_{PSQ} * \hat{C}_{PS}) + (\hat{N}_{FSQ} * \hat{C}_{FS}) + (\hat{N}_{ARS} * \widehat{VOL}) + \hat{C}_{EnvImp} \quad (5.16)$$

Where

$\hat{C}_{PS}$ is the net benefit of a passenger vehicle journey shifting to railways

$\hat{C}_{FS}$ is the net benefit of a freight vehicle journey shifting to railways

$\hat{C}_{EnvImp}$ is the environmental impact cost due to a shift from other modes to railway transport

$\hat{N}_{PSQ}$ is the average number of passenger vehicles shifting to railways as a result of the average track quality achieved during year, *n*

$\hat{N}_{FSQ}$ is the average number of freight vehicles shifting to railways as a result of the average track quality achieved during year, *n*

$\hat{N}_{ARS}$ is the average number of road accidents reduced due to mode change during year, *n*

$\widehat{VOL}$ is the average economic value of a person's life

#### 5.1.1.1.4. End of Life costs

The discounted costs incurred to dispose, or recycle, each track asset, *x*, at the end of its useful life, is given by Equation 5.17.

$$\hat{C}_{EndofLife(Q)_n} = \sum_{x=1}^{X} \sum_{m=1}^{M} (\hat{C}_{Emn} * \hat{E}_{mn} * L) + (\hat{C}_{EOImx} * L) - Rav \quad (5.17)$$

Where

$C_{EOIm}$ is the cost of using a piece of equipment, m, to dispose of, or recycle a track component, *x*, per metre

$R_{av}$ is the residual asset value

#### 5.1.1.2. Track Deterioration Modelling

As shown in the above equations, the timing of maintenance and track use costs are a function of track condition. In order to know how track condition changes over time it was necessary to utilize a track deterioration model. This involved choosing both the type (s) of deterioration to model as well as the model form.

Current standards and assessment methods of ballasted track quality are based on measured track geometry. Track geometry condition is compared with predefined intervention limits to compute the maintenance requirements (see Section 2.3.2). Among these measures, the vertical track geometry is the most illustrative of the track quality (Audley et al., 2013; Thom et al., 2006) and most decisive for maintenance planning purposes (Guler, 2013; Sadeghi et al., 2010). Rolling stock operating costs have also been shown to be a function of vertical track geometry (Zarembski et al., 2010). Consequently, the vertical track geometry was used within the WLCCA model to compute maintenance requirements and track use costs.

Vertical track geometry serves as the basis for various academically developed track deterioration models reviewed within Section 2.3.2.2 (see Table 2.2). Generally, these track deterioration models can be categorised as deterministic or stochastic in nature (Elkhoury et al., 2018).

Deterministic models adopt an approach by which the track performance is based on the factors that affect its deterioration (e.g. speed, axle load, gradient). The interaction between these factors are established experimentally (Andrews, 2012) and the track quality prediction is most often based on linear (Guler et al., 2011), polynomial (Jovanovic, 2004), exponential (Veit, 2007) or multi-stage linear (Chang et al., 2014) models. Such models do not account for uncertainty (Elkhoury et al., 2018; Andrews, 2012).

Stochastic models are based on historical data and maintenance records (Andrews, 2012). The main components of stochastic models are current track condition and transition probabilities (Costello et al., 2005). While the current track condition is informed by the data, the transition probabilities specify the likelihood of the track moving from one condition to another in a given period of time. Accordingly, transition probabilities are based on what has actually happened and account for the variability in deterioration rates through the use of probability (Quiroga et al., 2011; Costello et al., 2005).

Based on the above rationale, a stochastic deterioration modelling approach was chosen for the purposes of the case study to inform the maintenance strategies for a ballasted track (Section 2.3.2.2). The basic properties of such a track deterioration model are as listed below (Quiroga et al., 2011):

- The deterioration rates can be described as an exponential or linear function.
- Both deterioration rate and value of vertical track settlement after a maintenance intervention are dependent on the number of accumulated track realignments.

#### 5.1.1.2.1. Development of track deterioration model

The steps involved in the development of the track deterioration model are described below.

*Conceptual railway track sections*

In order to facilitate the process of carrying out a WLCCA for sections of the railway network, the sections to be considered were grouped into several representative (or conceptual) sections and a single deterioration model was developed for each representative section. A representative section has homogeneous characteristics in terms of construction, maintenance history, traffic and the environment so that all such sections within a homogenous group may be considered to deteriorate at a similar rate (Burrow et al., 2009).

*Model form*

Consider a linear regression model of the form shown in Figure 5.4, in which the linear regression estimates the coefficients of the linear equation involving one or more independent parameters that best predict the value of the dependent parameter. Such a model for railway vertical track settlement of a single section of railway track between two consecutive maintenance interventions is generally given by (Guler et al., 2011):

$$y = (a.x) + b + e \tag{5.18}$$

Where,

$y$ is track quality measure,

$x$ is cumulative tonnage or time,

$a$ is the slope of the line (deterioration rate)

$b$ is the y-axis intercept

*e* is the error value

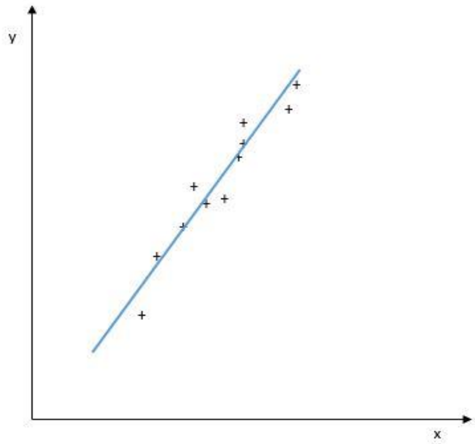



Figure 5.4 Linear Regression

Let $y_1, y_2, \ldots, y_n$ be the values of track settlement at time $t_1, t_2, \ldots, t_n$, for a section of the track, and then the value of the constants *a* and *b* in Equation (5.18) can be determined by using Equations 5.19-5.21, where *n* is the sample size:

$$a = \frac{n(\sum xy) - (\sum x)(\sum y)}{n(\sum x^2) - (\sum x)^2} \tag{5.19}$$

$$b = \frac{(\sum y)(\sum x^2) - (\sum x)(\sum xy)}{n(\sum x^2) - (\sum x)^2} \tag{5.20}$$

Often, the error value, *e* is normally distributed and is represented as:

$$e \sim N(0, \sigma^2) \tag{5.21}$$

Let, $y_{i,n} = \{y_i(t_i), \ldots . y_i(t_n)\}$ be the series of available measurements of *y* at section *i* between *t* and $t_n^{th}$ time in the analysis period. By means of system identification techniques, such as least squares, the SD of the available measurements can be calculated (see Appendix D).

Since the SD defines the condition of a track section at a given point of time, it is necessary to have a series of measurements over a time period (refer to Figure 5.5), in order to appropriately define the degradation of the track geometry. As an alternative to time, the accumulation of traffic or tonnage is also used commonly. To obtain these functions, it is also necessary to know the maintenance history of the particular track section in question.

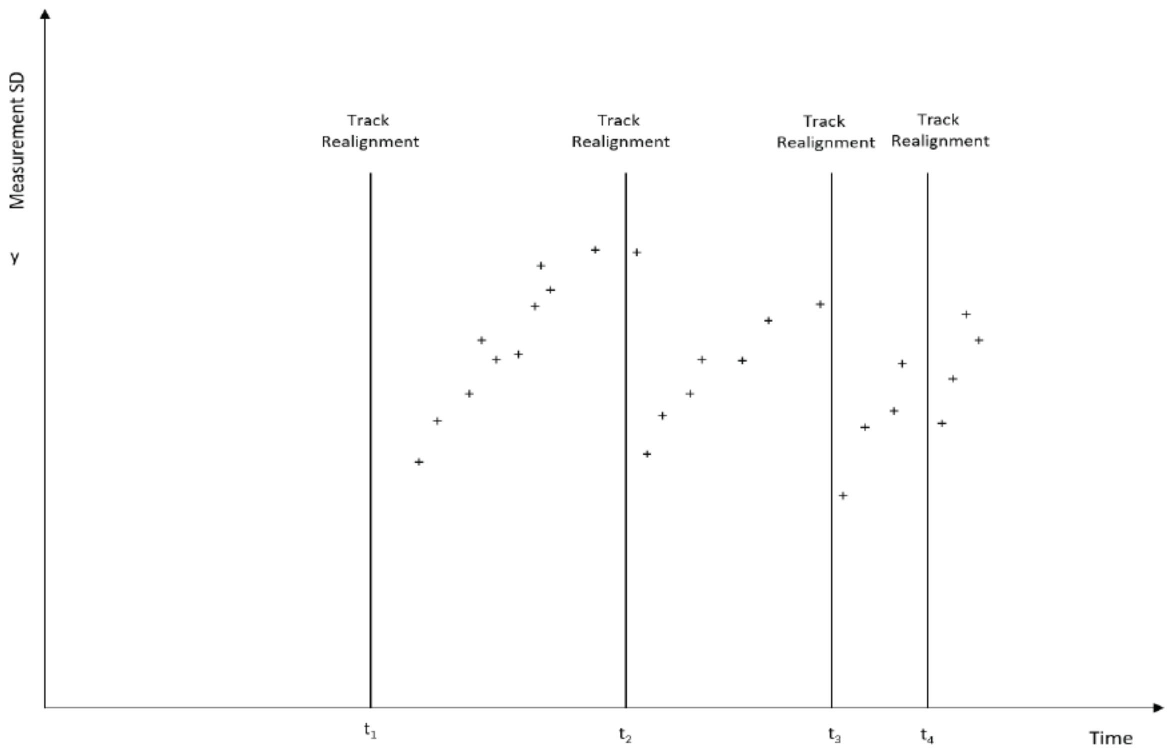



Figure 5.5 Data Points Recorded for a Single Section of Track after Maintenance Intervention

Stochastic models use probability distributions of historical track condition data taken from many homogenous track sections, to determine an appropriate single deterioration curve for a representative track section (Caetano et al., 2016). A typical plot of historical track conditions for a homogenous section of track at three successive time intervals is shown in Figure 5.5. Monte Carlo simulation was identified as an efficient method for such stochastic modelling (Quiroga et al., 2011), as it can be used to run hundreds of thousands of iterations before arriving at a track condition with the highest probability of occurrence (Raimbault, 2016).

The approach to determining a deterioration model, following a particular type of maintenance intervention, for a representative section of track was as follows:

1. Obtain historical values of vertical SD track condition for each homogenous 200 m section of track between two successive similar maintenance interventions (refer to Figure 5.5)

2. Use MCS to determine probability distributions for a set time period (e.g. half yearly or annually) of the above data (see figure 5.6)

3. Identify from the probability distribution, the most likely track condition (see figure 5.7) for the set time period from the track condition data.

4. Use a linear regression model (see Equation 5.18) which makes use of the 90% confidence level values from the probability distribution for the set time period, to fit the track deterioration curve between successive maintenance interventions.

5. It should be noted that the deterioration rate of a section of track can change following maintenance intervention and, while initially improving the track condition in most instances, maintenance does not necessarily return the track condition to that which it was before it was renewed (refer to Figure 5.1). Furthermore, it is possible in some instances that maintenance reduces track quality.

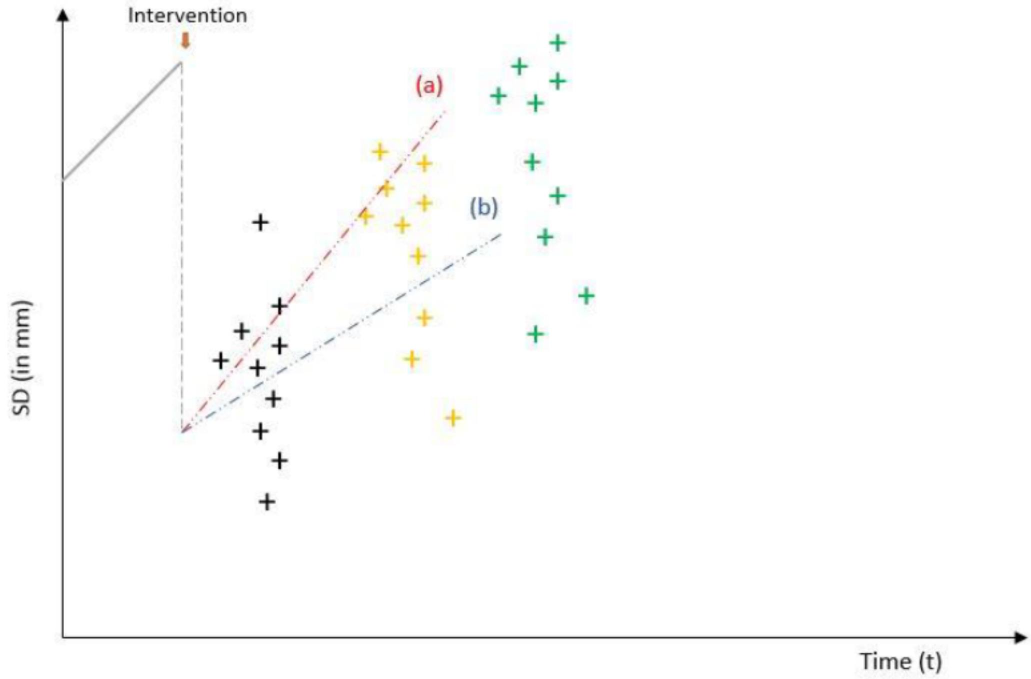



Figure 5.6 Modelling track behaviour following a maintenance intervention

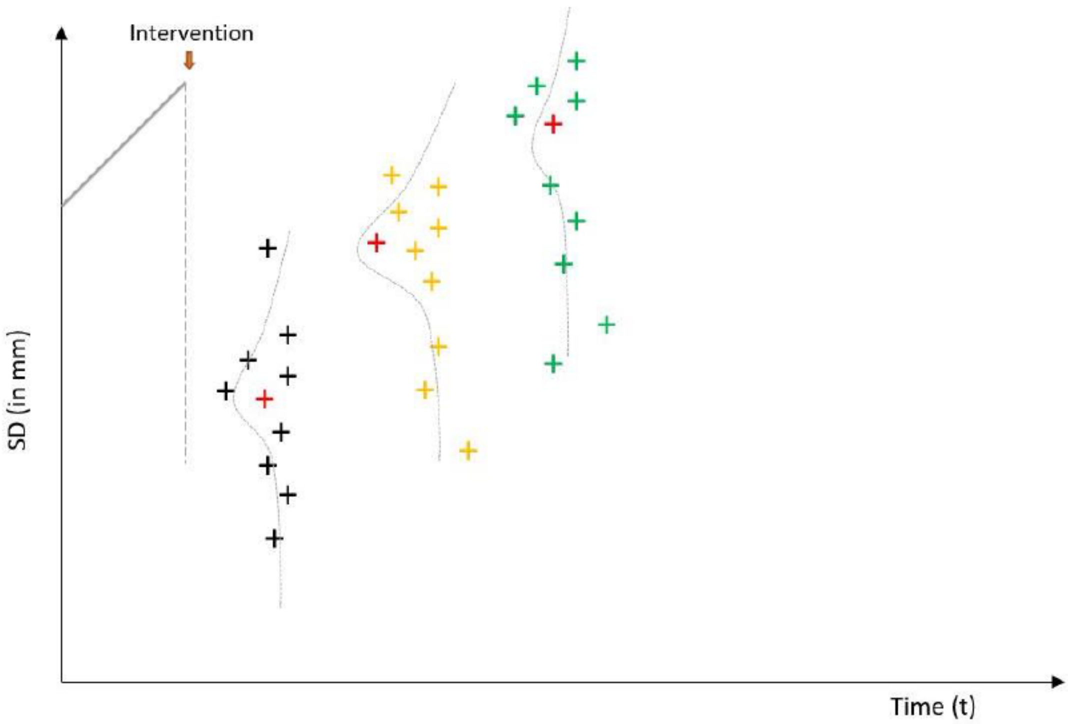



Figure 5.7 Probability Distribution to identify best trend fit

The deterioration models so determined were used to:

1. Determine when the next intervention is due by comparing the track condition at time, *t*, with the appropriate maintenance standard.

2. Calculate the average track condition for time period, *n*, using the linear regression model. The average track condition during time period, n, was used to calculate those track use costs which are a function of track condition (see Equations 5.12 - 5.16).

### 5.1.2. Stage 2: Risk Modelling

The focus of this component of the framework is to evaluate the risk of derailments where track geometry was a contributing factor. A track section with higher quality has a comparatively lower risk of derailment compared to a track section of lower track quality (Qing et al., 2015). Risk in the context of safety within the railway industry is a '*measure of average number of injuries, fatalities or equivalent fatalities that could occur per year as a result of the construction, operation, maintenance, alteration, renewal, decommissioning and demolition of a system'* (RSSB, 2002).

An example of a risk assessment process for hazardous railway related events is shown in Table 5.1. Note that only the risk of derailment in Table 5.1 is appropriate for this research.

Table 5.1 Example for Risk Assessment Results (RSSB, 2002)

| **Hazardous event description** | **Frequency ($f_d$)** (Events/Year) | **Consequences ($c_d$)** (No. of equivalent fatalities/event) | **Risk** (Equivalent Fatalities/Year) |
|---|---|---|---|
| Collision between two trains | 1.8 | 3.32 | 5.8 |
| Collision of train with object on line - no derailment | 49.7 | 0.006 | 0.3 |
| Collision with buffer stops | 40.9 | 0.029 | 1.2 |
| Train Derailment | 14.3 | 0.30 | 4.3 |
| Total collective risk from these 4 hazardous events | | | 11.6 |

Generally, the risk assessment processes chosen depends upon the type of risk involved, the aim of the analysis, the availability of data and resources (Chen, 2012). The methods to determine the risk components (frequency of occurrence and consequence - see Equation 5.14) could be quantitative, qualitative or semi-quantitative in nature (see Table 3.1). As described in Chapter 3, while quantitative methods use numerical values for the analysis of probability and consequences, qualitative methods are based on the knowledge and judgement of the assessor, which often gives rise to uncertainties within the decision-making process. Within the scope of this research, a combination of both the quantitative and qualitative methods are used to deal with uncertainties.

In many situations, it might be extremely difficult to predict probability and consequence of hazards through probabilistic risk assessment, due to the lack of historical data. The use of expert opinion is often suggested as a means of overcoming such issues (Torbaghan et al., 2015).

#### 5.1.2.1. Expert Opinion in Risk Assessment

The UK's RSSB (2002) identifies the use of expert judgement where no other data is available for assessing risks of hazardous events. BSI (2010) suggests that, expert opinion can be captured through questionnaires, interviews and brainstorming workshops. Within this research, expert opinion was used, in the case studies described in Chapter 6, to inform the consequence of derailment as a function of track quality.

#### 5.1.2.2. Integrated Monte Carlo – Fuzzy Approach (MCFA)

When there is access to accurate and reliable data, probabilistic modelling such as Monte Carlo (MC) can be employed. If the risk assessment involves expert opinion or judgement, a

Fuzzy approach (FA) is a more suitable approach (Sasidharan et. al., 2017). Chapter 3 reviewed the literature that combined MC and Fuzzy approach employed in risk management practices within different industries (Table 3.1).

The data concerned with the probability and severity of derailments as a function of track condition is not generally available in the railway industry (Personal correspondence with RSSB). Consequently, for the case studies in this research the probability or frequency of track quality related derailment was assumed to follow a Poisson's distribution (refer to the Case Studies and in particular Section 6.4).

Expert opinion was solicited to gather information about the severity of derailments. Expert opinion informed the possible range of impacts, which was later modelled using a combination of MC and Fuzzy approach. To this end, fuzzy approach was employed to analyse the expert opinion data, and Monte Carlo was then used as an interface into the fuzzy model for arriving at the most-likely scenario (of severity).

The strengths of using an Integrated Monte Carlo - Fuzzy Approach (MCFA) model, within the context of the framework developed in this research are as follows:

(i) When investigating derailments, most of the incidents are unique and only limited data is available, causing uncertainties within the risk assessment.
    a. MC simulation has been employed widely for addressing probabilistic uncertainty (refer to Section 3.2.1.1), while the Fuzzy approach is suitable for non-probabilistic uncertainties arising from subjective and linguistically expressed data, i.e. expert opinion (refer to 3.2.1.2).
    b. MC simulation enables the user to sample from a known or estimated distribution.

c. By combining MC simulation with Fuzzy approach, the ambiguous nature of events in the distribution can also be dealt with.

##### 5.1.2.2.1. Integrated Monte Carlo - Fuzzy Approach

All the input data required for the calculation procedure, including probability distributions and/or membership functions for uncertain parameters are defined. Generally, the output Y (severity or impact of derailments) of a function (M) that has $R_1, R_2, \dots, R_n$ random variables (e.g. ) represented by probabilistic distributions and $F_1, F_2, \dots, F_m$ fuzzy sets can be represented as shown in Figure 5.8.

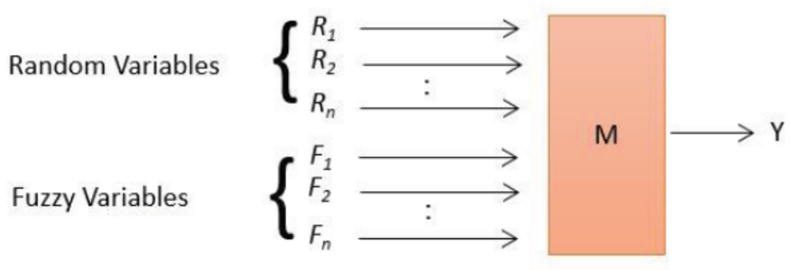



Figure 5.8. A function (M) with both fuzzy and random inputs (Sadeghi et al., 2010)

On the other hand, in MCFA, the samples $r_1, r_2, \dots, r_n$ are derived from the probabilistic distributions of the fuzzy variables $F_1, F_2, \dots, F_n$ (see Figure 5.9).

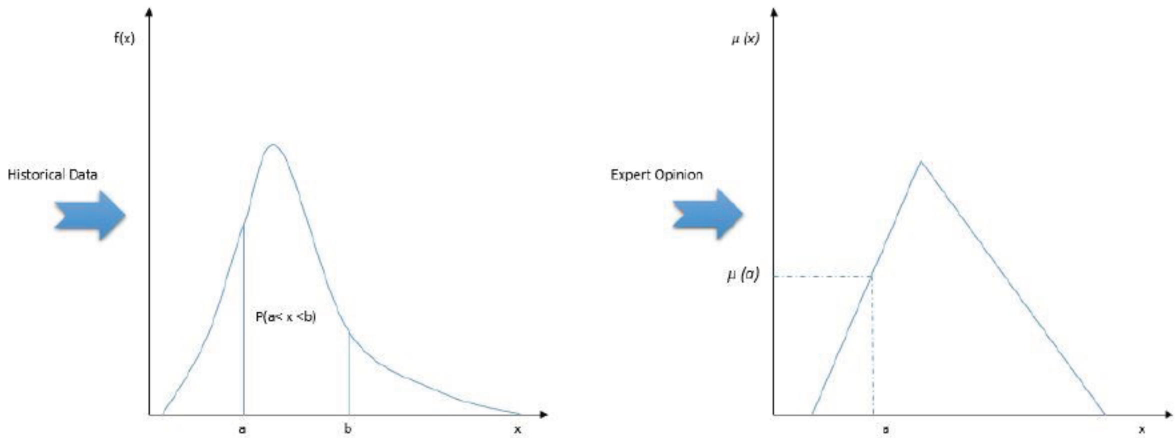



Figure 5.10 (a) Probability Density Function developed from historical data (b) A fuzzy membership function based on expert opinion

The following steps describe how the Monte Carlo - Fuzzy approach has been used within this research (refer to Section 6.4 to see how the approach has been used for the three case studies):

**Step 1: Probability of derailment**

The probability of track quality related derailments is calculated from the Probability Mass Function (PMF) of a Poisson distribution (refer to Section 6.4). Poisson distribution is used to describe rare and random incidents related to a time or area of reference (Rose et al., 2018).

**Step 2: Severity of derailments**

2.1 Triangular membership functions were selected to model the severity of derailments as they are commonly used in railway safety risk analysis (An et al., 2006; Jafarian et al., 2011; El-Cheikh et al., 2013).

2.2 Expert opinion was solicited to choose the severity of derailments associated with poor, good and medium track quality.

2.3 Fuzzification: Severity Indicators were defined as linguistic variables: 'Minor' (MIN) and 'Major' (MAJ) for the experts to choose from. These severity indicators describe the consequences of a derailment i.e. damage to infrastructure and rolling stock, service disruptions, casualties and harm to the environment. Table 5.2 shows the ranking criteria for the severity indicators used in this research.

Table 5.2 Severity of Derailments

| Linguistic Variables | Description | Membership Function parameters |
|---|---|---|
| **MIN** | Derailment is PHRTA* with less than 50% delay | 0,0.25,0.50 |
| **MAJ** | Derailment is PHRTA* with more than 50% delay or train cancellation | 0.50,0.75,1 |

**PHRTA – Potentially Higher Risk Train Accident resulting in at least one death, considerable delay costs, track downtime and damage to property (ORR, 2015)*

2.5 Both the linguistic variables (i.e. Minor and Major) were assigned triangular membership functions to estimate the severity of derailments as mentioned earlier in Step 2.1 (see Figure 5.11).

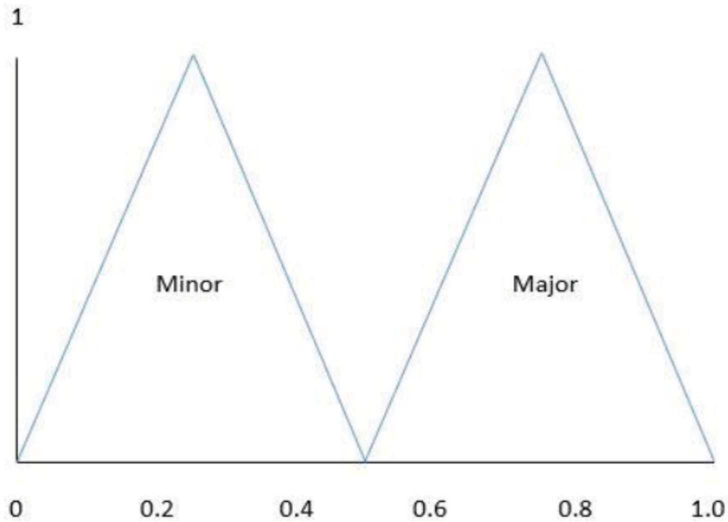



Figure 5.11 Membership Function for Severity

2.6 Allocation of Weights to Experts: The risk assessment process in this research involves experts from different backgrounds and disciplines, with experience in railway asset management and safety. Since the experts may have varied experience, an Expert Weighting (EW) was introduced to capture the variation effectively (Huang et al., 2007).

The EW of i-th expert within 'n' number of experts can be obtained from:

$$EW_i = \frac{RE_i}{\sum_{i=1}^{n} RE_i} \tag{5.23}$$

Where

$RE_i$ is the weight assigned to the $i^{th}$ expert based on their experience.

$RE_i$ takes a value between 0 and 1. RE is defined in a way that the higher the number the greater the importance is assigned to the expert's opinion.

2.7 Each Fuzzy input is multiplied by each EW's and are matched to their respective membership functions (refer to Section 6.4 for the case study examples)

2.8 A single aggregated fuzzy set is obtained by combining the outcomes of each rule, by using the maximum aggregation method (Mitropoulos et al., 2017). Hence, the aggregated fuzzy set $\mu_i(x)$ is obtained using Equation (5.24) where $\mu^1(x)$ and $\mu^2(x)$ are the individual fuzzy sets.

$$\mu_i(\mathrm{x}) = \max(\, \mu_i^1(x)\; \mu_i^2(x)) \tag{5.24}$$

2.9 Monte Carlo Simulation is used to calculate the distribution percentiles of the aggregated fuzzy set $\mu_i(x)$ which follows a triangular membership function. The most probable crisp value with a 90% confidence level of occurrence is selected (refer to Section 6.4 and particularly Figure 6.25 for example).

**Step 3**: Outputs from Step 1 (probability) and Step 2 (severity) are used in Equation 5.14 to calculate the risk of derailment for each maintenance strategy under consideration.

## Summary

This chapter has described the WLCCA under uncertainty approach developed in this research to assess maintenance strategies for ballasted railway track. Briefly, the theoretical framework comprised of two elements (i) Whole Life Cycle Cost Analysis (WLCCA) under uncertainty and (ii) Risk model. For the WLCCA, the NPV is used as the metric to determine and compare the cost effectiveness of alternative maintenance strategies. The NPV comparison considers the direct and indirect costs and benefits of different strategies to all stakeholders, and where appropriate as a function of track condition. The uncertainty of data associated with costs, benefits and track deterioration rates was dealt with by employing the widely used Monte Carlo simulation.

A track deterioration model was presented to predict the track behaviour and track condition associated with different maintenance strategies. The proposed risk model uses expert opinion, to deal with uncertainties associated with the unavailability of data relating the risk of derailment to track quality. An integrated Monte Carlo-Fuzzy approach technique was proposed to handle both probabilistic (i.e. historical data associated with occurrence of derailments) and linguistic inputs (i.e. expert opinion concerning severity of derailments).

Chapter 6 demonstrates the applicability and usability of the proposed risk-informed approach via case studies on three different route types within the UK mainline railway networks.

# Chapter 6

## Case Studies

The theoretical framework for a risk-informed approach for appraising railway track maintenance strategies was described in Chapter 5. This chapter demonstrates the proposed approach by presenting case studies to identify the most economically justifiable strategy of those considered, for three routes within the UK mainline railway network. The chapter first describes the data used for the case study and outlines the development of the deterioration models that were informed by the collected data. The outputs from the deterioration models were used to model the costs associated with construction, maintenance and renewal, track use and end of life.

### 6.1. Case study routes

The three routes were selected, namely a high-speed passenger route, a mixed freight-passenger route and a commuter route on the UK mainline railway network (see Figure 6.1). The high speed passenger route runs from London to Birmingham for 160 km (100 miles) via Coventry allowing a top speed of 200 km/h. From Coventry onwards, it operates as a mixed passenger-freight route for 27 km (17 miles). The commuter route chosen is a 51 km (32 miles) long route in the Midlands running from Sutton Coldfield to Lichfield City. All three train routes have competing road transport, but do not have any competing canal, sea or air routes.

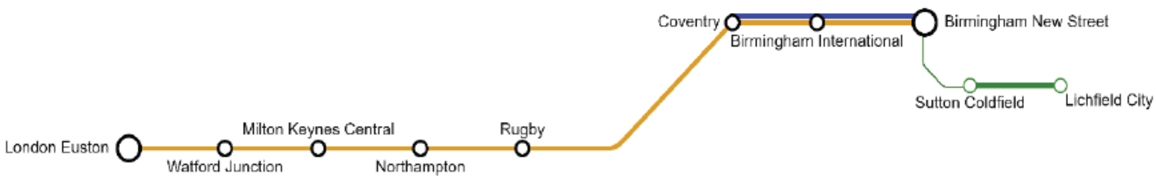



Figure 6.1 Routes Selected for the Case Studies

Track condition and maintenance history data was obtained from Network Rail (NR), the UK's railway infrastructure operator and maintainer. Firstly, 200 m long track sections of homogenous construction, traffic, and maintenance and renewal history were chosen for each route. The chosen homogeneous track sections were compared to identify a representative section for each route with similar socio-economic characteristics. To this end the Digimap$^{TM}$ tool was employed to compare the proximity of the homogenous track sections to clusters of housing and business settlements.

The track maintenance standards for railway operation in the UK are specified by the Railway Safety and Standards Board (RSSB) (BSI, 2012). In order to simplify the analysis for comparison purposes, the average track quality levels expressed in SD for the vertical profile of 200m representative homogeneous track sections were classified into poor (2.6-4.0 mm), medium (1.3-2.6 mm) and good (0-1.3 mm). The different maintenance strategies considered for the analysis of the three representative homogeneous track sections are presented in Section 6.2.1 (see Table 6.2).

The data required for the Whole Life Cycle Cost Analysis (WLCCA) (see Section 6.3) and Risk model (see Section 6.4) were obtained from a variety of sources and is presented within the respective sub-sections below. The WLCCA model presented in Section 5.1.1 determines the costs and benefits on an annual basis for the period of study. In order to be able to compute these costs and benefits, it is necessary to predict the annual track condition for each year of the analysis period. The track condition primarily informs the amount and type of maintenance and the track use costs (see Sections 5.1.1.1.2 and 5.1.1.1.3). The approach considered herein determines the track condition annually using historical track condition data provided by NR for the three case study routes. The annual average value of track condition is used to determine the track use costs. The process for determining the annual average track condition is described below.

## 6.2. Development of the track deterioration model

Network Rail periodically uses its High-Speed Track Recording Coach (HSTRC) to measure the vertical alignment of the track across its network. Examples of these measurements for the 200m long homogeneous track sections on both the high-speed passenger and mixed passenger-freight routes in August 2012 are presented in Figures 6.2 and 6.3 respectively.

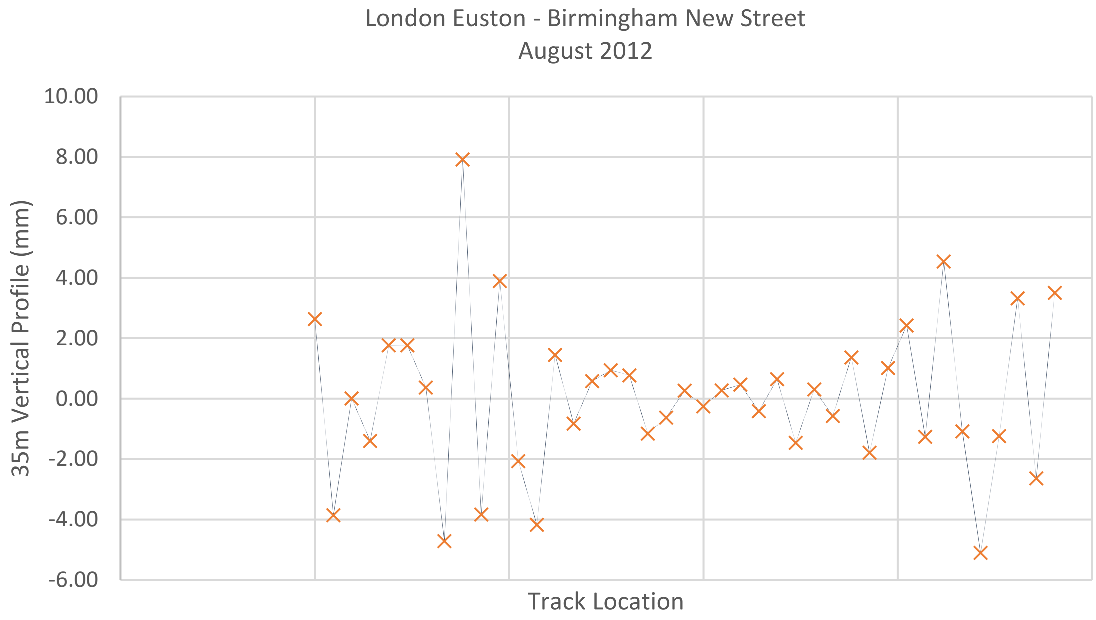



Figure 6.2 Track Condition Measurements on the High Speed Passenger route (Source: Network Rail)

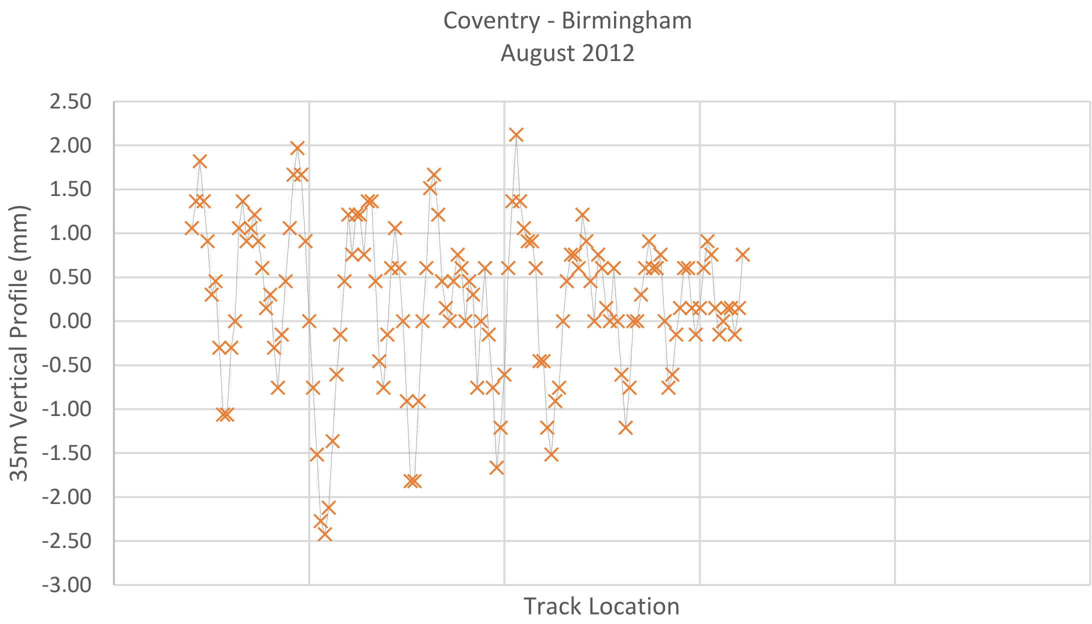



Figure 6.3 Track Condition Measurements on the Mixed Freight-Passenger route (Source: Network Rail)

For the case study routes SD of the vertical profile for every 200 m length of track is calculated by averaging the filtered data using the least square method (Equations 5.17-5.32). Typically, a 35m filter is used for this purpose (see Section 2.3.1.2).

The resulting SD values for the 200 m representative homogeneous sections of the high-speed passenger and mixed freight-passenger routes (refer to Figure 6.2 and 6.3) are 2.60mm and 1.0mm respectively (used as initial track conditions for the analysis). The SD values of typical track sections for the high-speed passenger, mixed-traffic and commuter routes between December 2013 and the end of 2017 are shown in Figures 6.4-6.6. It is interesting to note that some maintenance appears to have taken place on these routes despite the maintenance intervention level (prescribed by RSSB) not being reached (for e.g. potential maintenance intervention on 31-Jan-2016 for the high-speed passenger route shown in Figure 6.4).

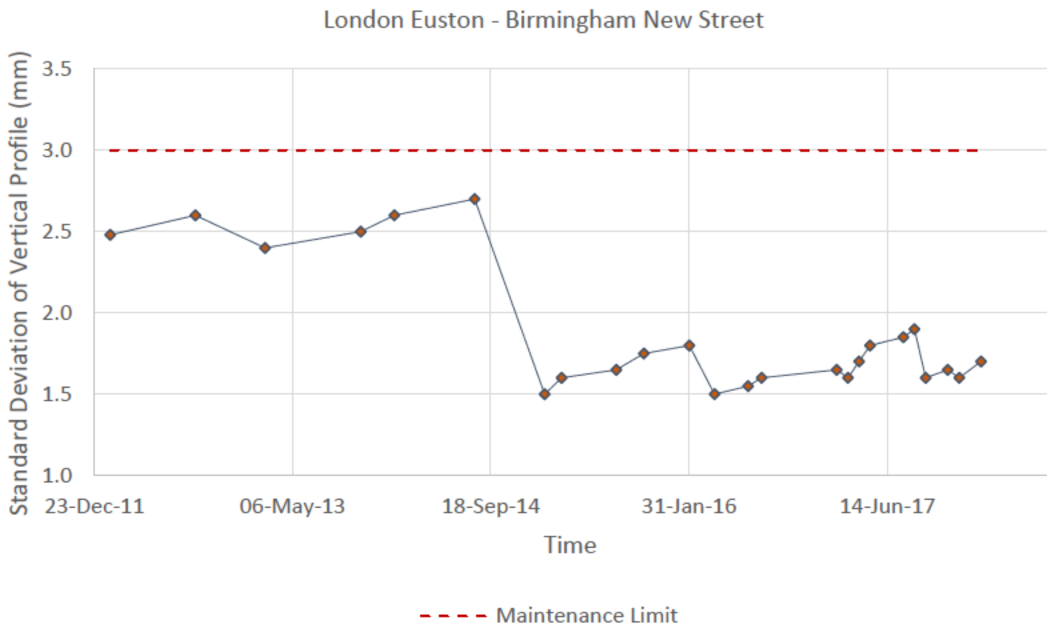



Figure 6.4 SD Values of vertical profile for the track section on High-Speed Passenger route

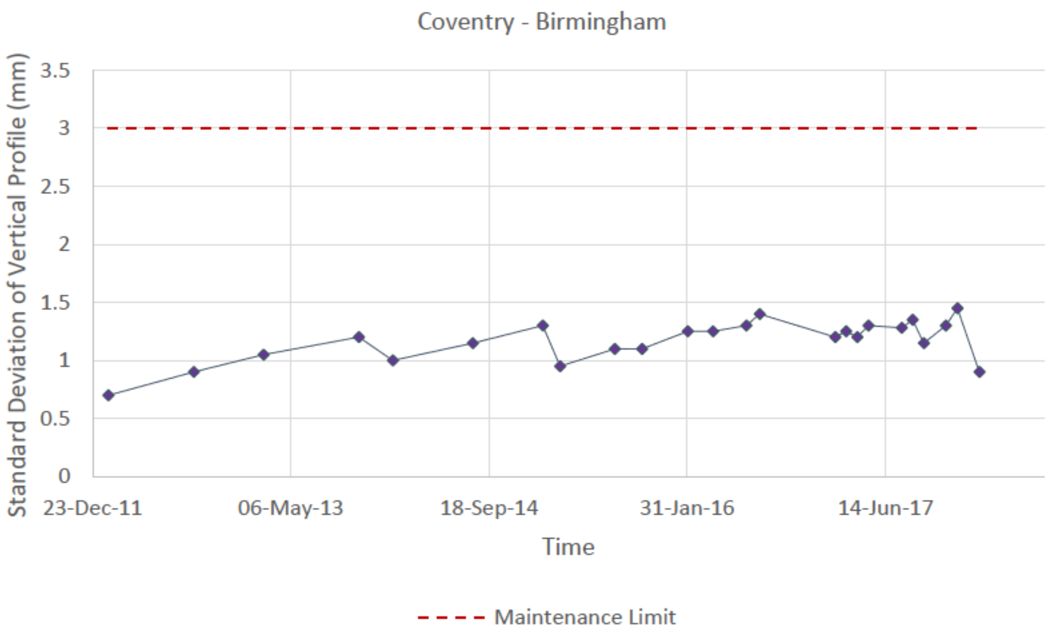



Figure 6.5 SD Values of vertical profile for the track section on Mixed Freight-Passenger route

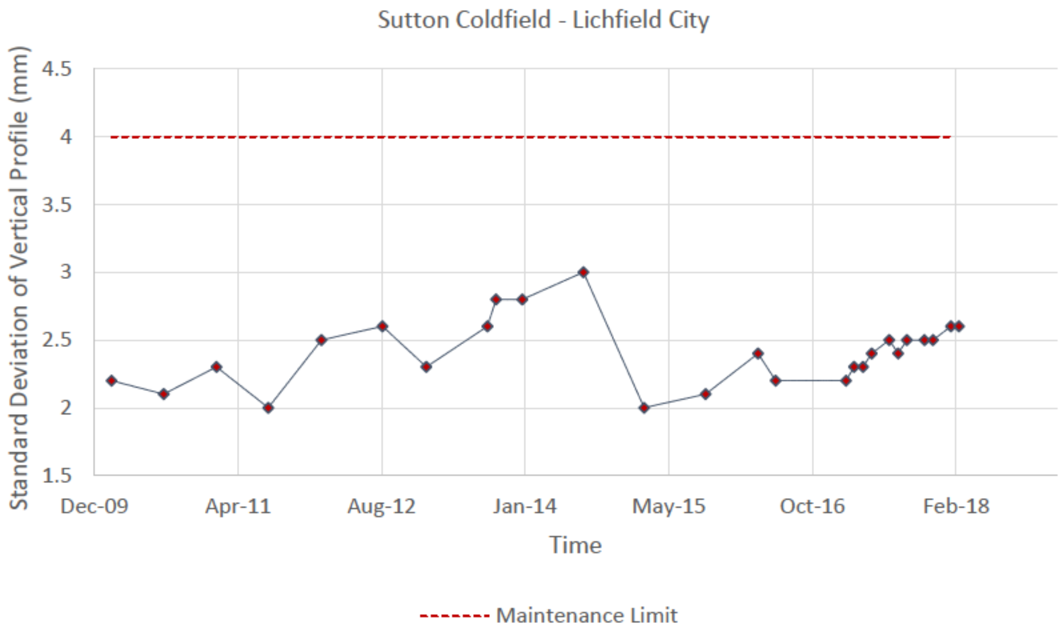



Figure 6.6 SD Values of vertical profile for the track section on Commuter route

The maintenance and renewal data for all the three track sections are presented in Table 6.2.

Table 6.1 History of Maintenance Intervention
(Source: Personal Correspondence with Network Rail)

| Route | Type of Intervention | Date of Intervention |
|---|---|---|
| Sutton Coldfield - Lichfield City | Ballast Renewal | Feb-15 |
| | Track Realignment | Jan-16 |
| | | Sep-16 |
| | | Feb-17 |
| London Euston - Birmingham New Street | Ballast Renewal | Feb-15 |
| | Track Realignment | Mar-16 |
| | | Aug-17 |
| | | Aug-18 |
| Coventry - Birmingham | Ballast Renewal | every 5th year |
| | Track Realignment | Dec-15 |
| | | Apr-16 |
| | | Sep-17 |

The process described in Section 5.1.1.2.1 was used to determine the track deterioration models for each of the three 200 m long representative track section. The SD values of the vertical profile between two successive maintenance interventions were calculated. To this end, Monte Carlo Simulation (MCS) was used to determine the most likely SD value at specific points in time (e.g. half yearly or annually) within the analysis (see Section 5.1.1.2.1 and Figures 5.6-5.7).

Figures 6.7 to 6.9 present an example, of the distributions of track quality for each of the three representative sections, determined using MCS for a specific time within the analysis period. The most likely track condition (expressed in SD value) with a 90% confidence level of occurrence was selected and inputted into the track deterioration model as the track quality for the specific point in time.

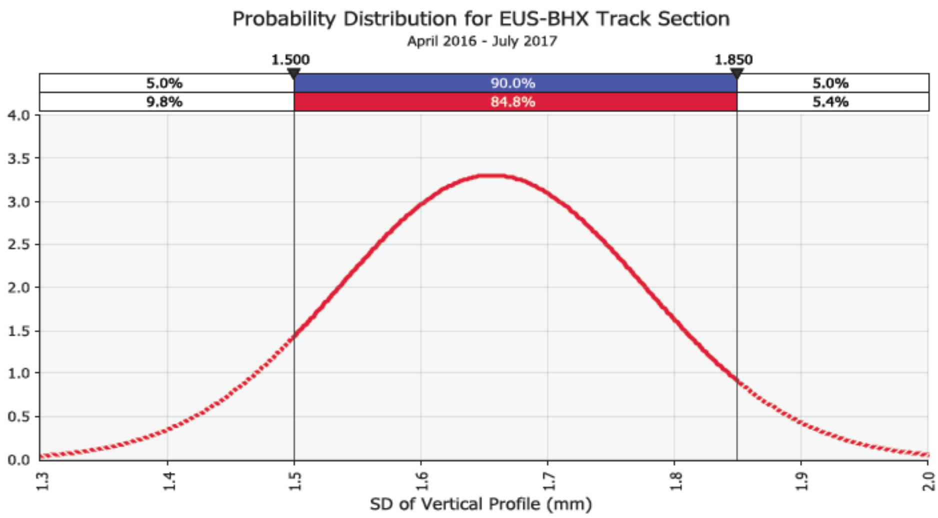



Figure 6.7 Probability Distribution of SD Values during a maintenance cycle on the High-Speed Passenger route

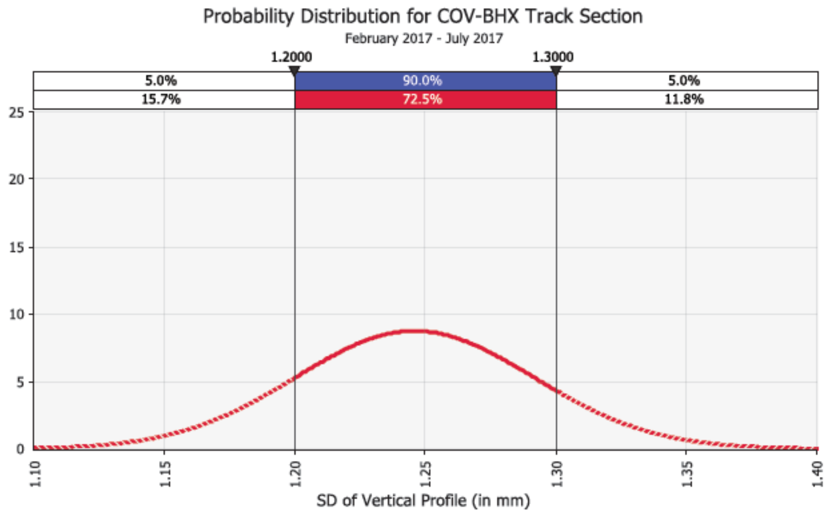



Figure 6.8 Probability Distribution of SD Values during a maintenance cycle on the Mixed Freight-Passenger route

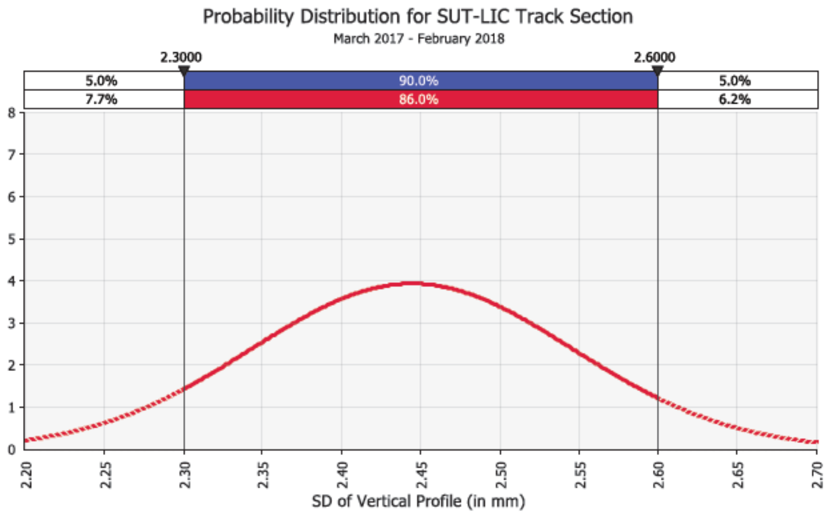



Figure 6.9 Probability Distribution of SD Values during a maintenance cycle on the Commuter route

Linear regression (See section 5.1.1.2.1) was subsequently used on the SD values (with 90% confidence level) to determine the track deterioration between successive maintenance interventions (see Section 5.1.1.2.1) Example deterioration curves for the representative sections for a 10-year time period are shown in Figures 6.10 - 6.12.

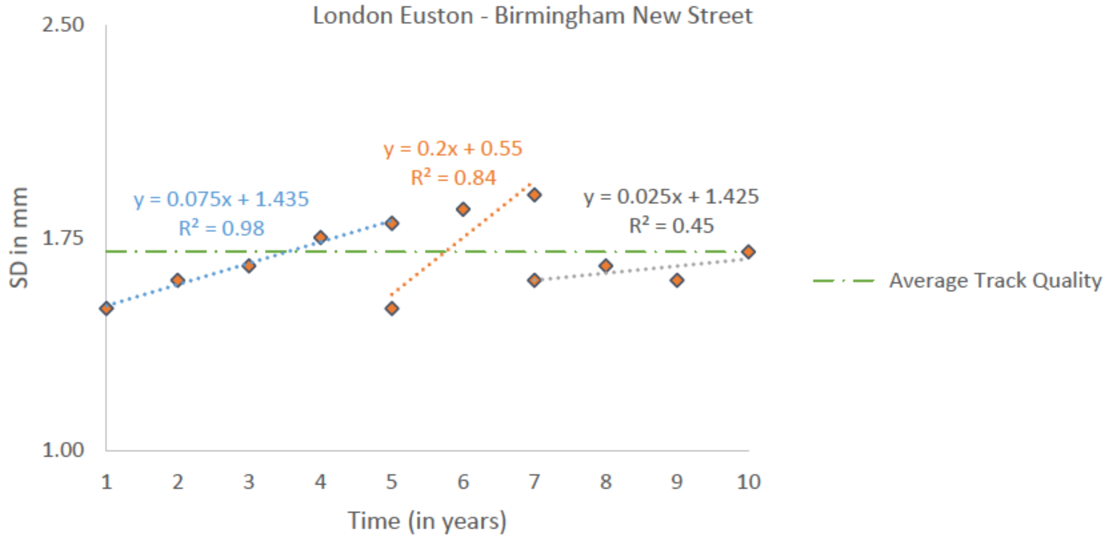



Figure 6.10 Deterioration trend of the representative track section with homogenous characteristics on the High-Speed Passenger route

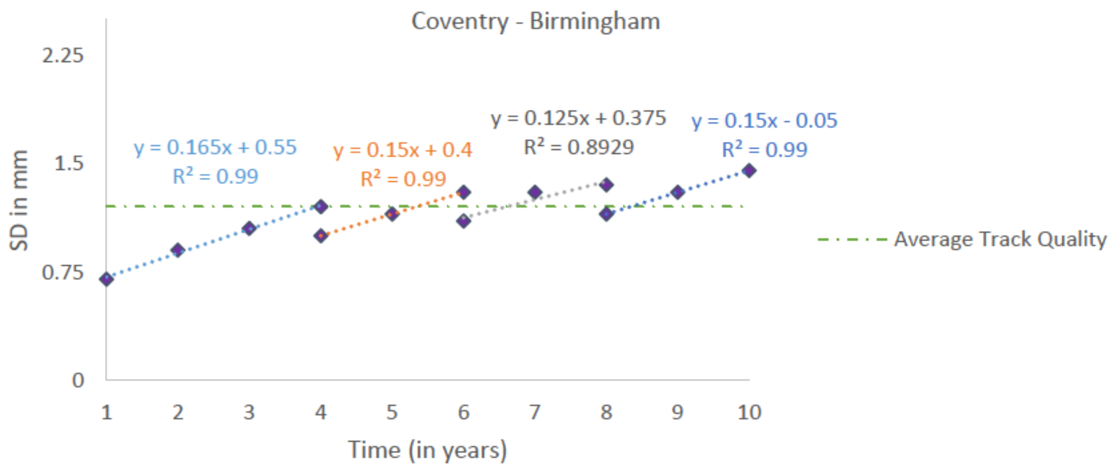



Figure 6.11 Deterioration trend of representative track section with homogenous characteristics on the Mixed-Freight Passenger route

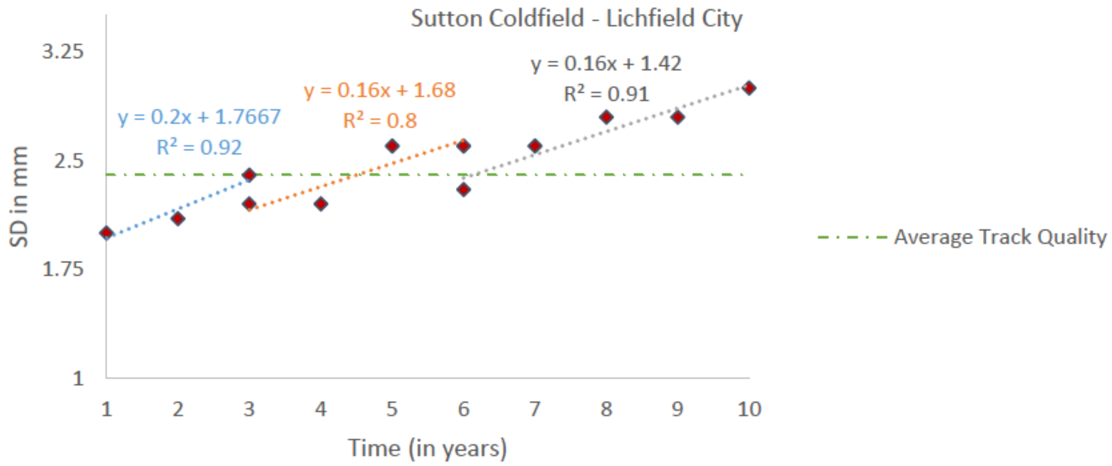



Figure 6.12 Deterioration trend of representative track section with homogenous characteristics on the Commuter route

In addition to determining the average track condition in each year of analysis, the linear regression models were also used to predict the average track condition during each maintenance cycle over a 25-year analysis period. These average track conditions were used to inform the maintenance strategies. For example, tamp every 2 years to achieve an average track condition of 2.4 mm for the representative homogeneous track section on the Sutton Coldfield - Lichfield City (see Section 6.2.1 & Table 6.2).

### 6.2.1. Maintenance strategies considered

Maintenance strategies were investigated to achieve a number of different average track quality values for the three routes. The range of track quality values considered for each of the three routes during the 25-year analysis period are shown in Table 6.2.

For the three track sections, initial track conditions were taken to be 2.4mm, 2.6mm and 1.0mm SD, as informed by the historical track condition data for the commuter, high-speed passenger and mixed-traffic route respectively (See Section 6.2).

The time interval between consecutive track realignment activities were delayed, realising different average track qualities across each maintenance cycle (see Table 6.2). The time interval between renewals were adapted from the historical data provided by NR (for e.g. renew every 10$^{th}$ year on the Sutton Coldfield - Lichfield City route). The annual average track quality for each maintenance cycles were calculated to inform the annual track use costs associated with each strategy (see Section 6.3.4).

To achieve these average track quality values, NR carries out different combinations of track maintenance activities including track realignment (tamping and stone blowing), ballast cleaning and routine maintenance. Although the impact of routine maintenance and ballast cleaning was not specifically modelled within this analysis (due to lack of associated data), it was considered to take place based on the assumptions stated within Section 6.3.3.4 and 6.3.3.5. The number of different maintenance activities and renewals carried out to achieve different average track quality levels for the three routes are presented in Tables 6.3-6.8.

The average track quality levels shown in Table 6.2 could also be realised if the track is allowed to deteriorate without any periodic maintenance but renewed when necessary. The railway industry does not adapt such a strategy, as this would result in higher safety risks (of derailments) and affect ride qualities (driving up track use costs). Consequently, such strategies were not considered within this analysis.

## Table 6.2 Maintenance strategies adopted for the homogeneous track sections

| Route | Average Track Quality (in SD mm) | Year 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sutton Coldfield-Lichfield City | 2.4 | | TRA | | TRA | | BR | TRA | | TRA | | | TRA | | TRA | | BR | TRA | | TRA | | | TRA | | TRA | |
| | 2.5 | | TRA | | TRA | | BR | | TRA | | TRA | | TRA | | TRA | | BR | | TRA | | TRA | | TRA | | TRA | |
| | 2.6 | | | TRA | | | BR | | | TRA | | | | TRA | | | BR | | | TRA | | | | TRA | | |
| | 2.7 | | | | TRA | | BR | | | | TRA | | | | TRA | | BR | | | | TRA | | | | TRA | |
| | 2.9 | | | | | TRA | | BR | | | | | | | | TRA | | BR | | | | | | | | TRA |
| | 3.1 | | | | | TRA | | | BR | | | | | | | TRA | | | BR | | | | | | | TRA |
| | 3.4 | | | | | | | TRA | | | BR | | | | | | | TRA | | | BR | | | | | |
| | 3.5 | | | | | | | TRA | | | BR | | | | | | | | TRA | | BR | | | | | |
| | 3.6 | | | | | | | | TRA | | BR | | | | | | | | TRA | | BR | | | | | |
| London Euston-Birmingham New Street | 1.9 | | TRA | TRA | TRA | | TRA | TRA | | TRA | BR | | TRA | TRA | TRA | | TRA | TRA | | TRA | BR | | TRA | TRA | TRA | |
| | 2.2 | | TRA | | TRA | | TRA | | TRA | TRA | BR | | TRA | | TRA | | TRA | | TRA | TRA | BR | | TRA | | TRA | |
| | 2.4 | | | TRA | | TRA | | TRA | | TRA | BR | | | TRA | | TRA | | TRA | | TRA | BR | | | TRA | | TRA |
| | 2.5 | | | | TRA | | TRA | | TRA | | TRA | BR | | | TRA | | TRA | | TRA | | TRA | BR | | | TRA | |
| | 2.6 | | | | | TRA | | TRA | | TRA | BR | | | | | TRA | | TRA | | TRA | BR | | | | | TRA |
| | 2.7 | | | TRA | | | TRA | | TRA | | BR | | | TRA | | | TRA | | TRA | | BR | | | TRA | | |
| | 2.8 | | | TRA | | | | TRA | | | BR | | | TRA | | | | TRA | | | BR | | | TRA | | |
| | 2.9 | | | | | | | | TRA | | BR | | | | | | | | TRA | | BR | | | | | |
| | 3.0 | | | | | | | | | TRA | | BR | | | | | | | | TRA | | BR | | | | |
| Coventry-Birmingham | 1.2 | TRA | TRA | BR | | TRA | TRA | | TRA | BR | TRA | TRA | TRA | BR | | TRA | TRA | | TRA | BR | TRA | TRA | TRA | BR | | TRA |
| | 1.4 | TRA | TRA | TRA | | TRA | TRA | TRA | | TRA | T B | TRA | TRA | TRA | | TRA | TRA | TRA | | TRA | T B | TRA | TRA | TRA | | TRA |
| | 1.6 | | TRA | TRA | TRA | | TRA | TRA | | TRA | BR | | TRA | TRA | TRA | | TRA | TRA | | TRA | BR | | TRA | TRA | TRA | |
| | 1.9 | | TRA | | TRA | | TRA | | TRA | | T B | | TRA | | TRA | | TRA | | TRA | | T B | | TRA | | TRA | |
| | 2.1 | | TRA | | TRA | | | TRA | | TRA | BR | | TRA | | TRA | | | TRA | | TRA | BR | | TRA | | TRA | |
| | 2.3 | | | TRA | | | TRA | | TRA | | BR | | | TRA | | | TRA | | TRA | | BR | | | TRA | | |
| | 2.4 | | | TRA | | | TRA | | | | T B | | | TRA | | | | TRA | | | T B | | | TRA | | |
| | 2.5 | | | | TRA | | | | | TRA | T B | | | | TRA | | | | TRA | | T B | | | | TRA | |
| | 2.6 | | | | | | | | TRA | TRA | BR | | | | | | | | TRA | TRA | BR | | | | | |
| | 2.7 | | | | | | | | TRA | | BR | | | | | | | | TRA | | BR | | | | | |

| | |
|---|---|
| TRA/T | Track Realignment |
| BR/B | Ballast Renewal |

## 6.3. Whole Life Cycle Costs

The total transport costs and Net Present Value (NPV) associated with the strategies presented in Table 6.2 were evaluated using Equations 5.1 and 5.2 described in Chapter 5. For each component in Equation 5.2, the possible uncertainties in the associated data were modelled using Monte Carlo Simulation (MCS) (see Section 2.3.3.1). In each case, widely used normal probability distribution was assumed for the data values associated with costs and benefits, and defined using the @Risk$^{TM}$ library (Palisade, 2017). The ranges of values chosen for each of the components are described below.

Thereafter, the NPV (Equation 5.1) and total transport costs (Equation 5.2) for each of the strategies (see Table 6.2) for the three homogeneous track sections were determined. In each case MCS was performed for 10, 000 iterations.

### 6.3.1. Discount rate

UK's Department of Transport (DfT) guidelines for transport appraisal suggests a discount rate of 3.5% for discounting costs and benefits, for less than 30 year analysis period (DfT, 2004). The case studies models this discount rate (of 3.5%) using a normal distribution as shown in Figure 6.13.

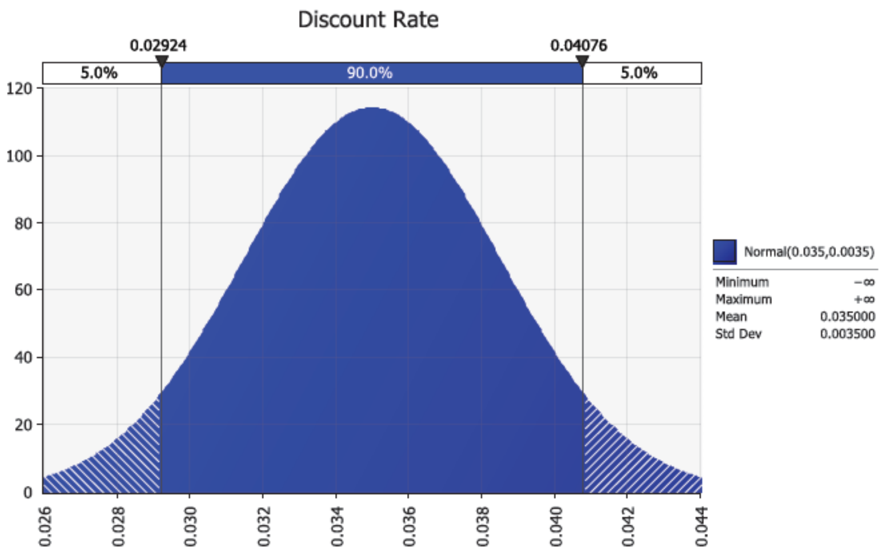



Figure 6.13 Probability distribution for Discount Rate

### 6.3.2. Construction

The costs associated with the construction of ballasted railway tracks are related to surveying, procuring the land, staff, machinery and materials. The representative track sections considered within this case study are built abiding to the same engineering standard and therefore it was assumed that all the three representative track sections were built to the same track quality.

The construction costs for a single ballasted track ranges from £1.2m to £1.4m per mile (Compass, 2017). For the uncertainty analysis, this case study considered the minimum, maximum and most likely (with 90% confidence level) track construction costs to be £1.2m, £1.4m and £1.3m per mile respectively and was modelled using a normal distribution.

### 6.3.3. Maintenance

The total maintenance costs for all the three representative track sections were calculated using Equation 5.4. As discussed in Section 5.1.1, the maintenance costs is a cumulative cost of inspection, track realignment, ballast cleaning, ballast renewal, routine maintenance, delays and spillage. The cost values associated with each cost components are presented within the following subsections.

#### 6.3.3.1. Inspection

The cost is related to High Speed Track Recording Coach (HSTRC) used by Network Rail to measure the track geometry periodically. The cost includes both the cost of operating the HSTRC and labour costs. Across the three routes considered, the HSTRC is used to inspect the track geometry every 8-10 weeks as mandated by the Track System Requirements (GC/RT5021) (RSSB, 2002). For the purpose of this case study it was therefore assumed that an inspection was carried out every 8 weeks. Data obtained from Network Rail suggests that the cost of track inspection is £15,000/shift. A shift equates to measuring 250 km of the track using the HSTRC (ORR, 2012). The minimum, maximum and most likely (with 90% confidence level) values of inspection costs within the uncertainty analysis were assumed to be £14,000, £16,000 and £15,000 per shift respectively and modelled using a normal distribution. Manual inspections usually carried out by the local track engineers (e.g. of earthworks/ drainage) and ad hoc track structural condition assessments were not considered within the calculation.

#### 6.3.3.2. Track realignment

Track realignment costs are related to operating the track treatment fleet of stone-blowers and tamping machines and the associated labour costs. Typically track realignment costs £5,000/shift and a typical shift covers 100m of track (ORR, 2012; Personal correspondence, 2018). For the purposes of the uncertainty analysis, the minimum, maximum and most likely (with 90% confidence level) costs for the realignment of each 200 m homogenous section was assumed to be £9000, £11,000 and £10,000 respectively and modelled using a normal distribution.

For the case study, a track realignment activity was assumed to occur when a desirable average track quality levels was realised for each maintenance cycle of the track section (see Section 6.2.1). The track deterioration model informed the number of track realignments carried out during the analysis period, in order to achieve different average track quality levels (see Table 6.2). Tables 6.3 - 6.5 show the number of track realignments carried out for each of the three representative track sections for each strategy.

Table 6.3 Number of Track Realignments for the Commuter Route

| **Average Track Quality** | SD (mm) | **2.4** | **2.5** | **2.6** | **2.7** | **2.9** | **3.1** | **3.4** | **3.5** | **3.6** |
|---|---|---|---|---|---|---|---|---|---|---|
| | Level | Medium | | | Poor | | | | | |
| **Number of Track Realignments** | | 10 | 10 | 5 | 5 | 3 | 3 | 2 | 2 | 2 |

Table 6.4 Number of Track Realignments for High Speed Passenger Route

| **Average Track Quality** | SD (mm) | **1.9** | **2.2** | **2.4** | **2.5** | **2.6** | **2.7** | **2.8** | **2.9** | **3.0** |
|---|---|---|---|---|---|---|---|---|---|---|
| | Level | Medium | | | | | Poor | | | |
| **Number of Track Realignments** | | 15 | 12 | 10 | 9 | 7 | 7 | 5 | 2 | 2 |

Table 6.5 Number of Track Realignments for Mixed Passenger-Freight Route

| **Average Track Quality** | SD (mm) | **1.2** | **1.4** | **1.6** | **1.9** | **2.1** | **2.3** | **2.4** | **2.5** | **2.6** | **2.7** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Level | Good | Medium | | | | | | | | Poor |
| **Number of Track Realignments** | | 15 | 20 | 15 | 12 | 10 | 7 | 7 | 7 | 4 | 2 |

#### 6.3.3.3. Ballast Renewal

The cost is related to replacing the ballast, which is usually carried out overnight. The associated costs depends upon type of ballast renewal requirement (i.e. including or excluding formation renewal). The cost of ballast with and without formation is £1,000,000/km and £700,000/km respectively (Personal correspondence, 2018). In order to consider the uncertainty analysis, the minimum, maximum and most likely (with 90% confidence level) costs for the two types of activities were assumed to be £900,000, £1,100,000, £1,000,000/km and £600,000, £800,000, £700,000/km respectively and modelled using a normal distribution.

For the different intervention scenarios on the three homogeneous track sections considered, the number of ballast renewals associated with different levels of average track quality were informed by the track deterioration model (see Table 6.2). Tables 6.6 - 6.8 presents the number of ballast renewals required for each track sections considered.

Table 6.6 Number of Ballast Renewal for Commuter Route

| **Average Track Quality** | SD (mm) | **2.4** | **2.5** | **2.6** | **2.7** | **2.9** | **3.1** | **3.4** | **3.5** | **3.6** |
|---|---|---|---|---|---|---|---|---|---|---|
| | Level | Medium | | | Poor | | | | | |
| **Number of Ballast Renewal** | | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |

Table 6.7 Number of Ballast Renewal for High Speed Passenger Route

| **Average Track Quality** | SD (mm) | **1.9** | **2.2** | **2.4** | **2.5** | **2.6** | **2.7** | **2.8** | **2.9** | **3.0** |
|---|---|---|---|---|---|---|---|---|---|---|
| | Level | Medium | | | | | Poor | | | |
| **Number of Ballast Renewal** | | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |

Table 6.8 Number of Ballast Renewal for Mixed Passenger-Freight Route

| Average Track Quality | SD (mm) | 1.2 | 1.4 | 1.6 | 1.9 | 2.1 | 2.3 | 2.4 | 2.5 | 2.6 | 2.7 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Level | Good | Medium | | | | | | | | Poor |
| Number of Ballast Renewal | | 5 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |

#### 6.3.3.4. Ballast cleaning

The cost is related to the operation of the High Output Ballast Cleaning System (HOBCS) and associated labour costs. The HOBCS covers approximately 800 metres of track in a shift (Plasser & Theurer, 2019; ORR, 2012) costing £10,000/shift (Personal communication with Network Rail, 2018). Within this case study, it was assumed that the minimum, maximum and most likely (with 90% confidence level) costs are £7,500, £12,500 and £10,000/shift respectively. Ballast cleaning is carried out occasionally and the time interval between consecutive ballast cleaning activities was assumed to be 6 years, based on Personal communication with Network Rail (2018) and Wenty (2007).


Figure 6.14 High Output Ballast Cleaning System operated by Network Rail (Source: Network Rail)

#### 6.3.3.5. Routine maintenance

The cost involved is associated with carrying out various activities such a weed spraying, vegetation removal and drainage cleaning. Network Rail often carries out these routine maintenances manually at £10,000/shift. This case study assumed that each shift covers approximately 100 metres along the railway track (ORR, 2012). This case study assumed the minimum, maximum and most likely costs (with 90% confidence level) to be £7,500, £12,500 and £10,000/shift respectively and modelled using a normal distribution.

#### 6.3.3.6. Capacity lost

The capacity lost cost is associated with the delays and capacity lost caused due to speed restrictions and disruptions resulting from maintenance activities and track related faults (see section 2.3.1.2). For this case study, the capacity lost was assumed to be equal to the penalties NR pays to the Train Operating Companies (TOC's) for such delays. These delay penalties vary across routes based on their importance within the network.

West Midland Trains (WMT) currently operates approximately 96 daily passenger services on the commuter route between Sutton Coldfield and Lichfield City. Approximately 40% of these services are a minimum of 10 minutes late (ORR, 2018), with track related delay accounting for approximately 7% (see Table 6.9). The delay penalty on this route is £50/minute/train (Personal correspondence, 2018). For the purposes of the uncertainty analysis the minimum, maximum and most likely costs (with 90% confidence level) for the penalty for each train was assumed to be £30, £70 and £50 per minute per train respectively.

Table 6.9 Delays for West Midland Train services (ORR, 2018)

| Year | Track related delays (min) | Total delays (min) | Track Related Delay % |
|---|---|---|---|
| 2011-12 | 46,526 | 579,584 | 8.03% |
| 2012-13 | 52,623 | 604,991 | 8.70% |
| 2013-14 | 39,740 | 615,479 | 6.46% |
| 2014-15 | 39,119 | 613,079 | 6.38% |
| 2015-16 | 47,499 | 648,034 | 7.33% |
| 2016-17 | 42,266 | 656,901 | 6.43% |
| 2017-18 | 47,920 | 761,026 | 6.30% |
| **Average** | **45,099** | **639,870** | **7.09%** |

Both the high-speed passenger route and the mixed passenger-freight route selected for this case study are of high importance. Virgin West Coast (VWC) operates approximately 51 daily passenger services between London Euston and Birmingham New Street. Approximately 60%

of these services were delayed by at least 10 minutes (ORR, 2018), with track related delays accounting for approximately 9.5% (see Table 6.10). The delay penalty on both the high-speed passenger route and the mixed passenger-freight routes is £250/minute/train (See Table 6.1). For the uncertainty analysis, the minimum, maximum and most likely costs (with 90% confidence level) for this penalty for each train was assumed to be £210, £290 and £250 per minute per train respectively.

Table 6.10 Delays for Virgin West Coast services (ORR, 2018)

| Year | Track related delay (min) | Total Delay (min) | Track Related Delay % |
|---|---|---|---|
| 2008-09 | 64,658.0 | 787,689 | 8.21% |
| 2009-10 | 53,970.0 | 657,505 | 8.21% |
| 2010-11 | 67,033.0 | 597,932 | 11.21% |
| 2011-12 | 74,071.4 | 585,806 | 12.64% |
| 2012-13 | 63,448.0 | 665,582 | 9.53% |
| 2013-14 | 52,417.0 | 639,408 | 8.20% |
| 2014-15 | 52,698.0 | 632,339 | 8.33% |
| 2015-16 | 69,323.0 | 632,514 | 10.96% |
| 2016-17 | 45,912.2 | 523,866 | 8.76% |
| 2017-18 | 59,412.4 | 614,041 | 9.68% |
| **Average** | **60,294.3** | **633,668.3** | **9.57%** |

In addition to the VWC operated passenger services, the mixed passenger-freight route runs approximately four freight trains every day. On an average, two out of ten freight services on the UK mainline railway network are delayed (Network Rail, 2010). Due to the lack of route specific data on delays, this research used this national average for delays of freight services within its analysis.

Across the three routes, this research assumed a 5% increase in the annual delays as the average track quality deteriorates from Good to Poor. The average delay data presented in Tables 6.9 and 6.10 was used in the Equation 5.10 to calculate the capacity lost costs associated with different levels of average track quality on the three routes (see Appendix B).

#### 6.3.3.7. Spillage

The cost involved is associated with the clean-up, train delay costs on the network and reduced service life of track due to the spillage of materials such as fuel, coal and chemicals. Network Rail carries out both machine and manual interventions on its freight lines to treat spillages on the track. Rail Vac machinery is used for the removal of coal impregnated ballasts from the railway track. The cost involved in manual intervention is based on direct labour, materials, supervision and planning overheads. Network Rail estimates that the coal spillage reduces the service life of plain line track by 9%. The annual cost of spillage used within this case study was adapted from ORR (2013) and is given in Table 6.11.

Table 6.11 Spillage Costs for 2019-24 on UK Freight Line (ORR, 2013)

| Item | Annual Cost (per mile) |
|---|---|
| Cost of Clean-up and delay minutes | £195 |
| Cost of plain line service life reductions | £1923 |
| **Total** | **£2118** |

For the purposes of the uncertainty analysis the minimum, maximum and most likely costs (with 90% confidence level) for the annual spillage costs per mile was assumed to be £2000, £2300 and £2100 respectively was modelled using a normal distribution.

### 6.3.4. Track use

The track use costs are associated with train operation and derailments, environmental impacts and travel mode change; and is calculated using Equations 5.12. The annual average track quality (expressed in SD of vertical profile) between maintenance cycles, for the three representative track sections were used to calculate the track use costs (see Appendix B). The associated data and methodology are discussed in Sections 6.3.4.1 - 6.3.4.4.

### 6.3.4.1. Train operation

The costs related to train operation are associated with staff, fuel and maintenance of rolling stock (ORR, 2015). The train operating costs incurred by passenger services of WMT and VWC operating on the selected routes are presented in Fig 6.15. The freight train operation costs were found to be 20% more than their passenger counterparts (Serco, 2013). In the UK, the staff costs and Network Rail track access charges have remained relatively steady over the past decade. The fuel and rolling stock maintenance costs are directly impacted by the quality of the railway track on which it operates.

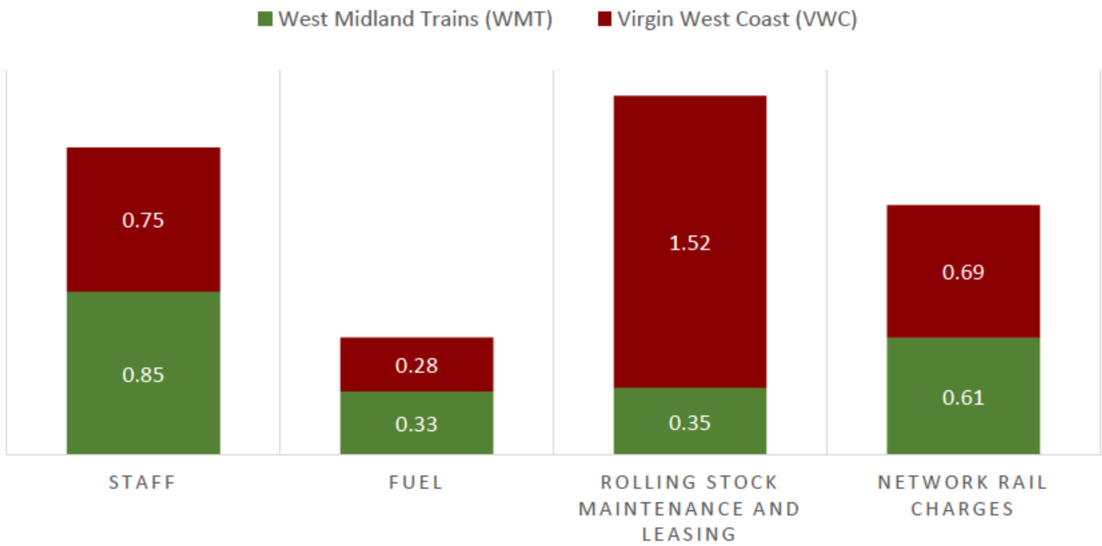



Figure 6.15 Train Operating Costs in £ per vehicle mile (ORR, 2015)

The fuel consumed by the fleets used on each route and the associated costs were adapted from the data provided by Network Rail. While the Class 323 fleet currently consumes 43.366 kWh/mile fuel on the commuter route, the Class 390 fleet consumes 87.629 kWh/mile on the high-speed passenger and mixed freight-passenger route (Personal correspondence, 2018). The fuel tariffs were provided by Network Rail, and it costs £0.28/kWh on both the London-Birmingham and Coventry-Birmingham routes, and £0.14/kWh on the Sutton Coldfield –

Lichfield city route (Personal correspondence, 2018). The associated fuel costs and their three-point estimates are presented in Table 6.12.

Table 6.12 3-Point estimates for Fuel costs across the selected routes

| Route | Minimum | Maximum | Most Likely |
|---|---|---|---|
| | £/kWh | | |
| Sutton Coldfield - Lichfield city | £4.33 | £7.80 | £6.07 |
| London Euston - Birmingham New Street | £17.53 | £31.56 | £24.55 |
| Coventry - Birmingham | £17.53 | £31.56 | £24.55 |

The increase in fuel consumption ($Fuel_{Loss}$) due to deteriorating track quality adapted the approach of Zarembski et al. (2010). This research adapts the approach of Zarembski et al. (2010) to calculate the $Fuel_{Loss}$, as a function of the vertical track geometry condition ($Q$) as shown in Equation 6.1;

$$Fuel_{Loss} = (8 * 10^{-6})Q^{2.0681} \qquad (6.1)$$

Where $Q$ is the vertical track geometry condition expressed in SD (mm) and E is the regression coeeficient.

The annual fuel consumption on the three representative track sections are presented in Figures 6.16 - 6.18, as a function of different levels of average track quality.

Track quality not only impacts the fuel consumption, but also directly contributes to the wear and tear of the wheelsets and dampers of rolling stock. Due to its commercial criticality, data pertaining to such specifics of rolling stock maintenance was unavailable for this case study. To this end, the relative rolling stock maintenance data for both VWC and WMT was determined from ORR (2015) (See Figure 6.15)

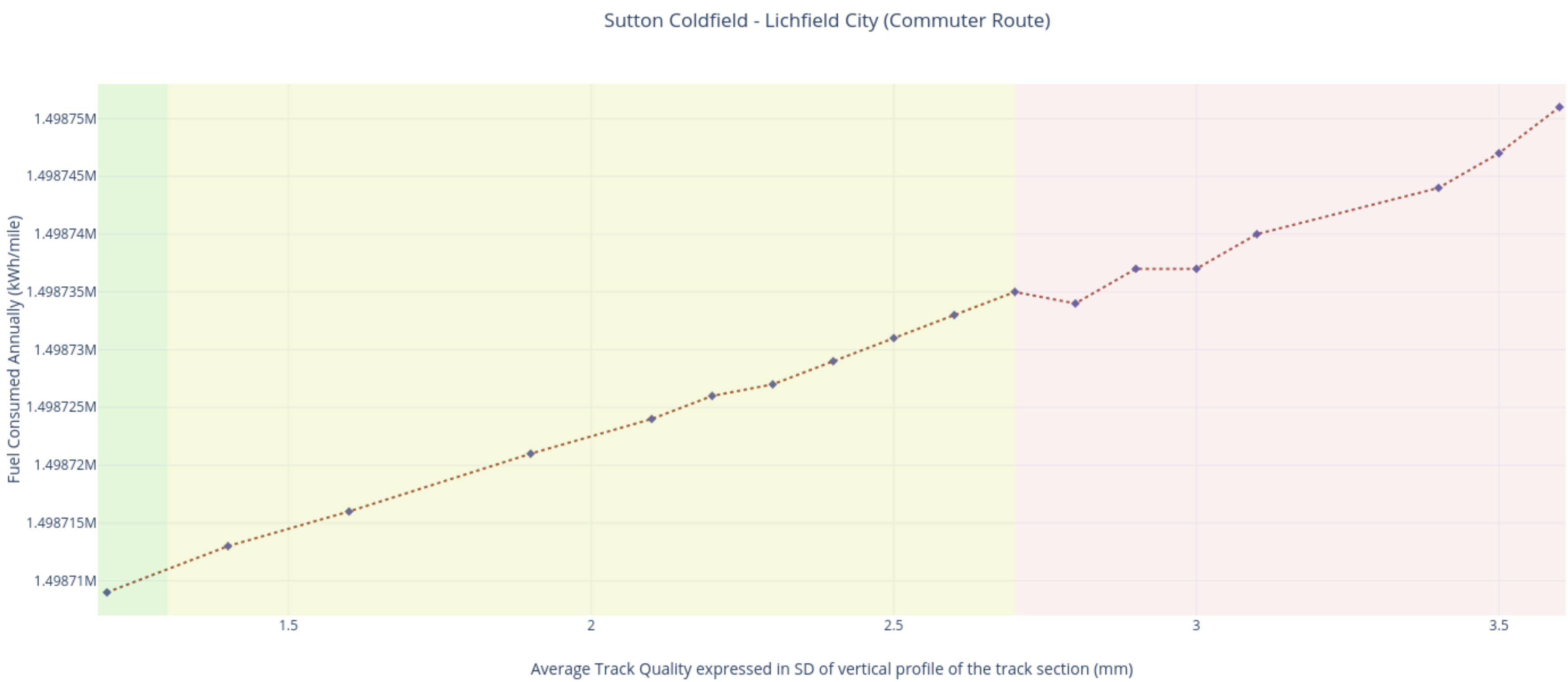



Figure 6.16 Fuel consumed annually on the Commuter Route as a function of Track Quality

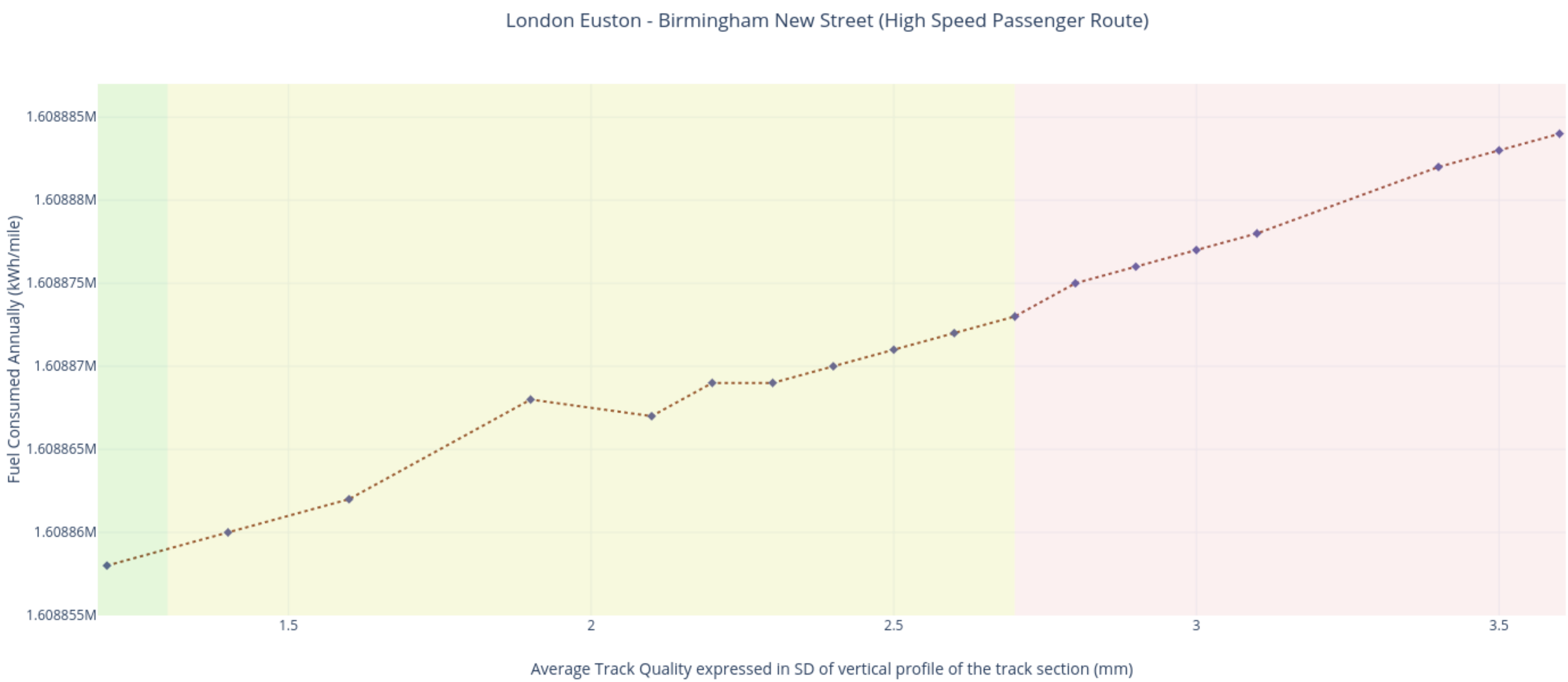



Figure 6.17 Fuel consumed annually on the High-Speed Passenger Route as a function of Track Quality

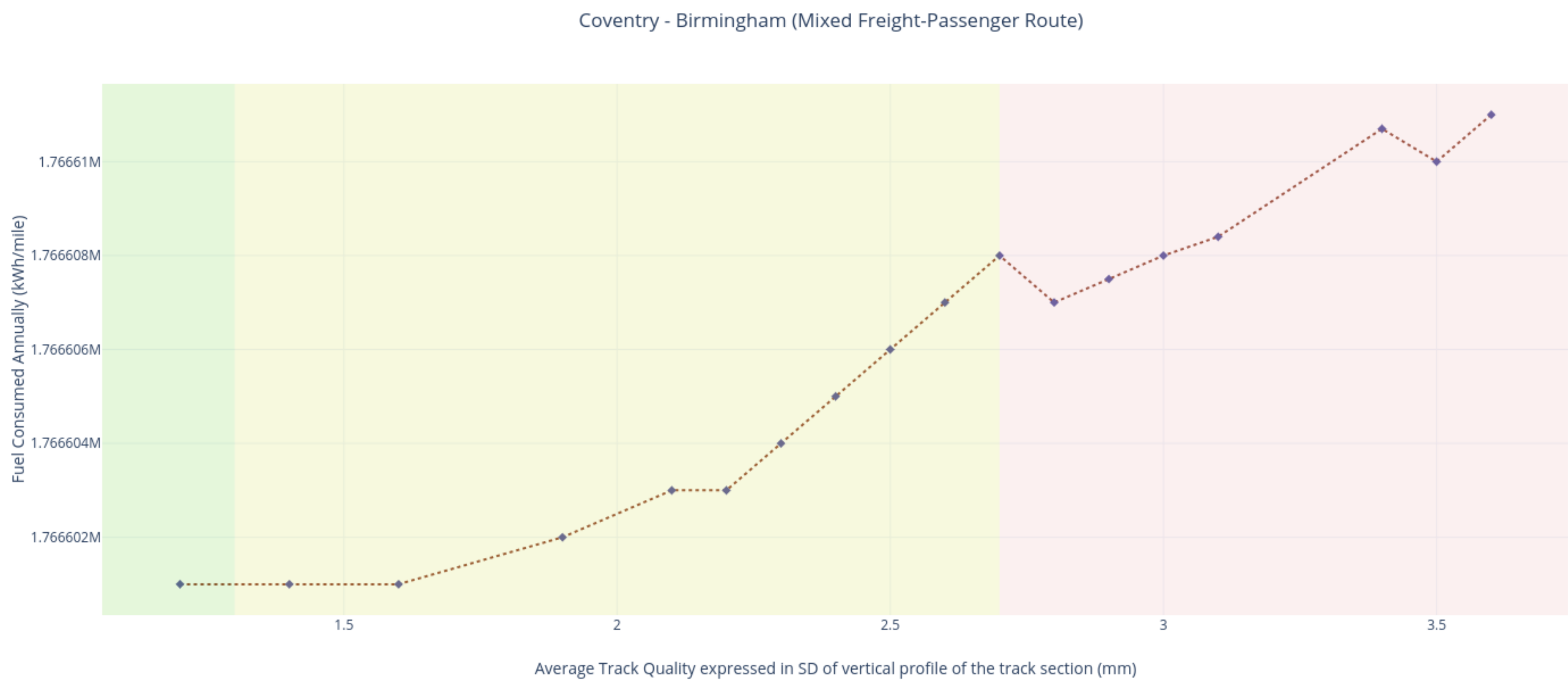



Figure 6.18 Fuel consumed annually on the Mixed Freight Passenger Route as a function of Track Quality

#### 6.3.4.2. Risk of derailment

The costs associated with the risk of derailments are concerned with the damage caused to track infrastructure, rolling stock and environment, service disruptions and casualties. The results from the risk model presented in Section 6.5 informed the probability and severity of derailments associated with maintaining the three track sections at different average track quality levels. They were applied to Equation 5.15 to calculate the derailment risk cost associated with each of the average track quality levels. The results are presented in Table 6.20.

#### 6.3.4.3. Environmental

Environmental costs are related to the environmental impact caused by rolling stock associated pollutants during train operation. The quantity of $CO_2$ emissions ($CO_{2e}$) were assumed to be proportional to the amount of fuel consumed (see Figures 6.19 to 6.21) and was calculated using Equation 6.2 adapted from AEA (2008).

$$CO_{2e} = 3.6667 * F_C * C_{CF} \quad (6.2)$$

Where

$F_C$ is the amount of fuel consumed (see Figures 6.17 - 6.19)

$C_F$ is the carbon content in the fuel (see Table 6.13)

Table 6.13 Carbon Content in Fuel (AEA, 2008)

| Year | Carbon Content in Fuel |
|---|---|
| 2015 | 0.863 |
| 2020 | 0.863 |
| >2030 | 0.863 |

The quantity of annual $CO_2$ emissions for the three routes within the case study, calculated using Equation 6.2, are presented in Figures 6.19 - 6.21. The environmental impact costs of $CO_2$ emissions used for policy appraisals in the UK is based on BEIS (2018) forecasts (See Table 6.14). The quantity of $CO_2$ emissions ($CO_{2e}$) calculated using Equation 6.2 is multiplied with the yearly unit costs presented in Table 6.14 to arrive at the three-point estimates of the impact costs of CO2 emissions associated with different track qualities.

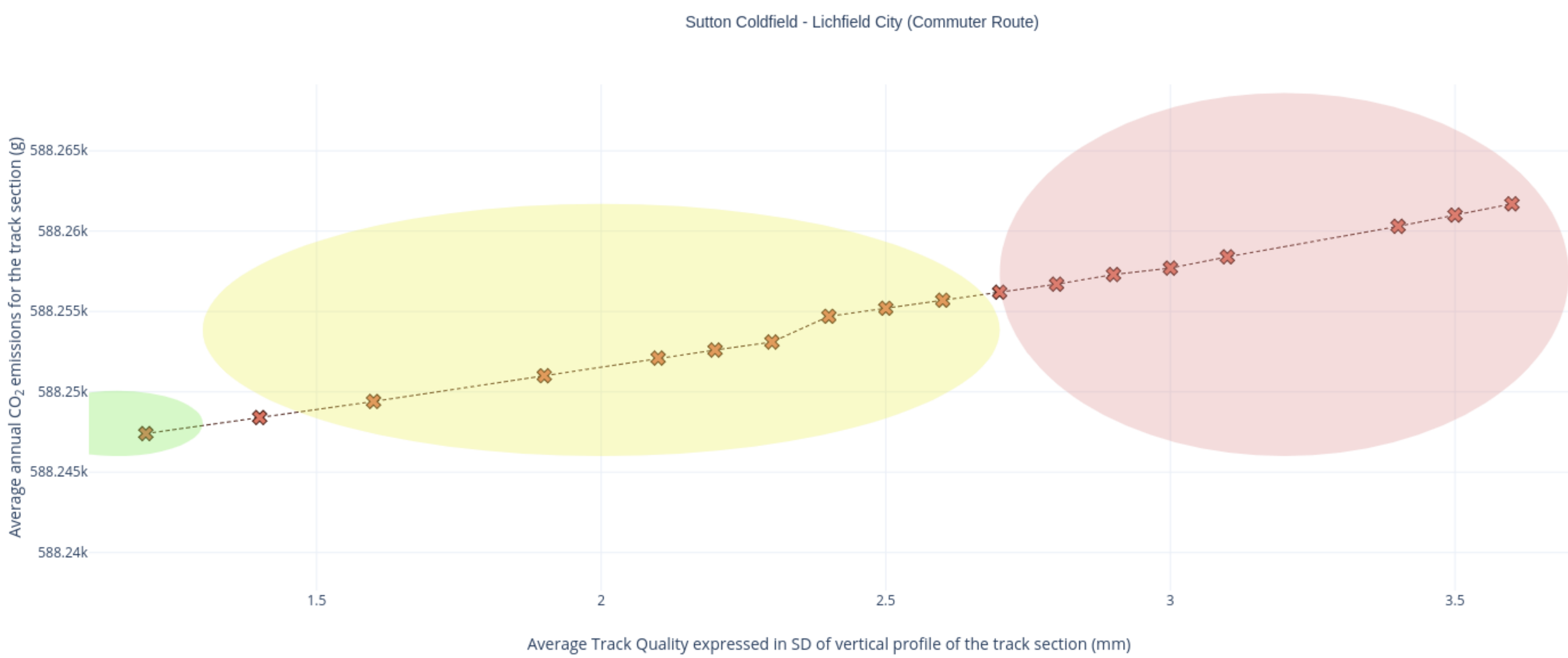



Figure 6.19 Annual $CO_2$ emissions on the Commuter Route track section

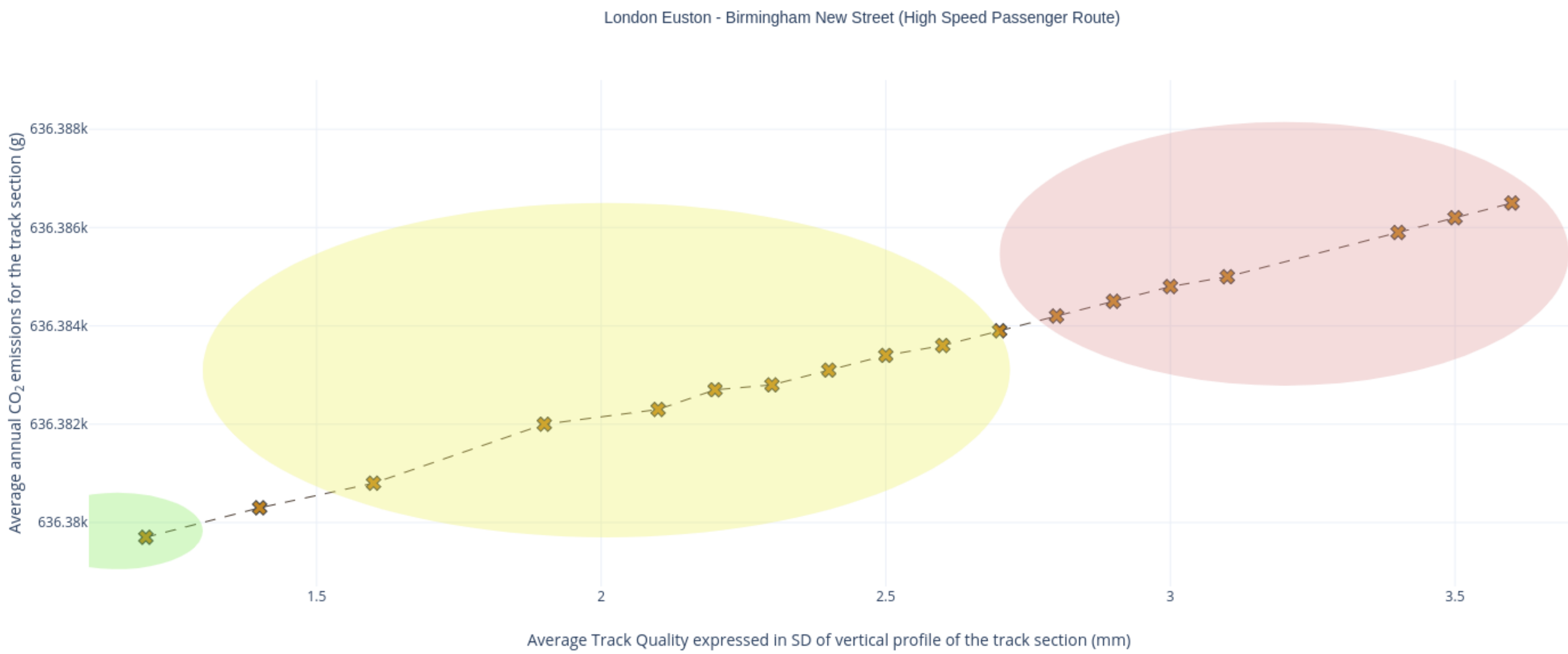



Figure 6.20 Annual $CO_2$ emissions on the High-Speed Passenger route track section

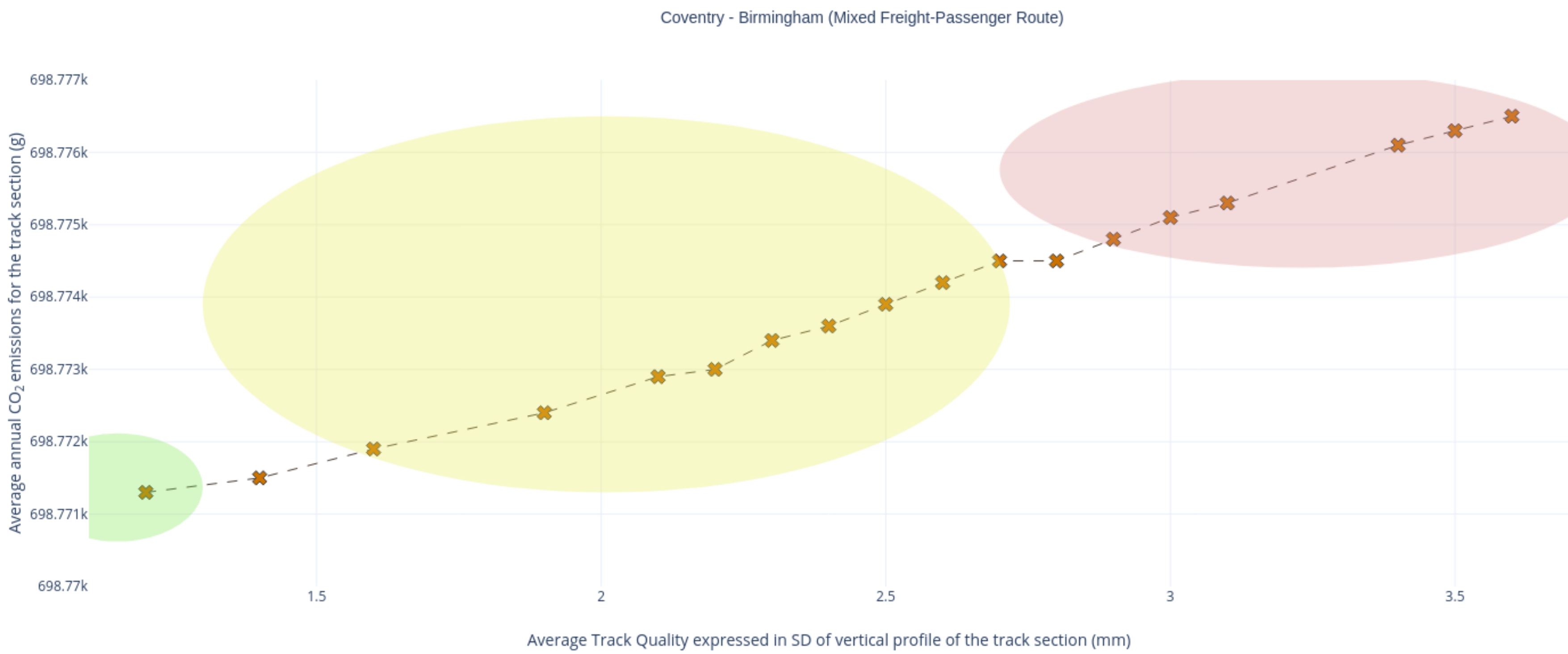



Figure 6.21 Annual $CO_2$ emissions on the Mixed Freight-Passenger route track section

Table 6.14 Impact Cost of $CO_2$ emissions in £/$tCO_{2e}$ (BEIS, 2018)

| Year | Low | Central | High |
|---|---|---|---|
| **2015** | £0 | £3.82 | £5.94 |
| **2016** | £0 | £3.94 | £4.18 |
| **2017** | £0 | £4.13 | £4.79 |
| **2018** | £0 | £4.19 | £6.51 |
| **2019** | £0 | £4.37 | £7.92 |
| **2020** | £0 | £4.56 | £9.83 |
| **2021** | £3.97 | £12.05 | £20.76 |
| **2022** | £7.91 | £19.53 | £31.69 |
| **2023** | £11.83 | £26.99 | £42.63 |
| **2024** | £15.73 | £34.45 | £53.56 |
| **2025** | £19.60 | £41.90 | £64.49 |
| **2026** | £23.46 | £49.34 | £75.42 |
| **2027** | £27.29 | £56.77 | £86.35 |
| **2028** | £31.12 | £64.20 | £97.28 |
| **2029** | £34.93 | £71.62 | £108.21 |
| **2030** | £39.72 | £79.43 | £119.15 |
| **2031** | £37.71 | £81.38 | £116.7 |
| **2032** | £40.56 | £87.73 | £125.0 |
| **2033** | £43.41 | £94.07 | £133.3 |
| **2034** | £46.28 | £100.41 | £141.6 |
| **2035** | £49.12 | £106.75 | £149.9 |
| **2036** | £51.97 | £113.09 | £158.2 |
| **2037** | £54.82 | £119.44 | £166.5 |
| **2038** | £57.67 | £125.78 | £174.8 |
| **2039** | £60.52 | £132.12 | £183.1 |

The quantities of NOx and $SO_2$ emissions for Class 390 and Class 323 fleets operated by VWC and WMT respectively, were adapted from AEA (2007) and presented in Table 6.14. The three-point environmental impact costs of transport related NoX and $SO_2$ emissions varies for different regions within the UK and has been adapted from DEFRA (2018) (See Table 6.16).

Table 6.15 Quantity of NOx and SO2 emissions (AEA, 2008)

| Fleet Type | Relevant route within the case studies | Pollutant Type | Emission per trip (g/kWh) |
|---|---|---|---|
| **Class 323** | Sutton Coldfield – Lichfield City | NoX | 5.22 |
| | | $SO_2$ | 0.11 |
| **Class 390** | London Euston - Birmingham New Street<br>Coventry - Birmingham | NoX | 5.22 |
| | | $SO_2$ | 0.11 |

Table 6.16 Impact Cost of transport related NOx and $SO_2$ emissions (DEFRA, 2018)

| Pollutant | Region | Relevant route | Impact Cost (£/tonne emissions) | | |
|---|---|---|---|---|---|
| | | | Low | Central | High |
| **NOx** | Central London | London Euston - Birmingham New Street | £46,162 | £115,405 | £184,648 |
| | Urban Large | Coventry - Birmingham | £14,647 | £36,617 | £58,587 |
| | Urban Small | Sutton Coldfield - Lichfield City | £7,273 | £18,182 | £29,091 |
| **$SO_2$** | All | All | £1,581 | 1,956 | £2,224 |

The data presented in Figures 6.20 - 6.22 and Tables 6.14 - 6.16 was applied to the Equation 5.15 to calculate the environmental impact costs of different pollutants associated with different levels of average track quality (refer to Table 6.2) on the three routes (see Appendix B for the results)

#### 6.3.4.4. Modal shift

All three train routes selected for this case study have competing road transport but do not have competing canal, sea or air routes. The cost involved with the modal shift is concerned with the reduction in road congestion, accidents and environmental damage. For the purpose of the case study, the benefits were calculated by determining the average benefit of removing a passenger and freight vehicle from the road network, obtained from DfT (2011) and presented in Figures 6.22 and 6.23.

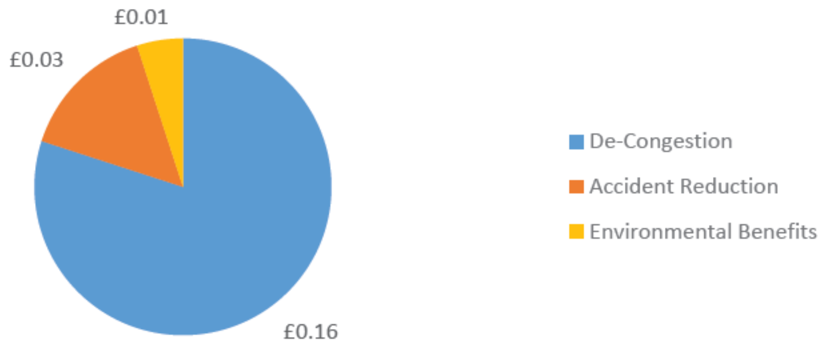



*Figure 6.22 Average value per passenger vehicle mile removed from the road network in pence per mile (DfT, 2011)*

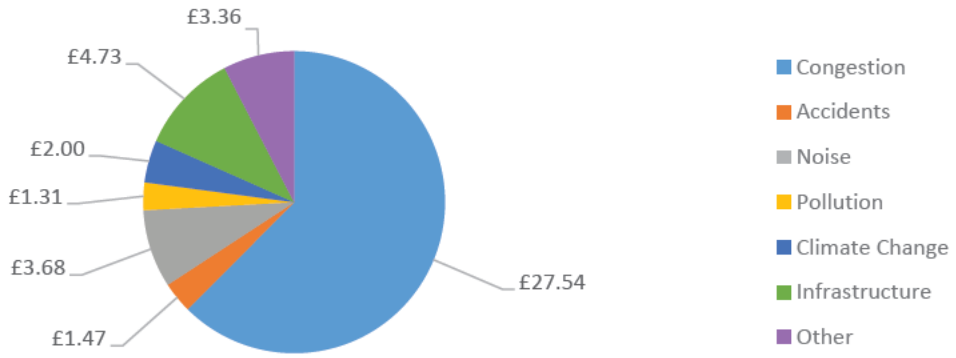



*Figure 6.23 Average value per lorry mile removed from the road network in pence per mile (DfT, 2011)*

Improvement of the railway track condition enhances the journey quality and safety on railways, which in turn encourages users to shift from road to rail. For illustrative purposes, it was assumed that the 10% of the current road users using the alternative road route will shift to rail when the track is maintained in good track condition and reduce linearly to 0% when the track is maintained in poor condition. While there is no particular evidence to prove such a shift could materialise, this assumption was inspired from the study by Kemp (2016), who found that the scope of a 10% modal shift from road to rail for both passenger and freight services was feasible, without a significant expansion of the railway infrastructure/services. To this end, this case study assumed that the same number of services to be run throughout the analysis period.

In order to calculate the benefit of modal shifts, the number of vehicles currently operating on the major road alternatives for each of the three train routes were calculated from the DfT Road Count Point data (DfT, 2018). These are presented in Table 6.17

Table 6.17 Competition from Road for selected Train routes (DfT, 2018)

| Train Route | Competing Road | Daily Passenger Vehicles | Daily Freight Vehicles | 10% Daily Passenger vehicle shift | 10% Daily Freight vehicle shift |
|---|---|---|---|---|---|
| Sutton Coldfield - Lichfield City | A5127 | 8,330 | NA | 833 | NA |
| London - Birmingham | M40 | 40,000 | NA | 4000 | NA |
| Coventry - Birmingham | A45 | 30,000 | 1825 | 3000 | 182 |

The data presented in Figures 6.22 - 6.23 and Table 6.17 is applied to the Equation 5.16 to calculate the benefit of modal shift associated with different average track quality levels across the three routes.

### 6.3.5. End of life

The end-of-life costs are associated with the decommissioning of the asset at the end of its useful life. Whilst NR has a policy to recycle old materials wherever possible, the recycled ballast for instance is primarily used in other industries such as highway construction. For example, NR recycled 91% of old ballast removed from railway infrastructure but the majority was sold to other industries (ORR, 2012).

ORR (2012) in its review of railway assets stated that reusing the recycled ballast can cost 7% to 10% of the total track maintenance cost over the asset life. To this end, for the uncertainty analysis, it is assumed that the associated minimum, maximum and most likely end-of-life costs to be 7%, 10% and 8.5% of the total maintenance costs across the life cycle.

## 6.4. Risk modelling

The method employed for calculating the risk of derailments is described in Section 5.1.2. The number of track quality related derailments for the case study sections of track were quantified based on information in the Train Accident Precursor Indicator Model and Safety Risk Model of RSSB (2018). The Safety Risk Model states that track quality related derailments have a national frequency of 0.053 events/year although the model does not relate these to particular values of track quality (RSSB, 2018).

For the three representative sections, the frequency of occurrence of derailments was assumed to follow a Poisson's distribution. The probability of track quality related derailment over a 25-year period for each of the representative sections was then calculated from the Probability Mass Function (PMF) for a Poisson distribution using Equation 6.3. Such an approach was advocated by Febiyani et al. (2019), Rose et al. (2018) and Liu et al. (2017) for predicting flooding, train derailments and nuclear accidents respectively.

The probability of at least one track quality related derailment over 25 years is given by:

$$P_{25}(atleast\ 1) = \frac{(0.053*25)^1}{1!} e^{-0.053*25} = 0.014 \qquad (6.3)$$

To quantify the severity of derailments associated with different average track quality, a workshop was conducted with a panel of 4 experts (see Section 5.1.2). The experts were asked to rate, using a questionnaire, the impact or severity of derailment (Major or Minor) associated with maintaining the track at the different average quality levels associated with the chosen maintenance scenarios, for all the three routes selected (see Appendix C).

Using the information provided by the four experts, the impact associated with each average track quality was determined by employing the integrated Monte Carlo - Fuzzy Approach (MCFA). This process is demonstrated below

The answers provided by each expert were weighted according to an expert weighting system based on the experience of the experts as shown in Table 6.18.

Table 6.18 Expert Weightage for Case Studies

| | Experience | Expert Weightage (EW) |
|---|---|---|
| Expert 1 | 25+ years' of academic and research experience in railway asset management and safety | 0.3 |
| Expert 2 | 25+ years' of academic and research experience in railway asset management | 0.2 |
| Expert 3 | 5+ years' of industry experience in railway asset management | 0.2 |
| Expert 4 | 10+ years' of industry experience in railway safety | 0.3 |

The derailment severity indicators (Minor and Major) were assigned triangular membership functions as presented in Table 5.2. The aggregated membership function of each severity indicator selected by the expert was multiplied with the respective expert weight by employing Equation 5.36 (see Table 6.19 for example).

Table 6.19 Aggregated Membership Function after employing Expert Weight (EW) for maintaining the Commuter Route at poor Track Quality

| | Response | Expert Weightage (EW) | Membership Function | Aggregated Membership Function after applying EW |
|---|---|---|---|---|
| Expert 1 | Major | 0.3 | (0.5, 0.75, 1) | (0.4, 0.65, 0.9) |
| Expert 2 | Major | 0.2 | (0.5, 0.75, 1) | |
| Expert 3 | Major | 0.2 | (0.5, 0.75, 1) | |
| Expert 4 | Minor | 0.3 | (0, 0.25, 0.5) | |

Thereafter, MCS was employed to give the most likely value of occurrence (with 90% confidence level) for derailment severity associated with maintaining each route at different average track quality levels. A representative example of the results (severity of derailment) associated with maintaining the commuter route at poor track quality is presented in Figure 6.24, where the blue line depicting the probability distribution.

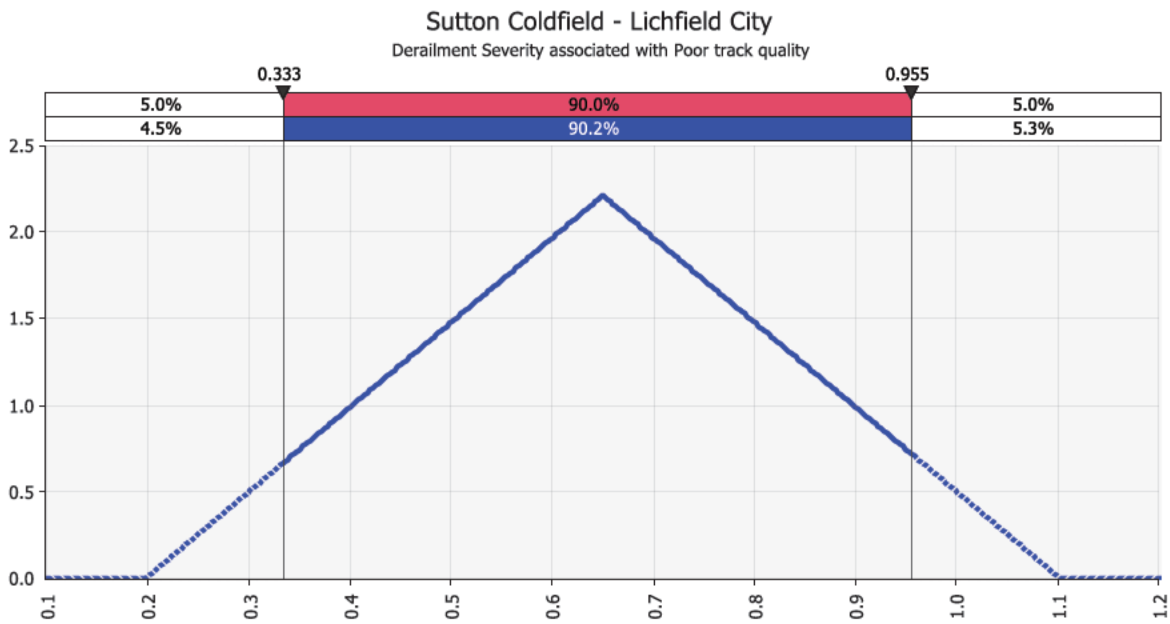



Figure 6.24 Probabilistic Analysis of Derailment Severity on Commuter Route

Figure 6.24 shows that there is a 90% confidence level in the derailment severity being 0.95 on the commuter route when maintained at poor average track quality. The risk of derailment associated with different track quality levels on the three routes, at the 90% confidence level were then calculated by inputting the severity values into Equation 5.33. For example, the risk of derailment of maintaining the commuter route at a poor track quality, at the 90% confidence level, is calculated as shown below:

$$\text{Derailment Risk} = 0.014 \times 0.95 = 0.013$$

Similarly, derailment risk associated with different track maintenance strategies were calculated, at the 90% confidence level, for all the three routes and presented in Table 6.20.

Table 6.20 Risk of Derailment during the analysis period

| Train Route | Average Track Quality Level | Probability | Severity | Risk |
|---|---|---|---|---|
| Sutton Coldfield - Lichfield City | Poor | 0.014 | 0.95 | 0.013 |
| | Medium | 0.014 | 0.55 | 0.007 |
| | Good | 0.014 | 0.55 | 0.007 |
| London - Birmingham | Poor | 0.014 | 1 | 0.014 |
| | Medium | 0.014 | 1 | 0.014 |
| | Good | 0.014 | 1 | 0.014 |
| Coventry - Birmingham | Poor | 0.014 | 1 | 0.014 |
| | Medium | 0.014 | 1 | 0.014 |
| | Good | 0.014 | 1 | 0.014 |

While considering the damage to track infrastructure and rolling stock, service disruptions, casualties and environmental impacts, the average impact cost of a derailment is £661,073 (RSSB, 2016b). The average impact costs is multiplied with the risk values presented in Table 6.20 (see Equation 5.15) to calculate the impact cost of derailment risks (presented in Table 6.21).

Table 6.21 Impact Cost of Derailment Risks

| Route | Average Track Quality Level | Impact Cost of Derailment Risks |
|---|---|---|
| Sutton Coldfield - Lichfield City | Poor | £195,917 |
| | Medium | £113,426 |
| | Good | £113,426 |
| London - Birmingham | Poor | £206,229 |
| | Medium | £206,229 |
| | Good | £206,229 |
| Coventry - Birmingham | Poor | £206,229 |
| | Medium | £206,229 |
| | Good | £206,229 |

## 6.5. Results

The above analyses were used to compare on an economic basis the track maintenance strategies (see Table 6.2) for the representative track sections of homogeneous characteristics across the three routes and are presented in Section 6.5.1 - 6.5.4. The detailed statistical results of each case studies are given in Appendix B.

### 6.5.1. Commuter route

The costs associated with the maintenance and use of representative track section on the commuter route between Sutton Coldfield (SUT) to Lichfield City (LIC), when maintained at different average track quality levels over the 25-year analysis period are presented in Figures 6.25-6.28. The commuter route has been maintained historically by NR to an average track quality SD of 2.4 mm.

Figures 6.27 and 6.28 show that, with a 90% confidence level, maintaining the commuter route at medium average track quality of 2.6mm SD would achieve an NPV of -£2.3 m with a total transport cost of £2.85m. For the same average track quality, the maintenance and track use costs would be £1.1m and £1.2m respectively (see Figures 6.25-26). While comparing the different strategies that realise medium level of track quality, the total transport cost of maintaining the track section at 2.4mm SD would be at least 12% more than that of maintaining the track to 2.6mm SD.

Instead, if the track section was allowed to deteriorate further to a poor average track quality of 3.6mm SD (the do minimum strategy with the lowest maintenance costs), it would result in at least 25% increase in track use costs in comparison with achieving and average track quality of 2.6 mm SD (see Figure 6.26) (at a 90% confidence level). Although it would also have resulted in approximately 2.5% lower NPV, the impact of derailment risks would increase by at least 75% increase and benefit from modal change would be minimum 60% less.

Figure 6.27 shows maintaining the commuter track section at average track qualities of 2.6mm SD (medium) and 2.9mm SD (poor) respectively, would result in relatively similar total transport costs. However, the track use costs associated with 2.9mm SD is 21% more than that of 2.6mm SD, suggesting that latter strategy is likely to provide a statistically significant trade off than the former for the commuter route (from a track user perspective).

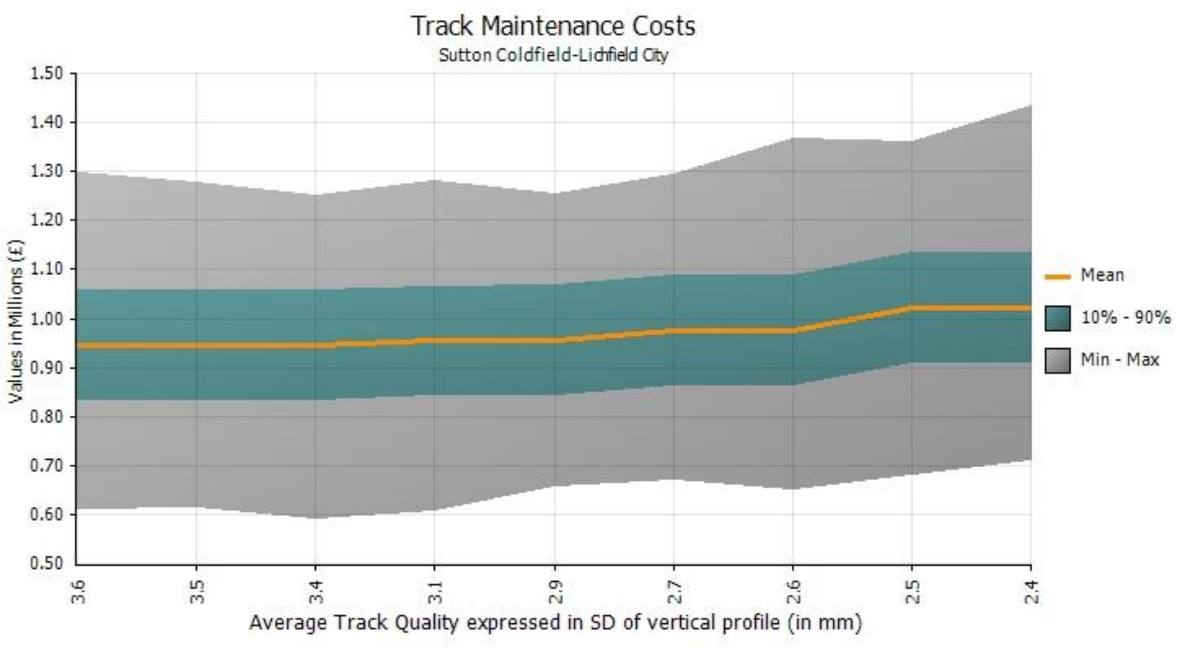



Figure 6.25 Track Maintenance Costs on Commuter Route as a function of average track quality

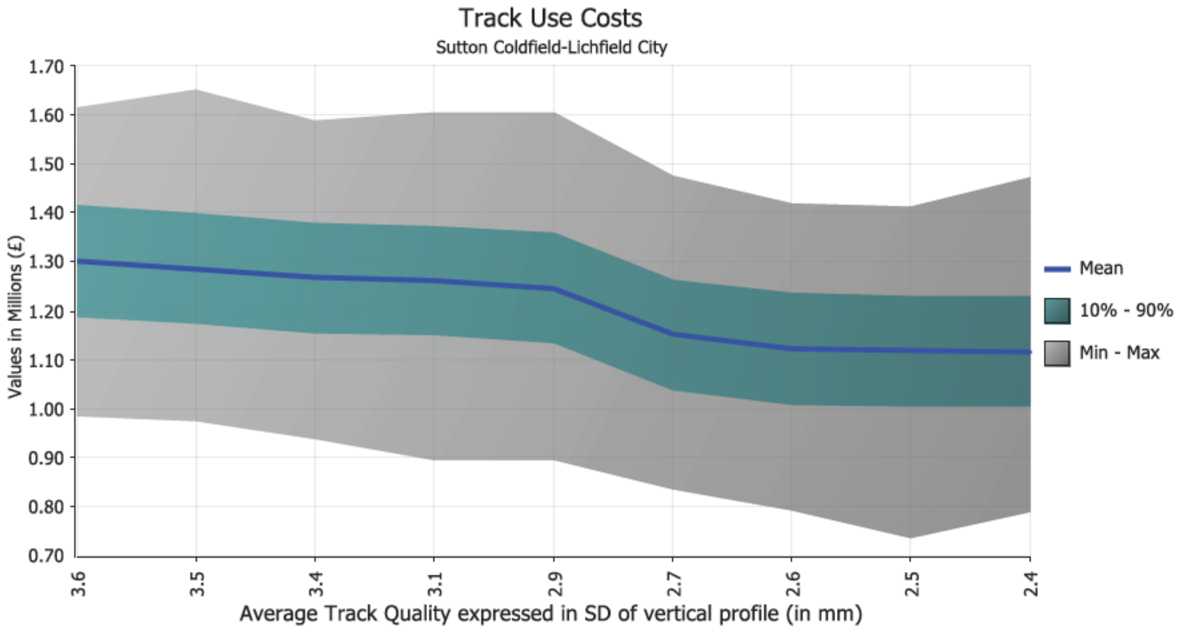



Figure 6.26 Track Use Costs on Commuter Route as a function of average track quality

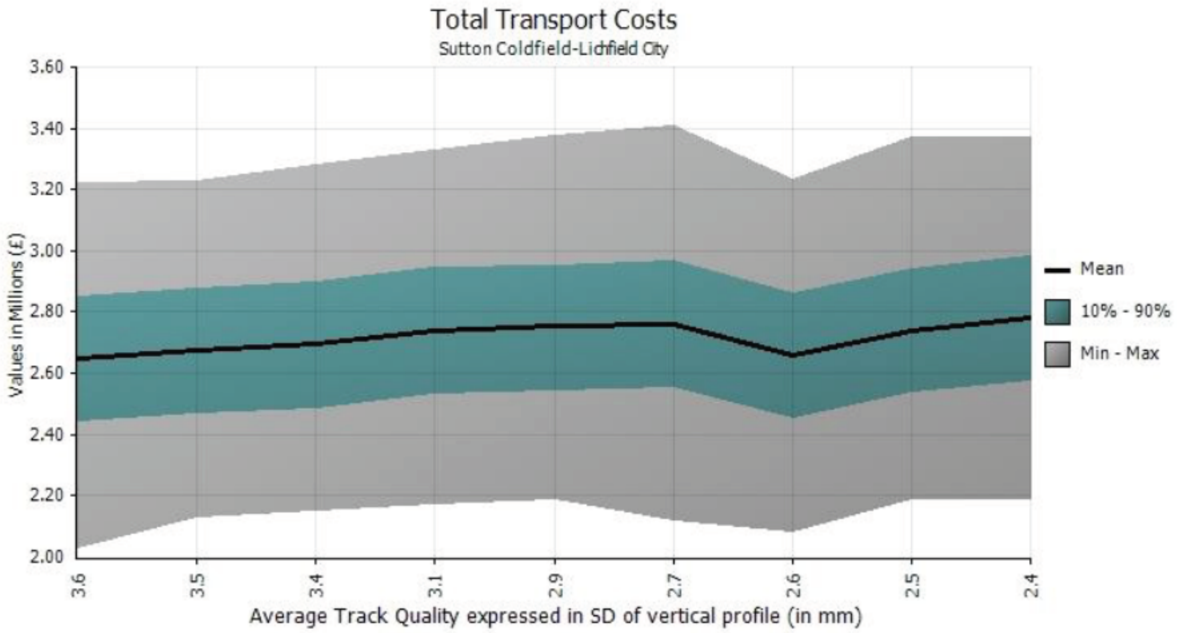



Figure 6.27 Total Transport Costs on Commuter Route as a function of average track quality

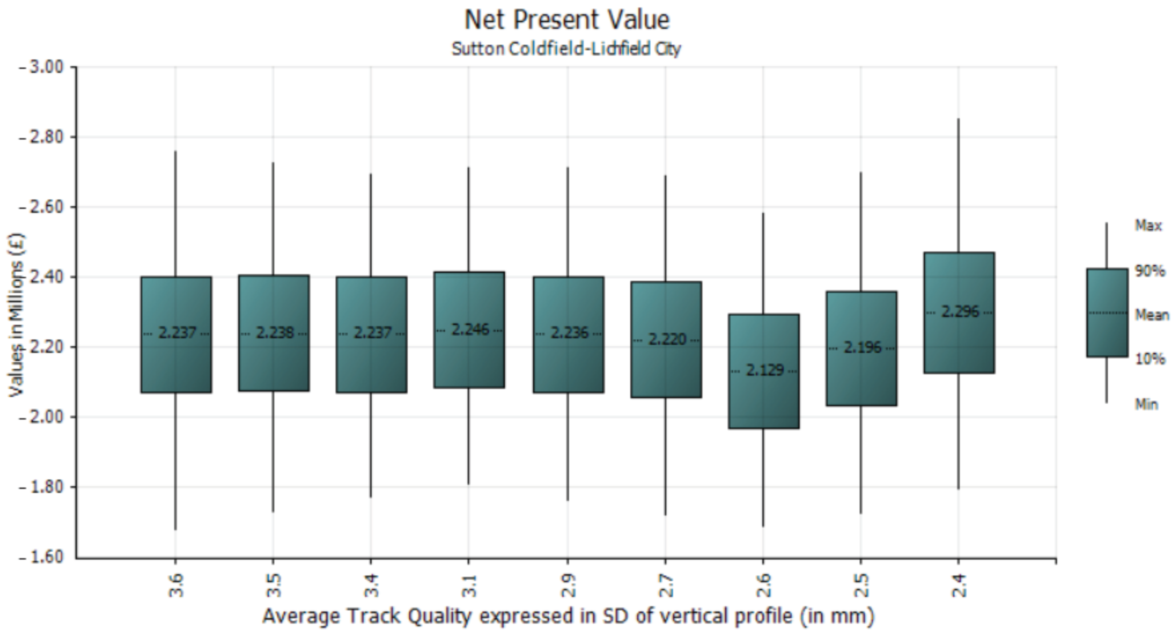



Figure 6.28 NPV of track section on Commuter Route as a function of average track quality

### 6.5.2. High Speed Passenger route

From Figure 6.32, at the 90% confidence level, maintaining the high-speed passenger track section between London Euston and Birmingham New Street at an average quality of 2.4mm SD (medium) is predicted to cost £4.5m; is the most economically justifiable strategy attaining an NPV of -£3.2m. If the track was maintained to a comparatively lower quality, i.e. 3.0mm SD, though the maintenance costs would reduce by approximately 20%, the track use costs would increase by approximately 33% (see Figures 6.29-6.30). It would also result in an increase of both derailment risk costs and train operation costs by approximately 60% and 3% respectively.

However, maintaining the same track section to a higher average quality of 1.9mm SD (i.e. good track quality) would yield a lower NPV (approximately 6% higher) and reduced track use costs (by approximately 2%) in comparison with 2.4mm SD. But the requirement of more frequent maintenance interventions would result in at least 11% increase on the track maintenance costs. While considering a trade-off within the total transport costs on the high-speed passenger route, maintaining the track section at a medium track quality, giving an average SD of 2.4mm is the most economically beneficial strategy.

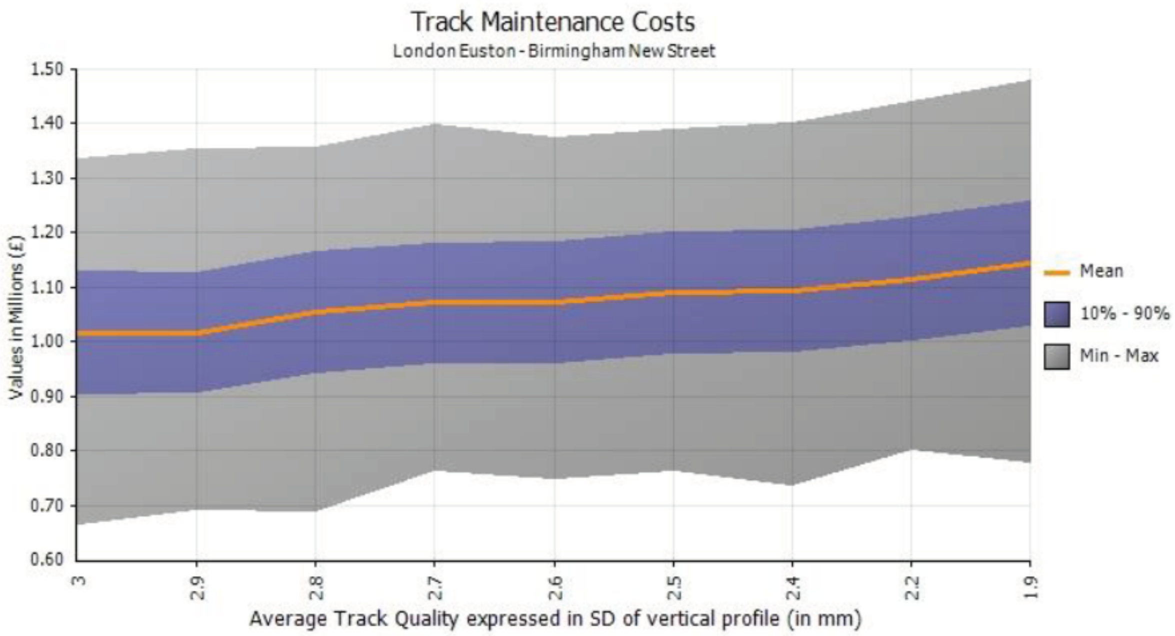



Figure 6.29 Track Maintenance Costs on High Speed Passenger Route as a function of average track quality

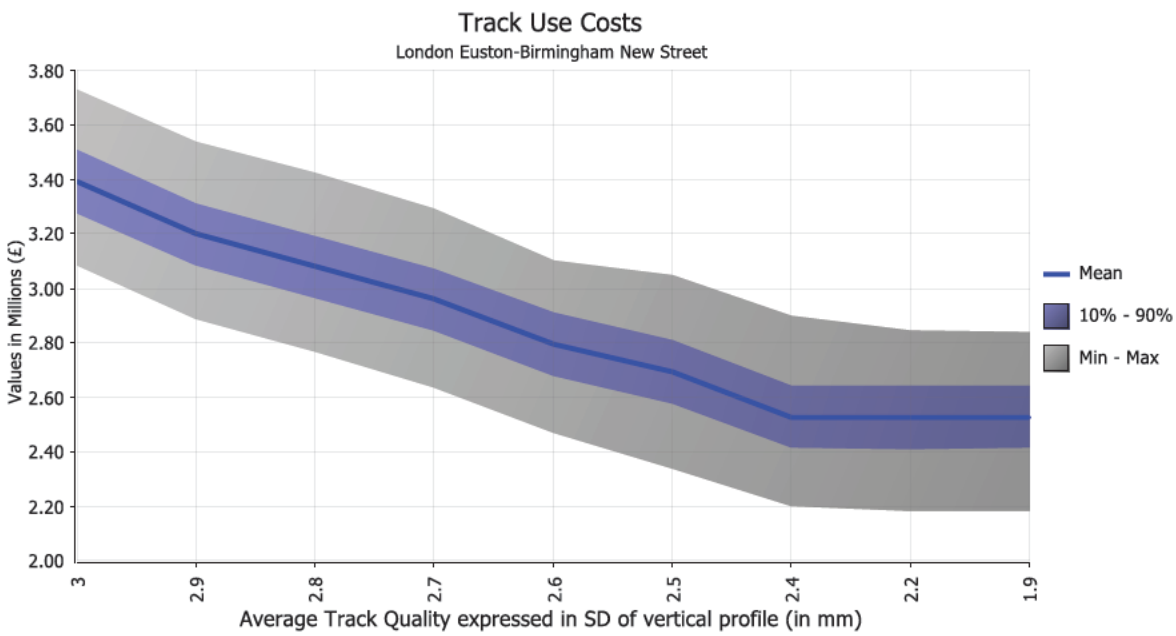



Figure 6.30 Track Use Costs on High Speed Passenger Route as a function of average track quality

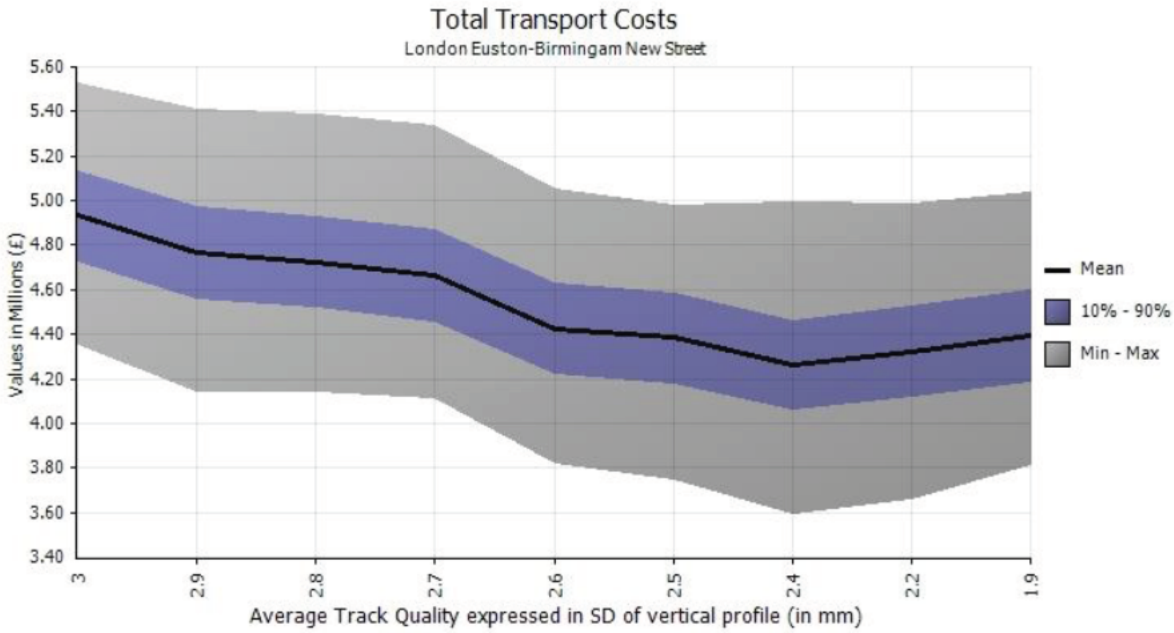



Figure 6.31 Total Transport Costs on High Speed Passenger Route as a function of average track quality

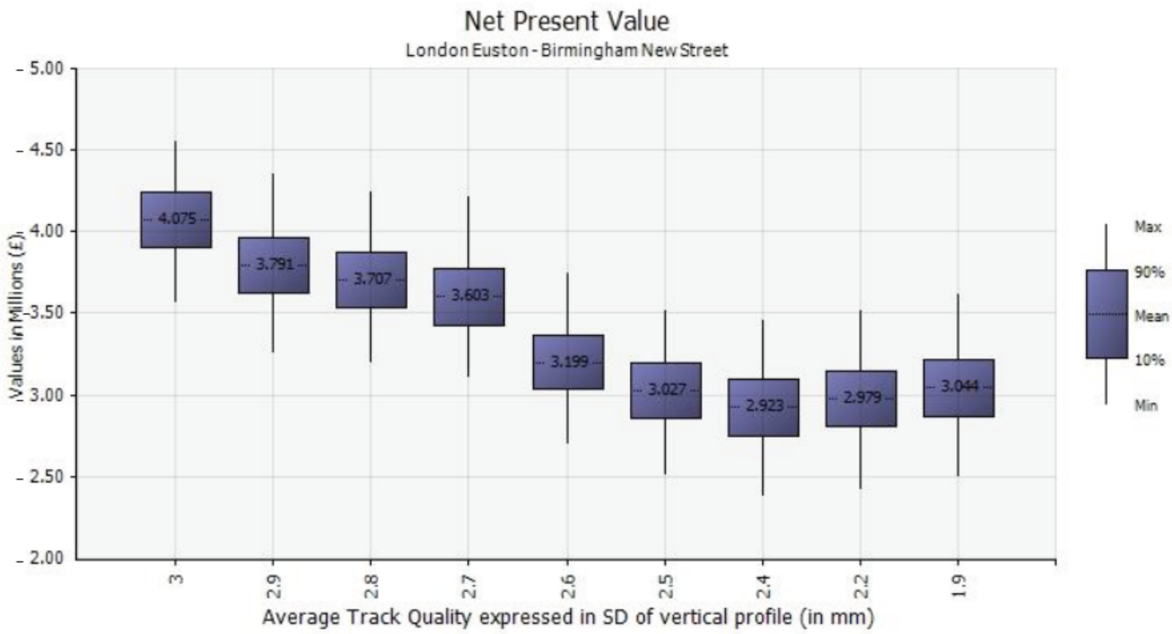



Figure 6.32 NPV for track section on High Speed Passenger Route as a function of average track quality

### 6.5.3. Mixed Freight Passenger route

The high-speed passenger route section has been maintained by Network Rail to a lower quality compared to the Coventry-Birmingham mixed-traffic portion. Whilst the high-speed passenger route has been maintained to an average SD of 2.6mm historically, the mixed passenger-freight section has been maintained to an average SD of 1.2 mm during the same period, with comparatively more frequent renewals. The WLCCA results shows that it is economically justifiable to maintain the mixed-traffic track section between Coventry and Birmingham at a medium average track quality of 2.4 mm SD; realising the highest NPV of -£2.9m at the lowest total transport cost of £4.2m (see Figures 6.33-6.36) (at 90% confidence level). However, this section of the track serves Network Rail's headquarters and is therefore maintained in such a good condition (of SD = 1.2mm) for political reasons.

On comparison with maintaining at a better track quality of 1.4mm average SD, at a 90% level of confidence, the latter would cost approximately 30% more to maintain than the economically justifiable strategy (see Figure 6.33). The NPV attained would be 16% lower for 1.4mm SD, and the associated total transport costs would be approximately 14% more than 2.4mm SD (see Figure 6.5-6.36). The track use costs associated with maintaining the track section at 2.4mm SD and a good track quality of 1.2mm SD are relatively similar. However, the more frequent maintenance interventions within the latter strategy (see Table 6.2) results in 63% higher maintenance costs than the former strategy. Spillage on the tracks by freight trains were also considered within the analysis, but they were found to be negligible in comparison to other costs (see Figure 6.42).

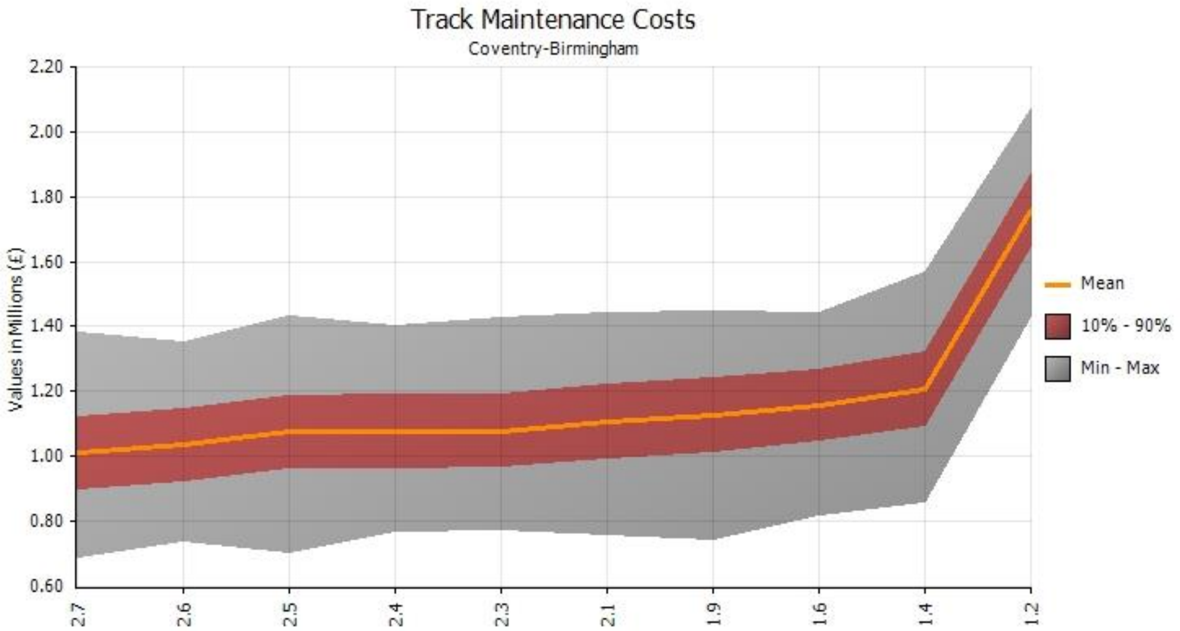



Figure 6.33 Track Maintenance Costs on Mixed Freight-Passenger Route as a function of average track quality

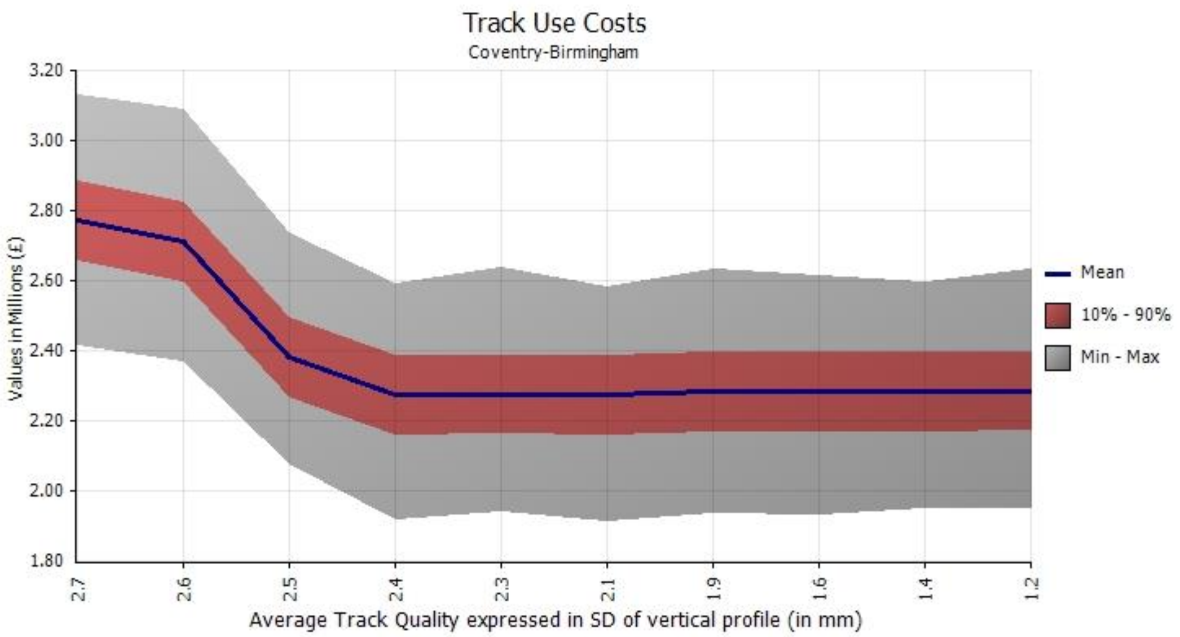



Figure 6.34 Track Use Costs on Mixed Freight-Passenger Route as a function of average track quality

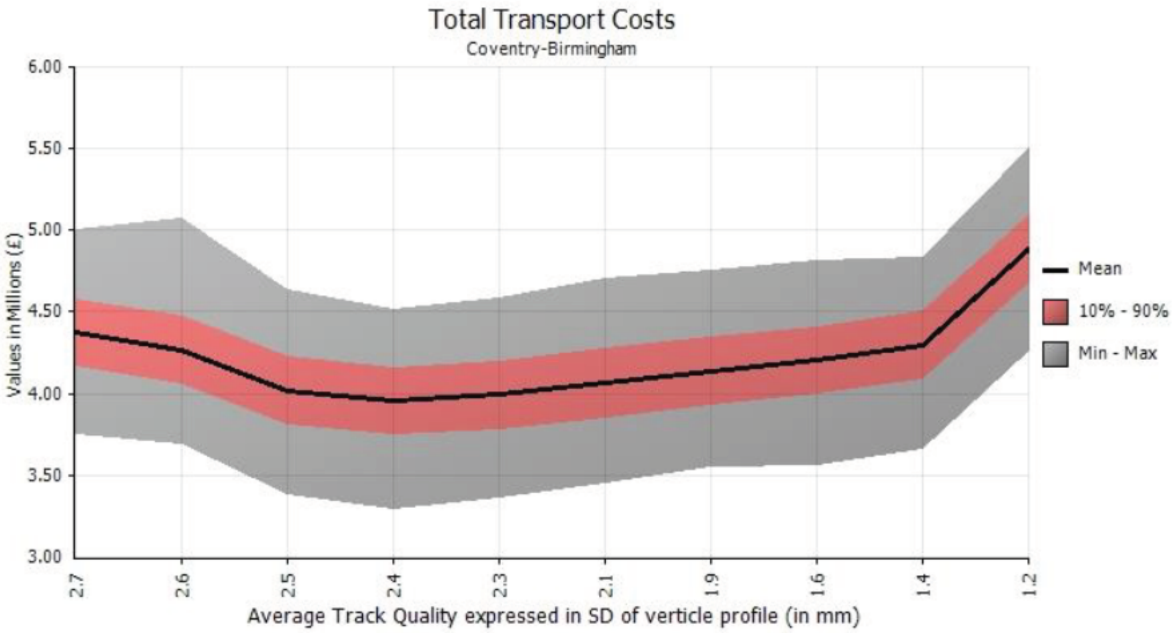



Figure 6.35 Total Transport Costs on Mixed Freight-Passenger Route as a function of average track quality

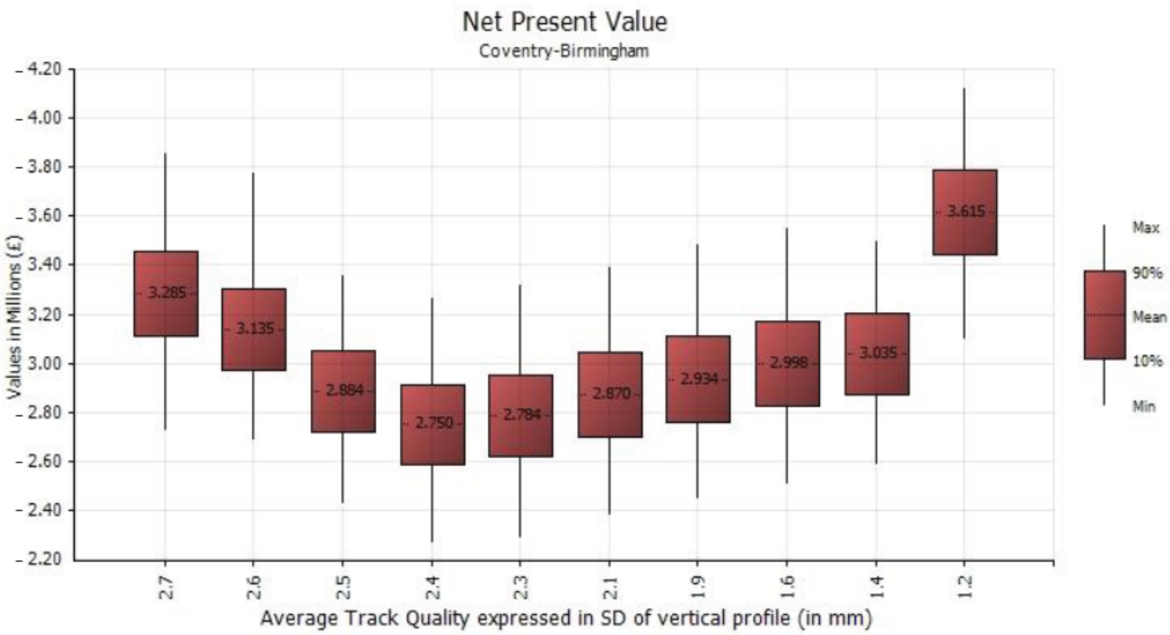



Figure 6.36 NPV of track section on Mixed Freight-Passenger Route as a function of average track quality

### 6.5.4. Economically justifiable maintenance strategies

Figures 6.37-6.39 show the impact of construction, track maintenance and renewal (M&R), track use and end-of life costs on the total transport cost associated with the most economical strategies for each of the three route sections, during the 25-year analysis period. The scatter plots have been generated by running 10,000 iterations of MCS, with total transport cost on the ordinate and cost associated with each WLCC element on the abscissa.

It can be observed from Figure 6.37-6.39 that track use costs have the greatest impact on the total transport costs for all three routes. The proposed risk-informed approach calculates track use costs as a function of the average track quality (see Sections 5.1.1 and 6.3). To this end, it can be argued that the track quality achieved during construction and track M&R are the primary indicators of track use costs. It may be expected that a higher initial quality track as a result of higher construction standards would require higher construction costs but result in lower end-of-life costs and lesser deterioration rates, provided track usage and efficiency of maintenance activities remain the same. On the other hand, the end-of-life costs have least impact on the total transport costs (see Figures 6.37-6.39). Current practices in the industry is that, when replacing materials from site at the end-of-life, they are seen as life expired. However, if they are refurbished to a quality that is acceptable for re-use, the need and cost of procuring new materials can be reduced (ORR, 2012).

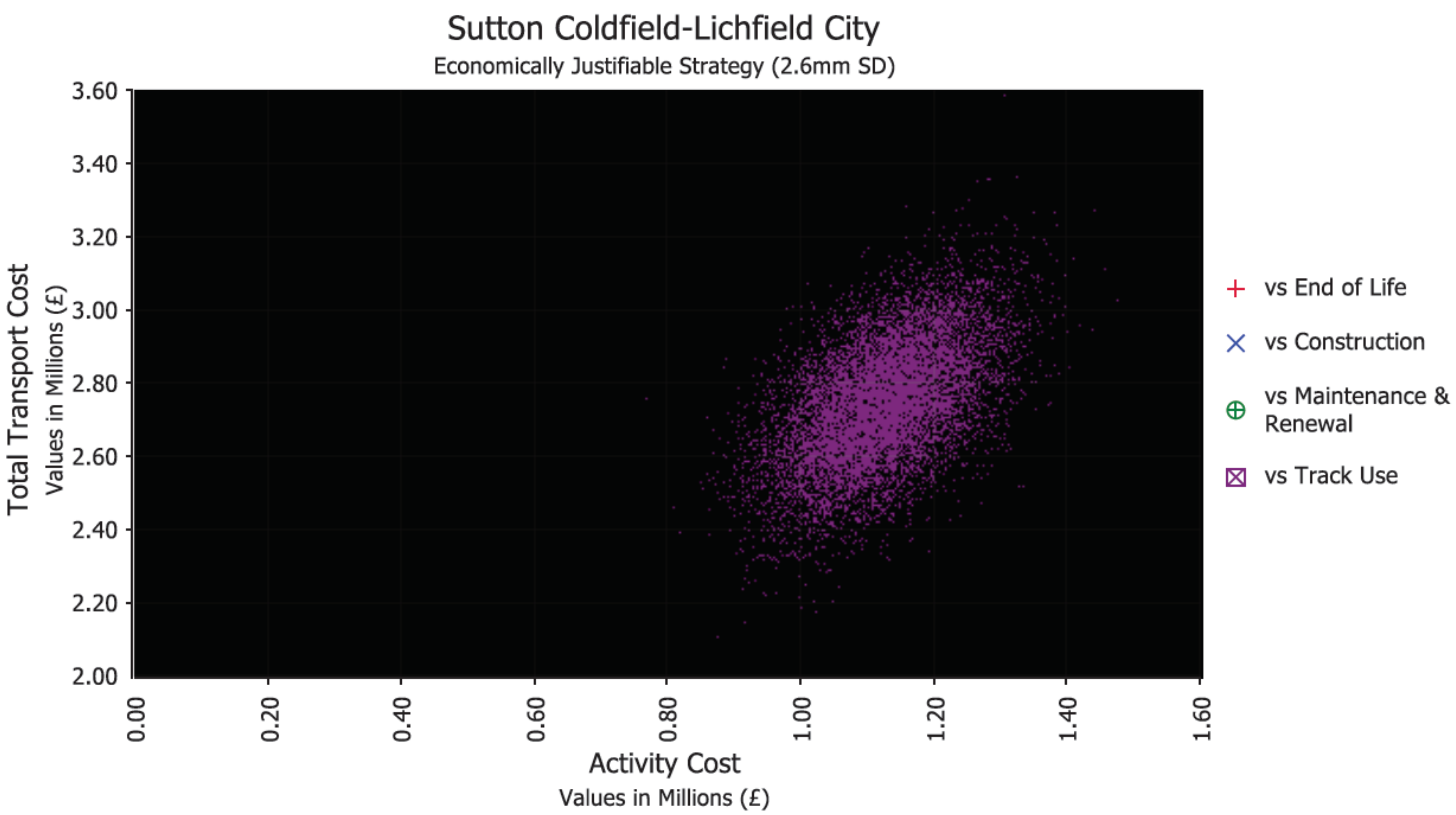



Figure 6.37 Contribution of WLCC elements to the Total Transport Cost for the economically justifiable strategy for Commuter route


Figure 6.38 Contribution of WLCC elements to the Total Transport Cost for the economically justifiable strategy for High Speed Passenger route

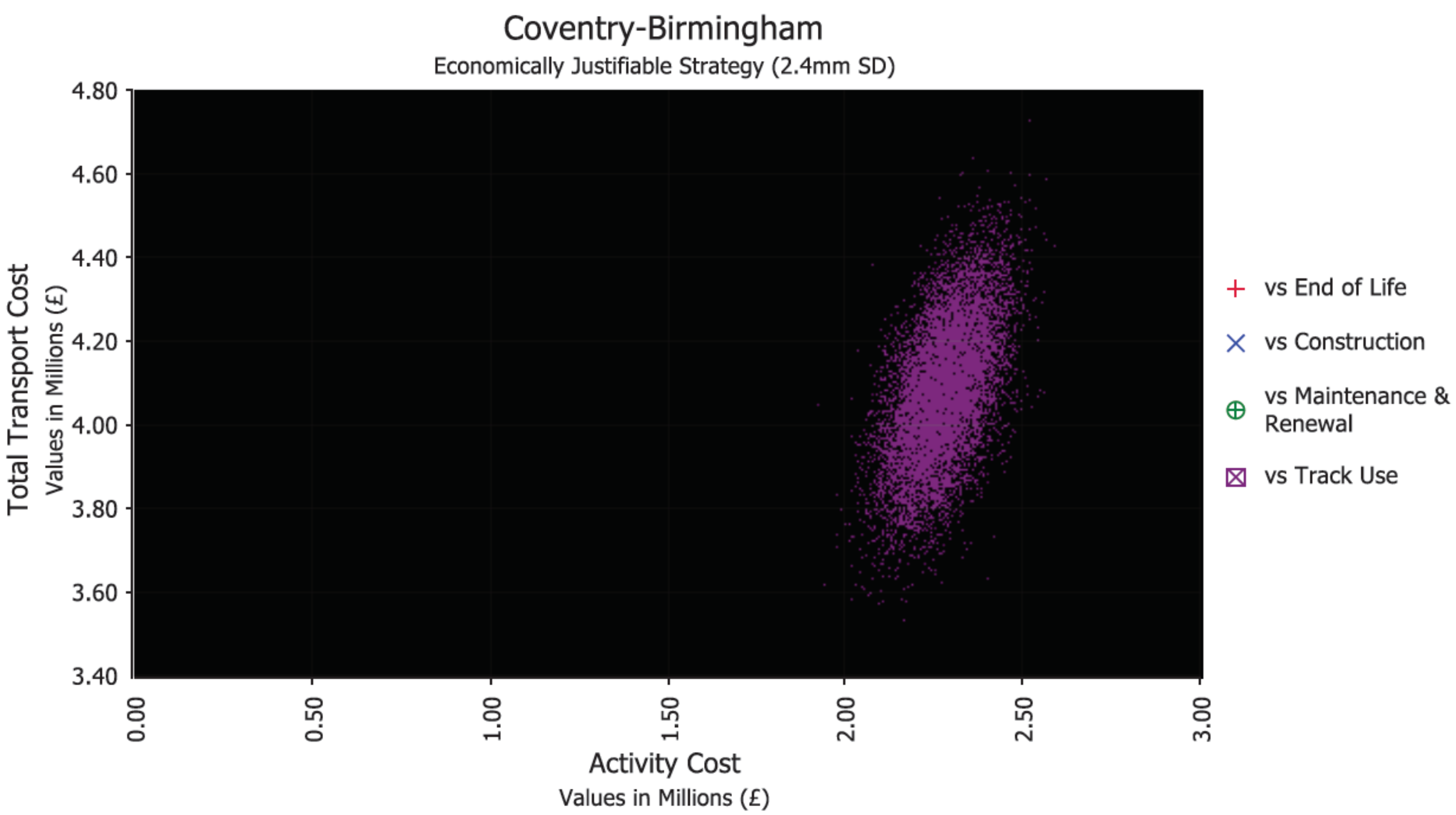



Figure 6.39 Contribution of WLCC elements to the Total Transport Cost for the economically justifiable strategy for Mixed Freight-Passenger route

Figures 6.37-6.39 and the results presented earlier from the case studies employing the proposed WLCCA suggests that if railway track use costs are considered, more economically beneficial maintenance standards could be adopted. For example, by maintaining the mixed freight-passenger route at an average SD of 2.4 mm instead of the current strategy (SD of 1.0 mm), maintenance and total transport costs can be reduced by at least £50,000 annually.

Figures 6.40-6.42 examines, in the form of scatter plots, how the different cost elements that make up the track M&R and track use contribute to the total transport costs over the 25-year period of analysis, for the most economic strategies of those tested. The scatter plots have also been generated using MCA, with total transport cost on the ordinate and cost associated with each activity on the abscissa. By inspection of Figures 6.40-6.42, it may be seen that environmental impacts and modal change costs have the highest cost impacts, in terms of total transport costs, for both high-speed passenger and mixed-traffic routes. The higher impact cost of modal change and environmental emissions on the mixed-traffic route costs also suggests the positive impact of shifting freight from road to rail. The track use costs (train operations, delays, speed-restrictions) contributed more to the total transport costs for the commuter route. The comparatively higher contribution of track use costs on the commuter route is due to the more frequent daily train services in comparison to the other two routes, resulting in more impact costs of delays and speed restriction for a given maintenance standard.

Though the impact costs of at least one derailment occurring has a similar impact trend across all the three routes, it is comparatively more prominent on the mixed-freight route. The impact costs of $CO_2$, NoX and $SO_2$ emissions are different for each location, with large urban areas, and London in particular, having higher impact costs (DEFRA, 2015). Despite this variation, across all three routes, it may be seen that the environmental emissions are highest in terms of impact to total transport costs.

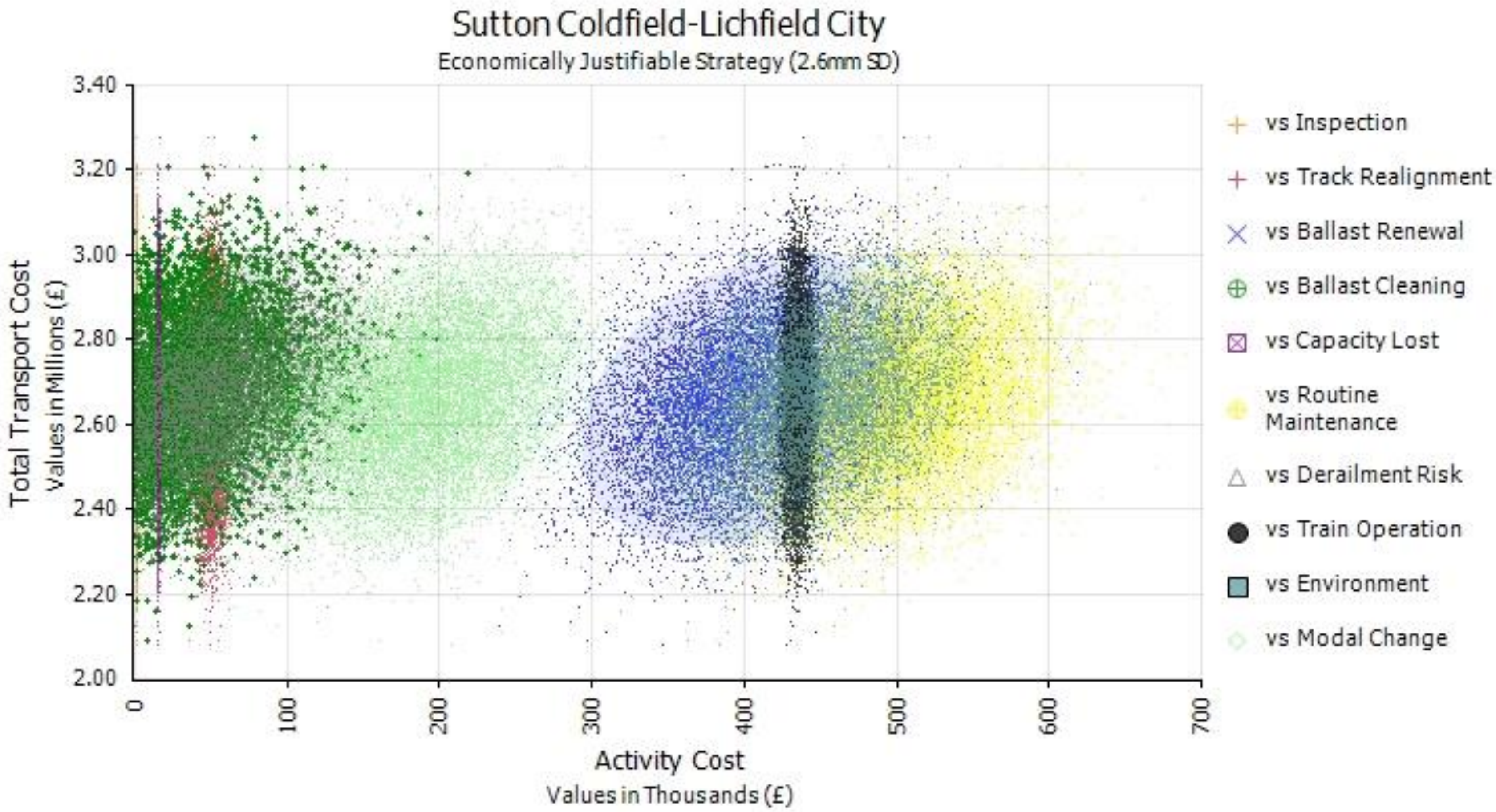



Figure 6.40 Contribution to the Total Transport Cost for the economically justifiable track maintenance strategy for Commuter route

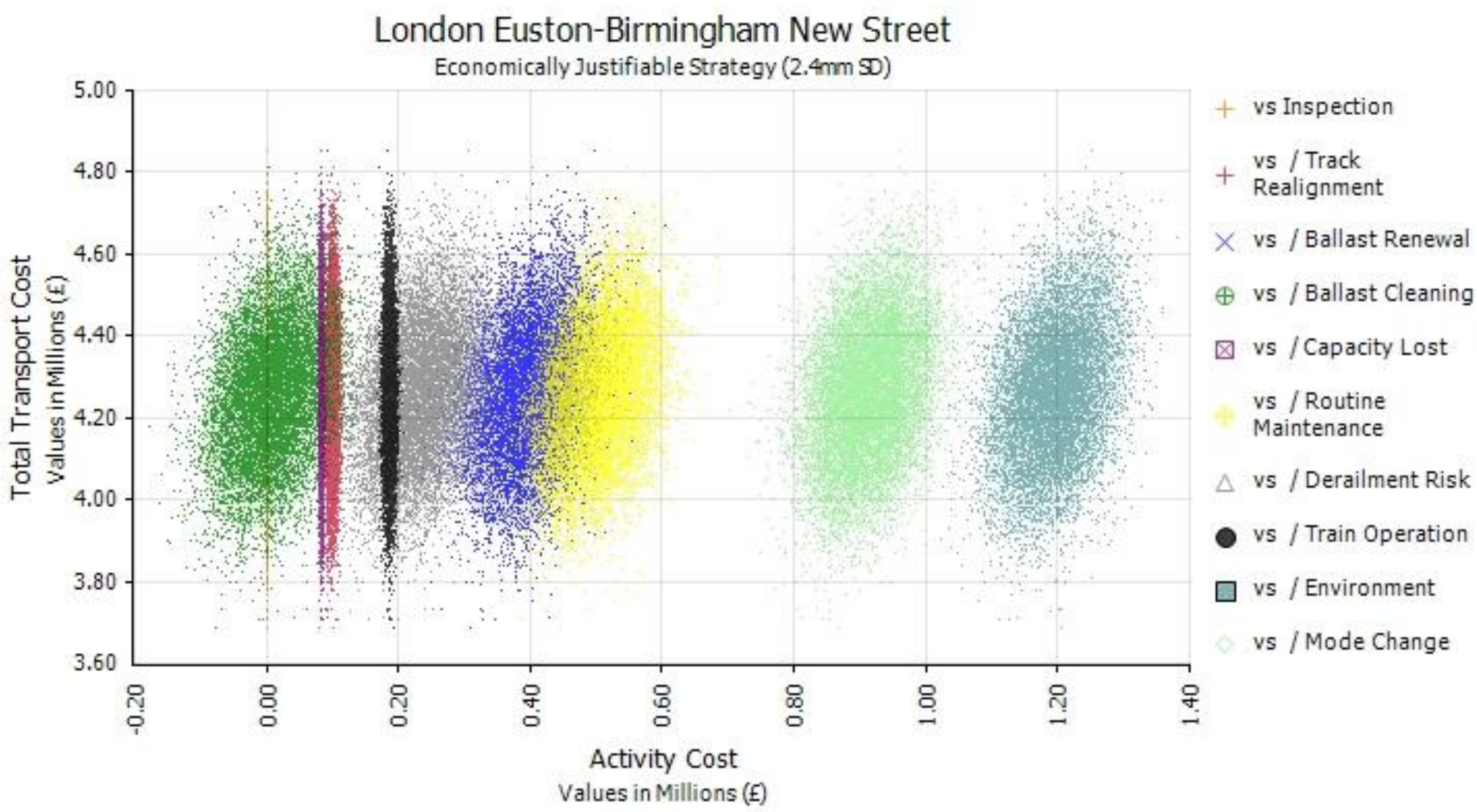



Figure 6.41 Contribution to the Total Transport Cost for the economically justifiable track maintenance strategy for High Speed Passenger route

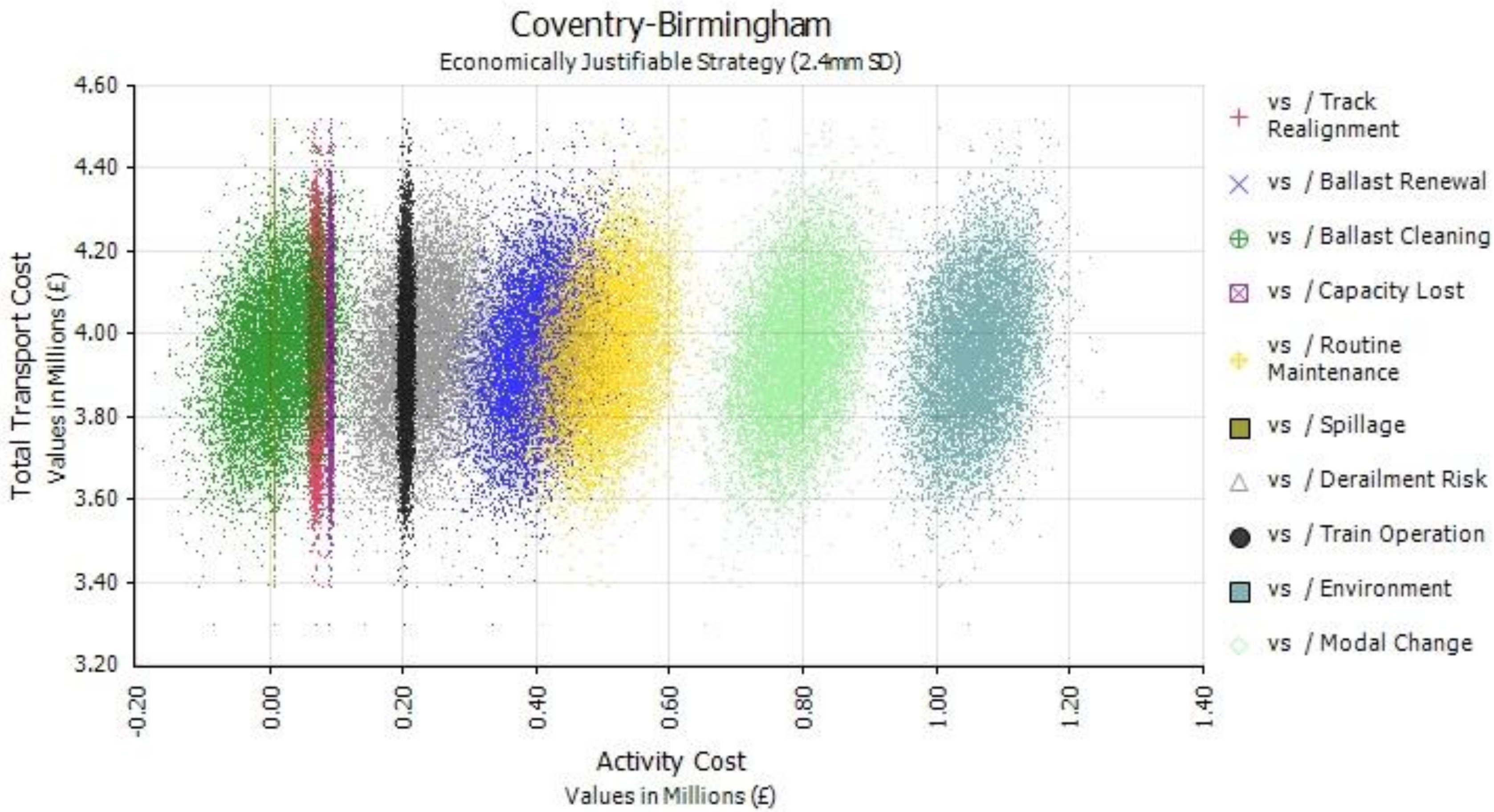



Figure 6.42 Contribution to the Total Transport Cost for the economically justifiable track maintenance strategy for Mixed Freight-Passenger route

## 6.6. Summary

Chapter 6 described how three different routes on the UK mainline railway network were utilised as case studies to demonstrate the risk informed approach to appraising, on an economic basis, maintenance strategies for ballasted railway tracks.

The results from the case study suggested that different economically justifiable maintenance strategies need to be specified for different route types. It also indicated that the contribution of whole life cycle cost elements varies for different route types. For e.g. while derailments had highest impact on high-speed passenger and mixed passenger-freight route, delays due to speed restrictions were found to impact the commuter route more. Across all route types, track user costs and environmental impacts were found to increase with deteriorating track quality. The case study also demonstrated the need to consider track use (train operation, modal change, derailment risks and environmental emissions) and associated total transport costs while setting track maintenance strategies.

Accordingly, the proposed risk-informed asset management approach can aid in identifying economically beneficial track maintenance strategies, in comparison with the current industry practices that fail to consider the lifecycle costs and benefits of the operation and maintenance of each individual assets. The following chapter critically analyses the research methodology used to develop this risk-informed asset management approach.

# Chapter 7

# Discussion

The aim of this research is to develop a risk-informed approach to appraise economically beneficial maintenance strategies for the ballasted railway tracks. To this end, A Whole Life Cycle Cost Analysis (WLCCA) model under uncertainty was developed that incorporates (i) a track deterioration model to predict the progression of track quality over time and to infer the track use and train operation costs and (ii) a risk model to determine the impacts of derailment and associated safety costs.

This chapter provides a critical overview of the research methodology used to develop such a risk-informed asset management approach. The development of the approach has been described earlier in Chapters 4 and 5, and demonstrated using three case studies in Chapter 6.

## 7.1 Summary of the Research

The research carried out in this study can be summarised as follows:

a) **Development of a theoretical framework to compare railway track maintenance strategies using a risk-informed economic approach under uncertainty**

The literature reviewed in Chapter 2 and 3 identified the need for a risk-informed asset management approach to appraise investment in railway track maintenance. Such an approach uses economic criteria to compare on a whole life cost basis, possible track maintenance strategies.

The framework of such an approach is shown in Figure 5.1 and consists of a WLCCA model.

The WLCCA model consists of components which:

(i) Estimates the direct and indirect costs to all stakeholders of the railway track on a Whole Life Cycle (WLC) basis;

(ii) Deals with uncertainty in data;

(iii) Incorporates a track deterioration model to predict the deterioration of track quality when subjected to different maintenance strategies, and infers the associated train operation and track use costs.

(iv) Employs a risk model to quantify the risk of derailments and associated safety costs as a function of the ballasted railway track quality. In order to deal with the uncertainty or lack of related data, expert opinion was solicited to inform the risk assessment process.

**b) Development and demonstration of a prototype tool that employs the proposed risk-informed approach for setting economically beneficial periodic track maintenance strategies**

The risk-informed asset management approach (see Chapter 5) informed the development of a Microsoft Excel™ based prototype tool. The @RISK™ plug-in was employed within the tool to run Monte Carlo simulations, a technique to deal with risk and also uncertainty in data (see Section 3.2.1). The use of the tool, and therefore the proposed approach, was demonstrated with three case studies on different routes on the UK's mainline railway network, as described in Chapter 6.

## 7.2 Objectives of the Research

This research had six objectives described in Chapter 1 and the progress achieved in meeting them are described below.

**Objective 1** - *To scrutinise, by means of a literature review, the factors that contribute to the deterioration of ballasted railway track and how railway track deterioration may be modelled.*

The literature reviewed in Chapter 2 presents the different factors that contribute to the structural and functional deterioration of the ballasted railway track. These can be summarised in terms of environmental and geographical factors, and train operation (see Figure 2.2). Research suggests that track sections have their own deterioration characteristics which vary according to their maintenance history and environmental and structural condition. The literature also shows that track condition can impact the train loads experienced by the track, i.e. worse track condition causes higher dynamic loads. Such higher train-track forces can result in the faster deterioration of train components (such as wheelset and dampers), resulting in higher train maintenance costs.

Chapter 2 also reviewed stochastic and deterministic track deterioration models, most of which have been used to predict railway track integrity. To inform the WLCCA model a stochastic model was chosen for the case studies (see Section 5.1.1.2) to account for the variability in deterioration rates through the use of probability. To this end, the studies by Costello et al. (2005), Quiroga et al. (2011), Andrews et al. (2012), Prescott et al. (2013), and Andrews et al. (2014) were found to be particularly useful.

**Objective 2** - *To identify how railway track deterioration is assessed and measured in practice, the maintenance techniques available to address deterioration and the effectiveness of these techniques.*

Chapter 2 provides a comprehensive review of different measures of ballasted railway track deterioration (e.g. track geometry and track stiffness). For maintenance and renewal planning, track geometry is often used as a measure of the functional integrity of the railway track and of the safety of train travel (Guler, 2014). Track geometry is described in terms of vertical and horizontal geometry, both of which should be maintained within acceptable levels of quality during track construction and operation (see Figure 5.2). Vertical track geometry was found to be a commonly used indicator to inform maintenance requirements. Chapter 2 also presented different maintenance techniques employed by the railway industry for remedying the vertical track geometry, and each of these techniques were discussed in detail (See Section 2.3.1.3). Tamping and stone blowing are often used routinely to correct track geometry faults. Tamping however has been known to damage the ballast and therefore stone blowing is often preferred. When cycles of tamping/stone blowing become less effective in correcting track geometry on a section of track, a renewal is carried out.

**Objective 3** - *To explore how railway track condition impacts the operation of the railway and contributes to stakeholder benefits and costs.*

As the track condition deteriorates over time railway operating costs increase as a results of a rise in fuel consumption, environmental emissions and train maintenance requirements. Passenger comfort also reduces (See Figure 5.3). As mentioned above, lower track quality results in higher dynamic loads, which in turn aggravates track quality deterioration. Deterioration of track condition also poses a safety issue due to potential derailments.

Further, when the track condition is below unacceptable levels speed restrictions are imposed to avoid derailments and this can result delays. Reduced travel comfort and the increase in delays on lines where track quality is poor may also result in passengers and goods shifting to other modes of transportation like roads. This can in turn result in more road congestion, a higher probability of road accidents and an increase in the emission of road vehicles (which are less environmentally friendly in this respect than trains).

The literature reviewed in Chapter 2 found that current railway track maintenance standards fail to take into account the costs of train operation and maintenance, and rather they are based on the knowledge and experience of the track maintainers, and pre-determined standards. Such approaches may therefore be wasteful of resources. This situation is exacerbated in many railway networks where train and track operation are separated.

**Objective 4** - *To explore approaches to assess the costs and benefits of different types of railway track maintenance strategies.*

A number of techniques for the appraisal of investment in transport infrastructure were identified in the literature and their components were scrutinised for the task at hand WLCC methods (Section 2.3.2). Relevant aspects of these techniques were used to inform the development of WLCCA model under uncertainty.

The WLCCA model considers the direct and indirect costs to all stakeholders and includes track construction; track inspection; track maintenance (realignment; ballast renewal and cleaning; routine maintenance); capacity lost; spillage; risk of derailments; train operation; environmental costs; transport mode change and end-of-asset-life value.

The studies by Patra et al. (2009), Arasteh Khou et al. (2013), Gattuso et al. (2014) and Milenkovic et al. (2016) were especially useful in developing the WLCCA model and in identifying its components.

The uncertainties arising from the cost estimation of different investments and benefits were informed by the review described in Section 2.3.3.1. In order to address possible uncertainties in the data, the widely used Monte Carlo technique was employed to compare the total transport costs and the Net Present Value (NPV) of each periodic track maintenance strategy analysed as part of the analysis of the case studies (see Chapter 6).

**Objective 5** - *To review the literature to determine if and how risk management concepts and techniques can be used to model railway accident risk and data uncertainty.*

The literature review described in Chapter 3 determined the risk management concepts which can be employed for the task in hand. To this end, literature reviewed in Chapter 3 identified risk management approaches that are used by other industries and which could be suitable for this research (see Table 3.1 and 3.2). Furthermore the specific requirements to further develop the WLCCA model (see Objective 4) and incorporate these risk management approaches were identified in Chapters 2 and 3. This included identifying a suitable risk assessment technique that which can deal with events with low probability of occurrence but high severity of impact (such as derailments). To this end, employing an integrated Monte Carlo and Fuzzy Approach for risk assessment was explored.

Uncertainty associated with the inaccuracy and lack of data were observed as major challenges to the approach advocated herein. Approaches associated with utilizing expert opinion were identified from the literature as plausible solutions.

Following consideration of the advantages and disadvantages of possible risk assessment techniques identified from the literature, a risk assessment model employing an integrated Monte Carlo - Fuzzy reasoning approach was incorporated within the WLCCA model. This techniques deal with uncertainties associated with lack of data associated with track quality related derailments and utilize use expert opinion to understand the relationship between derailment severity and track quality (See Sections 3.2.5 and 5.1.2.2).

The approaches advocated by An et al., (2006), Sadeghi et al. (2010), Jafarian et al., (2011), Arunraj et al. (2013), El-cheikh et al., (2013) and Mitropoulos et al. (2017) were found to be particularly useful in in this regard.

**Objective 6** - *To validate and demonstrate the proposed risk-informed approach through a variety of suitable case studies.*

Chapter 6 presents the case studies that demonstrates the applicability of the approach developed to compare alternative track maintenance strategies using a WLCCA, while dealing with uncertainty in the available data and derailment risk. Three route types on the UK mainline railway network (i.e. commuter, high speed passenger, mixed passenger-freight) were analysed using the developed prototype tool.

The results from the case studies showed that track use costs (train operation costs, derailments, environmental impacts and travel mode change) have the maximum impact on the total transport costs for all three routes analysed. It also demonstrated that economically beneficial maintenance standards could be adopted if railway track use costs are considered, and by so doing validated the applicability and usability of the developed approach.

The following section critically reviews the research carried out and discusses avenues of possible further research to refine the developed model.

## 7.3 Critical Review of the Research

The development of the risk-informed asset management approach for appraising periodic maintenance strategies for the ballasted railway track is discussed under the following headings:

- Railway track deterioration
- Appraisal of railway track maintenance
- Railway safety
- Risk assessment
- Uncertainty
- Prototype tool
- Case studies

### 7.3.1 Railway track deterioration

The effects of repeated traffic loading and the environment causes the track substructure (i.e. ballast, the underlying sub-ballast and the subgrade layers) to deteriorate over time, resulting in track settlement and worsening track geometry. Track geometry is generally used in the railway industry as the predominant measure of track quality and the safety of train travel and it can be assessed rapidly using specially instrumented trains travelling at normal track speeds. Track geometry is therefore used as the primary indicator for maintenance planning (Guler, 2014; Dahlberg, 2004; Audley, 2013). Furthermore, since track use costs are primarily a function of the functional track condition, the track geometry was the only measured of track condition used within the developed WLCCA model.

That said, the vertical track geometry measurement is a reflection of the functional condition of the track and it does not necessarily inform its structural condition. The structural condition of the track is an indicator of the long-term health of the track sub-structure. Traditionally, railway track structural condition is measured by track deflection and or track stiffness (Pita et al., 2004; Dahlberg et al., 2009).It might therefore be considered that by taking into account both the functional and structural condition of the railway track within the developed WLCCA model the prediction of maintenance requirements could be improved. A possible issue with such an approach is that many railway track owners and operators, such as Network Rail, do not measure track structural condition frequently as it is expensive to do so. Consequently, it might be problematic to identify enough data to inform the model. However, research is undergoing to develop means of assessing track structural condition using train mounted systems which will allow structural condition to be measured frequently. This would allow its use within a refined version of the WLCCA model developed here.

Estimating the relative cost of track damage caused by different types of rolling would enable the cost impacts of different vehicle types to be identified. This would aid infrastructure managers and policy makers to differentiate the impact costs of different rolling stock type on the track, and enable the establishment of incentive schemes to use more track-friendly trains. The approach taken in the case studies to estimate track damage used historical track condition data. This did not allow the relative damage of different types of vehicles to be identified. In order to determine the different amounts of damage caused by different types of rolling stock, methods such as that advocated by Smith et al. (2017) to analyse track damage costs for different types of rolling stock, could be utilised within the approach advocated herein. Moreover, the UK railway industry has employed VTISM (2012) to set differential track access charges for different types of rolling stocks based on track damage.

### 7.3.2 Appraisal of railway track maintenance

The literature review of various studies and techniques within different industries suggested that, Cost Benefit Analysis (CBA) is the most widely used technique for investment appraisal. The NPV of the life cycle costs and benefits was selected as the economic indicator for appraising investments for railway track maintenance for the case studies, although there are a number of alternative economic indicators to NPV available such as the Cost-Benefit Ratio (CBR) and Internal Rate of Return (IRR) (Bristow et al., 2000). NPV was chosen because it is widely used for similar approaches in other industries and. However, it is noted that the other economic indicators might be more appropriate for decision making in other instances (e.g. limited budget to carry out maintenance activities). For example, the NPV/Cost ratio is often employed since it negates the tendency for more expensive projects to be chosen using the NPV metric alone. More expensive projects often have a higher NPV than less expensive ones since their costs and benefits are greater in magnitude and therefore more expensive projects tend to be identified as the most beneficial when using the NPV metric.

The thesis argued, based on the reviewed literature, that there is a lack of whole-transport-system based approach to identify railway track maintenance strategies. Consequently, track maintenance strategies do not consider the impact to all the stakeholders involved, resulting in failure to minimise total transport costs. It appears that the main reason for this is the misalignment of incentives provided to track maintainers and train operators, resulting in each stakeholder seeking to reduce their own costs without considering the needs of all stakeholders (Nash et al., 2014). E.g. track owners and maintainers tend to have little concern for the operational costs of rolling stock. Various approaches and techniques are used to try to overcome this challenge. In the UK this has been through the use of performance based regimes and various forms of contracts, but none has been shown to be fully successful in minimising total transport costs (Nash et al., 2014).

The risk-informed approach advocated herein addresses this as it aids the decision maker to compare different track maintenance investment strategies using economic criteria, and to thereby choose the strategy with the greatest return on investment.

### 7.3.3 Railway safety

The proposed risk-informed approach can aid decision makers to select safe-minimum track maintenance strategies, and it also allows derailment-risk trade-offs with other aspects of a WLCCA. For example, more frequent maintenance to improve track quality and therefore safety but on the other hand increased journey time costs and lower track accessibility. Derailments are often the result of a combination of uneven loading, trains exceeding speed limits and a sudden deterioration in track geometry quality. Furthermore, derailments have been shown to be more effectively controlled by ensuring adequate inspection and timely maintenance.

As discussed earlier, there is a higher risk of derailments as the track quality deteriorates.

The approach proposed within this research allows the impact of different maintenance interventions in terms of safety to be modelled. However, the case studies that demonstrated the proposed approached does not explicitly take into account the impact of different maintenance intervention types (such as tamping, stone blowing etc.) on the derailment risks due to the lack of associated data. The collection and use of such data within the WLCCA model would enable the railway industry to better understand the efficiency of its track maintenance strategies from a safety perspective.

### 7.3.4 Risk Assessment

For the three case studies, historical data pertaining to the risk of derailments due to track quality was scarce. The UK's Office of Rail and Road (ORR) and Railways Safety Standard Board (RSSB) officials confirmed that they *'do not hold data at a further level of disaggregation'* for derailments. The use of expert opinion was identified as a useful approach for overcoming such issues (Torbaghan et al., 2015). UK's Railway Group Guidance Note (2002) also identifies the use of expert judgement in assessing risks of hazardous events when no data is available. To this end, a questionnaire based survey was selected to gather the judgement of four experts for the case studies. When capturing the knowledge of the experts' weights were applied to the knowledge provided by each expert to reflect their experience in railway safety risk assessment. Ideally, experts with more experience in the task at hand (quantifying the impact of track quality on risk of derailments) should have been consulted. In order to partially address the varying experience of the experts, an expert weighting system was used.

Nevertheless, it is recognised that careful consideration of the number and diversity of experts would be important for the real application of the theoretical framework to ensure the accuracy of the risk assessment and to avoid bias. The engagement of experts could also be further enhanced by adopting more interactive techniques such as Hazard and Operability Study (HAZOP), Structured What-IF Technique (SWIFT) or gamification through a set of structured workshops. Such an approach was not conducted herein due to the resource and scheduling constraints namely (i) costs associated with recruiting experts (ii) difficulties associated with bringing a sufficient number of experts together in one location at the same time.

In order to jointly consider both randomness and uncertainty within the risk assessment process, a combination of probabilistic and qualitative approaches is necessary (Aven, 2016). To this end, an integrated Monte Carlo - Fuzzy approach (MCFA) was used to assess the risk of derailments associated with different track maintenance strategies. It was found to be an appropriate approach to modelling unique failure events with only limited historical data. Albeit its infancy in the railway industry, MCFA has considerable opportunity for use (see Sasidharan et al., 2017 within Appendix A).

### 7.3.5 Uncertainty

The concept of uncertainty with respect to asset management and risk management have been discussed in Section 2.3.3.1 and 3.2.4 respectively. Since the WLCCA technique in asset management is based on the predictions of future scenarios, one could encounter uncertainties due to the lack of data or due to the inherent variability within projected estimates (Salling et al., 2006). This can result in over-estimations or under-estimation of the CBA results. While various risk assessment methodologies can be employed to deal with such challenges, and for this research the Monte Carlo Simulation (MCS) approach was adopted to calculate a probability distribution for the data values associated with costs, benefits and deterioration rates. Similarly, the lack of data or specialist knowledge can give rise to uncertainty within the risk assessment process. As discussed previously in Section 7.3.4, expert opinion was used to addresses these issues (see Sections 3.2.5 and 5.1.2.2).

### 7.3.6 Prototype tool

The WLCCA model was implemented using Microsoft Excel™ software. Microsoft Excel™ was chosen as the platform for the prototype tool because of the ease at which input data and mathematical calculations associated with the WLCCA could be carried out. Since the functionality to perform Monte Carlo simulations were limited within Microsoft Excel™, a plug-in @Risk™ was employed to provide the required additional functionality. The case studies discussed in Chapter 6 were performed using the prototype tool and demonstrated its applicability and usability. One of the limitations of the prototype tool in its current form is that, organisations or individuals would need a valid license of @Risk™ to use the tool.

It is recognized that further refinement of the tool needs to include a track maintenance possession regime that would support a more comprehensive assessment of the WLCC. Extending the prototype tool to considering deterioration of other track infrastructure components such as, sleepers, subgrades and turnouts is also suggested.

### 7.3.7 Case studies

The prototype tool provided a means to demonstrate the WLCCA method through case studies. To validate and demonstrate the approach, data collected from three different route types on the UK mainline railway was used (see Chapter 6).

The case studies used the operational cost per train-km as an important indicator of track use, because it measures the level of financial inputs required per train (ITF, 2013). Staff costs are a large component of these operational costs, but they have remained relatively steady over the past decade (ORR, 2015). Track quality impacts fuel consumption and directly contributes to the wear and tear of the wheelset and dampers of rolling stock (i.e. rolling stock maintenance). However, such data for the three case study sites was unavailable. Five Train Operating Companies (TOCs) were contacted but were unable to make such data available for commercial reasons. Consequently, the results from a study carried out by Zarembski et al. (2010) which focused on freight routes were used. More accurate results may have been obtained, particularly for the passenger and commuter routes, had other similar studies been available for these types of routes.

For demonstration purposes, the case studies assumed that the number of train services remained the same throughout the analysis period. However, it is recognised that in reality there might be a change in train services to reflect demand, which in turn would impact the track maintenance and use costs. Further, it was assumed that road and air users would shift to railways, if the track infrastructure is maintained at a higher quality. However, it is recommended that, in practice demand forecasting analysis should be used to provide a more accurate understanding of various socio-economic and demographic factors that contribute to railway service demand and mode shifts.

The case studies models the environmental costs by employing the Rail Emission Model proposed by AEA (2008). Rail Emission Model was commissioned by the UK's Department for Transport (DfT) to assess the most significant environmental impacts and damage costs associated with railway services in particular. Rail Emission Model employs the unit damage cost values for CO2 and other air pollutants as suggested by DfT policy guidelines (AEA, 2008). WEBTAG (DfT, 2007) values can also be used to calculate environmental costs.

For the risk assessment within the case studies, four experts were consulted to gather their opinion about the relationship between risk of derailments and track quality. The experts were from industry and academia, with specialist skills in railway asset management and railway safety. Ideally a larger number of experts should be consulted in practice. However, as the case studies were used to demonstrate the proposed theoretical framework, not having a large number of experts may not be considered significant in that the intention of the case studies was to demonstrate the use and applicability of the research.

## 7.4 Value of the research

The UK railway industry post-privatization created a vertically separated industry in which the UK government sets the investment strategy and specifies high level policy deliverables for Network Rail, the infrastructure maintainer. The Office of the Rail and Road (ORR) regulates the industry and private companies operate freight and passenger train services. Similar operational models exist in many other countries. Consequently, infrastructure owners operating under such regimes have little concern for the impact of track quality on the rolling stock (fuel and maintenance) operation costs, nor is there any incentive for Network Rail to consider such costs. Similarly, rolling stock operators too are incautious about the same. It is in the interests of both parties, and the railway system as a whole, to maintain the infrastructure and rolling stock appropriately, so that total transport costs can be minimised. The tool presented herein is a means by which this aim can be achieved in part, by enabling an equitable and transparent comparison of track maintenance strategies.

Expert opinion was used to deal with lack of historical data was demonstrated within this study. The lack of sufficient data or knowledge can often complicate the adaptation of risk-informed approach to asset management within the railway industry.

## 7.5 Summary

This chapter critically reviewed the research carried out within this study. In particular, the effectiveness of the developed WLCCA approach under uncertainty, including the assumptions made within the study were discussed. Where appropriate, suggestion have been offered for future refinement of the approach.

A major assumption concerns the premise that track maintenance requirements can be determined solely on the basis of the functional performance of the railway track. However, although the functional performance of the railway track is used by many railway infrastructure operators and maintainers, such as Network Rail, to set maintenance standards and identify the majority of track maintenance needs, considering the structural condition of the track also might allow for better prediction of long term track performance. This may help to promote the benefits of track maintenance strategies, such as track renewal, which deal with the structural, long term, performance of the railway track.

The unavailability of rolling stock maintenance history and associated cost data due to their commercial sensitivity and the lack of historical derailment data were challenges in utilizing the WLCCA for the three case studies. To overcome these issues expert opinion for the risk assessment process were used.

Possible refinements to the advocated approach discussed included using travel demand forecasting and taking into account railway track possession planning for maintenance. In addition, incorporating a method to predict the effectiveness of maintenance interventions on derailments risks were also suggested. The following chapter presents the main findings from this research and makes recommendations for future research.

# Chapter 8

## Conclusions and Recommendations

The governments on behalf of the taxpayer looks for the best value for its expenditure, by maximising the benefits derived from the investments it provides to railway infrastructure and train operating companies. However, current practices in the railway industry do not consider design, or track renewal and maintenance on a WLCC basis. Indeed, the railway industry worldwide does not consider total transport costs while setting track design and maintenance strategies.  Furthermore, the concept of risk has not been embraced in railway track infrastructure investment planning.

To address these issues this research has presented a risk-informed asset management approach to set economically justifiable maintenance strategies for ballasted railway track maintenance. The approach enables maintenance options to be judged on a total transport cost basis that considers the costs and benefits to track maintainers and users. The developed approach compares the costs and benefits of different strategies, while considering the uncertainties within the available data.

The proposed approach has been demonstrated via case studies on three different route types on the UK mainline network.

## 8.1. Accomplished Work

Currently railway track maintenance decisions are largely based on short-term, subjective criteria (often based on limited and uncertain data), which not only ignore a whole-system perspective, but also fail to consider the downstream costs and benefits of operation and maintenance. This situation is exacerbated in many countries, including the UK, where the ownership of the track infrastructure and the operation of rolling stock are formally separated. This results in a lack of consideration of the damage that the track infrastructure may cause to rolling stock and vice versa. Further, existing railway maintenance management tools and methodologies rarely take into account risk and uncertainty.

The research presented in this thesis attempts to address these shortcomings. The risk-informed asset management approach proposed takes into account the uncertainties and risks in establishing costs and benefits of railway track maintenance. The approach therefore provides, for the first time, railway policy and decision makers with a transparent means to appraise track maintenance strategies using a whole life cycle approach under uncertainty which takes into account the requirements of all stakeholders. To this end, the research has achieved the objectives outlined in Chapter 1 by:

- Exploring the viability of risk-informed techniques for the proposed railway track asset management tool (Chapters 2 and 3);
- Developing a Whole Life Cycle Cost Analysis (WLCCA) model under uncertainty to quantify the total transport costs associated with the maintenance of ballasted railway tracks (Chapters 2 and 5);

- Incorporating an engineering model within the WLCCA to predict the deterioration in quality of ballasted tracks over their life cycle when subjected to different maintenance strategies (Chapters 2 and 5);
- Developing a risk model to facilitate within the WLCAA model the assessment of risk of derailments associated with track quality using expert opinion(Chapters 3 and 5);
- Integrating the engineering, economic and risk models to develop a prototype railway track asset management tool that employs a risk-informed approach (Chapters 4 and 5);
- Demonstrating the use of the prototype tool through case studies of three different route types on the UK mainline railway network (Chapter 6).

## 8.2. Conclusions

The following are the key conclusions from the research:

- A risk-informed approach is suitable for taking into account risks and uncertainties within railway maintenance management;
- The appraisal approach developed is suitable for comparing on an economic basis periodic track maintenance and renewal strategies;
- A whole-system view enables total transport costs to fully consider direct and indirect costs and benefits to all stakeholders.

## 8.3. Main Findings

This research found that the developed risk-informed asset management approach for ballasted railway tracks may be implemented successfully by using the techniques discussed below:

### 8.3.1. Railway track asset management

The asset management of railway track infrastructure involves the disciplines of engineering, economics and management to ensure required levels of service and safety. While the engineering aspect deals with maintaining the railway track at engineering associated levels of quality, economics focuses on setting standards associated with minimizing total transport costs. Management skills are required to utilize the information provided to make investment decisions.

The engineering model employed within this research predicts how different track maintenance strategies can affect track geometry deterioration over time (see Figure 5.3).

In order to devise an economically justifiable track maintenance strategy, it is necessary to weigh the railway track inspection and maintenance costs required for each strategy, against the associated railway track use costs. A Whole Life Cycle Cost Analysis (WLCCA) approach was used for this purpose. The different cost components for the WLCC model were identified from the literature (see Section 2.3.2.1). These are the costs associated with the construction, maintenance, renewal and end-of life of ballasted railway tracks, and delays, safety, environment, travel mode change and train operation.

For the WLCCA model, a Cost Benefit Analysis (CBA) approach under uncertainty was found to be a suitable method to compare different track maintenance strategies where data required for the CBA is uncertain. Within the CBA, Monte Carlo simulation was found to be an appropriate method to deal with uncertainties associated with forecasting future track performance and risks, and estimating the direct and indirect costs and benefits to all stakeholders of the railway track.

It was found that the developed tool can help manage the challenges of restricted budgets and limited data in managing railway infrastructure assets.

### 8.3.2. Risk Assessment

The proposed safety risk model is capable of combining expert knowledge and engineering judgement with historical data to assess derailment risks associated with different track maintenance strategies. The safety risk model employs an integrated Monte Carlo - Fuzzy Approach (MCFA) which has been found to be appropriate for dealing with ambiguous, incomplete and uncertain information in risk assessment within many other applications. The MCFA was also found in the research to be appropriate for assessing risks (such as derailments) with low probability of occurrence but having high severity of impact. This confirms the findings of the literature (see for example, Sasidharan et al., 2017).

In situations where historical risk data is unavailable, subjective and linguistic expressions can be used for risk assessments. The proposed safety risk model allows imprecise expressions such as “minor” and “major” to be used to capture expert opinion to assess the impacts or severity of derailments. Weighting expert judgement according to their specialist knowledge and experience allows the opinions of a variety of experts to be considered. .

In terms of the identified case studies (see Chapter 6), a workshop was conducted involving two experts from the railway industry, and two academics from the Department of Civil Engineering at the University of Birmingham. The experts provided their individual judgement on the severity of derailments associated with different track maintenance strategies, on three different routes on the UK mainline railway network. It was found that strategies to maintain these routes at low and medium average track quality conditions, resulted in higher risks of derailments on the high-speed passenger and mixed-passenger-freight routes. The experts were of the opinion that the commuter route would have a high risk of derailment only when maintained at a lower average track quality. All the experts unanimously agreed that, higher average track quality resulted in a low severity of derailments across all three selected route types.

## 8.4. Recommendations for further research

While the case studies and results presented in Chapter 6 have demonstrated the usability of the prototype tool, further recommendations to improve its capability are suggested below:

### 8.4.1. WLCCA model under uncertainty

Enhancements to the WLCCA model under uncertainty could be achieved as follows:

1. The WLCCA approach demonstrated within the case studies used historical track condition data to predict future track condition and assumed that the operational environment remained unchanged. Further research could investigate the development and use of track deterioration models which are a function of different types of rolling stock. This would allow the impact of different rolling stock on track life cycle costs to be studied (see Section 7.3.1). A potentially useful avenue of research could explore using a tool such as the Vehicle Track Interaction Strategic Model (VTISM) that enables the track damage costs associated with vertical impact forces from different types of rolling stock to be determined (Serco, 2013). Similarly, Smith et al. (2017) proposed a technique combining engineering and economic approaches to analyse track damage costs due to different types of rolling stock.

2. An enhanced estimation of track use costs could be achieved by incorporating a travel demand model. This would enable a better understanding of the factors that contribute to railway service demand and mode shifts, and thereby track use costs.
3. Modelling the structural performance (e.g. via track stiffness) and including maintenance intervention levels associated with both structural and functional condition (see Section 7.3.1). This would improve the accuracy of the WLCCA model in dealing with maintenance activities which improve the life of the railway track (e.g. re-ballasting or subgrade improvement). Research would be required to develop suitable models of structural performance and to specify intervention levels which are a function of both structural and functional performance (For e.g. if the track geometry is poor and the track structural condition is poor carry out a particular type of renewal).
4. Including other track railway track components such as, the rails, sleepers and turnouts. This would require research to develop suitable deterioration models for each of these components.
5. Incorporating models of rolling stock deterioration as a function of track quality (e.g. wheelsets and dampers). This would enable better quantification of train operating costs within the WLCCA model.
6. The risk model presented in Chapter 5 quantifies the risk of derailments associated with different track maintenance strategies over the analysis period i.e. the useful life of the track. However, a study to understand the impact of track quality improvements on the risk of derailments could be undertaken (see Section 7.3.3). Such an approach would allow a better understanding of the effectiveness of different track maintenance strategies in relation to safety.

7. Given that the life cycle of railway track is greater than 25 years and preventative maintenance decisions are planned several years in advance, it is also recommended to consider a track possession planning model that takes into account the scheduling of track maintenance under operational constraints.

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# Appendix A Published Papers

A.1 Sasidharan M., Burrow M. P. N., Ghataora G. S., Torbaghan M. E. (2017) 'A review of risk management applications for railways', 14$^{th}$ International Conference of Railway Engineering, Edinburgh, DOI:10.25084/raileng.2017.0065

A.2 Sasidharan M. (2019) 'A risk-informed asset management approach to setting sustainable transport maintenance strategies', 15$^{th}$ World Conference on Transport Research, Mumbai

A.3 Sasidharan M. Burrow M. P. N., Ghataora G. S. (2019) 'A Whole Life Cycle Approach for Economically Justifiable Ballasted Railway Track Maintenance', Journal of Transport Economics

*A risk-informed asset management approach to setting sustainable transport maintenance strategies*

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**Abstract**

Railways have a crucial role in a sustainable, safer and greener evolution of the transport systems around the world. Given the pressure to increase track utilization, the ageing infrastructure on which much of the world's railway systems are founded, and the constrained budgets under which the infrastructure is managed, appropriate maintenance needs to be predicted, prioritized, planned and carried out efficiently and effectively. Asset management of railway track infrastructure is a challenging problem with added values on safety, security and durability. To this end, this paper proposes a risk-informed asset management approach to arrive at economic and optimal maintenance intervention limits, by predicting the material behaviour, costs and accidents under uncertainty. This is significant for the industry as it will help to optimise the maintenance regimes based on risk, and enable effective balancing of investment against the impact of asset failure. The proposed approach is applied to case studies on heavy haul lines in Sweden and Australia.

Keywords: Risk Management, Asset Management, Sustainable Transport, Railways, Safety

## 1. Introduction

Mobility is an enabler to sustainability - a concept introduced by Brundtland Commission in UN (1987), which still holds relevance to evaluating impacts of investment decisions on the economy, environment and society. Sustainability can be defined as *'development that meets the needs of the present without compromising the ability of future generations to meet their own needs'*. Sustainability in any activity can also be described as achieving balance between economy, society and environment as presented in Figure 1.

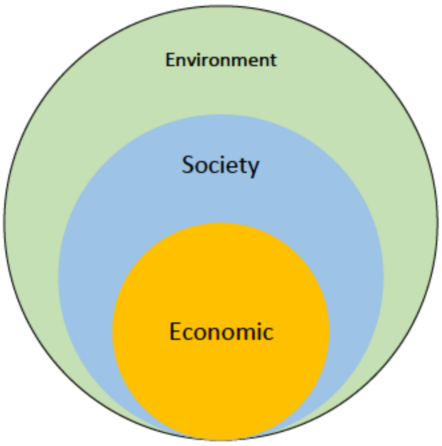


*Figure 1 Sustainability Objectives (Cato, 2009)*

Linear transport networks i.e. roads and railways, not only provide mobility, but also drive economic development, influence land use, urban planning, impact the environment and enhance liveability of both cities and rural communities. Although not explicitly mentioned as one of the UN's 17 sustainable development goals, transport could be considered to contribute to at least 8 of these, especially those related to climate change, infrastructure, cities and human settlements, health, energy and food security (Sasidharan, 2017a). There has been a recent drive for transport to be made more sustainable i.e. economically and environmentally, with 8 development banks allocating $175 billion towards sustainable transport projects over the next decade (UNCRD, 2014).

## 2. Sustainability and Transport

Within transportation, sustainability can be considered in terms of equity, economy and ecology (Burrow et al., 2016). Since maintaining balance between the three objectives is challenging, sustainability can be achieved only when there is a trade-off between economic development and its impacts on the environment and human life (May et al., 2007). In other words, decision makers should consider the *'impacts including depletion of non-renewable fuels, climate change, air pollution, fatalities and injuries, congestion, noise pollution, low mobility, biological damage, and lack of equity'* within the transport policy making and investment appraisals (Gilbert, 2006). Previous transport development programmes have focussed on automobiles/highways and often resulted in higher road fatalities, increasing air pollution and traffic congestions (UNEP, 2011). These challenges resulted in the recent shift of policy and investment from automobiles/highways towards public transportation, walking and cycling - generally referred to as sustainable transport (UNCRD, 2014). Indeed, sustainable transport has become a fundamental goal of transport planning and policy worldwide (Castillo et al., 2010).

In many countries, railways are seen as greener, more efficient and safer than road transport, and thus serves as a major component to the sustainable public transport policy (RSSB, 2018). While urbanisation and advancement in technology drives the evolution of the railways, many countries experience significant economic, environmental, social and political pressures to increase railway operation and safety. Within transportation, accidents are one of the most critical problems to the society. More than 1.25 million fatalities per year due to road accidents were estimated, with majority of them being young people aged 15-29 (WHO, 2015). Apart from having a huge effect on human life, these accidents also hinders economic development. This is exacerbated particularly in low and middle income countries where the costs associated with fatalities and injuries is approximately 3% of GDP (Nantulya et al., 2002). Railways being safer than roads, directly contributes to the sustainability of transport systems by fulfilling the economic and social objectives (Evans, 2013; May et al., 2007).

Transportation sector as a whole consumed 28.8% of the global energy, while contributing to 24.7% of global $CO_2$ emissions (UIC, 2017). Figure 2 shows that, railway is one of the most environment friendly modes of transport, with many countries setting ambitious environmental targets for their railway industry (See Table 1). With quarter of the world's railway lines being electrified, electricity constituted more than one-third of the energy use in railways (UNCRD, 2014).

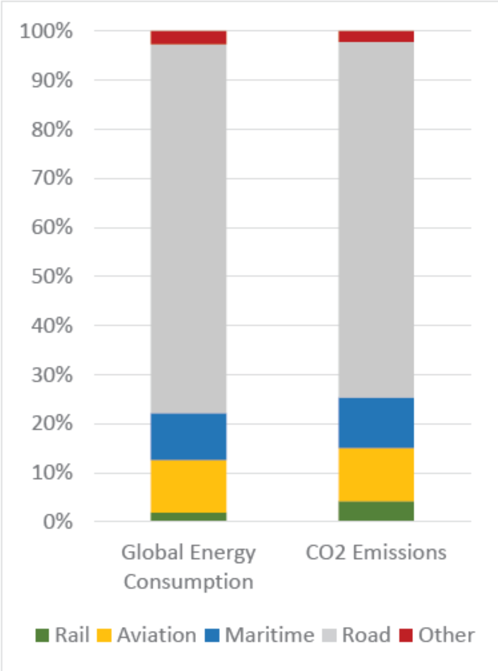


*Figure 2 Comparison of different modes of Transportation (UIC, 2017)*

*Table 1 Country specific environmental targets for Railways (UNCRD, 2017)*

| Country | Environmental Targets for Railways |
|---|---|
| Germany | By 2020, reduction of specific $CO_2$ emissions from all transportation modes by20% compared to 2006 levels.<br>By 2050, rail transport to be completely $CO_2$-free |
| India | Saving of 3.33 million tonnes of $CO_2$ emissions (approximately 80%) by 2020 |
| France | Cutting GHG emissions by 20% between 2014 and 2025 |
| Japan | Halving of CO2 emissions from its railway business by 2030 compared to 1990. |
| Russia | Reduction of the negative environmental impact due to $CO_2$ emissions by 15% in 2030 compared to 2012 |
| United Kingdom | Carbon emission reduction by 34% by 2020 and by 80% by 2050 |

## 3. Transport Asset Management

Transport is an important part of many countries economic and social development, with linear transport infrastructure often considered to be the largest public owned asset in terms of size and investment (FHWA, 2012). Transport policy makers are often faced with two basic decisions- the decision to add to the transportation system and the decision to maintain the existing asset. Within the linear transportation systems of both developing and developed countries, the issue of maintaining the existing system is often larger than the decision to add to the system, where adding refers to constructing new links. Also the damaging environmental impacts of transportation sector (see Figure 2) is a worsening global problem that needs to be tackled with local solutions such as, maintaining the infrastructure sustainably.

The condition of linear transport surfaces deteriorates over time due to the combined effect of traffic and climate. This in turn impacts the capacity, safety, user costs and the environment. For a well-functioning transport system, maintaining the asset to an optimum quality, while ensuring safe levels of operation is of crucial importance. Maintenance activities involve direct costs in the form of labour, machinery and planning, while indirectly resulting in capacity loss (delays, speed restrictions, road closures and cancellations of train services), social and environmental costs. Hence it is a costly and time consuming affair to plan and carry out maintenance activities.

Typical maintenance strategies are corrective and preventive. Corrective maintenance is ideally carried out when the system fails or a hazard happens (such as derailments, rail breaks, earthwork slips, potholes etc.). Preventive maintenance includes routine-based and condition-based maintenances, generally carried out to mitigate failure and maintain quality. For a given section of road or railway, choices need to be made between alternative maintenance strategies. This situation is exacerbated when there are limited maintenance budgets and competition between different road or railway sections within the network in terms of their maintenance needs. While deferring maintenance intervention for a short term is an easy solution, it can be expensive in the long term with increase in maintenance and operation costs, safety risks and environmental impacts.

## 4. Railways

Railways are considered to be the *'backbone of sustainable transport'* due to the reasons mentioned in the earlier sections (SLoCaT, 2018). With the rise in road traffic and congestions, there is an increasing demand in the railway industry to expand capacity, availability and higher speeds. Railways serve as a key mode of transportation of passenger and freight traffic in urban, suburban, regional and national levels. Since 1975, rail passenger activity has grown by 130% and freight by 76% (UIC, 2017). Such an increasing trend of usage results in a faster degradation of railway assets, rise in safety risks, higher associated maintenance costs and emissions (Mattioli, 2016). Globally, dedicated freight-corridors are gathering interest and substantial investment, due to their capability in increasing capacity at much lower unit transport costs, in comparison with mixed passenger-freight routes (World Bank, 2011).

Safety is a paramount consideration in the sustainable operation of the railway, but the intensive usage increases the likelihood of accidents (Sasidharan et al, 2017). In many of the accidents, such as derailments, preventive maintenance is a key factor to mitigating risks before they impact operations, revenue or safety. Maintenance is one of the largest controllable expenditures for the railway industry, as it can reduce cost and improve equipment effectiveness, reliability and performance. To effectively manage the railways under these constraints, there is a need to develop asset management approaches incorporating risk management concepts so that, periodic maintenance requirements can be predicted in advance of track failure and prioritised, and identified risks and uncertainties can be considered within the decision-making processes

### 4.1. Risk Management in Railways

In the railway industry, risk is primarily associated with safety and economic management (Cox et al., 2007). Train derailments are the most common type of main-line railway accidents in many countries (Liu et al., 2011). Generally, the railway industry is safety conscious and accordingly much of risk management in railways focuses on the prevention of accidents resulting from derailments and system failures or degradation, which can result in a derailment (Zarembski et al., 2006).

Derailments cause damage to infrastructure and rolling stock, service disruptions, casualties and harm the environment. Even though the probability of a derailment occurring is quite low, while compared to other accidents, the severity of such incidents is high (RSSB, 2018). On an average, a derailment in the UK while excluding safety, amounts to £138,500 (RSSB, 2016). While considering infrastructure damage and operational delay costs, a single derailment can cost up to £6.5 million (Sasidharan et al., 2017). Derailments caused due to track quality represents one of the largest derailment categories worldwide. An average cost of such major derailments was estimated to be approximately £661,073 (RSSB, 2016). The risk of train derailment is an ongoing concern for the railway industry, government and the public (Sasidharan et al., 2017).

Network Rail, owner and operator of UK's railway network approaches risk management, through the application of Enterprise Risk Management (ERM) process, which employs a framework with a standardised approach to the identification, assessment and recording of risks for analysis and mitigation purposes. The ERM identifies risks on a day to day operational basis aiding the risk management strategies. The Rail Technical Strategy Europe (2014) states that, risks associated with operational, safety-related or commercial is a major barrier to interoperability. It also mentions that more risk mitigation methods should be developed, even though some already exists. Recent developments in the risk assessment and management throws light on the importance of considering both quantitative and qualitative uncertainties to manage risks effectively.

Railway track maintenance strategies are currently based on time, tonnage or predetermined maintenance standards. They not only ignore the downstream costs of maintenance, but also fail to optimise maintenance strategies against safety risks and environmental impacts (Atkins, 2011). Ideally, the standards should help the railway regulators, operators and suppliers to prioritise their area of efforts in achieving sustainability within the railway transport system.

Such risk-informed approaches to asset management would have tremendous impacts on the developing countries, since their increasing transport demands are not often met by the allocated maintenance budgets (Giuliano et al., 2004). Many of the developing countries are forced to invest massively in new infrastructure to meet both passenger and freight demand with investment on rail projects in Asia remaining unbalanced towards rail transport (UIC, 2017).

### 4.2. Risk-Informed Asset Management of Railways

In order to deliver a sustainable railway system, asset management of railway infrastructure should focus on the impact that a change in asset condition would have on the required level of safety. Following the lead of other industries, the railway industry worldwide, because of pressures associated with growing demand on already congested networks, is increasingly focusing on the application of risk management approaches to railway maintenance and management (see Elcheikh et al., 2016). In such approaches failure is predicted using a variety of methods (see Sasidharan et al., 2017). If we consider accidents as the highest impactful event in a safe operation; preventive maintenance is then a key factor for their reduction. The quantification of risk of the predicted failure, enables preventative maintenance to be carried out and prioritised.

Maximum benefit of maintenance investment can be achieved by determining sustainable maintenance strategies using reliable Life Cycle Cost (LCC) models, while considering a safety perspective. In other words, maintenance strategies for the railway track should not only consider the costs of track maintenance, but also the impact to safety (Patra et al., 2009). To this end, it is important to factor in the risk of an accident (predominantly derailments) to ensure that safety is of paramount importance while considering track maintenance strategies (Sasidharan et al., 2017). To this end, this paper proposes a risk-informed approach that would facilitate the same, while tackling the challenges of restricted budget and safety impacts of maintenance.

Since LCC analysis is based on the predictions of future scenarios, it is often the case that decision makers face situations where there is insufficient or unreliable data, giving rise to uncertainties within the decision making process. It is under such conditions of uncertainty that decision makers must evaluate, compare and select the sustainable maintenance strategy from the available alternatives. Risk assessment practices such as Monte Carlo simulation, Bayesian, Fuzzy Sets theory and Petri Net are recommended to solve uncertainties in asset management practices (D. Rama et al., 2016; Zhang et al., 2014). Since its introduction in 1970s, Monte Carlo analysis is currently the most widely used technique to deal with uncertainty, as it can combine multiple probability density functions to quantify uncertainty within a probabilistic framework (Sasidharan et al., 2017; Elcheikh et al., 2016).

## 5. Proposed Approach

A risk-informed asset management approach can aid in enabling a railway transport system that is resilient and offers good value for money (RSSB, 2018). It is difficult to fully optimise track maintenance against costs and benefits, due to unavailability of suitable data and the associated computational challenges. To this end, the proposed approach (see Figure 3) compares the costs of different ballasted railway track maintenance strategies against the associated safety risks, to arrive at a trade-off and thus determine a sustainable strategy.

The proposed approach is outlined in Figure 3 and detailed below.

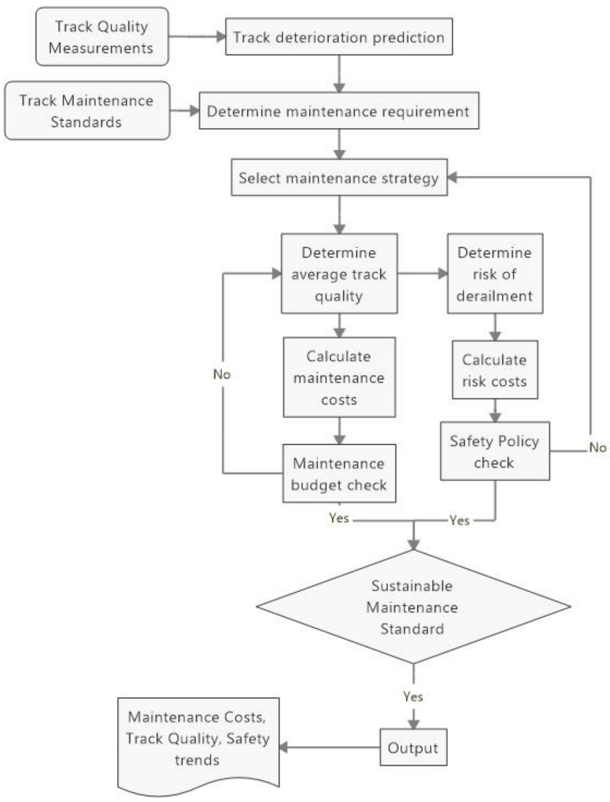


*Figure 3 Risk-informed Asset Management approach to setting sustainable maintenance standards*

## 5.1. Deterioration Model

Track quality is commonly quantified by Standard Deviations (SD) of track geometry parameters, such as vertical geometry, alignment, and cross-level; with higher TQI depicting poorer track quality. While all the parameters are equally significant, widely used track deterioration models within the railway industry considers the prediction of vertical track settlement as the main controlling factor for track geometry and therefore for ballasted track maintenance planning (Dahlberg, 2001; Burrow et al., 2009; Sadeghi et al., 2010; Milosavijevic et al., 2012). The required track condition data can be assessed by measuring the geometry of the railway tracks with track deterioration models, both statistical and stochastic, being employed to predict the track behaviour. Statistical models based on simple linear (Corbin et al., 1981) and exponential (Quiroga et al., 2011) regressions have been researched widely over the last three decades (Andrade et al., 2016). Stochastic models have also been proposed within different academic literature (Andrews et al., 2013; Zhang et al., 2014), but unlike statistical models, they have not been adapted widely within the railway industry.

This paper adopts the track quality deterioration to be a linear function of cumulative tonnage or time and is given by Equation 1

$$T_{VP} = (a.x) + b \qquad (1)$$

Where
$T_{VP}$ is the vertical profile of the track section measured in SD (mm)
$x$ is time or cumulative tonnage
$a$ and $b$ are linear coefficients

## 5.2. Safety Risks

Risk can be defined as a function of system failure and the severity of losses or damages from the failure. Derailment risk is defined as the product of derailment frequency and the average consequences of the derailment. Mathematically, we can determine derailment risk ($R_{DQ}$) associated with track quality, $Q$, as shown in Equation 2.

$$R_{DQ} = D_{RQ} \times D_{SQ} \qquad (2)$$

Where
$D_{RQ}$ is the derailment rate associated with maintaining the section of track at quality $Q$,
$D_{SQ}$ is the severity of derailment associated with maintaining the section of track at quality $Q$

## 5.3. Maintenance Costs

Track inspection is carried out periodically to assess the track quality. A variety of maintenance activities are carried out to treat the ballasted tracks. The vertical track geometry of ballasted railway track is usually restored by tamping and stone blowing. Ballast cleaning is carried out to remove the fines within the ballasts. Routine maintenance activities such as weed spraying, vegetation removal and drainage cleaning are also often carried out.

The discounted direct costs of maintaining the ballasted railway track ($C_{MaintenanceQ}$) at an average track quality, $Q$, is calculated as a cumulative cost of inspection ($C_{INS}$), tamping ($C_{TA}$), stone blowing ($C_{SB}$), routine maintenance ($C_{RM}$), and ballast cleaning ($C_{BC}$), as expressed as in Equation 3.

$$C_{Maintenance} = \sum_{j=1}^{N-1} \frac{C_{INS}+C_{TA}+C_{SB}+C_{RM}+C_{BC}}{(1+r)^j} \quad (3)$$

Where

*r* is the discount rate

*j* is the time period in years

## 6. Case Studies

The proposed risk-informed asset management approach described above was demonstrated for mixed passenger-freight routes in Australia and Sweden. On both the routes, the track quality data and maintenance history for a 200 m long track section was obtained from railway infrastructure managers in both countries. Deterioration rates for these section were estimated using the deterioration model (see 5.1). The deterioration model was also employed to identify the maintenance requirements for different levels of track quality based on the average value of SD i.e. poor (3-4 mm SD), medium (2-3 mm SD), good (1-2 mm SD) and high (0-1 mm SD), based on the average value of SD. The associated maintenance costs, safety risks and environmental impacts for each level of track quality was calculated by using data in Table 2. The results with a 90% confidence level (see Figures 5a-5c and 7a-7c) were generated by running 10,000 iterations using Monte Carlo Analysis (MCA) to deal with uncertainty within the data.

The trade-offs between maintenance costs and safety requirements needs to be considered when making decisions regarding infrastructure improvements for railway tracks. For both the routes, three maintenance strategies were considered in terms of upgrading the track quality. Namely, poor to medium, medium to good, good to high levels of track quality. The results from Liu et al., (2011) was adapted to analyse the reduction in the risk of track quality related derailments, while upgrading the track quality.

*Table 2 Costs considered in the Case Studies*

| Element | Average Cost | | Source |
|---|---|---|---|
| | Sweden | Australia | |
| Inspection | \$132/km | \$250/km | Swedish Transport Administration and Australian data |
| Tamping | \$2208/km | \$4020/km | |
| Stone Blowing | \$2208/km | \$4020/km | |
| Ballast Cleaning | \$5520/km | \$7014/km | |
| Routine Maintenance | \$1000/km | \$2000/km | |
| Derailment (Major) | \$1,656,050/derailment | \$7,230,919/derailment | |

### 6.1. Sweden

The case study was performed on a track section of the 473 km long Iron Ore Line (Malmbanan), that runs between Lulea in Sweden and Narvik in Norway. The traffic on this only heavy haul line of Europe is dominated by iron ore freight services, connecting the mines of Gallivare and Kiruna with the ports in Narvik and Lulea. The heavy haul line is also used by few passenger trains and other freight trains, amounting to around 25-30 tonnes annually. The train speed varies from 50-60 km/h for loaded iron ore trains, 60-70km/h for unloaded ones and 80-135km/h for passenger lines. The geographical constrains and severe weather conditions including snowstorms and sub-zero temperatures of up to -40C, puts immense strain on the track infrastructure (Nielsen et al., 2018).


*Figure 4 Iron Ore Line in Sweden*

The quality of the track section on the northern branch of the line (Kiruna to Narvik), deteriorates at a maximum rate of 0.9mm/year and at 0.3mm/year, following a renewal. Similar deterioration trends were recognised by Guler et al. (2011), Audley et al., (2013) and Nielsen et al, (2018). Such higher trends in deterioration is often explained by local substructure property variations due to temperatures rising above freezing point during April to July annually (Arasteh khouy et al., 2016). The existing maintenance programme on the Swedish side of the line is based on engineering judgements and maintenance standards from Trafikverket, the track infrastructure manager of Swedish railways (Soderholm et al., 2017). Track is inspected regularly, with the frequency of inspection being dependent on train speed, loading, geotechnical and environmental conditions. Data collected from Trafikverket suggests that, track realignment and renewal activities are carried out every 2 and 10 years respectively. Ballast cleaning and routine maintenance activities are done occasionally.

This study calculated the associated maintenance costs of track section on the Iron Ore line, for different maintenance strategies resulting in poor, medium, good and high average track quality, is adopted (See Figure 5a). However, the percentage of track geometry related derailments on this route is very small; approximately 0.38% (Kumar et al., 2008). The risk cost of derailments associated with different track quality is shown in Figure 5b. Similarly, the reduction of derailment risks due to upgrading the track quality is also studied and showcased in Figure 5c. All the results shown in Figures 5a-5c have a confidence level ranging from 10% to 90%.

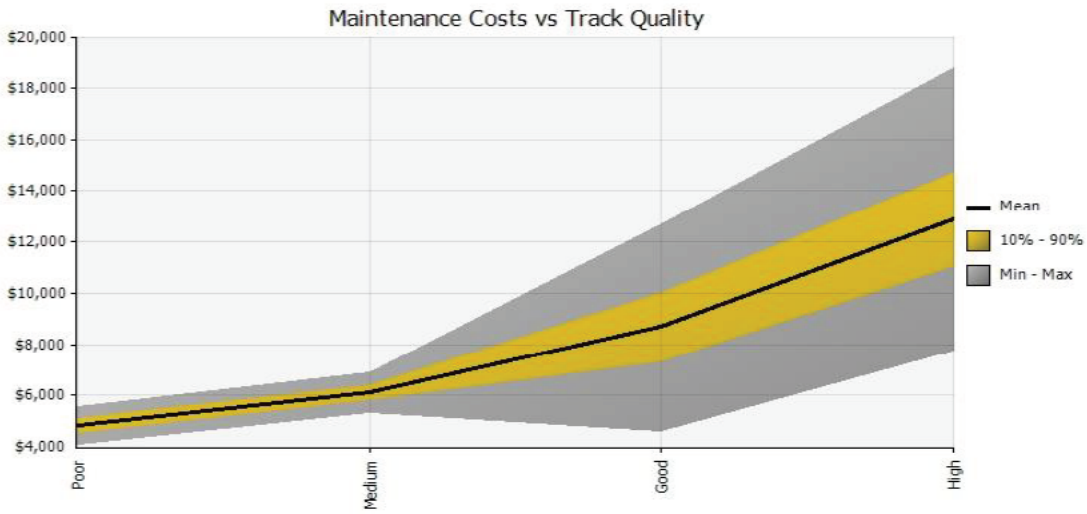


*Figure 5(a) Maintenance Costs vs Track Quality on the Iron Ore Line in Sweden*


*Figure 5(b) Safety Risk of Derailments vs Track Quality on the Iron Ore Line in Sweden*

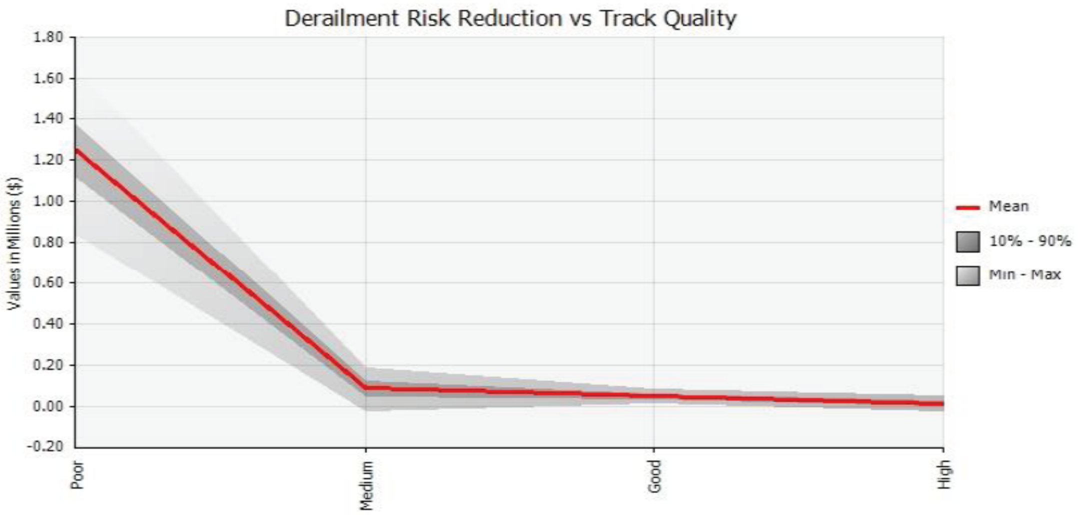


*Figure 5(c) Derailment Risk reduction by upgrading Track Quality on the Iron Ore Line in Sweden*

## 6.2. Australia

A track section from the 478 km long Trans-Australian railway line that connects Port Augusta and Kalgoorlie was selected for the case study. The line forms an important freight route between western and eastern states of Australia, with less passenger service operation. Majority of the coal mines links to the ports through this railway route. Australia's freight usage is expected to triple by 2050, and railways are currently the preferred mode of freight transport for long distance.

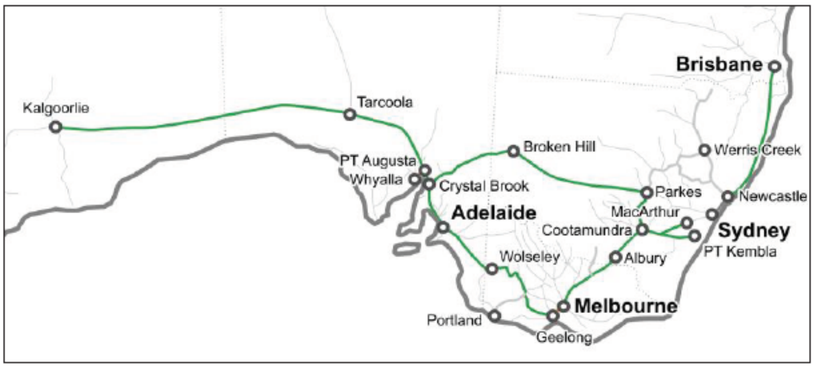


*Figure 6 Trans-Australian Railway line in Australia*

Track maintenance takes up 25% - 35% of the freight railway operational expenses in Australia (Indratna et al., 2012). Therefore significant savings can be achieved if sustainable track maintenance strategies are adopted. Coal spillages causes ballast fouling and is the primary cause of track deterioration on Australian freight routes. Track maintenance had to be intensified due to coal spillage related issues. The deterioration rate of the track section analysed was found to be 0.12mm/year, with track realignment being carried out once every 1-2 years. Ten year long historical data informed a major and minor derailment each, due to track quality related faults.

The maintenance costs associated with different track quality levels are shown in Figure 7a. The impact of track quality on the risk of derailments is higher as the track quality deteriorates (See Fig 7b). Upgrading the track quality from poor to medium and medium to good was found to have higher impact on reduction of derailment risks than upgrading from good to high (see Fig 7c). All the results have a confidence level ranging from 10% to 90%, as shown within Figures 7a-7c.

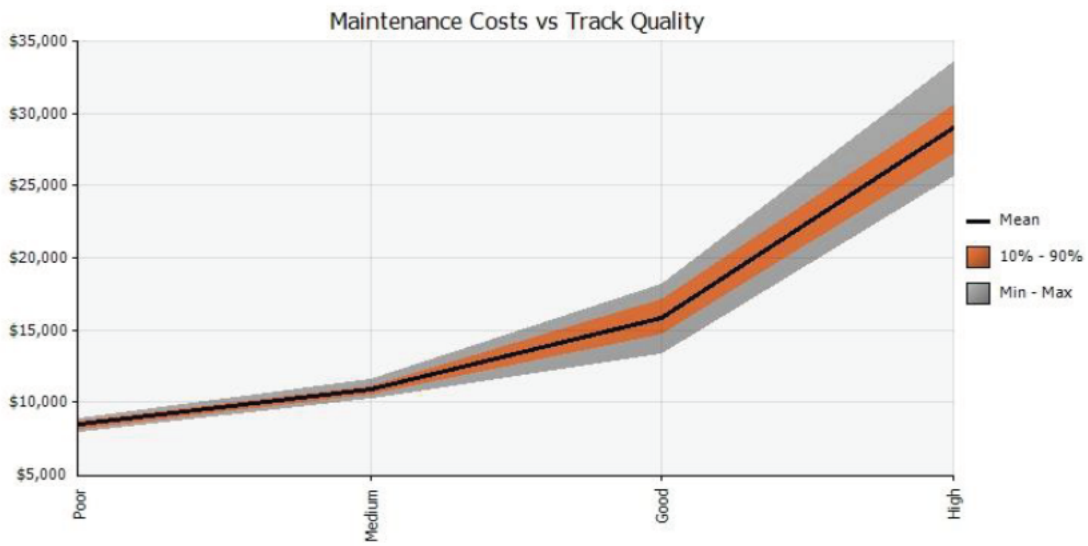


*Figure 7 (a) Maintenance Costs vs Track Quality on Trans-Australian route*


*Figure 7 (b) Safety Risk of Derailments vs Track Quality on the Trans-Australian line*


*Figure 7(c) Derailment Risk reduction by upgrading Track Quality on the Trans-Australian Route*

## 7. Analysis

The railway networks in both Sweden and Australia are managed and operated in a similar way i.e. the railway infrastructure is owned and governed by a public organisation/government, while maintenance is carried out by a separate organisation. The routes selected for the analysis are both heavy haul freight lines. Though both the routes operates in different environmental conditions, the maintenance performance indicators were found to be similar (Ahren et al., 2004).

The safety performance of the railway track is often compromised by the occurrence of derailments. Upgrading the track quality to improve safety was explored on both routes and found to have a similar trend (see Fig 6c and 7c). For e.g. upgrading the track quality from poor to medium offers the greatest risk reduction (more than 75%) for track quality related derailments. With 90% confidence level, it can be observed that the track quality upgradation from good to high, offers less risk reduction than from medium to good.

Apart from safety improvements, upgrading the track quality also reduces delays and environmental impacts. However, track quality upgradation results in increase of investments in the maintenance costs. Three maintenance strategies were considered in terms of upgrading the track quality: poor to medium, medium to good, good to high. It was based on the assumption that permissible train speeds increase in accordance with upgradation of track quality. With a 90% confidence, analysis on the Australian route shows that, upgrading the track quality from poor to medium would be approximately 26% costlier, while medium to good and good to high would cost more than 70%. Similar trend is observed in Sweden, where poor to medium track quality is approximately 17% costlier, with medium to good and good to high costing 83% and 51% respectively. While considering a trade-off between maintenance costs and associated safety impacts, maintaining the track sections on the heavy haul lines in Sweden and Australia at medium track quality would be a sustainable approach to track maintenance (see Figures 6 and 7).

## 8. Discussions

Infrastructure owners and maintainers, in both developing and developed countries are often pressurised to improve the safety performance of their transport systems. In order to avoid the risks of derailment, stringent safety standards have to be followed, which in turn increases railway maintenance investments. These investments depends on the availability of funds and the acceptable level of safety risks.

A sustainable maintenance strategy would be able to balance the maintenance costs with risks, while ensuring that the spending is within the maintenance budget. Train accidents, such as derailments, cause damage to infrastructure and rolling stock, service disruptions, casualties and harm the environment. The risk of train derailment is an ongoing concern for the railway industry, government and the public; bearing a heavy social imprint. Permissible safety risk limits could be imposed within track maintenance strategies for individual track sections, triggering track quality upgrades when required. Identifying high-risk track sections within the route would also aid in allocating maintenance budgets effectively.

To this end, the proposed risk-informed approach can aid the decision makers to arrive at safe-minimum track maintenance appraisals. The above notwithstanding, the proposed risk-informed approach aids the decision maker to compare the track maintenance budget with the associated safety performance and thus set sustainable track maintenance strategies.

## 9. Conclusion

The railway industry is undertaking significant efforts in involving risk-informed methods for optimising cost and safety at different stages. Railways is seen as the backbone of sustainable transport policy and there is an increasing trend in its demand and usage. This in turn puts pressure on the railway track infrastructure to be maintained economically, while ensuring operational safety. To this end, a risk-informed approach to setting maintenance strategies for the ballasted railway track is proposed and applied to case studies of heavy haul routes in Sweden and Australia. The paper also discusses the improvement of railway track quality as a measure to reduce risk of derailments, while ensuring a balance between maintenance budgets and safety policies. To this end, the proposed approach aids the decision makers to get a better understanding of safety risks, the impacts of risk mitigation decisions and thus enable seamless operation.

## 10. Acknowledgements

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# A REVIEW OF RISK MANAGEMENT APPLICATIONS FOR RAILWAYS

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ABSTRACT

The UK railway infrastructure is carrying ever increasing amounts of railway and freight traffic which in turn is causing accelerated rates of infrastructure deterioration. Given the pressure to increase track utilization, the ageing infrastructure on which much of the UK's railway is founded, and the constrained budgets under which the infrastructure is managed, appropriate maintenance needs to be predicted, prioritized, planned and carried out efficiently and effectively. Safety is also a paramount consideration in the operation of the UK's railways. To effectively manage the railways under these constraints, there is a need to develop asset management procedures which incorporate risk management concepts so that, periodic maintenance requirements can be predicted in advance of track failure and prioritised, and identified risks and uncertainties can be considered within the decision-making processes. The paper critically reviews current risk management practices in the railway industry to identify suitable risk management models and suggests recommendations for their further improvement and incorporation within asset management.

INTRODUCTION

The railways are an important part of many countries economic and social development and in recent years, many such countries have experienced significant economic, environmental, social and political pressures to increase operation and safety. In Great Britain, although there has been significant investment in several high-profile schemes, the size of the railway network has not changed significantly in the last 20 years and the network is now the second most intensively used in Europe. Passenger journeys reached 1.69 billion in 2015-16, representing a 129.8% increase from the 735.1 million passengers recorded at privatisation in 1994-95 (Office of Rail and Road, 2016). Although safety is of critical importance to railway operators, such intensive use of the railways increases the likelihood of accidents. In Great Britain, there were 759 train accidents reported in 2015-16 of which 25 were Potentially Higher Risk Train Accident (PHRTA), resulting in at least one death, considerable delay costs, track downtime and damage to property. For many accidents (such as derailments) preventive maintenance is a key factor in their reduction. The total rolling stock and railway track infrastructure costs of a significant derailment in Great Britain is estimated to be £6.5 million (RSSB, 2015). Great Britain's Railway Safety Standard Board (RSSB) in its efforts to improve railway safety suggests that, the railway industry needs to consider in decision making factors such as the costs and benefits of reducing risks. Integrating risk management and asset management would facilitate this and tackle the challenges of restricted budget and limited data in managing assets.

RISK MANAGEMENT

The Institute of Risk Management (IRM) states that *"risk management should be a continuous and developing process"* and should be able to address all the risks of past, present and future. Risk management, per ISO3100 (2009) is defined as *"coordinated activities to direct and control an organisation with regard to risk"*. In its simplest form risk is given by:

$$\text{Risk} = \sum_i N_i \, p_i \qquad \text{- Equation 1}$$

where $N_i$ is the consequence (e.g., persons killed or injured, damage caused) and $p_i$ is the probability of occurrence of the risk.

Risk management involves the processes of risk identification, risk assessment, risk evaluation, risk response and risk monitoring (see Figure 1). Risk identification enables the activities involved to be identified and the associated risks to be defined. Risk assessment allows the evaluation of the likelihood of a risk occurring together with its possible outcomes or consequences. The objective of risk assessment is to develop a rational foundation for objective decision making by systematically using the available information to estimate the risks involved (Sadeghi et al., 2010; Salling, 2011; Chen, 2013; Grote, 2015; Torbaghan et al., 2015). This allows the decision-maker to foresee the effect of any risk (Salling, 2011). The risk assessment depends upon the type of risk involved, aim of the analysis, availability of data and resources (Chen, 2012). The assessment methods could be quantitative, qualitative or semi-quantitative in nature. While quantitative methods use numerical values for the analysis of probability and consequences, quantitative methods are based on the knowledge and judgement of the assessor. The risk evaluation phase determines whether a risk is tolerable or not allowing decision makers to take steps or actions to control or monitor the risk. Risk monitoring is the final stage where risk control methods are implemented.

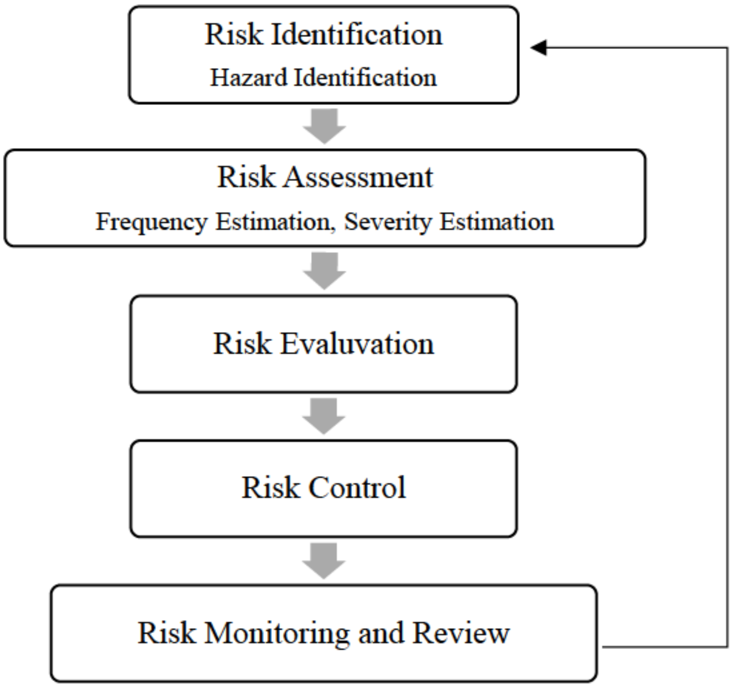


*Figure 6 Risk management process*

Various techniques to carry out risk management are described in the literature. These include using decision trees, Markov models, Monte Carlo simulation, survival and hazard functions, fuzzy logic, fault trees and sensitivity analysis for applications in heat transfer, transportation, health risk assessment, computer models etc. (Cho et al., 2011; Tom et al., 1997; An et al., 2006, 2011, 2013; Sadeghi et al., 2010; Peng et al., 2014; Trivedi et al., 2015). Several authors have developed integrated approaches for various applications. While Karunarathna et al. (2013) developed Markov-Monte Carlo simulation for bridge deterioration modelling; Faghih-Roohi et al. (2014) used it for accident risk assessment in marine transportation. Fuzzy-Analytic hierarchy process was used by Verma et al. (2014) for risk assessment in mining industry. Gharehdaghi et al. (2015) employed an integrated Fuzzy and Markov for solving a system of linear algebraic equations. Fuzzy reasoning and Monte Carlo were combined for uses in various industries which are illustrated in Table 2 (Sadeghi et al., 2010; Arunraj et al, 2013; Jahani et al., 2014; Gharehdaghi et al., 2015). Monte Carlo-Bayesian network was developed by Smid et al. (2010) for microbial risk assessment. Risk analysis of high speed and conventional railway lines by integrating human errors was done using Markovian-Bayesian network (Castillo et al., 2015).

In the railway industry, risk is primarily associated with safety and economic management (Cox et al., 2003). In an idealized railway network, different stakeholders collaborate to effectively deliver their safety responsibilities through safety management systems (SMSs), reporting systems, safety standards and using common safety methods, techniques and tools. Railway safety risk assessment is designed to assess risks arising from hazards/events which could lead to fatalities, minor or major injuries, loss to private and public property. As the railway industry encompasses several stages of design, construction, operation and maintenance, there are various safety disciplines and regulations with which to comply. Each stage involved, has associated risks with different magnitude and nature. Furthermore, the total risk is influenced by the probability and consequence of the identified events. Considering the variability of parameters governing consequences, the range of conditions considered can be extensive.

Generally, the railway industry is safety conscious and accordingly much of risk management in railways focuses on the prevention of accidents resulting from derailments and system failures or degradation, which can result in a derailment (Zarembski et al., 2006). Berrado et al. (2010) argues that, in addition to the various legislative changes in the European railway industry, technical changes also create confusion resulting in an overall increase in accident risk. A variety of approaches to railway risk management have been developed to address these challenges. A number of these approaches are summarised in Table 1.

**Table 1: Risk Assessment methods in railway industry**

| Application | Qualitative | Quantitative |
|---|---|---|
| Buildings | Horner et al. (1997) | Dolsek (2012) |
| Lighting | Aberg (1988) | |
| Electricity | | Chattopadhyay et al. (1995), Cosulich et al. (1996) |
| Access ways | | Jafarian et al. (2012) |
| Level crossings | RTA of NSW (2011) Rajayogan et al. (2012) | Cirovic et al. (2013), Liu et al. (2014) |
| Engineering structures | | Stein et al. (1999), Liu et al. (2004), Lounis (2006), Frangopol et al. (2007), Orcesi et al. (2010), O'Connor et al. (2011), Yuan et al. (2013) |
| Ground | Power et al. (2016) | Vanneuville et al. (2005), Jaedicke et al. (2013), Rathje et al. (2013) |
| Tracks | | Budai et al. (2004), Zio et al. (2007), Zhao et al. (2006, 2007, 2009), Zhang et al. (2013b) |
| Station | | Liu et al. (2015) |
| Network | | An et al. (2007) |
| General | Haile (1995) | |

Network Rail, the owner, operator and asset manager of the majority of Great Britain's railway network, approaches risk management through the application of Enterprise Risk Management (ERM) process. ERM employs a framework with a standardised approach to the identification, assessment and recording of risks for analysis and mitigation purposes. The ERM identifies risks on a day to day operational basis feeding the risk management strategies put in place.

Following the lead of other industries, the railway industry, because of pressures associated with growing demand on already congested networks, is increasingly focusing on the application of risk management approaches to railway maintenance and management (Elcheikh and Burrow, 2016; Zhao et al., 2014, Cheeseman., 2006). In such approaches failure is predicted using a variety of methods, the risk of the predicted failure quantified, enabling preventative maintenance to be carried out and prioritised. In such approaches fault diagnosis methods and failure prediction are key components (Dadashi et al., 2011). The first step required is to reduce the probability of failures by identifying when the interventions should be executed (Martani et al., 2016). Hence the mechanism involved should be based on a predictive identification of the boundaries of safe operation and maintenance. Ideally, such a mechanism would involve a dynamic function based on expert knowledge and historical data, albeit where uncertainty cannot be avoided. Network Rail, for example, has developed a strategic Decision Support Tool (DST) known as SCAnNeR (Strategic Cost Analysis for Network Rail), which prioritises intervention and budgets for the maintenance of earthworks based on the risk profiles of asset portfolios (Power et al. (2016)

There are several challenges associated with such an approach in the railway context, where the risk data is incomplete or there is a high uncertainty involved in the risk data (An et al., 2016). In many situations, it might be extremely difficult to predict probability and magnitude of hazards through probabilistic risk assessment, due to the uncertainty with the risk data. Patra et al., (2009) observed that uncertainty in railways could also exist in costing, reliability and maintainability parameters

The use of expert opinion is often suggested as a means of overcoming such issues (Torbaghan et al. 2015). Important considerations when utilizing expert option include (Terje, 2016):

- How can the risk assessment results, which currently are based on expert judgement and historical data, aid effective decision making?
- How can we know that the expert judgement is good enough?
- How can we accurately represent uncertainties, for proper justification of risk management practices?

The possibility of using an integrated Monte Carlo – Fuzzy approach to address these issues, is discussed below.

## INTEGRATED MONTE CARLO - FUZZY APPROACH

While solving real-life problems, both uncertainty and imprecision could be encountered. When there is access to accurate and reliable data, probabilistic modelling like Monte Carlo (MC) could be employed. If the risk assessment involves expert opinion or judgement, a Fuzzy Reasoning approach (FRA) would be essential. Many authors have combined MC and Fuzzy reasoning to arrive at risk management practices for different sectors (refer to Table 2).

The Monte Carlo (MC) method is a widely used statistical method in probabilistic risk assessment, which involves simulation of uncertain and variable ranges applicable to the situation and provides probable results and their probability of occurrence (Loyd, 2004). It generates results that depend on variables or factors defined as probability distributions. The method selects input values based on the probability of the event happening, to simulate the model, where the variables have a definite range of values but an uncertain value for any time or event. It has been proved mathematically that through iterations, an accurate result of the entire range of possible scenarios can be examined.

It has been studied that the accuracy of the result from MC simulation depends on precision of the input parameters. The major disadvantage faced with respect to this simulation is the unavailability of sufficient data to establish the accuracy of input parameters. The MC technique is employed to solve any problem, irrespective of its complexity, dimension, or non-linearity (Jahani et al., 2014). The output of the probability distribution can greatly affect the outcome of the MC analysis and it is extremely important that a proper distribution is selected. A drawback of MCS is that large amounts of data are required to generate the required probabilistic distributions, since it helps the better characterization of variability. Furthermore, the MCS produces samples of the data set are more likely to be centred on areas of high probabilities of occurrence in the distribution, resulting in that distribution being sampled more often around the expected value than at the low and high-end values. The values outside the range of distributions inputted are not represented in the outputs and hence their impacts on the results are not incorporated in the simulation output. Clustering becomes a major problem when trying to model events with low probability outcomes but high impact, for example, accidents in railway can be caused due to several reasons with different probabilities and consequences. It could range from risks due to fire hazards to derailments due to train collisions, both of high impacts but with different probability of occurrence.

As mentioned earlier, decision makers often resort to expert opinion due to lack of suitable data. Expert opinion could however be lacking for events which has low probability of occurrence. In railways, most of the risks involved are of low probability but high impact, which are not accurately portrayed using Monte Carlo. Techniques which can appropriately deal with sources of uncertainty and cope with events of low probability but high impact are necessary to model expert opinion within a railway risk management approach. One of the appropriate tool for such situations, is Fuzzy Reasoning. The fuzzy reasoning theory was introduced in 1965 by Lotfi A Zadeh, who proposed it for dealing with sources of uncertainty or imprecision that is of non-statistical nature. Fuzzy reasoning successfully handles non-probabilistic uncertainties arising from subjective and linguistically expressed data and is therefore appropriate for capturing expert opinion (Sadeghi et al., 2010; An et al., 2006 & 2011). Furthermore, fuzzy mathematical reasoning considers extreme events to be of the same importance as the most likely ones which makes it application to the railway environment attractive. In a railway context, An et al. (2006) proposed fuzzy reasoning in the risk assessment of accidents in railway depots. For such accidents at platform train interface, the probability for minor injury was high and fatality was low. Even though the risk scores were different, employing fuzzy logic ensured that all the possible outcomes were equally considered.

Hence a combination of MC Simulation and FRA will be able to study both the likelihood and consequences of a failure event that is uncertain in natural and linguistic form. A combination of MCS and FRA has been used in a variety of industries, as summarized in Table 2. However, as yet the approach is in its infancy in the railway industry, albeit there is considerable opportunity for it to be used. The approach could be used successfully in risk management of derailments where most of the incidents are unique and only limited data is available. In a risk management approach, MC may be used to model costs involved, whereas Fuzzy logic would be more appropriate to ensure the operation of unmanned level crossings. By combining the advantages of both simulation techniques, the decision makers can resort to subjective judgment, as they have access to both fuzziness and probabilistic uncertainties (Sadeghi et al., 2010).

**Table 2: Applications of Risk management models combining MC and FRA**

| Industry | Models | Applications |
|---|---|---|
| Health | Kental et al. (2005)<br>Sallak et al. (2008) | Health risk modelling<br>Health safety instrumented systems |
| Environment | Chen et al. (2003, 2010)<br>Baudrit et al. (2005, 2006)<br>Li et al. (2007)<br>Hall et al. (2007)<br>Heng et al. (2008)<br>Rehana et al. (2009)<br>Qin (2012)<br>Yu et al. (2013) | Ground water systems<br>Ground water contamination<br>Ground water contamination<br>Climate change<br>Health impact from air pollution<br>River water quality management<br>Pollution control problems<br>Flood damage assessment |
| Construction | Davis et al. (1997)<br>Sadeghi et al. (2010)<br>Jahani et al. (2014) | Slope stability predictions<br>Cost range estimating<br>Reliability assessment |
| Electricity | Reddy et al. (2008)<br>Wenyuan et al. (2008)<br>Canizes et al. (2011)<br>Canizes et al. (2012)<br>Nascimento et al. (2016) | Faults on transmission lines<br>Power system risk assessment<br>Electricity network distribution<br>Electricity network reconfiguration<br>Power optimization |
| Chemical | Arunraj et al. (2013) | Benzene extraction risk analysis |
| Nuclear | Baraldi et al. (2008) | Maintenance modelling |
| Information Technology | Ustundag et al. (2010) | Radio frequency identification |
| Transportation | Zonouz et al. (2006)<br>Duru et al. (2010)<br>Wanke et al. (2016) | Reliability of critical systems<br>Uncertainty in ship investment<br>Airline industry safety |
| Hybrid MC-Fuzzy methodologies | Guyonnet et al. (2003)<br>Diego et al. (2009)<br>Banomyong et al. (2010)<br>Innal et al. (2013)<br>Gharehdaghi et al. (2015)<br>Dreakar (2015) | Authors developed methodologies for models integrating MC and Fuzzy |

## CONCLUSION

The railway industry worldwide is undertaking significant efforts in involving risk-informed methods to support decision making. A number of such approaches have been described in this paper. Many railway networks are under pressure to increase track utilization and at the same time maintain or improve safety. To address this, asset management procedures which incorporate risk management concepts are being developed. These enable periodic maintenance requirements to be predicted in advance of track failure and prioritised, and identified risks and uncertainties can be taken into account within the decision-making process. For some such applications in the railway industry, there is a lack of data required for accurate analyses and often expert opinion is used to augment the available data sets. Whilst a number of risk assessment models may be utilized, the integration of Monte Carlo with Fuzzy Reasoning has been proven to be effective for a number of applications in various industries. It could be especially pertinent to the railway industry as it would enable the uncertainties associated with data and the credibility of expert judgement to be dealt with. Such an approach would enable risk management officials and the decision makers to get a better understanding of risks, the impacts of risk mitigation decisions and thus enabling efficient asset management.

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A Whole Life Cycle Approach under Uncertainty for Economically Justifiable Ballasted Railway Track Maintenance


## Abstract

Historically, railway track maintenance strategies have been based on engineering judgement taking into account available budgets and operational safety. This has led to insufficient concern of the socio-economic and environmental costs and benefits of track maintenance. Given the pressure to increase track utilization, the ageing infrastructure of railway networks, constrained maintenance budgets, the vertical separation of the ownership and operation of railway track infrastructure and rolling stock in many countries, and concerns about the environmental impacts of transport, there is a need to implement economically justifiable maintenance strategies. To this end, this paper presents for the first time an approach to appraise the investment in railway track maintenance. The approach uses a whole life cycle cost analysis under uncertainty approach which considers the costs and benefits of track maintenance to train operators, users and the environment. Monte Carlo simulation technique is used to address data uncertainties associated with the costs and benefits of track and train operation and maintenance. The proposed approach is applied to three different route types on the UK main-line railway network to compare a number of alternative maintenance strategies. In all the three cases more economically beneficial strategies were identified in comparison to those currently adopted.

## 1. Introduction

Railways are a major component of a sustainable transport policy in many countries since they are considered as green, efficient and a safe mode of transportation. Consequently, there is an increasing demand for the railway industry to expand capacity, availability and to transport goods and people at higher speeds. By 2025, railways are expected to carry 11,912 billion tonne-kilometre of freight and 5,149 billion passenger-kilometre worldwide, increases of 14.75% and 37.2% respectively from 2015 (SCI, 2017). However, in many countries, investment in the expansion of railway infrastructure has not kept up with the demand for increased usage. In the United Kingdom for example, passenger journeys have increased by approximately 4.8% between 2010-11 and 2016-17 without any significant increase in the amount of railway infrastructure, making the UK railways Europe's second highest congested railway network (ORR, 2017). Similarly, during the same period passenger numbers in the United States have risen by 11% with only a 4.8% increase in railway track length (APTA, 2017) and in India the corresponding figures are 6.0% and 4.5% respectively (MoIR, 2017). Such increasing track usage will result in faster degradation and therefore higher maintenance costs. For example, the spending on maintaining railway track infrastructure in USA (FRA Class 1 rail roads), UK and India during 2016-17 was \$9.8 million, \$775 million and \$2.08 billion respectively, which was 1.2%, 3.8% and 24% higher than in the previous year (APTA, 2017; ORR, 2017; MoIR, 2017).

There is therefore an increasing pressure for railway infrastructure maintainers to make the best use of their available resources. For traditional ballasted railway track in particular, railway track maintenance directly affects the condition of the railway track and therefore, the likelihood of accidents, rolling stock fuel and maintenance costs, travel time costs and emissions. A well-maintained track not only guarantees ride comfort and safety but also increases the life of the track as well as track availability (due to the lack of imposition of speed limits). Therefore, to enable a green, efficient and safe railway system there is a need for effective asset management which systematically considers Whole Life Cycle Costs (WLCC) and benefits over the lifetime of the asset (See Figure 1) (ISO, 2008). Such an approach helps to identify cost drivers and cost-effective improvements, enables the comparison of alternative maintenance strategies and the prioritization of maintenance funds (Jun et al., 2007).

Currently however, maintenance decisions for ballasted railway infrastructure are largely based on time, tonnage or predetermined subjective maintenance standards, which ignore the costs of operation and maintenance. Thus they fail to optimise maintenance interventions and therefore do not deliver maximum benefits (Atkins, 2011). This culture is gradually changing for the reasons described above and the sector is moving towards preventative condition-based maintenance (van Noortwijk et al., 2004). The publication of asset management standards and guidelines which advocate WLCC approaches, including ISO 15686-5 (2008) and EN 60300-3-3 (2009) has added additional impetus. As a result, railway infrastructure and rolling stock organisations have started to develop their own asset management tools which incorporate some WLCC principles. These initiatives have been supported by academic research, a summary of which is presented in Table 1.

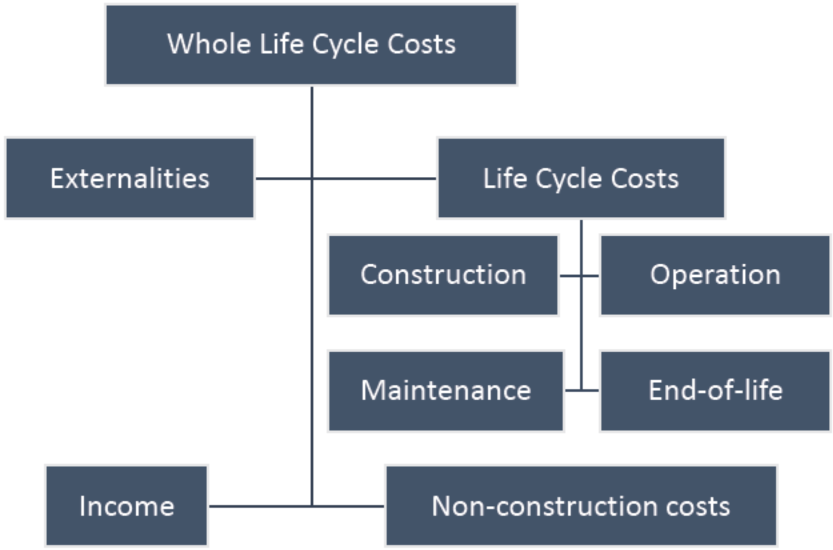



*Figure 7 Whole Life Cycle Costs adapted from ISO 15686-5 (2008)*

There are, however, a number of limitations of the suggested approaches to track substructure maintenance shown in Table 1. In particular, they do not consider all transport costs which, as well as future railway track infrastructure maintenance costs, should also take into account railway track use costs and mode change costs. Railway track use costs include rolling stock operation costs (i.e. fuel consumption and maintenance costs), capacity lost costs, accident costs and environmental impacts. Mode change costs are those associated with the change in use of rail compared to other modes (primarily road and air) due to track infrastructure investment. However, Whole Life Cycle Cost Analysis (WLCCA) approach requires predicting these future costs and benefits of railway track. For existing railway track in particular there is often a paucity of construction, condition and historical maintenance data. This makes future predictions of track deterioration, and therefore track condition and track use costs uncertain (Andrade, 2016; Asplund et al., 2016; Kirkwood et al., 2016; Skinner et al., 2011). It is under conditions of uncertainty that decision makers must evaluate, compare and select among alternative strategies, the economically justifiable one. To address these issues, this paper describes a WLCCA approach under uncertainty to determine the most economically beneficial railway track substructure maintenance strategy for traditional ballasted railway track. To this end, the proposal approach provides railway policy and decision makers, for the first time, a means to appraise maintenance investment strategies by considering environmental, safety, social and economic costs and benefits.

*Table 1 Overview of Life Cycle Costing Models for Railway Track and Rolling Stock*

| Author/Project | Description | Features considered within the model | | | | | | | | | | WLCC Approach | Application | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Asset Deterioration | Cost Elements | | | | | | | | | | | | | | |
| | | | Design/Construction | Maintenance | | Operation | | | | | End of Life | | | | | | |
| | | | | Track | Rolling Stock | Capacity Lost | Fuel / Energy | Environment | Risk of Accident | Socio-Economic Impacts | | | Track | Signaling | Electrification | Rolling Stock | Infrastructure |
| Lamson et al., (1983) | Proposed a method for application of decision network analysis to railway track maintenance and replacement optimization. | ✓ | | ✓ | | | | | | | | | ✓ | | | | |
| STAMP (2000) | Network Rail's single asset decision modelling tool to evaluate maintenance and renewal options for structural assets | ✓ | | ✓ | | ✓ | | | | | | ✓ | | | | | ✓ |
| Zoeteman (2001) | A LCC approach to support decision-making system for design and maintenance decisions | ✓ | ✓ | ✓ | | ✓ | | | | | | | ✓ | | | | |
| Zhao et al., (2006) | Develops a LCC model for optimising railway ballast maintenance policies | ✓ | | ✓ | ✓ | ✓ | | | | | | | ✓ | | | | |
| Reddy et al., (2007) | Employs a LCC approach for optimising rail maintenance based on rolling contact fatigue, traffic wear, rail grinding interval and lubrication | ✓ | | ✓ | ✓ | ✓ | | | ✓ | | | | ✓ | | | | |
| Antoni et al., (2008) | Developed statistical model to estimate lifetime and maintenance costs throughout life cycle of railway assets | | | ✓ | | ✓ | | | | | | | ✓ | ✓ | ✓ | | |
| Patra et al., (2009) | Presents a methodology for estimating uncertainty related to LCC within a developed track maintenance cost estimation model | | | ✓ | | ✓ | | | | | | | ✓ | | | | |
| INNOTRACK (2009) | The project aimed to develop a cost-effective high-performance track through reduced LCC and improved RAMS and developed various tools such as D-LCC, CATLOC, LCCWare etc. | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | | | ✓ | | ✓ | | | | |
| InfraCaLCC (2010) | A commercial software that calculates rail infrastructure LCC from the existing databases. | | | ✓ | | ✓ | ✓ | ✓ | | ✓ | ✓ | | ✓ | | | | ✓ |
| De Jong et al., (2012) | An integrated LCC-SEC assessment approach proposed as part of Urban Track project to aid the development and construction of modular track systems for tram, metro and light rail. | | ✓ | ✓ | | ✓ | | ✓ | | ✓ | ✓ | | ✓ | | | | |
| VTISM (2012) | Integrates several models, i.e. VAMPIRE, WLRM, T-SPA, WPDM, and W-SPA to optimise rail and wheel life and maintenance regimes | ✓ | | ✓ | ✓ | | | | | | | ✓ | ✓ | | | ✓ | |
| Zhang et al., (2012) | A genetic algorithm approach for maintenance scheduling at a minimal overall cost | ✓ | | ✓ | | ✓ | | | | ✓ | | | ✓ | | | | |
| Mokrousov et al., (2013) | Developed a LCA method which can be applied to different rail elements | ✓ | | | ✓ | | | | | | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ |

| Author/Project | Description | Features considered within the model | | | | | | | | | | | Application | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Cost Elements | | | | | | | | | WLCC Approach | | | | | |
| | | | | Maintenance | | Operation | | | | | | | | | | | |
| | | Asset Deterioration | Design/Construction | Track | Rolling Stock | Capacity Lost | Fuel / Energy | Environment | Risk of Accident | Socio-Economic Impacts | End of Life | | Track | Signaling | Electrification | Rolling Stock | Infrastructure |
| LCAT (2013) | Life Cycle Assessment Tool was developed as part of the MAINLINE project to reduce the economic and environmental impacts of maintenance, renewal and improvement of railway infrastructure | ✓ | ✓ | ✓ | | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | | | |
| Arasteh khouy et al., (2014) | Proposes optimization of track geometry inspection interval to minimize total ballast maintenance costs while considering risk of accidents due to poor track quality | ✓ | | ✓ | | | | | ✓ | | | | ✓ | | | | |
| Caetano et al., (2014) | Introduced an optimization model to schedule track renewal operations using a LCC approach | ✓ | | ✓ | | | | | | | | | ✓ | | | | |
| Gattuso et al., (2014) | Proposes a set of cost functions for the estimation of regional railways investment and operating costs | | ✓ | ✓ | ✓ | | | ✓ | | | | | ✓ | ✓ | ✓ | ✓ | |
| Zhang et al., (2014) | An approach combining expert knowledge and historical data, and cost modelling for maintenance strategy optimization | ✓ | | ✓ | | | | | | | | | ✓ | | | | ✓ |
| Banar et al., (2015) | LCA and LCC method to assess the environmental and economic impact on transportation systems | | ✓ | ✓ | ✓ | | | ✓ | | ✓ | ✓ | | ✓ | | | ✓ | |
| Fang et al., (2015) | Model to predict LCC of maintenance strategies for rolling stocks | | ✓ | | ✓ | | | | | | | | | | | ✓ | |
| Zhang et al., (2015) | A LCC model for real-time condition monitoring in railways and metro systems under uncertainty approach | ✓ | | | ✓ | ✓ | | | | | | | | | | ✓ | |
| Fourie et al., (2016) | Developed and tested a LCC framework for mission-critical assets with emphasis on cost of ownership and effective maintenance and renewal strategies | ✓ | | | ✓ | | ✓ | | | | | | | | | ✓ | |
| Rama et al., (2016) | A modelling framework for evaluating multi-asset infrastructure LCC with a whole-system context | ✓ | | ✓ | ✓ | ✓ | | | | | | | ✓ | | | | ✓ |
| Jones et al., (2017) | A LCA approach to study the environmental impact of a high-speed rail | | | ✓ | ✓ | | | ✓ | | | | | ✓ | | | ✓ | |
| Smith et al., (2017) | A methodology to estimate the relative marginal cost of railway maintenance | ✓ | | ✓ | ✓ | | | | | | | | ✓ | | | | |
| Vitasek et al., (2017) | A LCC method to optimise design of railroad switches | | | ✓ | | ✓ | | | | | ✓ | | ✓ | | | | |
| Su et al., (2017) | A railway track maintenance optimisation approach considering uncertainty and train scheduling | ✓ | | ✓ | | ✓ | | | | | | | ✓ | | | | |
| Su et al., (2019) | An optimisation approach of maintenance considering uncertainty and maintenance scheduling | ✓ | | ✓ | | ✓ | | | | | | | ✓ | | | | |

## 2. Total Transport Costs

This WLCCA model proposed considers the direct and indirect costs and benefits to all stakeholders (owners, operators, maintainers and users). The WLCC considered are those associated with ballasted track construction, maintenance, de-commissioning, track use, mode change and the environment. Together these are considered herein to represent total transport costs. Railway track maintenance costs are those to do with the direct costs to inspect and maintain the railway track structure and the indirect costs associated with track maintenance such as delays, accidents and emissions (ITF, 2013). Track use costs include train operation costs (i.e. the maintenance of rolling stock, fuel consumption and derailments), environmental costs and travel time. Mode change is associated with perceived change in socio-economic costs incurred by railway users. De-commissioning costs are associated with disposing of track assets at the end of their useful life.

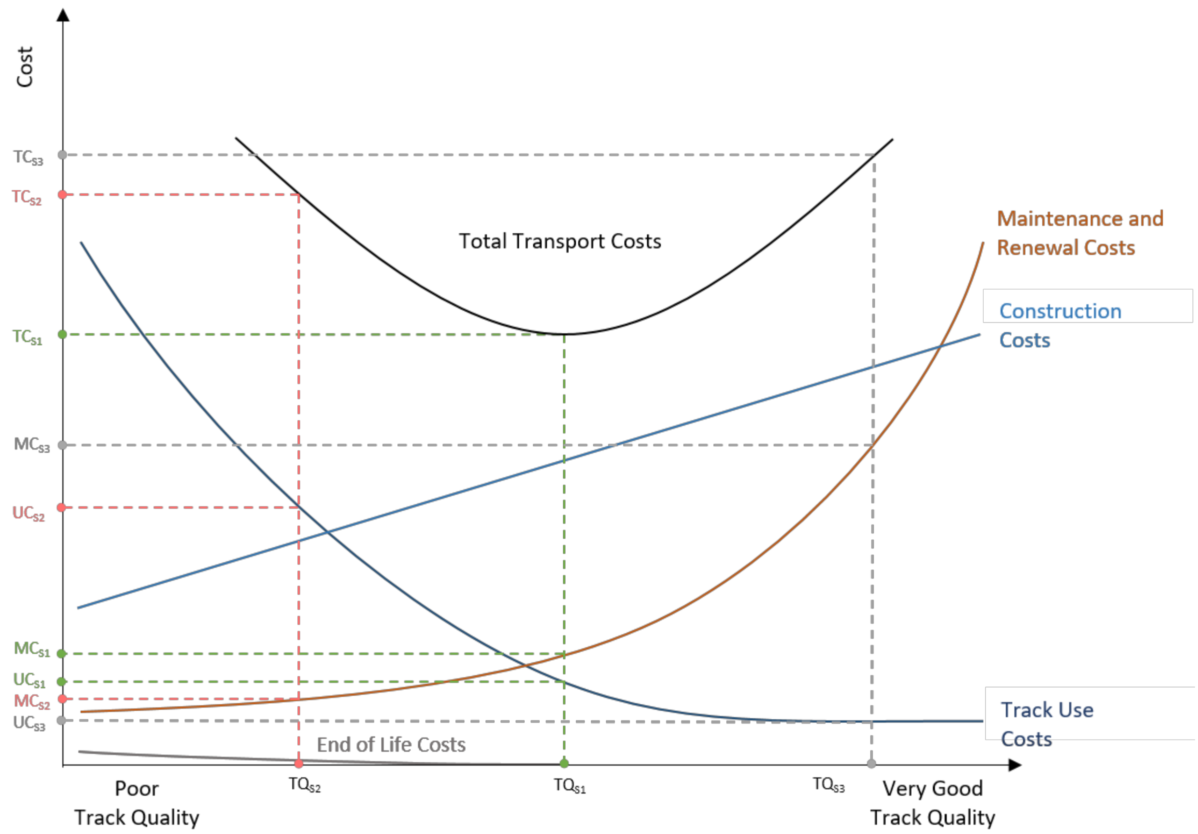



*Figure 8 Optimal railway track maintenance standard*

Figure 2 conceptualises the different cost elements that might occur within the life cycle of a section of railway track, as a function of the average track condition. Achieving a higher average track condition requires higher maintenance and construction costs. On the other hand, as track condition improves railway track use costs decrease non-linearly. The minimum total transport cost in Figure 2 (point $TC_{S1}$) yields the ideal average track condition $TQ_{S1}$, or optimal maintenance standard. Point $MC_{S1}$ is the maintenance cost of achieving this standard. Achieving a track condition ($TQ_{S2}$), less than the ideal track condition, saves in maintenance costs ($MC_{S2}$) but results in an increase of railway track use costs ($UC_{S2}$). This increase in track use costs is greater than the savings in maintenance costs compared to the optimal maintenance standard ($TQ_{S1}$) and therefore results in higher total transport costs. On the other hand, a track condition, $TQ_{S3}$, greater than the ideal condition causes a reduced railway track use costs of $UC_{S3}$ with an increase in maintenance costs ($MC_{S3}$). However, in this case the savings in track use costs compared to the increase in maintenance costs also result in higher total transport costs compared to the optimal maintenance standard.

## 3. Track deterioration and maintenance

For traditional ballasted railways, track geometry is used as a measure of the integrity of the track substructure, passenger comfort and the safety of train operation. It is also used by railway asset maintainers as the primary measure to trigger track substructure maintenance and renewal (M&R) activities (Guler et al., 2011). Furthermore, track use costs are also a function of track geometry (Zarembski et al., 2010). Consequently, for the research described herein the WLCC approach advocated uses track geometry as the sole measure of track condition. Maintenance intervention levels and track use costs therefore are assumed to be a function of track geometry (see Figure 3). Track geometry is usually described in terms of vertical and horizontal track geometry and it is normally measured using instrumented measuring trains (Guler, 2013) at time intervals based on the traffic volume and the line speed (Prescott et al., 2013). The standard deviation of these measurements over a predetermined length (e.g. track sections of 200m length in the UK) is used in track maintenance standards to specify permissible deviations from the ideal.

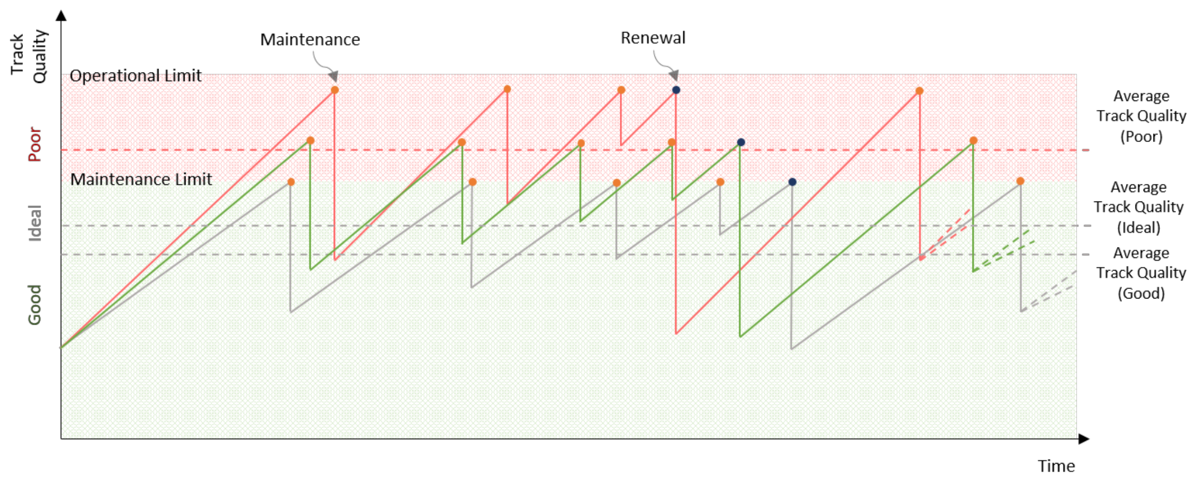



*Figure 9 Track Geometry Deterioration*

Over time, the combined damaging effects of rolling stock and the environment causes railway track geometry to worsen, necessitating track substructure maintenance. A variety of maintenance techniques are used depending on the component of the track substructure requiring maintenance. The most commonly used methods to correct vertical track geometry faults are tamping and stone blowing. These techniques are henceforth referred to as track realignment (Cellmer et al., 2016). Track realignment restores the track geometry by compacting the ballast under the sleepers, allowing the repositioning of the rails and sleepers. Poor track geometry coupled with the occurrence of fines within the ballast can necessitate ballast cleaning. The occurrence of fines within the ballast can be caused by ballast attrition resulting from loads imposed on the ballast by rolling stock, the upward migration of fines from the sub-ballast or subgrade, or the destructive effects of tamping on ballast particles during maintenance (Selig et al., 1994). Ballast attrition and the migration of fines are exacerbated by excessive dynamic train loads which can result from poor track or rolling stock condition (Burrow et al., 2017). The presence of fines within the ballast reduces interlocking between ballast particles and permeability, and therefore the ability of the ballast to carry train loads, subsequently affecting track geometry. Ballast cleaning removes the fine material and replaces the worn out ballast with fresh material. Eventually, when the ballast reaches the end of its useful life, it is replaced (i.e. renewed).

Track maintainers are therefore tasked with devising maintenance strategies which need to consider track deterioration rates, acceptable track geometry levels, and maintenance budgets, track down time and train schedules. Further, due to logistical constraints associated with budgets, machinery, human resources and the availability of the railway track, maintenance activities need to be planned at least one year in advance (Quiroga et al., 2011). Railway track maintenance is further complicated by the ever-increasing utilisation of railway networks and the pressure to make the railway continuously available, as mentioned above. Figure 3 shows how different maintenance strategies can result in different average track geometry values over time. Higher (worse) average track geometry values overtime result in higher railway track use costs. A challenge therefore when devising economic track maintenance strategies is to weigh the railway track inspection and maintenance costs required to keep the track to a given average value over time, against the associated railway track use costs.

## 4. Uncertainty

While employing WLCCA to aid decision making for railway track investments, there are some challenges concerning the lack of data associated with costs, benefits and the degradation rates of track infrastructure; giving rise to uncertainties (Andrade, 2016; Kirkwood et al., 2016; Skinner et al., 2011). Uncertainty can be defined as the chance of an event occurring where the probability distribution is unknown (Smith et al., 2006). Since the WLCCA approaches are based on the predictions of future scenarios, the sources of such uncertainty could also vary (see Figure 4) resulting in over-estimations or under-estimation of the WLCCA results. (Asplund et al., 2016).

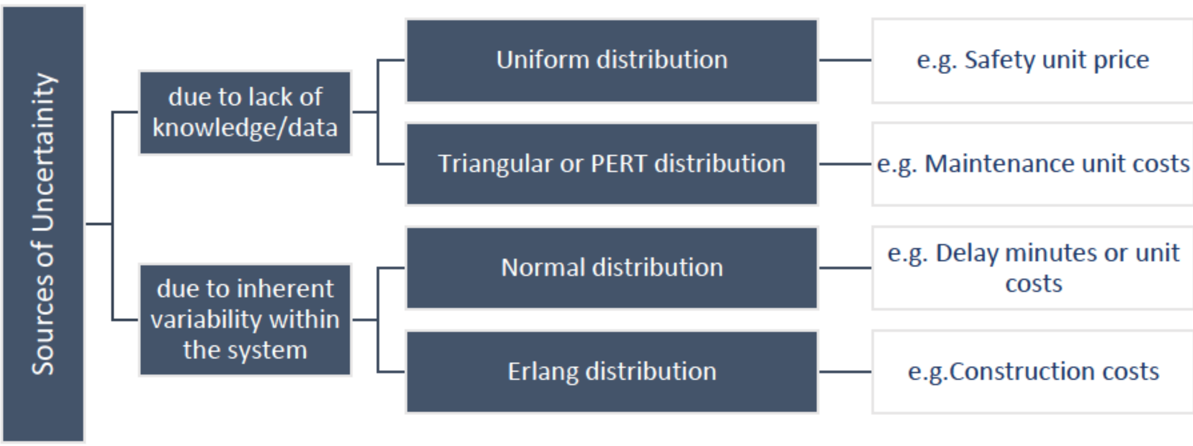



*Figure 10 Sources of uncertainty and associated probability distributions for WLCCA adapted from Salling et al., (2011)*

Risk assessment approaches such as Monte Carlo simulation, Bayesian, Fuzzy logic and Petri Nets are recommended to deal with such uncertainties (Zhang et al., 2014; Vogl, 2015; D. Rama et al., 2016). To a large extent, risk assessment techniques use historical data and probability judgements, and conclusions on the acceptability of solutions are often made directly based on derived probabilities. In many situations, it might also be extremely difficult to deal with uncertainty through probabilistic risk assessment, due to incomplete data (Sasidharan et al., 2017). The use of expert opinion is often suggested as a means of overcoming such issues (Terje, 2016; Torbaghan et al., 2015).

## 5. Proposed Model

An optimisation approach based on the concepts shown in Figure 2 requires consideration of a vast number of alternatives and is therefore computationally challenging. Therefore, the approach proposed uses WLCCA to compare railway track maintenance strategies to choose the most economically beneficial.

### 5.1. Whole Life Cycle Cost Analysis

The three most commonly used economic indicators to support decision making in transport investment appraisals are the Internal Rate of Return (IRR), the Benefit-Cost Ratio (BCR) and the Net Present Value (NPV) (Bristow et al., 2000). The IRR gives the rate of return on investments, or the discount rate at which the present-day values of benefits and costs are equal (Spiller, 2013). While comparing mutually exclusive investment options, the IRR may rank the options incorrectly if the time profile of benefits and costs differ (World Bank, 1998). The BCR is the ratio of benefits and costs expressed in present day values, with BCR ratios greater than one indicating economic viability. However, the BCR is often liable to misrepresentation due to its dependency on the degree of aggregation of benefits and costs over successive time periods.

The most widely used economic indicator for WLCCA is the Net Present Value (NPV) of current and future cost streams discounted to a reference time (Bristow et al., 2000) and it was therefore chosen for the task at hand. NPV is defined as follows (World Bank, 1998):

$$\widehat{NPV} = \sum_{\mathrm{n=0}}^{\mathrm{N}} \frac{(\widehat{\mathrm{B}}_n - \widehat{C_n})}{(1+\hat{r})^n} \tag{1}$$

ˆ is used to signify that the values are uncertain

Where the total transport cost, $\hat{\mathrm{C}}_n$ during the year, *n*, of a railway track section to achieve an average track quality, *Q* may be calculated using Equation 2 as follows:

$$\hat{\mathrm{C}}_n = \hat{\mathrm{C}}_{\mathrm{Construction}(Q)_n} + \hat{\mathrm{C}}_{\mathrm{Maintenance}(Q)_n} + \hat{\mathrm{C}}_{\mathrm{Use}(Q)_n} + \hat{\mathrm{C}}_{\mathrm{EndofLife}(Q)_n} \tag{2}$$

Where $\hat{\mathrm{C}}_{\mathrm{Construction}(Q)_n}, \hat{\mathrm{C}}_{\mathrm{Maintenance}(Q)_n}, \widehat{\mathrm{C}}_{\mathrm{Use}(Q)_n}, \hat{\mathrm{C}}_{\mathrm{EndofLife}(Q)_n}$ are the costs for year, *n*, and average track quality, *Q*, with respect to the track construction, maintenance, use and end of life respectively.. The terms are described in more detail below.

### 5.1.1. Construction Cost

The cost of construction is made up of costs associated with acquiring land and employing staff, procurement of materials and deployment of machinery of type, *m*. $\hat{C}_{\text{Construction}(Q)n}$ given by Equation 3, is the discounted cost to construct a railway track of length *L*.

$$\hat{C}_{\text{Construction}(Q)n} = \left(\hat{C}_{Prop} * L\right) + \sum_{m=1}^{M} \left[\left(\hat{C}_{Emn} * \hat{E}_{mn}\right) + \left(\hat{C}_{Cmn} * L\right)\right] \quad (3)$$

### 5.1.2. Maintenance costs

The direct and indirect costs associated with ballasted railway track maintenance are the sum of the costs of inspection ($\hat{C}_{\text{INS}}$), track realignment ($\hat{C}_{\text{TRA}}$), ballast cleaning ($\hat{C}_{\text{BC}}$), ballast renewal ($\hat{C}_{\text{BR}}$), routine maintenance ($\hat{C}_{\text{RM}}$), delays ($\hat{C}_{\text{CL}}$) and spillage ($\hat{C}_{\text{SPL}}$), as expressed in Equation 4.

$$\hat{C}_{\text{Maintenance}(Q)n} = \hat{C}_{\text{INS}_n} + \hat{C}_{\text{TRA}_n} + \hat{C}_{\text{BC}_n} + \hat{C}_{\text{BR}_n} + \hat{C}_{\text{RM}_n} + \hat{C}_{\text{CL}_n} + \hat{C}_{\text{SPL}_n} \quad (4)$$

The different cost elements that contribute to the maintenance costs of the ballasted track are calculated using Equations 5-11.

#### *Track Inspection Cost*

Track inspection is carried out periodically to assess the condition of the infrastructure. Track inspection costs depend upon the frequency of the inspections, *u*, in a year and the deployment of different types of equipment of type, *m.* The costs, are calculated via Equation 5.

$$\hat{C}_{\text{INS}_n} = \sum_{u=1}^{U} \sum_{m=1}^{M} \left(\hat{C}_{Emn} * \hat{E}_{mn} + \hat{C}_{TImn}\right) * L \quad (5)$$

#### *Track Realignment Costs*

Track realignment costs are a function of the number of times, *u*, the maintenance activity is carried out in a given year and on the deployment of the required machinery of type, *m.* Realignment costs are determined using Equation 6.

$$\hat{C}_{\text{TRA}_n} = \sum_{u=1}^{U} \sum_{m=1}^{M} \left(\hat{C}_{Emn} * \hat{E}_{mn} + \hat{C}_{TRAmn}\right) * L \quad (6)$$

#### *Ballast Cleaning Cost*

The cost of ballast cleaning is a function of the number of times ballast cleaning takes place in a year, *u*, and the deployment of the required machinery of type, *m.* Ballast cleaning costs are determined using Equation 7.

$$\hat{C}_{\text{BC}_n} = \sum_{u=1}^{U} \sum_{m=1}^{M} \left(\hat{C}_{Emn} * \hat{E}_{mn} + \hat{C}_{BCmn} + \hat{C}_{B}\right) * L \quad (7)$$

#### *Ballast Renewal Cost*

The costs incurred due to ballast renewal are a function of the number of ballast renewals, *u*, carried out in year *n* and the deployment of machinery of type, *m.* The costs are calculated using Equation 8.

$$\hat{C}_{\text{BR}_n} = \sum_{u=1}^{U} \sum_{m=1}^{M} \left(\hat{C}_{B} + \hat{C}_{Emn} * \hat{E}_{mn} + \hat{C}_{BRmn}\right) * L \quad (8)$$

*Routine Maintenance Costs*

Activities such as weed spraying, vegetation removal and drainage cleaning are considered as routine maintenance activities. Routine maintenance costs are calculated using Equation 9 as a function of the number of such activities in a year *u*, and the deployment of machinery type, *m*.

$$\hat{C}_{\mathrm{RM}_n} = \sum_{u=1}^{U}\sum_{m=1}^{M}(\hat{C}_{Emn} * \hat{E}_{mn} + \hat{C}_{RMmn}) * L \tag{9}$$

*Capacity Cost*

The capacity loss costs are those associated with speed restrictions, disruptions and maintenance activities. Speed restrictions on the railway are required when the track quality exceeds safety values specified in maintenance standards (see Figure 3), and result in travel time delays. Unplanned, or maintenance which over runs, can cause disruptions and or cancellations to services. Assuming that the number of train services remain the same during period, *n*, capacity loss cost is calculated using Equation 10.

$$\hat{C}_{\mathrm{CL}_n} = \left[\hat{C}_{PDn} * \left(\frac{L}{S_{RP}} - \frac{L}{S_L}\right) * \hat{N}_{PTSRn}\right] + \left[\hat{C}_{FDn} * \left(\frac{L}{S_{RF}} - \frac{L}{S_L}\right) * \hat{N}_{FTSRn}\right] + \left(\hat{C}_{PDn} * \hat{N}_{PTDn} * \hat{T}_{APDMn}\right) + \left(\hat{C}_{FDn} * \hat{N}_{FTDn} * \hat{T}_{AFDMn}\right) \tag{10}$$

*Spillage Cost*

These costs are to do with the clean-up using machinery type, *m*, train delays and reduced service life of a track section on the plain line, due to the spillage of materials such as fuel, coal and chemicals. Spillage costs are determined using Equation 11.

$$\hat{C}_{\mathrm{SPL}_n} = \left[\sum_{m=1}^{M}\left(\hat{C}_{Emn} * \hat{E}_{mn} * L\right) + (\hat{C}_{CSmn} * L)\right] + (\hat{C}_{PDn} * \hat{N}_{PTDn} * \hat{T}_{APDMn}) + (\hat{C}_{FDn} * \hat{N}_{FTDn} * \hat{T}_{AFDMn}) + (\hat{T}_{RSLn} * \hat{C}_{RSLn}) \tag{11}$$

### 5.1.3. Track use costs

The discounted railway track use costs, $\hat{C}_{\mathrm{Use}(Q)_n}$, for the year, *n*, for an average track quality, $Q_A$, are associated with train operation ($\hat{C}_{\mathrm{TO}_n}$), derailments ($\hat{C}_{\mathrm{DR}_n}$), environmental impacts ($\hat{C}_{\mathrm{ENV}_n}$) and modal change benefits ($\hat{C}_{\mathrm{MCC}_n}$). They are calculated using Equation 12.

$$\hat{C}_{\mathrm{Use}(Q)_n} = \hat{C}_{\mathrm{TO}_n} + \hat{C}_{\mathrm{DR}_n} + \hat{C}_{\mathrm{ENV}_n} - \hat{C}_{\mathrm{MCC}_n} \tag{12}$$

*Train Operating Cost*

The train operating costs considered are the costs associated with rolling stock fuel consumption, maintenance and replacement of spare parts of vehicle type, *v*, and are expressed by Equation 13.

$$\hat{C}_{\mathrm{TO}_n} = \sum_{v=1}^{V}(((\hat{F}_{CPnV(Q)} * \hat{C}_{FPnV} * L) + \left(\hat{N}_{TSPnV(Q)} * \hat{C}_{TSPnV(Q)}\right) + \hat{C}_{TMPnV(Q)}) * \hat{N}_{PnV}) + ((\hat{F}_{CFnV(Q)} * \hat{C}_{FFnV} * L) + \left(\hat{N}_{TSFnV(Q)} * \hat{C}_{TSFnV(Q)}\right) + \hat{C}_{TMFnV(Q)}) * \hat{N}_{FnV}) \tag{13}$$

*Risk of Derailment Cost*

The cost of derailments is estimated by multiplying the average cost of a derailment ($C_{DQ}$) with the probability of occurrence of a derailment ($P_{DQ}$) during the analysis period (Equation 14). The cost components of a derailment include damage to third party property and passengers' health, loss of life, damage to goods and costs involved in rescue, delays, investigation and repair and renewal of track and rolling stock.

$$\hat{\mathrm{C}}_{\mathrm{DR}_n} = P_{DQ} * \hat{C}_{DQ} \quad (14)$$

*Environmental Cost*

The environmental costs incurred due to pollutant type, *p*, during construction ($\hat{E}_{pCn}$), maintenance ($\hat{E}_{pMn}$) and renewal ($\hat{E}_{pRn}$), operation ($\hat{E}_{pOn}$) and disposal ($\hat{E}_{pDn}$) during year, *n*, are determined using Equation 15 as follows:

$$\hat{\mathrm{C}}_{\mathrm{ENV}_n} = \sum_{p=1}^{P} (\hat{E}_{pCn} + \hat{E}_{pMn} + \hat{E}_{pRn} + \hat{E}_{pOn} + \hat{E}_{pDn}) * \hat{C}_{pIn} \quad (15)$$

*Mode Change Benefit*

Improved track condition enhances the journey quality and safety, which in turn encourages users to shift from other modes of transportation to railways (Lingaitis, 2014). The costs taken into account in this work from such a shift are changes in travel times, reduced road congestion and road accidents and associated environmental costs. The mode change cost is determined using Equation 16.

$$\hat{\mathrm{C}}_{\mathrm{MCC}_n} = \left(\hat{N}_{PSQ} * \hat{C}_{PS}\right) + \left(\hat{N}_{FSQ} * \hat{C}_{FS}\right) + \left(\hat{N}_{ARS} * \widehat{VOL}\right) + \hat{C}_{EnvImp} \quad (16)$$

### 5.1.4. *End of Life costs*

For a section of track of length, L, the costs incurred to dispose of, or recycle, each track asset, *x*, at the end of the useful life of the asset, is given by Equation 17.

$$\hat{\mathrm{C}}_{\mathrm{EndofLife}(Q)_n} = \sum_{x=1}^{X} \sum_{m=1}^{M} \left(\hat{C}_{Emn} * \hat{E}_{mn} * L\right) + \left(\hat{C}_{EOImx} * L\right) - Rav \quad (17)$$

## 5.2. Track deterioration modelling

A number of the cost components and the timing of maintenance in Equations 7-11 are a function of the railway track condition (as measured by track geometry). Consequently, the WLCCA approach advocated requires both the future condition of the railway track and the effectiveness of track maintenance to be established (see Figure 3). Table 2 summarises from the literature a number of the track deterioration models which could be used for this purpose. Most of these models predicts vertical track settlement as a function of number of repetitions of train load. In some cases, train speed and the effectiveness of maintenance are also considered.

*Table 2 Track Deterioration Models*

| Country | Model name | Equation | Influencing Factors |
|---|---|---|---|
| UK | Shenton (1985) | $S = K_s \frac{A_e}{20}(0.69 + 0.028L)N^{0.2} + 2.7 \times 10^{-6}N)$ | *S* - track settlement<br>$K_s$ - structure factor<br>$A_e$ - equivalent axle load<br>*N* - cumulative number of axles<br>*L* - Lift given by tamping machines |
| Germany | DSM (Milosavljevic et al., 2012) | $S = S_1(1 + K_H \ln N)$ | $S_1$ - initial settlement after first loading cycle<br>$K_H$ - coefficient* |
| Japan | Hoshino (Milosavljevic et al., 2012) | $\Delta = L_H.J.Z$ | $\Delta$ - coefficient of track deterioration<br>$L_H$ - load factor<br>*J* - structure factor<br>*Z* - condition factor |
| | Sugiyama (2007) | $Z = 2.09 \times 10^{-3}.\ T^{0.31}.V^{0.98}.J^{1.10}.R^{0.21}.K_p^{0.26}$ | *Z* - average growth of track irregularities in the section<br>*T* - cumulative tonnage<br>*V* - average running speed<br>*J* - structure factor<br>*R* - influence factor for jointed rail<br>$K_p$ - influence factor for subgrade |
| | Satoh (1997) | $BS = \begin{cases} a_s(p_b - p_{g.br})^w, p_b > p_{g.br} \\ 0, p_b \leq p_{g.br} \end{cases}$<br>$BS = \alpha_s.p_b^w$ | *BS* - ballast settlement<br>$a_s$, $\alpha_s$ - coefficients*<br>$p_b$ - sleeper-ballast contact pressure<br>$p_{b.gr}$ - threshold limit value of sleeper-ballast contact pressure<br>*w* - exponent* |
| France | Guérin (1999) | $\frac{dS}{dN} = \alpha_G.y^{\beta_G}$ | *y* - maximum elastic deflection during a loading cycle<br>$\alpha_G$, $\beta_G$ - material parameters |
| South Africa | Frohling (1998) | $S = \left[\left[K_{F1} + K_{F2}.\left(\frac{D_{2mi}}{K_{F3}}\right)\right]\frac{Q_{tot}}{Q_{ref}}\right]^w \log N$ | $D_{2mi}$ - measured track stiffness at a particular sleeper i<br>$K_{F1}$, $K_{F2}$, $K_{F3}$ – settlement constants*<br>$Q_{tot}$ - prevailing wheel load<br>$Q_{ref}$ - reference wheel load<br>*w* - exponent* |
| | Exponential (Quiroga et al., 2010) | $TQ_m = Ae^{B(x-x_0)}$ | *$TQ_m$ - track quality measure*<br>*A, B - exponential coefficients*<br>*x*, $x_0$ - time or tonnage |
| | Linear (Soleimanmeigouni et al., 2018) | $TQ_m = (a.x) + b$ | $TQ_m$ - track quality measure<br>*x* - time or tonnage<br>*a, b* - linear coefficients* |

***** *- coefficients whose values depend on local conditions and are determined empirically*

## 6. Case Studies

The proposed WLCCA approach was used to calculate the NPV for the maintenance strategies outlined in Table 3 for representative sections of three different routes on the UK mainline railway network. A 25-year period of analysis and a discount rate of 3.5% were used in in accordance with UK Department for Transport (DfT, 2004) guidelines. The three selected routes are a commuter route (route 1), a high-speed passenger (route 2), and a mixed passenger-freight (route 3). The high-speed passenger route runs from London (LDN) to Birmingham (BHM) for 160 km (100 miles) via Coventry (COV). From Coventry onwards, it operates as a mixed passenger-freight route for 27 km (17 miles). The commuter route chosen is a 51 km (32 miles) long route in the Midlands running from Sutton Coldfield (SUT) to Lichfield City (LIC). All three train routes have competing road transport (see Table 4), but not competing canal, sea or air routes. For each route, a 200m long track representative section of homogenous construction, maintenance and renewal history, and social and economic geography were identified and used for the analysis.

The track geometry conditions and the effect of track realignment on track condition were determined

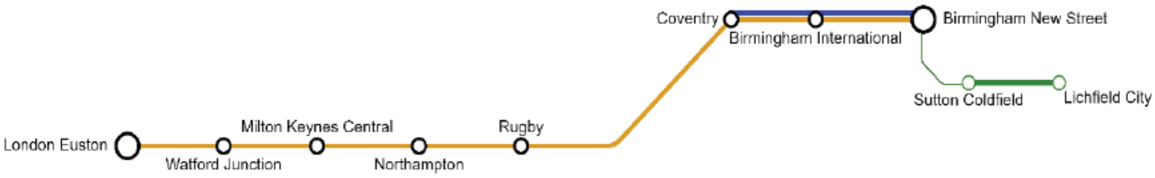



*Figure 11 Routes selected for Case Study*

from historical track data using a linear regression model of the form which has been used successfully to accurately model railway track degradation (see for example Soleimanmeigouni et al., 2018; Andrade et al., 2011; Faiz et al., 2009) (see Table 2). Monte Carlo Simulation (MCS) was employed to the historical track condition measurements to identify the most probable track condition for the representative section following maintenance following the procedure suggested by Quiroga et al. (2010).

The Table 3 shows the track maintenance strategies considered to achieve a given average track quality. For all the strategies track renewal takes place when track realignment is insufficient to achieve the given average track quality. Ballast cleaning was not considered due to the lack of available data. For the three representative sections the do-minimum strategies are 3.6 mm, 3.0 mm and 2.7 mm respectively. In order to realise different average track qualities the time interval between consecutive track realignment activities were delayed until a renewal is necessitated. The annual average track quality was used to inform the annual track use costs determined using equations 12 to 16.

The data required for the WLCCA was obtained from a variety of sources and is presented in Table 4. In order to address possible uncertainties with the data used to calculate the impacts and benefits, Monte Carlo Simulation was used to calculate a probability distribution for each input data value. In each case a normal distribution was assumed and determined using three-point following the approach suggested by Elcheikh et al., (2016). The three-point estimates were obtained from the sources listed in Table 4. The Monte Carlo Simulation was performed for 10,000 iterations using the @RISK™ software (Pallisade, 2017) to calculate the NPV and total transport costs for the maintenance strategies considered.

*Table 3 Maintenance strategies adopted for the Case Studies*

| Route | Average Track Quality (in SD mm) | Year 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sutton Coldfield-Lichfield City | 2.4 | | TRA | | TRA | | BR | TRA | | TRA | | | TRA | | TRA | | BR | TRA | | TRA | | | TRA | | TRA | |
| | 2.5 | | TRA | | TRA | | BR | | TRA | | TRA | | TRA | | TRA | | BR | | TRA | | TRA | | TRA | | TRA | |
| | 2.6 | | | TRA | | | BR | | | TRA | | | | TRA | | | BR | | | TRA | | | | TRA | | |
| | 2.7 | | | | TRA | | BR | | | | TRA | | | | TRA | | BR | | | | TRA | | | | TRA | |
| | 2.9 | | | | | TRA | | BR | | | | | | | | TRA | | BR | | | | | | | | TRA |
| | 3.1 | | | | | TRA | | | BR | | | | | | | TRA | | | BR | | | | | | | TRA |
| | 3.4 | | | | | | | TRA | | | BR | | | | | | | TRA | | | BR | | | | | |
| | 3.5 | | | | | | | TRA | | | BR | | | | | | | | TRA | | BR | | | | | |
| | 3.6 | | | | | | | | TRA | | BR | | | | | | | | TRA | | BR | | | | | |
| London Euston-Birmingham New Street | 1.9 | | TRA | TRA | TRA | | TRA | TRA | | TRA | BR | | TRA | TRA | TRA | | TRA | TRA | | TRA | BR | | TRA | TRA | TRA | |
| | 2.2 | | TRA | | TRA | | TRA | | TRA | TRA | BR | | TRA | | TRA | | TRA | | TRA | TRA | BR | | TRA | | TRA | |
| | 2.4 | | | TRA | | TRA | | TRA | | TRA | BR | | | TRA | | TRA | | TRA | | TRA | BR | | | TRA | | TRA |
| | 2.5 | | | | TRA | | TRA | | TRA | | TRA | BR | | | TRA | | TRA | | TRA | | TRA | BR | | | TRA | |
| | 2.6 | | | | | TRA | | TRA | | TRA | BR | | | | | TRA | | TRA | | TRA | BR | | | | | TRA |
| | 2.7 | | | TRA | | | TRA | | TRA | | BR | | | TRA | | | TRA | | TRA | | BR | | | TRA | | |
| | 2.8 | | | TRA | | | | TRA | | | BR | | | TRA | | | | TRA | | | BR | | | TRA | | |
| | 2.9 | | | | | | | | TRA | | BR | | | | | | | | TRA | | BR | | | | | |
| | 3.0 | | | | | | | | | TRA | | BR | | | | | | | | TRA | | BR | | | | |
| Coventry-Birmingham | 1.2 | TRA | TRA | BR | | TRA | TRA | | TRA | BR | TRA | TRA | TRA | BR | | TRA | TRA | | TRA | BR | TRA | TRA | TRA | BR | | TRA |
| | 1.4 | TRA | TRA | TRA | | TRA | TRA | TRA | | TRA | T B | TRA | TRA | TRA | | TRA | TRA | TRA | | TRA | T B | TRA | TRA | TRA | | TRA |
| | 1.6 | | TRA | TRA | TRA | | TRA | TRA | | TRA | BR | | TRA | TRA | TRA | | TRA | TRA | | TRA | BR | | TRA | TRA | TRA | |
| | 1.9 | | TRA | | TRA | | TRA | | TRA | | T B | | TRA | | TRA | | TRA | | TRA | | T B | | TRA | | TRA | |
| | 2.1 | | TRA | | TRA | | | TRA | | TRA | BR | | TRA | | TRA | | | TRA | | TRA | BR | | TRA | | TRA | |
| | 2.3 | | | TRA | | | TRA | | TRA | | BR | | | TRA | | | TRA | | TRA | | BR | | | TRA | | |
| | 2.4 | | | TRA | | | TRA | | | | T B | | | TRA | | | | TRA | | | T B | | | TRA | | |
| | 2.5 | | | | TRA | | | | | TRA | T B | | | | TRA | | | | TRA | | T B | | | | TRA | |
| | 2.6 | | | | | | | | TRA | TRA | BR | | | | | | | | TRA | TRA | BR | | | | | |
| | 2.7 | | | | | | | | TRA | | BR | | | | | | | | TRA | | BR | | | | | |

| | |
|---|---|
| TRA/T | Track Realignment |
| BR/B | Ballast Renewal |

*Table 4 Data used for Case Study*

| Item | Cost (£ per unit) | | | Source | Notes |
|---|---|---|---|---|---|
| | Minimum | Maximum | Most-Likely | | |
| Inspection | £14,000/shift | £16,000/shift | £15,000/shift | Data collected from Network Rail | The cost is related to High speed track recording coach (HSTRC) used by NR to measure periodically track geometry. The cost includes both the cost of operating the HSTRC and employee costs. For the three routes considered the HSTRC is used to inspect the track geometry every 8-10 weeks. A shift equates to measuring 250 km of track (ORR, 2012). For the purpose of this research it was therefore assumed that an inspection was carried out on average every 8 weeks (RSSB, 2003). Manual inspections carried out (e.g. earthworks/ drainage) and ad hoc track structural condition assessments were not considered. |
| Track Realignment | £4,500/shift | £5,500/shift | £5,000/shift | | The cost is related to operating the track treatment fleet and the associated employee costs. NR often operates the track treatment fleet during the night time and maintains approximately 100m of track during one shift (ORR, 2012) |
| Ballast Renewal with new components | £900,000/km | £1,100,000/km | £1,000,000/km | | The cost is related to operating the High Output Track Renewal System (HOTRS) used by NR for replacing the ballast, which is usually carried out overnight. The 800m long HOTRS is operated across all the routes considered, while the cost associated with it depends upon type of ballast renewal requirement (i.e. including or excluding formation renewal) |
| Ballast Cleaning | £7,500/shift | £12,500/shift | £10,000/shift | | The cost is related to the operation of the High Output Ballast Cleaning System (HOBCS) and associated employee costs. The half-a-mile long HOBCS is operated by NR to clean the ballast and replace any poor-quality ballast. HOBCS cleans approximately 100 meters of track during a shift. |
| Routine Maintenance | £7,500/shift | £12,500/shift | £10,000/shift | | The cost involved is associated with carrying out various activities such a weed spraying, vegetation removal and drainage cleaning, both manually and using machines. |
| Delay penalties on routes with low importance | £30/min/train | £70/min/train | £50/min/train | | The commuter route selected is classified as a low importance route with approximately 40% of WMT services running a minimum 10 minutes late, with track related delay accounting for approximately 7% of the delayed services (ORR, 2018) |
| Delay penalties on routes with high importance | £210/min/train | £290/min/train | £250/min/train | | Both the high-speed passenger route & the mixed passenger-freight route are of high importance, with approximately 60% of VWC services running minimum 10 minutes late, with track related delay accounting for approximately 9.5% of those delayed services (ORR, 2018). 2/10 freight services on UK mainline networks are delayed (NR,2010) |

| | | | | | |
|---|---|---|---|---|---|
| Spillage | £2000/mile/year | £2300/mile/year | £2100/mile/year | ORR (2013) | NR carries out both machine and manual interventions on the freight lines to treat spillages on the track. NR estimates that the coal spillage reduces the service life of the track by 9%. |
| Cost of track quality related derailment | £461,000/derailment | £761,000/derailment | £661,000/derailment | RSSB (2016) | |
| Environmental impact due to transport related NoX emissions in:<br>Central London area<br>Urban Large area<br>Urban Small area | £46,162/tonne<br>£14,647/tonne<br>£7,273/tonne | £184,648/tonne<br>£58,587/tonne<br>£29,091/tonne | £115,405/tonne<br>£36,617/tonne<br>£18,182/tonne | DEFRA (2015) | The quantities of NoX and SO2 emissions for Class 390 and Class 323 fleets were adopted from AEA (2007) |
| Environmental Damage due to Transport related $SO_2$ emissions | £1,581/tonne | £2,224/tonne | £1,956/tonne | DEFRA (2015) | |
| Environmental Damage due to Transport related $CO_2$ emissions | £3.97 - £60.52 /tonne | £5.94 - £183.10 /tonne | £3.82 - £132.12 /tonne | BEIS (2018) | The quantity of $CO_2$ emissions were assumed to be proportional to the fuel consumption and was calculated using the methodology specified by AEA (2008). $CO_2$ impact costs varies for each year and BEIS (2018) forecasts these costs |
| Road de-congestion (passenger service) | £0.15/vehicle mile | £0.17/vehicle mile | £0.16/vehicle mile | UIC (2015) | DfT Road Count Point data (DfT, 2016) were used to calculate the daily average number of passenger vehicles for the major road alternatives for each train routes. i.e. 40,000, 30,000 and 8,330 on M40 (LDN_BHM)), A45 (COV-BHM)) and A5127 (SUT-LIC)) roads respectively. Similarly, 1,825 freight vehicles were estimated to use the A45. For illustrative purposes, it was assumed that 10% of current road users using the alternative road route will shift to rail when the track is maintained in good track condition and reduce linearly to 0% when the track is maintained in poor condition; as suggested by Kemp (2016). |
| Reduction of road accidents (passenger service) | £0.02/vehicle mile | £0.04/vehicle mile | £0.03/vehicle mile | | |
| Environmental benefits (passenger service) | £0/vehicle mile | £0.02/vehicle mile | £0.01/vehicle mile | | |
| Modal Change Cost for passenger services | £0.10/vehicle mile | £0.30/vehicle mile | £0.20/vehicle mile | DfT (2011) | |
| Modal Change Cost for freight services | £0.40/vehicle mile | £0.60/vehicle mile | £0.50/vehicle mile | DfT (2011) | |
| Train Operating Cost on London-Birmingham route | £3.14/mile/train | £3.34/mile/train | £3.24/mile/train | ORR (2015) | The costs related with train operation is associated with staff, fuel, maintenance of rolling stock and the charges payable by the TOCs to Network Rail. VWC runs 51 passenger daily services on Class 390 fleets. WMT runs 96 passenger daily services on Class 323 fleets |
| Train Operating Cost on Sutton Coldfied-Lichfield city route | £3.92/mile/train | £4.12/mile/train | £4.02/mile/train | | |
| Freight Train Operating Cost on Coventry-Birmingham route | £3.78/mile/train | £3.98/mile/train | £3.88/mile/train | Serco (2013) | 4 daily average freight services are run on mixed-freight route (ORR, 2015). The operational costs of freight services are up to 20% more than their passenger counterparts (Serco, 2013). |
| Fuel Costs for London-Birmingham route (passenger service) | £17.53/kWh/mile | £31.56/kWh/mile | £24.55/kWh/mile | Data collected from Network Rail | The fuel consumed by the fleets used on each route were adapted from Network Rail's prediction data. The energy loss in the train suspension system increases exponentially as a function of the track geometry condition as suggested by Zarembski et. al., (2010). |
| Fuel Costs for Sutton Coldfield-Lichfield route (passenger service) | £4.33/kWh/mile | £7.80/kWh/mile | £6.07/kWh/mile | | |
| Fuel Costs for Coventry-Birmingham route (freight service) | £0.20/litre | £0.40/litre | £0.30/litre | | |
| Risk of track quality related derailments | 0.03 FWI/year | 0.23 FWI/year | 0.13 FWI/year | RSSB (2018) | Based on the analysis of derailment data from the UK's Train Accident Precursor Indicator Model, the frequency of occurrence was assumed to follow a Poisson's distribution |

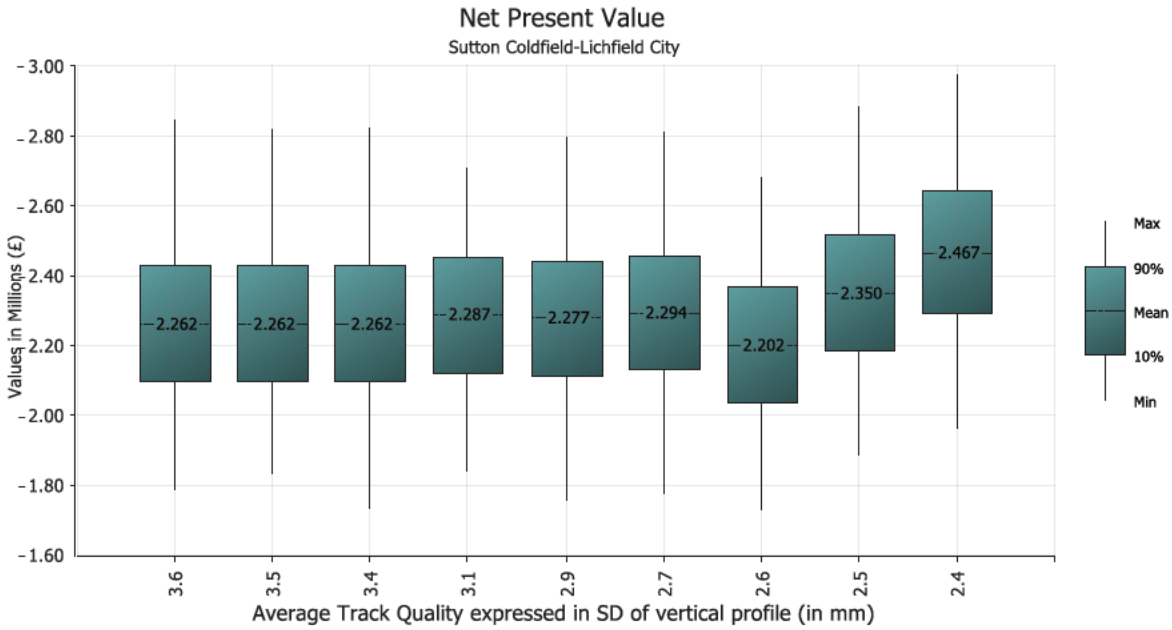
## 6.1. Results

The plausible ranges of NPV and total transport costs determined from the Monte Carlo Simulation for the three representative track sections are presented in Figures 6a-6e, 7a-7e and 8a-8e respectively as a function of track quality. The figures show the minimum, mean and maximum values of costs associated with WLCC and the NPV at confidence levels of 10% - 90%. The range of plausible values provides the decision maker with an effective insight into the variability of the associated costs i.e. the uncertainty associated within the WLCCA. The results from the WLCCA shows that for all three routes, higher average track quality levels result in higher maintenance costs and lower track use costs, as would be expected. The contribution of different cost elements for all three total transport costs across all three routes are presented in Figures 9a-9c.

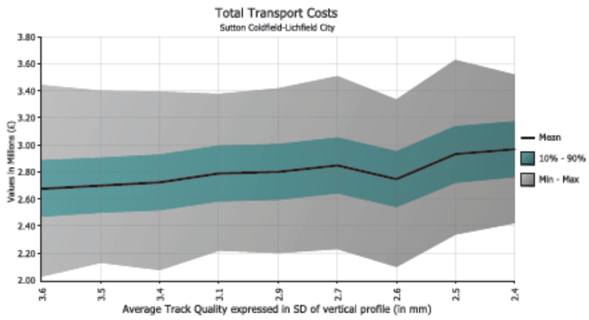
From Figures 6a and 6b it can be seen that maintaining the commuter route at an average track condition of 2.6 mm is the most economical of those strategies considered. At the 90% confidence level, the strategy results in an NPV of -£2.36 m and a lowest total transport cost of £2.95m with associated maintenance and track use costs of £1.1m and £1.2m respectively (see Figures 6d-6e). By contrast, the do-minimum strategy of maintaining the track condition at 3.6mm SD would result in a 25% increase in track use costs, at least a 75% increase in risk cost of derailments and a 60% less benefit from mode change at the 90% confidence level. Track maintenance costs however would reduce by approximately 50% (see Figure 6d).

Figures 7a and 7b shows that maintaining the high-speed passenger section at an average track condition of 2.4 mm SD is the most economic strategy. This strategy, at the 90% confidence level, has an NPV of -3.26m, a total transport cost of £4.62m with a maintenance cost of £1.3m. The do-minimum strategy, on the other hand, although it reduces maintenance costs by approximately 20%, results in an increase of track use costs of about 33% (Figures 7d-7e). The do-minimum strategy also increases derailment risk costs and train operation costs by 60% and 3% respectively. A strategy of maintaining a higher average track condition of 1.9mm, compared to the most economic strategy yields a 6% lower NPV and reduced track use costs of approximately 2% at the 90% confidence level. However, the more frequent intervention results in an 11% increase in maintenance costs.

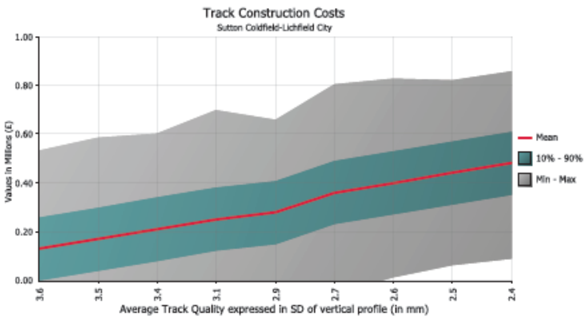
The most economic strategy for the mixed-traffic section is to maintain the section at an average track condition of 2.4 mm (see Figure 8a). At the 90% confidence level this will result in an NPV which is 13% lower than the do-minimum strategy and a total transport costs of £4.2m, the lowest of all strategies considered (see Figures 8a-8b). By comparison, maintaining the track at 1.4mm, at the 90% confidence level, would reduce the NPV by 16%, but would increase total transport costs by 14% (see Figures 8a-8b). The more frequent maintenance requirements of the latter strategy result in maintenance costs which are 60% higher than the most economic strategy.



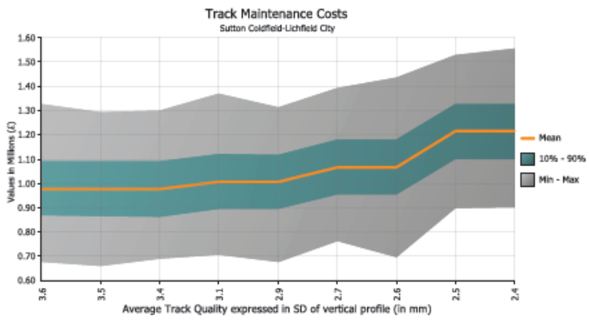

(6a)



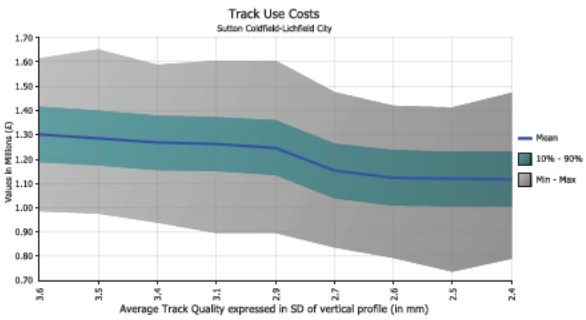

(6b)




(6c)

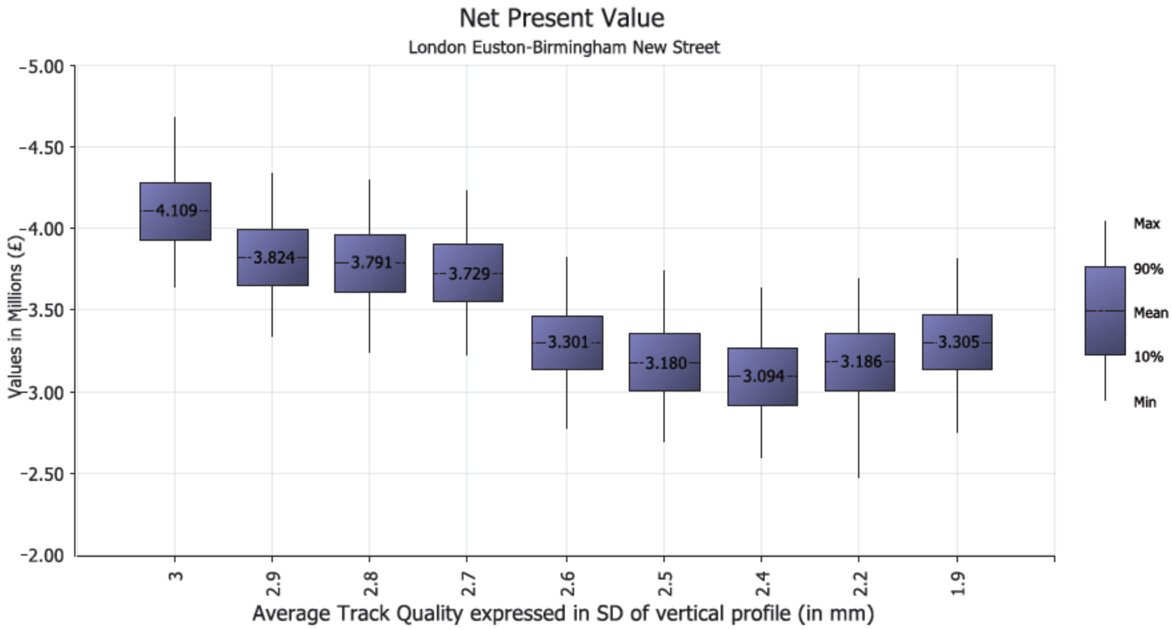



(6d)

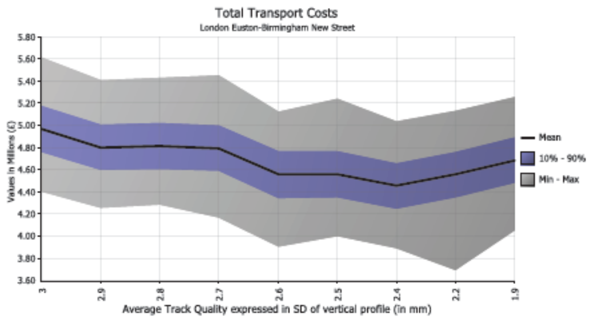



(6e)

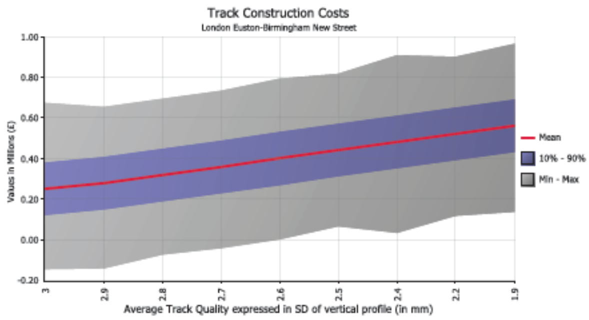
*Figure 12 WLCCA results for Commuter Route with (a) NPV (b) Total Transport Cost (c) Construction Costs (d) Maintenance Costs and (e) Track Use Costs as a function of average Track Quality*



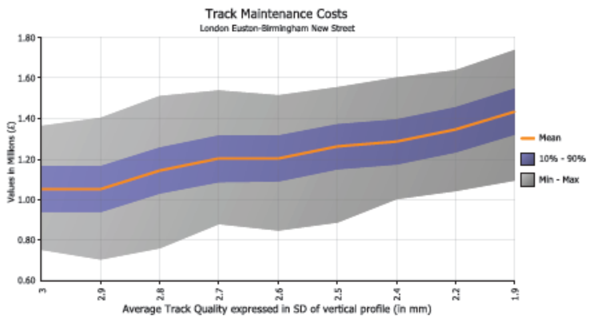

(7a)



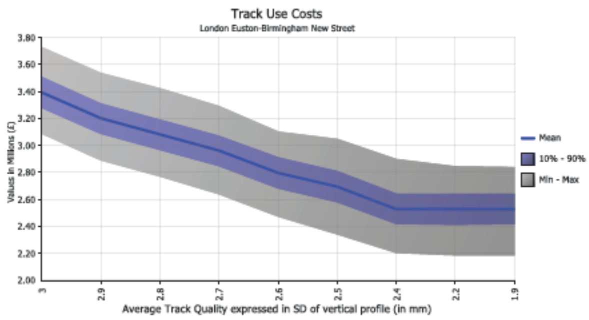

(7b)




(7c)




(7d)




(7e)

*Figure 13 WLCCA results for High-Speed Passenger Route with (a) NPV (b) Total Transport Cost (c) Construction Costs (d) Maintenance Costs and (e) Track Use Costs as a function of average Track Quality*

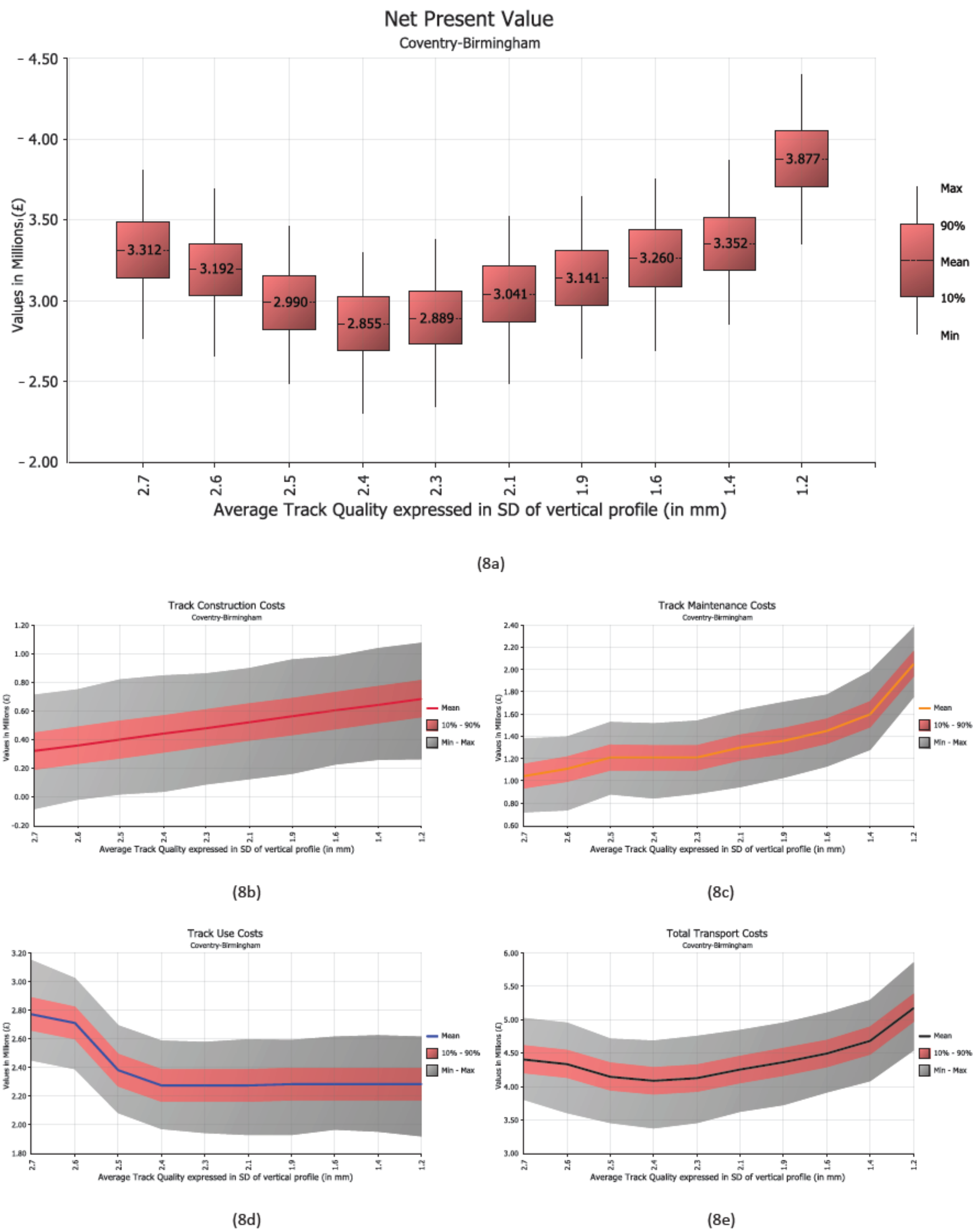
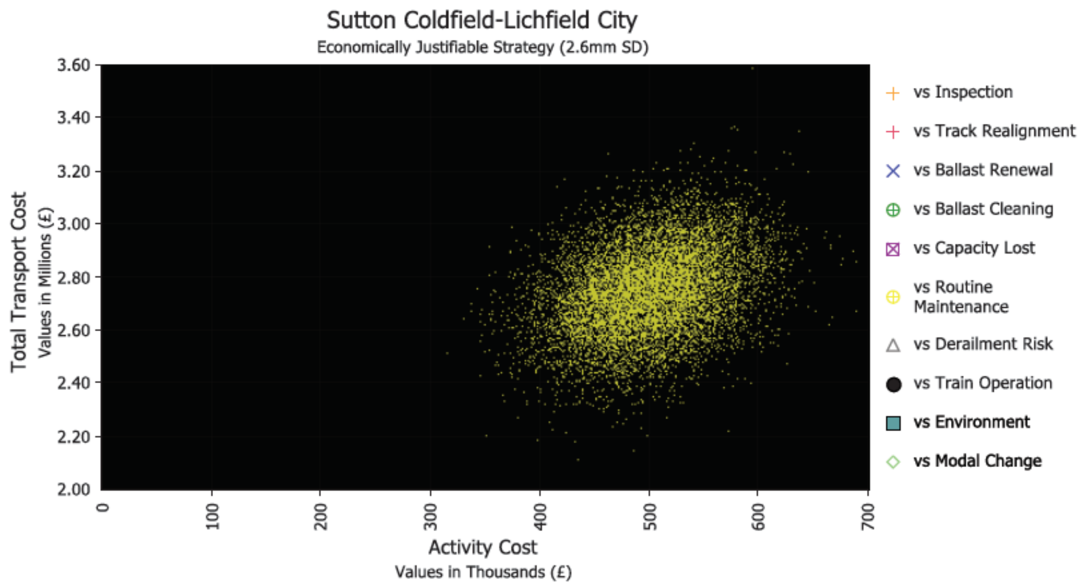
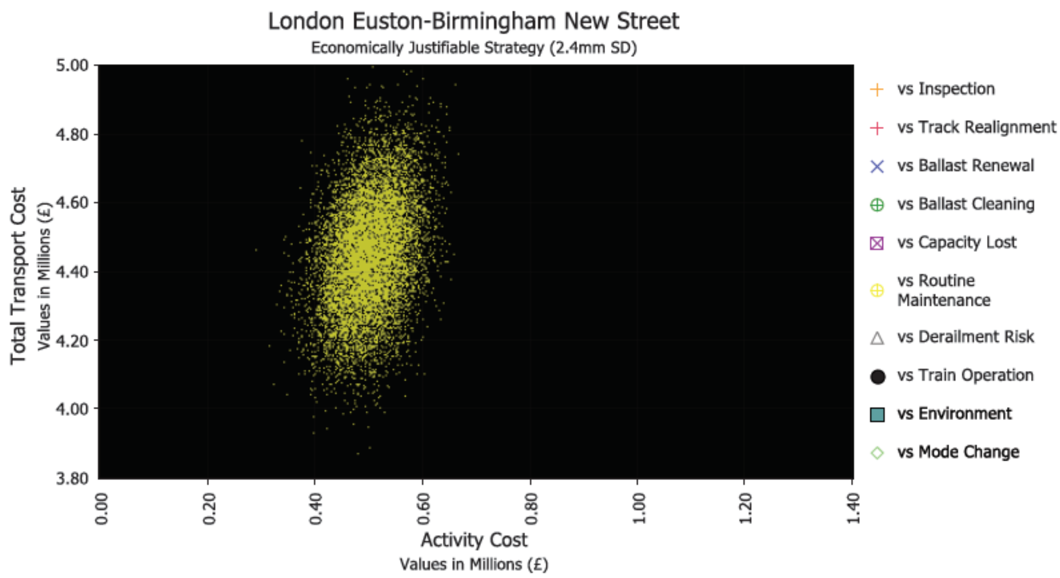



*Figure 14 WLCCA results for Mixed-Freight Passenger Route with (a) NPV (b) Total Transport Cost (c) Construction Costs (d) Maintenance Costs and (e) Track Use Costs as a function of average Track Quality*

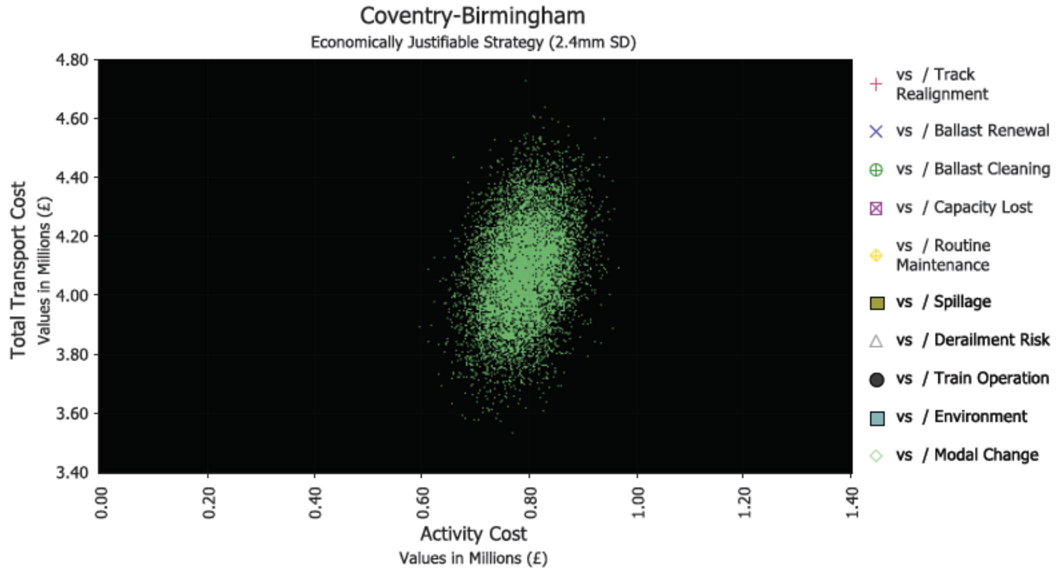
A sensitivity analysis was carried out to quantify the contribution of different costs to maintenance and track use costs for the most economic strategies for the three routes (see Figures 9a-9c). The scatter plots were generated by running 10,000 Monte Carlo Simulations iterations for each WLCC component. By inspection of Figures 9a-9c, it may be seen that the track use costs were found to contribute the greatest to the total costs for the commuter route. The comparatively higher contribution of train operation costs for the commuter route is due to the more frequent train services on this route compared to the other two routes. This results in greater costs of delays for a given strategy. On the other hand, the environmental impacts and mode change costs are the highest contributors to total transport costs for the high-speed and mixed-traffic routes (see Figures 9b-9c). This highlights the potential benefits of reducing environmental emissions, road congestion and accidents through a shift from road to rail. Although the cost of at least one derailment is similar across all three routes, it is highest on the mixed freight route (Figure 9c). This is due to impact of a potential freight derailment on the passenger train operations on the route in the form of delays




(9a)




(9b)




(9c)

*Figure 15 Contribution of cost elements of maintenance and track use to the Total Transport Cost for the economically justifiable strategy for (a) Commuter Route (b) High-Speed Passenger Route (c) Mixed-Freight Passenger Route*

## 7. Concluding Discussion

Governments, on behalf of the taxpayer, seek to maximize the benefits derived from investment in railway infrastructure and train operation. To facilitate this process, the WLCCA approach proposed is an effective means of evaluating the economics of maintenance strategies, while considering a whole transport system perspective. The WLCC considers the costs associated with track construction, maintenance, operation and end-of life. To address the uncertainties associated within the data, a probabilistic approach using Monte Carlo Simulation was used to examine the unit costs and project the impacts and benefits of different strategies in terms of probability distributions.

The approach was demonstrated on three route types on the UK mainline railway network namely commuter, high-speed passenger and mixed passenger-freight routes. The results from the case studies showed that different maintenance strategies are required for each route to maximise economic benefits. Further, the track qualities associated with the economically beneficial strategies suggested by the approach differ from those used by Network Rail.

The case studies also illustrate the impact of maintenance effectiveness on the total maintenance cost. As it is expected, the worsening track quality increases the track use costs and decreases the maintenances costs. Such a trend is clearly visible in the projection of track maintenance and use costs associated with different maintenance strategies across all the three routes (see Figures 5b-c, 6b-c and 7b-c). The train operational cost per m is an important indicator of railway operational efficiency because it measures the level of financial inputs required per train (ITF, 2013). Although, the staff costs are a large component of these train operational costs, it was assumed for the study that they have remained constant throughout in line with the data presented in ORR (2015). However, greater benefits can be achieved if the staff costs and wages were modelled to increase over the period of time. The fuel consumption was modelled based on Zarembski et al. (2010) as data for the case study was not made available by the respective train operating companies. Using the actual train fuel costs may therefore give different results. Assuming that the number of train services remain the same throughout the analysis period, our study shows that, if the track condition was was allowed to deteriorate from good to poor condition then train operating costs could rise by up to £500 per m annually through increases in fuel consumption and train maintenance across all three routes.

From Network Rail's perspective, it is financially preferable to carry out as little maintenance as possible e.g. the do-minimum strategy (see Figures 5b, 6b and 7b). However, the analysis suggests that if railway track use costs are considered then there are more economically and environmentally beneficial strategies. For example, for the high-speed passenger route, a maintenance standard of 2.4 mm SD instead of 2.6 mm SD would result in annual savings of approximately £3,000 per m. Considering the higher contribution of maintenance and train operation to the total transport costs for the commuter route (see Figure 8a), approximately £1,100 per m of annual savings could be achieved by maintaining the track at 2.4 mm SD instead of 2.6 mm SD. The above notwithstanding, it is interesting to note that for the for the mixed passenger-freight route a 10% reduction in total transport costs could be achieved by reducing the average track quality from the current SD of 1.2 mm to a SD of 2.4 mm. However, this section of the track serves Network Rail's headquarters and is therefore maintained in such a good condition for political reasons. Furthermore, it is noteworthy that the strategy chosen by Network Rail to maintain this section of track involves five ballast renewals and 15 track realignment operations over the track's lifecycle of 25 years (see Table 3). Maintaining the track condition to a slightly lower average track quality of 1.4 mm, a strategy that Network Rail uses on an adjacent section, could be achieved using three less ballast renewals and only five more track realignment operations. This would potentially save Network Rail approximately £16,000 annually.

The analysis also indicated that environmental impacts and mode change had the highest contribution to the total transport costs across all the route types (see Figures 8a-c). Reductions in environmental impacts can be achieved through eco-friendly construction and sustainable maintenance practices. For example, sourcing components such as sleepers, which contain recycled content, using where appropriate life-expired ballast within the sub-ballast ballast layer, reducing energy consumption on site and using renewable sources of power. Research is also on-going to develop plastic aggregates which can be used in the sub-ballast layer.

The proposed approach can thus be used to support strategic planning and programming levels of railway asset management (Robinson, 2008). For example, in the cases when there is a shortage in the annual track maintenance budget, the approach can be employed to inform plausible maintenance strategies that realise the maximum benefit for the available budget. Senior managers and decision makers can also use the approach advocated to improve long-term investment choices. For example, the approach allows the implications of reductions in maintenance budgets on total transport costs to be scrutinised and investment to be targeted to the areas of the railway network providing the greatest benefit.

For the analysis of large railway networks the approach would require a considerable amount of historical railway condition and maintenance and cost data. Much of this information is now routinely collected by railway infrastructure maintainers. However, the data requirements of the system, and therefore the computational time required to run the model and to analyse the results, can be reduced considerably by carefully selecting a sufficient number of representative track sections to portray adequately the characteristics of the entire network. A representative track section is considered to embody those sections of railway network which deteriorate at similar rates and have similar whole life cycle costs. An initial selection procedure could therefore utilize the construction standards and the speed and tonnage of the rolling stock utilizing track sections. Analyses such as those shown by Figure 9 could thereafter be used to refine the selected representative sections.

A number of countries have a vertically separated structure in which train operation and infrastructure provision are provided by different organisations. In such environments, infrastructure owners have little concern for the impact of track condition on train operating costs. Unless a suitable incentive scheme is provided by a regulator the infrastructure owner is likely to maintain the track at the lowest financial cost to meet track condition standards. These standards may not be the most economic nor may they be the most cost effective over the long term. Similarly, train operators also are unconcerned about the impact of poorly maintained vehicles on track damage. It is in the interests of all stakeholders and the environment, however, for the infrastructure and rolling stock to be maintained appropriately. The approach presented herein is a means by which the regulators of vertically separated railways can achieve this equitably and transparently.

Whether or not the operation of a railway is managed by a single entity or vertically separated, the use of the proposed approach is subject to the organization's culture and operational objectives. To overcome potential issues, stakeholders should be engaged to enable (i) improved appreciation of the WLCC approach and it's use in informing equitable decisions; (ii) access to accurate and reliable cost data, including track maintenance and train operation costs, and; (iii) more effective investment decision making which considers, on a WLCC basis, the costs and benefits to stakeholders and the environment.

Given that the life cycle of railway track can be 25 years or more, and maintenance interventions need to be planned several years in advance, future development of the proposed approach could consider a track possession planning model that takes into account the scheduling of track maintenance under operational constraints. The research carried out D'Ariano et al. (2019), Liden et al. (2017) and Luan et al. (2017), for example, would be useful in informing such further developments. For high speed rail in particular, the risks associated with track instability, ballast flight, vibrations and track constructed on soft soils could also be considered within the proposed approach.

## 8. Acknowledgement

The financial and technical support from the University of Birmingham's Department of Civil Engineering, within the School of Engineering are acknowledged with gratitude. The authors gratefully acknowledge Network Rail and in particular, Dr Mohamed Wehbi, Aaren Healy and Alan Bullock for providing data for the case studies.

## Notational List

$\widehat{B_n}$ are the benefits in the *n$^{th}$* year

$\widehat{C_n}$ are the costs accruing in the *n$^{th}$* year

$\hat{C}_{Bn}$ is the cost per metre of ballast material in year, *n*

$\hat{C}_{BCmn}$ is the cost of equipment, *m*, for ballast cleaning per metre in year, *n*

$\hat{C}_{BRmn}$ is the cost per metre of using equipment, *m*, for ballast renewal in year, *n*

$\hat{C}_{Cmn}$ is the cost per metre, of using a piece of equipment, m, for track construction in year, *n*

$\hat{C}_{CSmn}$ is the machinery cost per metre for cleaning up the spillage of materials using equipment, *m*

$\hat{C}_{DQn}$ is the average cost of a derailment on the track section during year, *n*

$\hat{C}_{Emn}$ is the average employee cost of operating a piece of equipment, *m*, in year, *n*.

$\hat{C}_{EnvImp}$ is the environmental impact cost due to a shift from other modes to railway transport

$C_{EOImx}$ is the cost of using a piece of equipment, m, to dispose of, or recycle a track component, *x*, per metre

$\hat{C}_{FDn}$ is the average delay cost for a freight train in year, *n*

$\hat{C}_{FPnV}$ is the unit cost of fuel during year, *n*, for passenger train of type, *V*

$\hat{C}_{FFnV}$ is the unit cost of fuel during year, *n*, for freight train of type, *V*

$\hat{C}_{pIn}$ is the impact cost of pollutant type, *p*, on the environment during year, *n*

$\hat{C}_{PS}$ is the net benefit of a passenger vehicle journeys shifting to railways

$\hat{C}_{FS}$ is the net benefit of a freight vehicle journeys shifting to railways

$\hat{C}_{Prop}$ is the cost of land procured per metre

$\hat{C}_{PDn}$ is the average delay cost for a passenger train in year, *n*

$\hat{C}_{RMmn}$ is the cost per metre of equipment, *m*, used for routine maintenance in year, *n*

$\hat{C}_{RSLn}$ the cost of reduced service life of the track per year during year, *n*

$\hat{T}_{RSLn}$ is the mean reduced service life of the track in years, n

$\hat{C}_{TImn}$ is the cost of using a piece of equipment, *m*, per metre for a track inspection in year, *n*

$\hat{C}_{TRAmn}$ is the cost of using equipment, *m*, per metre for track realignment in year, *n*

$\hat{C}_{TSPnV(Q)}$ is the unit cost of spare parts during year, *n*, for the components of passenger train of type, *V*, for the average track quality, $Q_A$, achieved in year n.

$\hat{C}_{TSFnV(Q)}$ is the unit cost of spare parts during year, *n*, for the components of freight train of type, *V*, for the average track quality, $Q_A$, achieved in year n

$\hat{C}_{TMPnV(Q)}$ is the average train maintenance cost during year, *n*, for a passenger train of type, *V*, for an average track quality, $Q_A$, achieved in year n

$\hat{C}_{TMFnV(Q)}$ is the average train maintenance cost during year, *n*, for a freight train of type, *V*, for an average track quality, $Q_A$, achieved in year n

$\hat{E}_{pCn}$ is the environmental costs incurred during construction of railway track during year, *n*

$\hat{E}_{pMn}$ is the environmental costs incurred during maintenance of railway track during year, *n*

$\hat{E}_{pRn}$ is the environmental costs incurred during renewal of railway track during year, *n*

$\hat{E}_{pOn}$ is the environmental costs incurred during operation of railway track during year, *n*

$\hat{E}_{pDn}$ is the environmental costs incurred during disposal of railway track during year, *n*

$\hat{E}_{mn}$ is the average number of employees required to operate a piece of equipment, *m*, in year, *n*

$\hat{F}_{CPnV(Q)}$ is the total fuel consumed during year, *n*, by passenger train of type, *V*, for an average track quality, $Q_A$, achieved in year n

$\hat{F}_{CFnV(Q)}$ is the total fuel consumed during year, *n*, by freight train of type, *V*, for an average track quality, $Q_A$, achieved in year n

*L* is the length of the track section in metres

*n* is the specific year of the WLCCA period

$\hat{N}_{ARS}$ is the average reduction in the number of road accidents due to mode change

$\hat{T}_{APDMn}$ is average passenger train delay in minutes in year, *n*, due to track possession for maintenance

$\hat{T}_{AFDMn}$ is average freight train delay in minutes in year, *n*, due to track possession for maintenance

$\hat{N}_{FnV}$ is number of journeys on freight train type, *V*, through the track section during year,n

$\hat{N}_{FTDn}$ is average number of delayed freight trains in year, *n*, due to track possession for maintenance

$\hat{N}_{FTSRn}$ is average number of delayed passenger trains in year, *n*, due to speed restrictions

$\hat{N}_{FSQ}$ is the average number of freight vehicle journeys shifting to railways during time period, *n*, for the average track quality achieved during time period, *n*

$\hat{N}_{PTDn}$ *is* the number of delayed passenger trains in year, *n*, due to track possession for maintenance

$\hat{N}_{PSQ}$ is the average number of passenger vehicle journeys shifting to railways during time period, *n*, for the average track quality achieved during time period, *n*

$\hat{N}_{PTSRn}$ is average number of delayed passenger trains in year, *n*, due to speed restrictions

$\hat{N}_{TSPnV(Q)}$ is the average number of train components renewed during year, *n*, per passenger train type, *V,* for an average track quality, $Q_A$, achieved in year n

$\hat{N}_{TSFnV(Q)}$ is the average number of train components renewed during year, *n*, per freight train type, *V,* for an average track quality, $Q_A$, achieved in year n

$\hat{N}_{PnV}$ is the number of journeys on passenger train type, *V*, through the track section during year, *n*

$P_{DQn}$ is the probability of at least one derailment occurring during year, *n*, on the track section of an average track quality, $Q_A$

$\hat{r}$ is the discount rate

$R_{av}$ is the residual asset value

$S_{RP}$ is average restricted speed for passenger trains along the track section

$S_{RF}$ is average restricted speed for freight trains along the track section

$S_L$ is the maximum permitted speed for trains along the track section

$\hat{T}_{APDMn}$ is average passenger train delay in minutes in year, *n*, due to track possession for maintenance

$\hat{T}_{AFDMn}$ is average freight train delay in minutes in year, *n*, due to track possession for maintenance

*u* is the number of times a piece of equipment, *m*, is used in year, *n*

$\widehat{VOL}$ is the average economic value of a person's life

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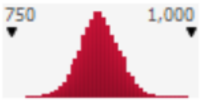
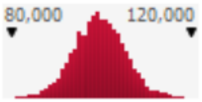
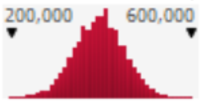
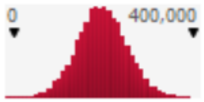
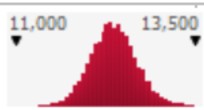
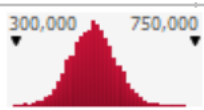
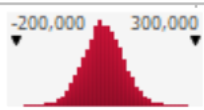
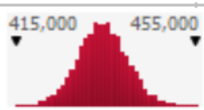
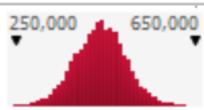
# Appendix B Outputs from @RISK$^{TM}$

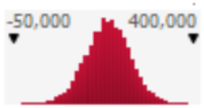
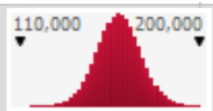
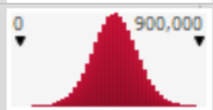
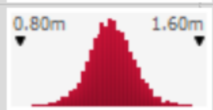
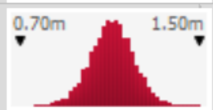
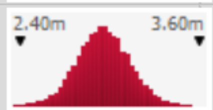
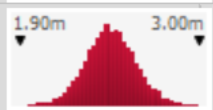
# @RISK Output Results

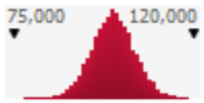
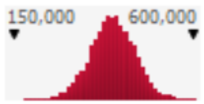
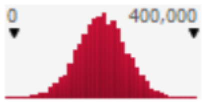
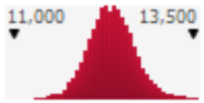
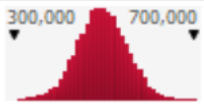
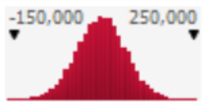
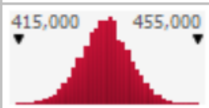
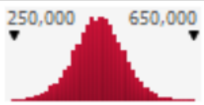
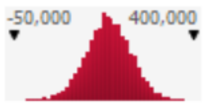
**Performed By:** Manu Sasidharan (School of Engineering)

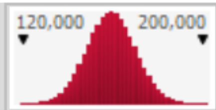
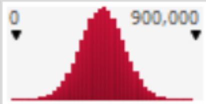
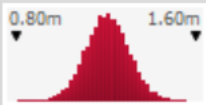
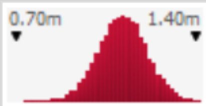
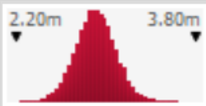
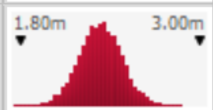
**Date:** 26 March 2019 20:33:35

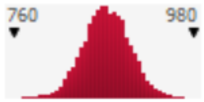
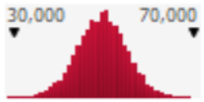
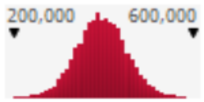
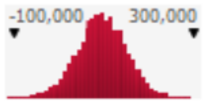
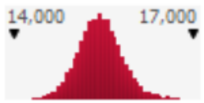
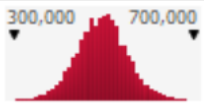
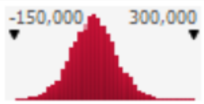
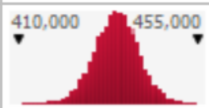
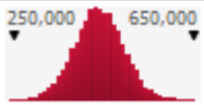
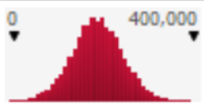
**Route** Commuter
**Line** Sutton Coldfield-Lichfield City
**Analysis Time Period** 25 Years

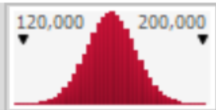
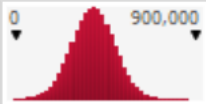
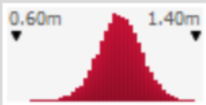
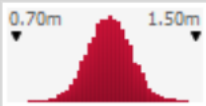
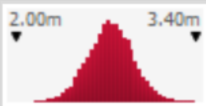
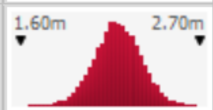
| SD (in mm) | Cost Element | Graph | Min | Mean | Max | 10% Confidence | 90% Confidence |
|---|---|---|---|---|---|---|---|
| 2.4 | / *Inspection* |  | £778 | £875 | £990 | £843 | £907 |
| | / *Track Realignment* |  | £82,352 | £100,000 | £117,390 | £93,521 | £106,508 |
| | / *Ballast Renewal* |  | £210,787 | £400,000 | £589,426 | £335,663 | £463,848 |
| | / *Ballast Cleaning* |  | £8,588 | £10,462 | £13,629 | £9,455 | £11,564 |
| | / *Capacity Lost* |  | £11,397 | £12,376 | £13,433 | £12,016 | £12,745 |
| | / *Routine Maintenance* |  | £315,984 | £500,000 | £715,549 | £436,224 | £564,536 |
| | / *Derailment Risk* |  | -£158,131 | £48,781 | £268,980 | -£16,000 | £113,033 |
| | / *Train Operation* |  | £416,532 | £434,762 | £454,516 | £428,465 | £441,202 |
| | / *Environment* |  | £262,768 | £442,951 | £621,274 | £377,795 | £507,089 |

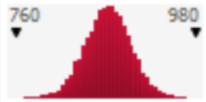
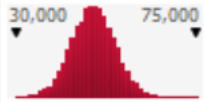
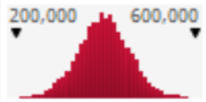
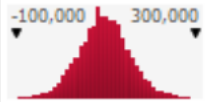
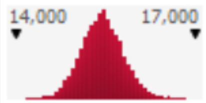
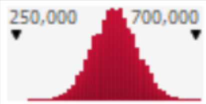
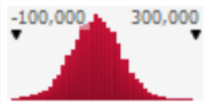
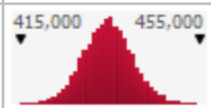
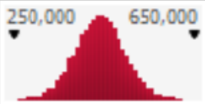
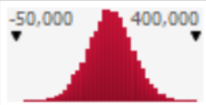
| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | */ Mode Change* |  | -£11,631 | £190,174 | £377,499 | £126,458 | £252,752 |
| | ***End of Life Costs*** |  | £118,337 | £160,000 | £198,556 | £147,184 | £172,813 |
| | ***Construction Costs*** |  | £97,811 | £481,331 | £858,345 | £353,142 | £609,431 |
| | ***Maintenance Costs*** |  | £629,886 | £1,023,713 | £1,450,417 | £887,722 | £1,160,108 |
| | ***Track Use Costs*** |  | £796,806 | £1,116,667 | £1,485,131 | £1,004,108 | £1,228,342 |
| | ***Total Transport Costs*** |  | £1,642,840 | £2,781,711 | £3,992,449 | £2,392,156 | £3,170,694 |
| | ***Net Present Value*** |  | £1,654,471 | £2,591,537 | £3,614,950 | £2,265,698 | £2,917,942 |

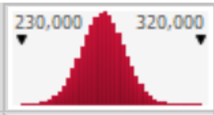
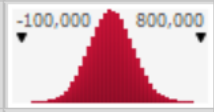
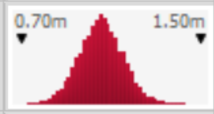
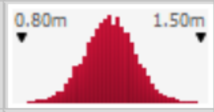
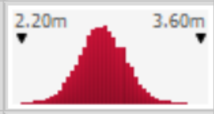
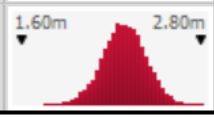
| SD (in mm) | Cost Element | Graph | Min | Mean | Max | 10% Confidence | 90% Confidence |
|---|---|---|---|---|---|---|---|
| **2.5** | / *Inspection* |   | £773 | £875 | £974 | £843 | £907 |
| | / *Track Realignment* |   | £79,072 | £100,000 | £117,691 | £93,684 | £106,321 |
| | / *Ballast Renewal* |   | £193,430 | £400,001 | £596,174 | £337,002 | £463,963 |
| | / *Ballast Cleaning* |   | £8,588 | £10,462 | £13,629 | £9,455 | £11,564 |
| | / *Capacity Lost* |   | £11,381 | £12,376 | £13,494 | £12,017 | £12,737 |
| | / *Routine Maintenance* |   | £325,982 | £499,999 | £693,909 | £436,011 | £564,258 |
| | / *Derailment Risk* |   | -£147,647 | £48,780 | £246,985 | -£14,729 | £112,921 |
| | / *Train Operation* |   | £416,329 | £434,814 | £454,129 | £428,338 | £441,192 |
| | / *Environment* |   | £264,634 | £443,327 | £640,352 | £379,266 | £507,207 |
| | / *Mode Change* |   | -£2,258 | £190,171 | £367,813 | £126,027 | £254,198 |

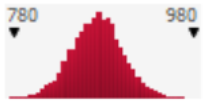
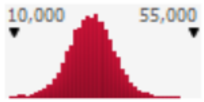
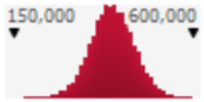
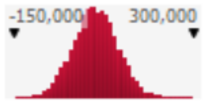
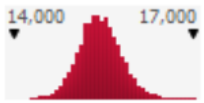
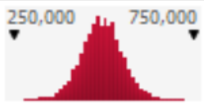
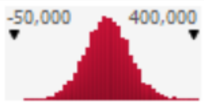
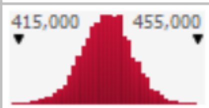
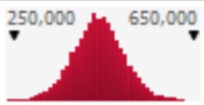
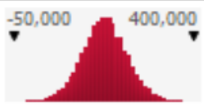
| | | | | | | |
|---|---|---|---|---|---|---|
| ***End of Life Costs*** |   | £122,706 | £160,001 | £199,724 | £147,183 | £172,814 |
| ***Construction Costs*** |   | £17,587 | £440,749 | £862,219 | £312,553 | £568,866 |
| ***Maintenance Costs*** |   | £585,686 | £1,023,715 | £1,443,318 | £886,546 | £1,160,968 |
| ***Track Use Costs*** |   | £761,370 | £1,117,092 | £1,398,883 | £1,006,390 | £1,227,349 |
| ***Total Transport Costs*** |   | £1,532,465 | £2,741,556 | £4,080,412 | £2,350,454 | £3,128,012 |
| ***Net Present Value*** |   | £1,477,038 | £2,474,830 | £3,510,430 | £2,160,163 | £2,786,720 |

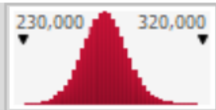
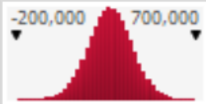
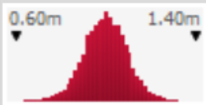
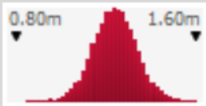
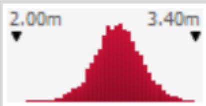
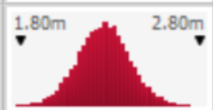
| SD (in mm) | Cost Element | Graph | Min | Mean | Max | 10% Confidence | 90% Confidence |
|---|---|---|---|---|---|---|---|
| **2.6** | */ Inspection* |  | £780 | £875 | £965 | £843 | £907 |
| | */ Track Realignment* |  | £30,284 | £50,000 | £68,484 | £43,641 | £56,335 |
| | */ Ballast Renewal* |  | £217,576 | £399,999 | £573,062 | £337,234 | £463,342 |
| | */ Ballast Cleaning* |  | £8,588 | £10,462 | £13,629 | £9,455 | £11,564 |
| | */ Capacity Lost* |  | £14,403 | £15,470 | £16,727 | £15,064 | £15,884 |
| | */ Routine Maintenance* |  | £322,230 | £499,999 | £675,551 | £436,723 | £563,657 |
| | */ Derailment Risk* |  | -£127,972 | £54,134 | £292,685 | -£10,205 | £118,841 |
| | */ Train Operation* |  | £412,649 | £434,869 | £453,459 | £428,451 | £441,187 |
| | */ Environment* |  | £258,996 | £443,321 | £641,285 | £378,575 | £507,555 |
| | */ Mode Change* |  | £7,603 | £190,173 | £382,989 | £126,045 | £255,119 |

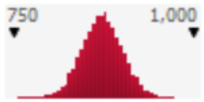
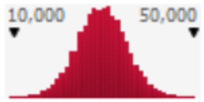
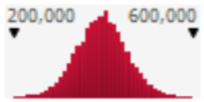
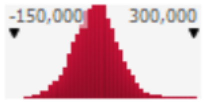
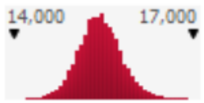
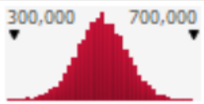
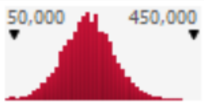
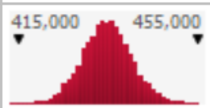
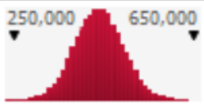
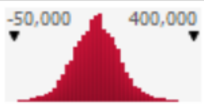
| | | | | | | |
|---|---|---|---|---|---|---|
| ***End of Life Costs*** |  | £120,231 | £160,000 | £198,856 | £147,183 | £172,814 |
| ***Construction Costs*** |  | £27,950 | £400,172 | £839,580 | £271,990 | £528,285 |
| ***Maintenance Costs*** |  | £437,764 | £876,809 | £1,271,931 | £738,243 | £1,011,751 |
| ***Track Use Costs*** |  | £787,285 | £1,122,497 | £1,447,577 | £1,010,684 | £1,235,368 |
| ***Total Transport Costs*** |  | £1,422,514 | £2,559,477 | £3,813,489 | £2,167,764 | £2,945,284 |
| ***Net Present Value*** |  | £1,354,678 | £2,326,376 | £3,304,788 | £2,010,344 | £2,639,681 |

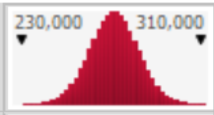
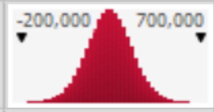
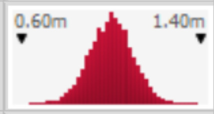
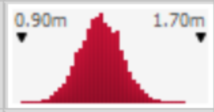
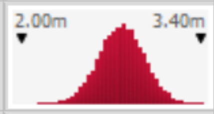
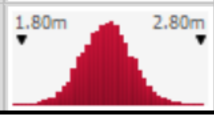
| SD (in mm) | Cost Element | Graph | Min | Mean | Max | 10% Confidence | 90% Confidence |
|---|---|---|---|---|---|---|---|
| 2.7 | / Inspection |  | £780 | £875 | £964 | £843 | £908 |
| | / Track Realignment |  | £31,712 | £50,000 | £74,652 | £43,598 | £56,370 |
| | / Ballast Renewal |  | £224,361 | £400,001 | £576,415 | £335,876 | £464,867 |
| | / Ballast Cleaning |  | £8,588 | £10,462 | £13,629 | £9,455 | £11,564 |
| | / Capacity Lost |  | £14,294 | £15,470 | £16,786 | £15,070 | £15,877 |
| | / Routine Maintenance |  | £297,054 | £500,003 | £699,495 | £435,152 | £564,856 |
| | / Derailment Risk |  | -£91,990 | £83,406 | £284,125 | £19,925 | £147,133 |
| | / Train Operation |  | £416,887 | £434,927 | £453,378 | £428,599 | £441,291 |
| | / Environment |  | £273,440 | £443,323 | £615,650 | £379,268 | £506,755 |
| | / Mode Change |  | -£9,963 | £190,171 | £388,933 | £125,227 | £255,048 |

| | | | | | | |
|---|---|---|---|---|---|---|
| ***End of Life Costs*** |   | £233,752 | £272,001 | £318,425 | £259,180 | £284,814 |
| ***Construction Costs*** |   | -£15,750 | £359,580 | £737,945 | £231,423 | £487,717 |
| ***Maintenance Costs*** |   | £504,327 | £876,817 | £1,311,993 | £736,106 | £1,013,890 |
| ***Track Use Costs*** |   | £849,360 | £1,151,826 | £1,468,549 | £1,039,048 | £1,263,394 |
| ***Total Transport Costs*** |   | £1,491,410 | £2,660,224 | £3,926,630 | £2,266,051 | £3,049,994 |
| ***Net Present Value*** |   | £1,447,924 | £2,418,146 | £3,436,295 | £2,104,564 | £2,734,989 |

| SD (in mm) | Cost Element | Graph | Min | Mean | Max | 10% Confidence | 90% Confidence |
|---|---|---|---|---|---|---|---|
| **2.9** | */ Inspection* |  | £784 | £875 | £965 | £843 | £907 |
| | */ Track Realignment* |  | £10,846 | £30,000 | £50,679 | £23,654 | £36,403 |
| | */ Ballast Renewal* |  | £195,342 | £400,003 | £583,751 | £337,014 | £463,795 |
| | */ Ballast Cleaning* |  | £8,588 | £10,462 | £13,629 | £9,455 | £11,564 |
| | */ Capacity Lost* |  | £14,372 | £15,470 | £16,952 | £15,070 | £15,880 |
| | */ Routine Maintenance* |  | £295,354 | £500,000 | £710,348 | £436,083 | £564,198 |
| | */ Derailment Risk* |  | -£5,153 | £187,280 | £399,086 | £123,045 | £251,345 |
| | */ Train Operation* |  | £415,404 | £435,049 | £453,536 | £428,517 | £441,438 |
| | */ Environment* |  | £255,248 | £443,325 | £622,207 | £379,169 | £508,038 |
| | */ Mode Change* |  | -£4,415 | £180,662 | £361,173 | £116,395 | £244,229 |

| | | | | | | |
|---|---|---|---|---|---|---|
| ***End of Life Costs*** |  | £234,322 | £272,001 | £315,478 | £259,182 | £284,811 |
| ***Construction Costs*** |  | -£148,342 | £278,409 | £671,755 | £150,200 | £406,516 |
| ***Maintenance Costs*** |  | £409,447 | £816,814 | £1,204,450 | £680,479 | £948,900 |
| ***Track Use Costs*** |  | £879,013 | £1,246,316 | £1,585,753 | £1,136,612 | £1,356,796 |
| ***Total Transport Costs*** |  | £1,365,095 | £2,613,539 | £3,817,803 | £2,221,245 | £3,004,195 |
| ***Net Present Value*** |  | £1,484,746 | £2,401,466 | £3,366,937 | £2,084,270 | £2,718,696 |

| SD (in mm) | Cost Element | Graph | Min | Mean | Max | 10% Confidence | 90% Confidence |
|---|---|---|---|---|---|---|---|
| **3.1** | / *Inspection* |  | £765 | £875 | £967 | £843 | £907 |
| | / *Track Realignment* |  | £10,665 | £30,000 | £49,066 | £23,534 | £36,411 |
| | / *Ballast Renewal* |  | £216,574 | £400,004 | £588,273 | £335,118 | £465,285 |
| | / *Ballast Cleaning* |  | £8,588 | £10,462 | £13,629 | £9,455 | £11,564 |
| | / *Capacity Lost* |  | £14,321 | £15,470 | £16,840 | £15,068 | £15,886 |
| | / *Routine Maintenance* |  | £302,428 | £500,004 | £688,330 | £435,616 | £565,008 |
| | / *Derailment Risk* |  | £50,900 | £221,903 | £417,673 | £158,949 | £285,427 |
| | / *Train Operation* |  | £415,079 | £435,181 | £454,226 | £428,798 | £441,561 |
| | / *Environment* |  | £251,478 | £443,323 | £628,959 | £380,035 | £507,728 |
| | / *Mode Change* |  | -£22,904 | £161,646 | £350,979 | £96,716 | £226,309 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | ***End of Life Costs*** |  | £234,400 | £272,000 | £309,880 | £259,180 | £284,813 |
| | ***Construction Costs*** |  | -£128,232 | £250,000 | £626,547 | £121,830 | £378,145 |
| | ***Maintenance Costs*** |  | £411,772 | £816,818 | £1,268,516 | £677,093 | £953,954 |
| | ***Track Use Costs*** |  | £934,507 | £1,262,052 | £1,613,375 | £1,151,750 | £1,371,387 |
| | ***Total Transport Costs*** |  | £1,409,942 | £2,600,870 | £3,849,637 | £2,210,800 | £2,985,693 |
| | ***Net Present Value*** |  | £1,464,806 | £2,411,122 | £3,439,837 | £2,098,226 | £2,725,407 |

| | |
|---|---|
| **Route** | Commuter |
| **Line** | Sutton Coldfield-Lichfield City |
| **Analysis Time Period** | 25 Years |

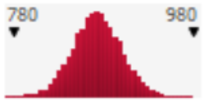
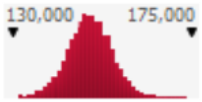
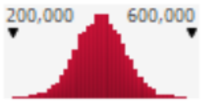
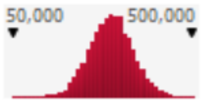
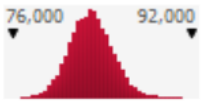
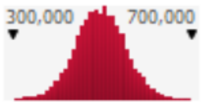
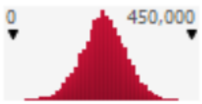
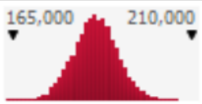
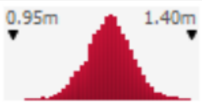
| SD (in mm) | Whole Life Cycle Costs | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Inspection | Track Realignment | Ballast Renewal | Ballast Cleaning | Capacity Lost | Routine Maintenance | Derailment Risk | Train Operation | Environmental Impacts | Mode Change |
| 2.4 | £990 | £117,390 | £589,426 | £13,629 | £13,433 | £715,549 | £268,980 | £454,516 | £621,274 | £190,174 |
| 2.5 | £974 | £117,691 | £596,174 | £13,629 | £13,494 | £693,909 | £246,985 | £454,129 | £640,352 | £367,813 |
| 2.6 | £965 | £68,484 | £573,062 | £13,629 | £16,727 | £675,555 | £292,685 | £453,459 | £641,285 | £382,989 |
| 2.7 | £964 | £74,562 | £576,415 | £13,629 | £16,786 | £699,495 | £284,125 | £453,378 | £615,650 | £388,933 |
| 2.9 | £965 | £50,679 | £583,751 | £13,629 | £16,952 | £710,348 | £399,086 | £453,536 | £622,207 | £361,173 |
| 3.1 | £967 | £49,066 | £588,273 | £13,629 | £16,840 | £688,330 | £417,673 | £454,226 | £628,959 | £350,979 |

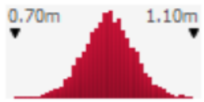
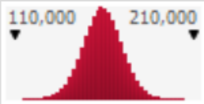
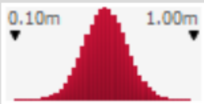
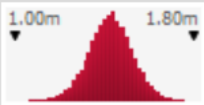
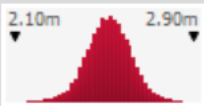
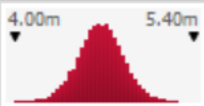
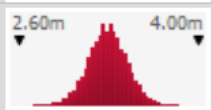
# @RISK Output Results

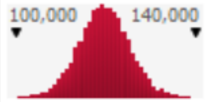
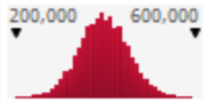
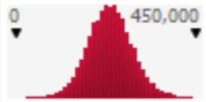
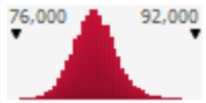
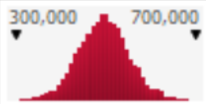
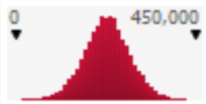
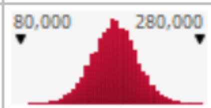
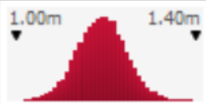
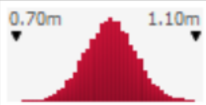
**Performed By:** Manu Sasidharan (School of Engineering)

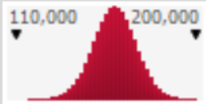
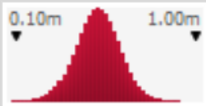
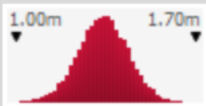
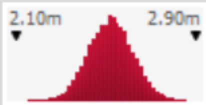
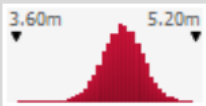
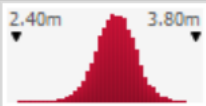
**Date:** 26 March 2019 20:33:35

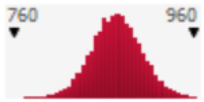
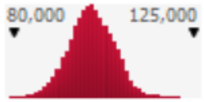
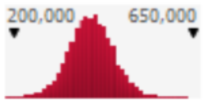
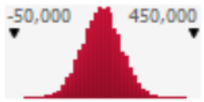
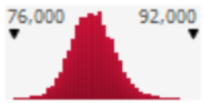
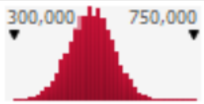
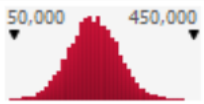
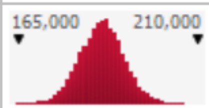
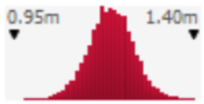
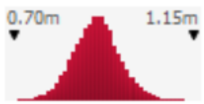
**Route** High Speed Passenger
**Line** London Euston-Birmingham New Street
**Analysis Time Period** 25 Years

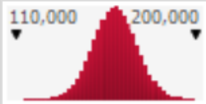
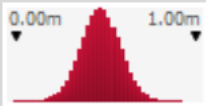
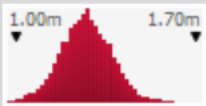
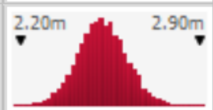
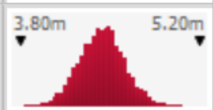
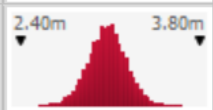
| SD (in mm) | Cost Element | Graph | Min | Mean | Max | 10% Confidence | 90% Confidence |
|---|---|---|---|---|---|---|---|
| 1.9 | / *Inspection* |   | £780 | £875 | £973 | £843 | £907 |
| | / *Track Realignment* |   | £133,442 | £150,000 | £172,445 | £143,677 | £156,349 |
| | / *Ballast Renewal* |   | £214,907 | £400,001 | £578,698 | £337,203 | £463,562 |
| | / *Ballast Cleaning* |   | £8,588 | £10,462 | £13,629 | £9,455 | £11,564 |
| | / *Capacity Lost* |   | £77,290 | £83,243 | £90,734 | £81,083 | £85,454 |
| | / *Routine Maintenance* |   | £321,817 | £499,998 | £685,921 | £435,890 | £564,877 |
| | / *Derailment Risk* |   | £46,126 | £232,829 | £405,704 | £168,903 | £296,317 |
| | / *Train Operation* |   | £165,327 | £186,286 | £205,910 | £179,842 | £192,560 |
| | / *Environment* |   | £998,681 | £1,195,365 | £1,386,743 | £1,130,265 | £1,258,770 |

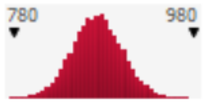
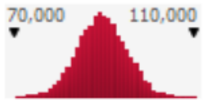
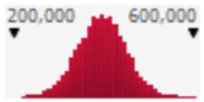
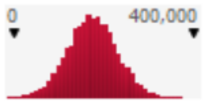
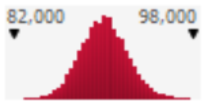
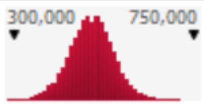
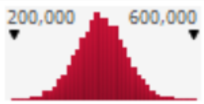
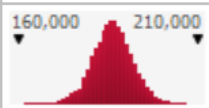
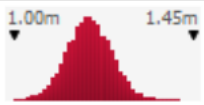
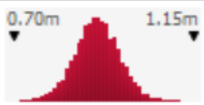
| | | | | | | |
|---|---|---|---|---|---|---|
| | */ Mode Change* |  | £716,439 | £913,185 | £1,087,099 | £848,298 | £977,052 |
| | ***End of Life Costs*** |  | £118,911 | £160,000 | £202,025 | £147,179 | £172,816 |
| | ***Construction Costs*** |  | £137,971 | £562,499 | £963,063 | £434,303 | £690,648 |
| | ***Maintenance Costs*** |  | £835,264 | £1,244,578 | £1,636,761 | £1,105,256 | £1,380,481 |
| | ***Track Use Costs*** |  | £2,185,168 | £2,527,667 | £2,834,358 | £2,416,013 | £2,638,627 |
| | ***Total Transport Costs*** |  | £3,284,307 | £4,494,743 | £5,714,861 | £4,104,530 | £4,880,565 |
| | ***Net Present Value*** |  | £2,419,883 | £3,429,783 | £4,462,117 | £3,107,397 | £3,752,825 |

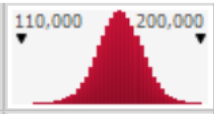
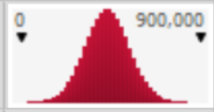
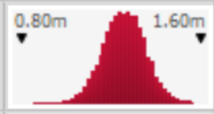
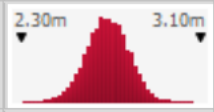
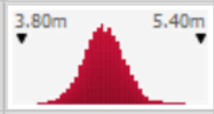
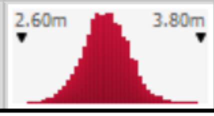
| SD (in mm) | Cost Element | Graph | Min | Mean | Max | 10% Confidence | 90% Confidence |
|---|---|---|---|---|---|---|---|
| 2.2 | / Inspection |   | £778 | £875 | £983 | £842 | £907 |
| | / Track Realignment |   | £102,153 | £120,000 | £137,890 | £113,583 | £126,434 |
| | / Ballast Renewal |   | £214,983 | £400,001 | £584,305 | £337,098 | £464,280 |
| | / Ballast Cleaning |   | £8,588 | £10,462 | £13,629 | £9,455 | £11,564 |
| | / Capacity Lost |   | £77,087 | £83,243 | £90,452 | £81,060 | £85,434 |
| | / Routine Maintenance |   | £323,452 | £500,000 | £674,315 | £436,322 | £565,172 |
| | / Derailment Risk |   | £34,208 | £232,831 | £416,805 | £167,920 | £298,168 |
| | / Train Operation |   | £96,247 | £186,424 | £277,860 | £157,300 | £215,735 |
| | / Environment |   | £1,033,128 | £1,195,368 | £1,382,621 | £1,134,112 | £1,257,212 |
| | / Mode Change |   | £730,102 | £913,184 | £1,085,557 | £848,547 | £977,126 |

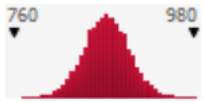
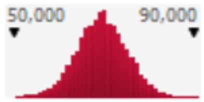
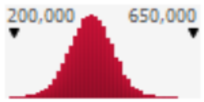
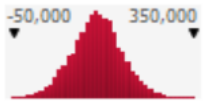
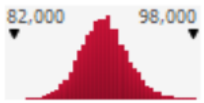
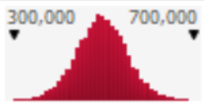
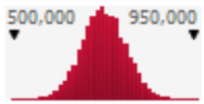
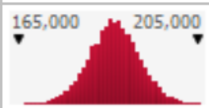
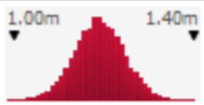
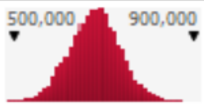
| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | ***End of Life Costs*** |   | £119,915 | £160,000 | £197,623 | £147,184 | £172,814 |
| | ***Construction Costs*** |   | £119,694 | £521,915 | £899,915 | £393,749 | £650,022 |
| | ***Maintenance Costs*** |   | £783,691 | £1,154,584 | £1,535,300 | £1,015,996 | £1,289,416 |
| | ***Track Use Costs*** |   | £2,187,372 | £2,527,807 | £2,840,897 | £2,413,258 | £2,642,380 |
| | ***Total Transport Costs*** |   | £2,924,909 | £4,364,306 | £5,592,406 | £3,973,009 | £4,752,308 |
| | ***Net Present Value*** |   | £2,141,766 | £3,310,847 | £4,335,604 | £2,983,542 | £3,634,796 |

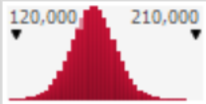
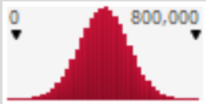
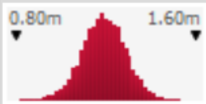
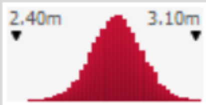
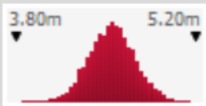
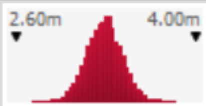
| SD (in mm) | Cost Element | Graph | Min | Mean | Max | 10% Confidence | 90% Confidence |
|---|---|---|---|---|---|---|---|
| 2.4 | *2.4 / Inspection* |   | £780 | £875 | £959 | £843 | £907 |
| | */ Track Realignment* |   | £80,726 | £100,000 | £120,705 | £93,475 | £106,519 |
| | */ Ballast Renewal* |   | £201,641 | £399,999 | £626,825 | £337,114 | £463,206 |
| | */ Ballast Cleaning* |   | £8,588 | £10,462 | £13,629 | £9,455 | £11,564 |
| | */ Capacity Lost* |   | £76,699 | £83,243 | £90,460 | £81,077 | £85,433 |
| | */ Routine Maintenance* |   | £318,278 | £500,000 | £746,500 | £434,818 | £564,394 |
| | */ Derailment Risk* |   | £59,203 | £232,828 | £418,233 | £169,561 | £296,630 |
| | */ Train Operation* |   | £166,219 | £186,529 | £205,638 | £180,152 | £192,910 |
| | */ Environment* |   | £991,139 | £1,195,370 | £1,389,631 | £1,130,691 | £1,259,442 |
| | */ Mode Change* |   | £728,940 | £913,182 | £1,115,115 | £848,632 | £978,210 |

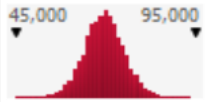
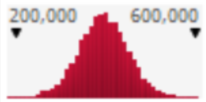
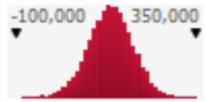
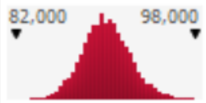
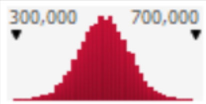
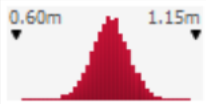
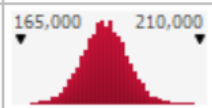
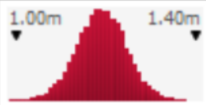
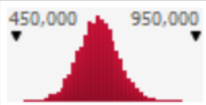
| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | ***End of Life Costs*** |  | £117,682 | £159,999 | £197,349 | £147,181 | £172,810 |
| | ***Construction Costs*** |  | £33,680 | £481,330 | £909,122 | £353,125 | £609,443 |
| | ***Maintenance Costs*** |  | £742,362 | £1,094,581 | £1,500,127 | £957,229 | £1,229,556 |
| | ***Track Use Costs*** |  | £2,204,901 | £2,527,908 | £2,896,451 | £2,417,662 | £2,640,324 |
| | ***Total Transport Costs*** |  | £3,121,655 | £4,263,819 | £5,499,845 | £3,873,975 | £4,648,492 |
| | ***Net Present Value*** |  | £2,258,327 | £3,218,930 | £4,284,361 | £2,896,140 | £3,543,208 |

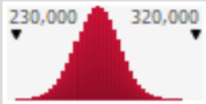
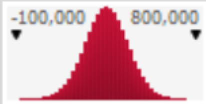
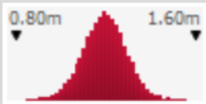
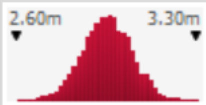
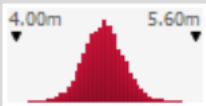
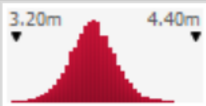
| SD (in mm) | Cost Element | Graph | Min | Mean | Max | 10% Confidence | 90% Confidence |
|---|---|---|---|---|---|---|---|
| 2.5 | / Inspection |  | £784 | £875 | £970 | £843 | £907 |
| | / Track Realignment |  | £72,228 | £90,000 | £109,641 | £83,636 | £96,509 |
| | / Ballast Renewal |  | £232,480 | £400,001 | £595,328 | £336,646 | £463,408 |
| | / Ballast Cleaning |  | £8,588 | £10,462 | £13,629 | £9,455 | £11,564 |
| | / Capacity Lost |  | £83,461 | £90,180 | £97,386 | £87,797 | £92,592 |
| | / Routine Maintenance |  | £306,863 | £500,000 | £708,906 | £436,172 | £563,037 |
| | / Derailment Risk |  | £210,649 | £398,096 | £595,974 | £334,078 | £461,728 |
| | / Train Operation |  | £163,753 | £186,585 | £205,686 | £180,199 | £193,041 |
| | / Environment |  | £1,018,736 | £1,195,365 | £1,407,026 | £1,131,945 | £1,259,341 |
| | / Mode Change |  | £734,132 | £913,185 | £1,108,646 | £849,129 | £977,053 |

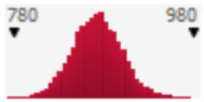
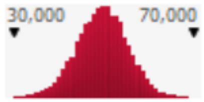
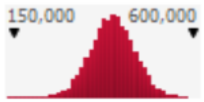
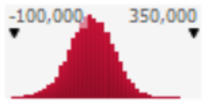
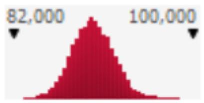
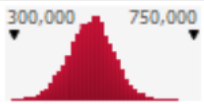
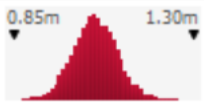
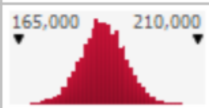
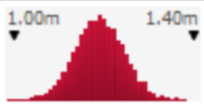
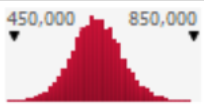
| | | | | | | |
|---|---|---|---|---|---|---|
| ***End of Life Costs*** |   | £119,476 | £160,000 | £198,549 | £147,182 | £172,811 |
| ***Construction Costs*** |   | £66,096 | £440,748 | £815,799 | £312,581 | £568,868 |
| ***Maintenance Costs*** |   | £628,646 | £1,071,519 | £1,451,740 | £931,885 | £1,206,294 |
| ***Track Use Costs*** |   | £2,341,862 | £2,693,232 | £3,047,656 | £2,580,749 | £2,804,514 |
| ***Total Transport Costs*** |   | £3,231,965 | £4,365,500 | £5,697,725 | £3,975,866 | £4,753,459 |
| ***Net Present Value*** |   | £2,356,567 | £3,304,312 | £4,392,430 | £2,979,946 | £3,629,391 |

| SD (in mm) | Cost Element | Graph | Min | Mean | Max | 10% Confidence | 90% Confidence |
|---|---|---|---|---|---|---|---|
| 2.6 | / Inspection |  | £779 | £875 | £977 | £843 | £907 |
| | / Track Realignment |  | £52,082 | £70,000 | £89,935 | £63,534 | £76,520 |
| | / Ballast Renewal |  | £211,364 | £400,000 | £600,179 | £336,286 | £463,782 |
| | / Ballast Cleaning |  | £8,588 | £10,462 | £13,629 | £9,455 | £11,564 |
| | / Capacity Lost |  | £83,667 | £90,180 | £97,804 | £87,842 | £92,635 |
| | / Routine Maintenance |  | £317,487 | £500,001 | £676,947 | £435,632 | £564,174 |
| | / Derailment Risk |  | £513,469 | £728,636 | £948,029 | £663,800 | £794,467 |
| | / Train Operation |  | £167,987 | £186,644 | £204,601 | £180,169 | £193,116 |
| | / Environment |  | £1,005,418 | £1,195,367 | £1,390,422 | £1,130,631 | £1,260,441 |
| | / Mode Change |  | £503,361 | £684,889 | £864,757 | £618,994 | £749,313 |

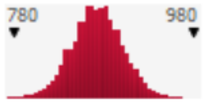
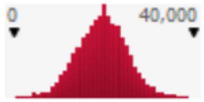
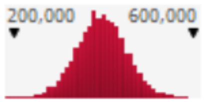
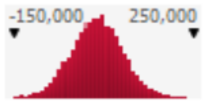
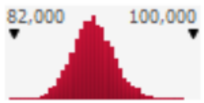
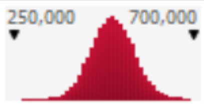
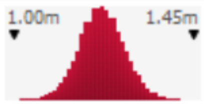
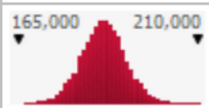
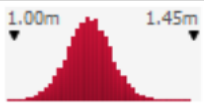
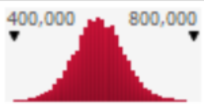
| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | ***End of Life Costs*** |   | £120,573 | £160,000 | £203,612 | £147,182 | £172,812 |
| | ***Construction Costs*** |   | £2,240 | £400,163 | £791,344 | £271,956 | £528,292 |
| | ***Maintenance Costs*** |   | £589,796 | £1,011,521 | £1,413,180 | £873,285 | £1,147,507 |
| | ***Track Use Costs*** |   | £2,472,733 | £2,795,536 | £3,098,818 | £2,684,467 | £2,907,827 |
| | ***Total Transport Costs*** |   | £3,140,279 | £4,367,220 | £5,587,507 | £3,972,441 | £4,756,857 |
| | ***Net Present Value*** |   | £2,440,915 | £3,425,765 | £4,467,712 | £3,111,867 | £3,738,626 |

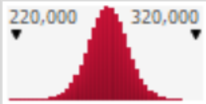
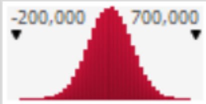
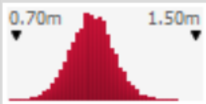
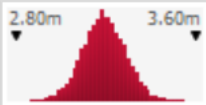
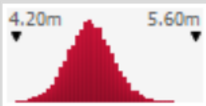
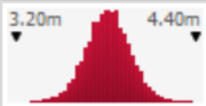
| SD (in mm) | Cost Element | Graph | Min | Mean | Max | 10% Confidence | 90% Confidence |
|---|---|---|---|---|---|---|---|
| **2.7** | */ Inspection* |  | £760 | £875 | £963 | £842 | £907 |
| | */ Track Realignment* |  | £47,096 | £70,000 | £92,409 | £63,629 | £76,302 |
| | */ Ballast Renewal* |  | £200,634 | £400,002 | £597,758 | £336,333 | £463,587 |
| | */ Ballast Cleaning* |  | £8,588 | £10,462 | £13,629 | £9,455 | £11,564 |
| | */ Capacity Lost* |  | £83,911 | £90,180 | £97,421 | £87,842 | £92,584 |
| | */ Routine Maintenance* |  | £312,928 | £500,002 | £684,082 | £436,217 | £564,093 |
| | */ Derailment Risk* |  | £643,586 | £893,902 | £1,120,730 | £828,980 | £958,607 |
| | */ Train Operation* |  | £169,430 | £186,704 | £207,438 | £180,244 | £193,171 |
| | */ Environment* |  | £1,002,856 | £1,195,370 | £1,370,675 | £1,131,050 | £1,259,426 |
| | */ Mode Change* |  | £493,773 | £684,889 | £902,722 | £621,447 | £748,644 |

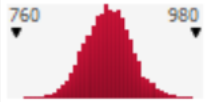
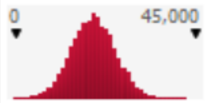
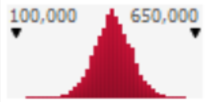
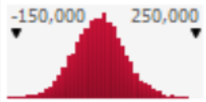
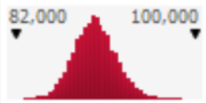
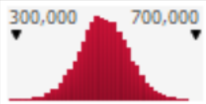
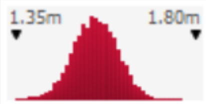
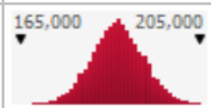
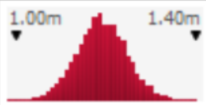
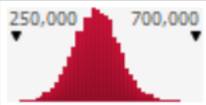
| | | | | | | |
|---|---|---|---|---|---|---|
| ***End of Life Costs*** |   | £233,846 | £272,000 | £311,761 | £259,182 | £284,815 |
| ***Construction Costs*** |   | -£38,546 | £359,579 | £734,136 | £231,372 | £487,702 |
| ***Maintenance Costs*** |   | £620,789 | £1,011,524 | £1,437,629 | £871,272 | £1,147,041 |
| ***Track Use Costs*** |   | £2,637,569 | £2,960,865 | £3,290,796 | £2,849,149 | £3,071,715 |
| ***Total Transport Costs*** |   | £3,403,242 | £4,603,969 | £5,909,946 | £4,214,288 | £4,991,417 |
| ***Net Present Value*** |   | £2,885,018 | £3,853,464 | £4,879,254 | £3,531,052 | £4,177,763 |

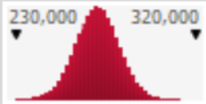
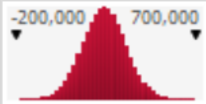
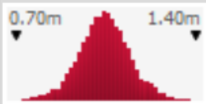
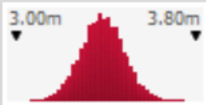
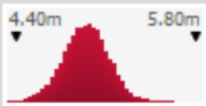
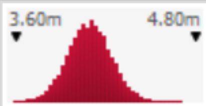
| SD (in mm) | Cost Element | Graph | Min | Mean | Max | 10% Confidence | 90% Confidence |
|---|---|---|---|---|---|---|---|
| 2.8 | / Inspection |   | £782 | £875 | £970 | £843 | £906 |
| | / Track Realignment |   | £31,610 | £50,000 | £67,842 | £43,415 | £56,478 |
| | / Ballast Renewal |   | £155,562 | £399,997 | £574,279 | £335,202 | £464,553 |
| | / Ballast Cleaning |   | £8,588 | £10,462 | £13,629 | £9,455 | £11,564 |
| | / Capacity Lost |   | £83,736 | £90,180 | £98,333 | £87,833 | £92,597 |
| | / Routine Maintenance |   | £314,359 | £500,000 | £704,458 | £435,259 | £563,733 |
| | / Derailment Risk |   | £890,449 | £1,059,171 | £1,251,038 | £995,463 | £1,121,246 |
| | / Train Operation |   | £169,626 | £186,768 | £205,444 | £180,389 | £193,190 |
| | / Environment |   | £1,005,242 | £1,195,366 | £1,376,034 | £1,132,670 | £1,259,113 |
| | / Mode Change |   | £452,710 | £639,226 | £832,742 | £575,706 | £703,288 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | ***End of Life Costs*** | 230,000 320,000 | £231,930 | £272,000 | £314,138 | £259,181 | £284,812 |
| | ***Construction Costs*** | -100,000 700,000 | -£70,665 | £318,995 | £693,952 | £190,830 | £447,144 |
| | ***Maintenance Costs*** | 0.70m 1.60m | £503,056 | £951,518 | £1,408,200 | £812,286 | £1,089,733 |
| | ***Track Use Costs*** | 2.70m 3.50m | £2,769,123 | £3,080,532 | £3,421,241 | £2,971,275 | £3,188,897 |
| | ***Total Transport Costs*** | 4.20m 5.60m | £3,515,035 | £4,623,045 | £5,887,574 | £4,234,211 | £5,010,136 |
| | ***Net Present Value*** | 3.20m 4.40m | £2,910,095 | £3,915,650 | £4,947,275 | £3,593,993 | £4,236,499 |

| SD (in mm) | Cost Element | Graph | Min | Mean | Max | 10% Confidence | 90% Confidence |
|---|---|---|---|---|---|---|---|
| 2.9 | */ Inspection* |  | £782 | £875 | £963 | £843 | £907 |
| | */ Track Realignment* |  | £2,034 | £20,000 | £38,059 | £13,590 | £26,244 |
| | */ Ballast Renewal* |  | £201,404 | £400,000 | £576,958 | £336,795 | £463,415 |
| | */ Ballast Cleaning* |  | £8,588 | £10,462 | £13,629 | £9,455 | £11,564 |
| | */ Capacity Lost* |  | £82,309 | £90,180 | £98,622 | £87,811 | £92,572 |
| | */ Routine Maintenance* |  | £290,475 | £500,001 | £678,933 | £435,946 | £563,998 |
| | */ Derailment Risk* |  | £1,032,795 | £1,224,438 | £1,408,621 | £1,160,695 | £1,288,672 |
| | */ Train Operation* |  | £168,319 | £186,833 | £209,313 | £180,445 | £193,229 |
| | */ Environment* |  | £1,004,473 | £1,195,370 | £1,429,911 | £1,131,143 | £1,259,025 |
| | */ Mode Change* |  | £419,124 | £593,569 | £775,276 | £529,572 | £657,603 |

| | | | | | | |
|---|---|---|---|---|---|---|
| ***End of Life Costs*** |  | £220,704 | £271,999 | £310,871 | £259,182 | £284,815 |
| ***Construction Costs*** |  | -£141,868 | £278,408 | £651,172 | £150,233 | £406,511 |
| ***Maintenance Costs*** |  | £4,258,844 | £4,801,677 | £5,405,119 | £4,601,711 | £5,002,753 |
| ***Track Use Costs*** |  | £2,891,180 | £3,200,212 | £3,536,018 | £3,090,010 | £3,311,398 |
| ***Total Transport Costs*** |  | £3,490,484 | £4,612,142 | £5,868,765 | £4,225,381 | £4,997,624 |
| ***Net Present Value*** |  | £3,004,121 | £3,948,866 | £4,992,082 | £3,627,931 | £4,269,535 |

| SD (in mm) | Cost Element | Graph | Min | Mean | Max | 10% Confidence | 90% Confidence |
|---|---|---|---|---|---|---|---|
| **3** | */ Inspection* |  | £778 | £875 | £971 | £843 | £907 |
| | */ Track Realignment* |  | £1,209 | £20,000 | £41,757 | £13,617 | £26,467 |
| | */ Ballast Renewal* |  | £150,258 | £400,000 | £610,882 | £336,284 | £462,975 |
| | */ Ballast Cleaning* |  | £8,588 | £10,462 | £13,629 | £9,455 | £11,564 |
| | */ Capacity Lost* |  | £83,564 | £90,180 | £98,241 | £87,822 | £92,563 |
| | */ Routine Maintenance* |  | £303,756 | £499,999 | £676,116 | £436,620 | £563,814 |
| | */ Derailment Risk* |  | £1,368,096 | £1,554,977 | £1,757,510 | £1,491,806 | £1,619,443 |
| | */ Train Operation* |  | £169,142 | £186,901 | £204,306 | £180,418 | £193,374 |
| | */ Environment* |  | £1,000,782 | £1,195,372 | £1,391,177 | £1,131,035 | £1,259,645 |
| | */ Mode Change* |  | £277,191 | £456,588 | £653,431 | £392,063 | £519,946 |

| | | | | | | |
|---|---|---|---|---|---|---|
| ***End of Life Costs*** |   | £233,802 | £272,000 | £310,755 | £259,183 | £284,815 |
| ***Construction Costs*** |   | -£145,812 | £250,003 | £671,303 | £121,806 | £378,122 |
| ***Maintenance Costs*** |   | £494,797 | £861,517 | £1,261,235 | £723,663 | £995,690 |
| ***Track Use Costs*** |   | £3,090,368 | £3,393,838 | £3,730,242 | £3,280,776 | £3,505,506 |
| ***Total Transport Costs*** |   | £4,404,103 | £4,966,894 | £5,609,844 | £4,764,280 | £5,170,005 |
| ***Net Present Value*** |   | £3,642,655 | £4,109,137 | £4,681,179 | £3,937,232 | £4,282,031 |

**Route** High Speed Passenger
**Line** London Euston-Birmingham New Street
**Analysis Time Period** 25 Years

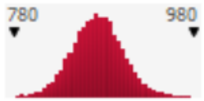
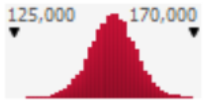
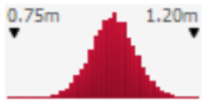
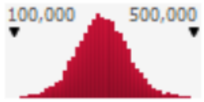
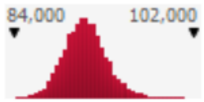
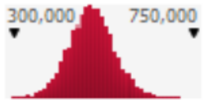
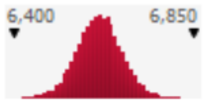
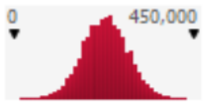
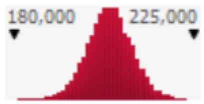
| SD (in mm) | Whole Life Cycle Costs | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Inspection | Track Realignment | Ballast Renewal | Ballast Cleaning | Capacity Lost | Routine Maintenance | Derailment Risk | Train Operation | Environmental Impacts | Mode Change |
| 1.9 | £973 | £172,445 | £578,698 | £13,629 | £90,374 | £685,921 | £405,704 | £205,910 | £1,386,743 | £1,087,099 |
| 2.2 | £983 | £137,890 | £584,305 | £13,629 | £90,452 | £674,315 | £416,805 | £277,860 | £1,382,621 | £1,085,557 |
| 2.4 | £959 | £120,705 | £626,825 | £13,629 | £90,460 | £746,500 | £418,233 | £205,638 | £1,389,631 | £1,115,115 |
| 2.5 | £970 | £109,641 | £595,328 | £13,629 | £97,386 | £708,906 | £595,974 | £205,686 | £1,407,026 | £1,108,646 |
| 2.6 | £977 | £89,935 | £600,179 | £13,629 | £97,804 | £676,947 | £948,029 | £204,601 | £1,390,422 | £864,757 |
| 2.7 | £963 | £92,409 | £597,758 | £13,629 | £97,421 | £684,082 | £1,120,730 | £207,438 | £1,370,675 | £902,722 |
| 2.8 | £970 | £67,842 | £574,279 | £13,629 | £98,333 | £704,458 | £1,251,038 | £205,444 | £1,376,034 | £832,742 |
| 2.9 | £963 | £38,059 | £576,958 | £13,629 | £98,622 | £678,933 | £1,408,621 | £209,313 | £1,429,911 | £775,276 |
| 3.0 | £971 | £41,757 | £610,882 | £13,629 | £98,421 | £676,116 | £1,757,510 | £204,306 | £1,391,177 | £653,431 |

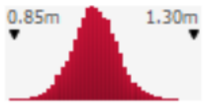
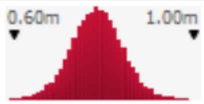
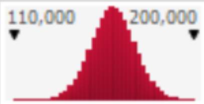
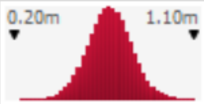
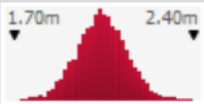
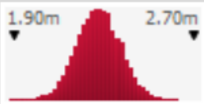
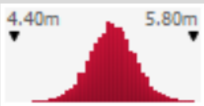
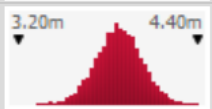
# @RISK Output Results

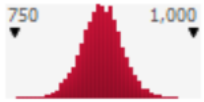
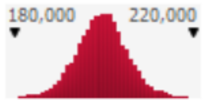
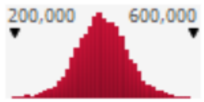
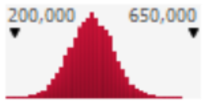
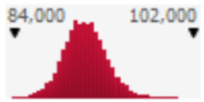
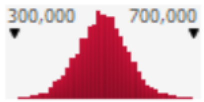
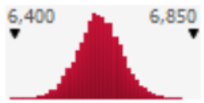
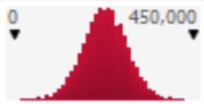
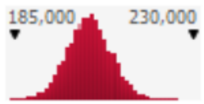
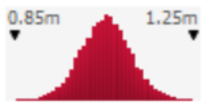
**Performed By:** Manu Sasidharan (School of Engineering)

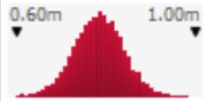
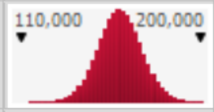
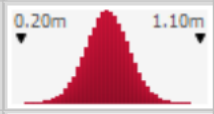
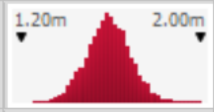
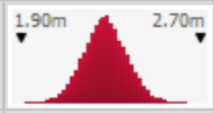
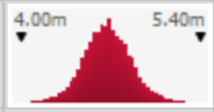
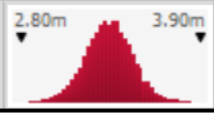
**Date:** 26 March 2019 20:23:49

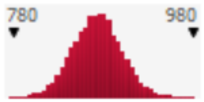
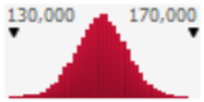
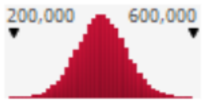
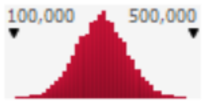
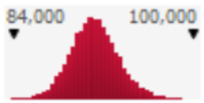
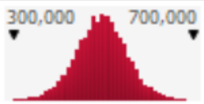
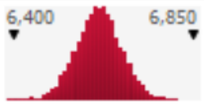
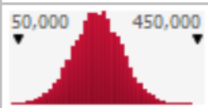
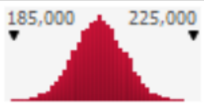
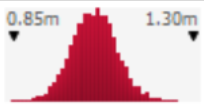
**Route** Mixed Freight-Passenger
**Line** Birmingham-Coventry
**Analysis Time Period** 25 Years

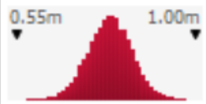
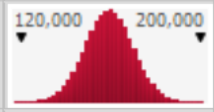
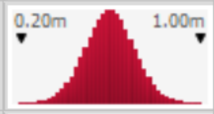
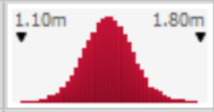
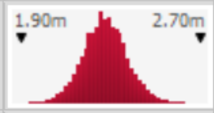
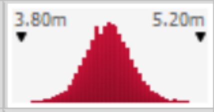
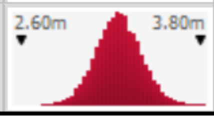
| SD (in mm) | Cost Element | Graph | Min | Mean | Max | 10% Confidence | 90% Confidence |
|---|---|---|---|---|---|---|---|
| 1.2 | / Inspection |  | £791 | £875 | £971 | £843 | £907 |
| | / Track Realignment |  | £129,870 | £150,000 | £168,502 | £143,606 | £156,387 |
| | / Ballast Renewal |  | £753,752 | £1,000,002 | £1,198,233 | £935,907 | £1,063,992 |
| | / Ballast Cleaning |  | £8,588 | £10,462 | £13,629 | £9,455 | £11,564 |
| | / Capacity Lost |  | £85,018 | £91,404 | £100,697 | £88,976 | £93,828 |
| | / Routine Maintenance |  | £316,255 | £499,997 | £706,883 | £435,218 | £564,643 |
| | / Spillage |  | £6,440 | £6,619 | £6,807 | £6,555 | £6,682 |
| | / Derailment Risk |  | £34,082 | £232,830 | £421,228 | £169,012 | £298,036 |
| | / Train Operation |  | £182,992 | £204,286 | £222,110 | £197,835 | £210,667 |

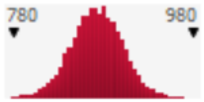
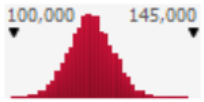
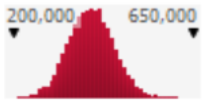
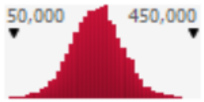
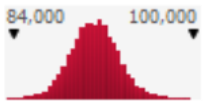
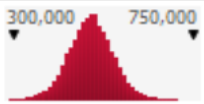
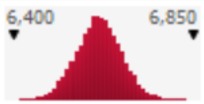
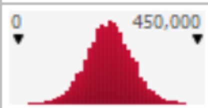
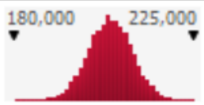
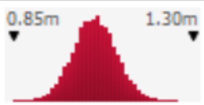
| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | */ Environment* |  | £859,111 | £1,057,864 | £1,252,361 | £993,707 | £1,121,176 |
| | */ Modal Change* |  | £607,955 | £788,968 | £978,755 | £724,324 | £853,792 |
| | ***End of Life Costs*** |  | £113,689 | £159,999 | £198,520 | £147,179 | £172,815 |
| | ***Construction Costs*** |  | £265,906 | £684,213 | £1,076,692 | £556,031 | £812,368 |
| | ***Maintenance Costs*** |  | £1,496,038 | £1,859,364 | £2,277,390 | £1,720,055 | £1,995,870 |
| | ***Track Use Costs*** |  | £1,920,426 | £2,283,949 | £2,615,900 | £2,170,672 | £2,395,987 |
| | ***Total Transport Costs*** |  | £3,824,013 | £4,987,525 | £6,236,582 | £4,597,230 | £5,378,460 |
| | ***Net Present Value*** |  | £3,027,420 | £4,001,205 | £5,025,266 | £3,676,185 | £4,326,100 |

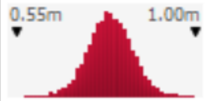
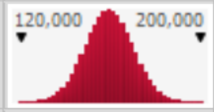
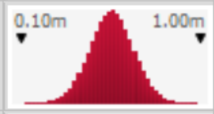
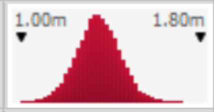
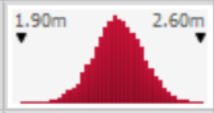
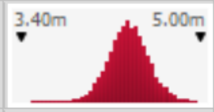
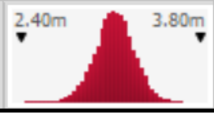
| SD (in mm) | Cost Element | Graph | Min | Mean | Max | 10% Confidence | 90% Confidence |
|---|---|---|---|---|---|---|---|
| **1.4** | */ Inspection* |  | £762 | £875 | £973 | £843 | £907 |
| | */ Track Realignment* |  | £182,646 | £200,000 | £217,900 | £193,464 | £206,419 |
| | */ Ballast Renewal* |  | £212,349 | £399,998 | £584,099 | £336,822 | £465,067 |
| | */ Ballast Cleaning* |  | £8,588 | £10,462 | £13,629 | £9,455 | £11,564 |
| | */ Capacity Lost* |  | £84,498 | £91,404 | £100,092 | £89,046 | £93,822 |
| | */ Routine Maintenance* |  | £324,664 | £500,000 | £688,695 | £435,710 | £562,702 |
| | */ Spillage* |  | £6,411 | £6,619 | £6,811 | £6,555 | £6,682 |
| | */ Derailment Risk* |  | £33,731 | £232,830 | £418,385 | £168,344 | £297,547 |
| | */ Train Operation* |  | £186,062 | £204,349 | £225,369 | £197,896 | £210,739 |
| | */ Environment* |  | £871,562 | £1,057,866 | £1,237,831 | £993,592 | £1,122,034 |

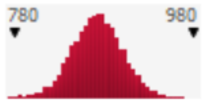
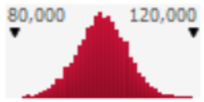
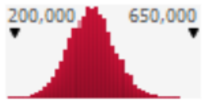
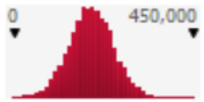
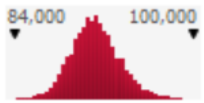
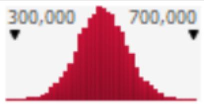
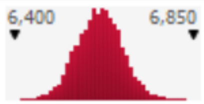
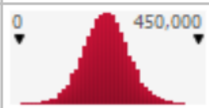
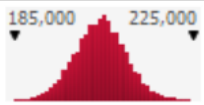
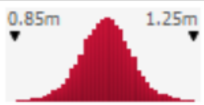
| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | */ Modal Change* |  0.60m – 1.00m | £616,328 | £788,970 | £972,432 | £724,753 | £852,481 |
| | ***End of Life Costs*** |  110,000 – 200,000 | £117,781 | £160,000 | £198,858 | £147,181 | £172,811 |
| | ***Construction Costs*** |  0.20m – 1.10m | £261,836 | £643,669 | £1,035,915 | £515,469 | £771,779 |
| | ***Maintenance Costs*** |  1.20m – 2.00m | £1,025,396 | £1,409,359 | £1,882,966 | £1,268,991 | £1,545,571 |
| | ***Track Use Costs*** |  1.90m – 2.70m | £1,951,796 | £2,284,015 | £2,621,646 | £2,172,008 | £2,397,372 |
| | ***Total Transport Costs*** |  4.00m – 5.40m | £3,364,038 | £4,497,042 | £5,711,113 | £4,109,144 | £4,883,911 |
| | ***Net Present Value*** |  2.80m – 3.90m | £2,559,760 | £3,476,368 | £4,465,053 | £3,162,772 | £3,792,465 |

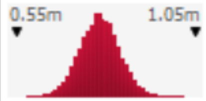
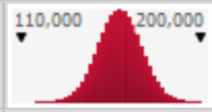
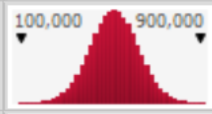
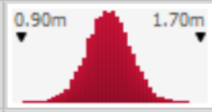
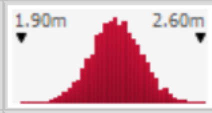
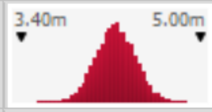
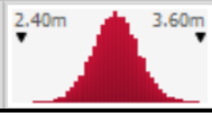
| SD (in mm) | Cost Element | Graph | Min | Mean | Max | 10% Confidence | 90% Confidence |
|---|---|---|---|---|---|---|---|
| **1.6** | */ Inspection* |   | £784 | £875 | £976 | £843 | £907 |
| | */ Track Realignment* |   | £130,981 | £150,000 | £167,794 | £143,449 | £156,559 |
| | */ Ballast Renewal* |   | £210,259 | £399,999 | £586,565 | £335,740 | £464,388 |
| | */ Ballast Cleaning* |   | £8,588 | £10,462 | £13,629 | £9,455 | £11,564 |
| | */ Capacity Lost* |   | £84,509 | £91,404 | £98,687 | £89,025 | £93,835 |
| | */ Routine Maintenance* |   | £318,410 | £500,001 | £675,801 | £435,748 | £564,162 |
| | */ Spillage* |   | £6,406 | £6,619 | £6,804 | £6,554 | £6,683 |
| | */ Derailment Risk* |   | £54,881 | £232,830 | £427,814 | £168,921 | £296,323 |
| | */ Train Operation* |   | £186,364 | £204,421 | £221,885 | £198,026 | £210,830 |
| | */ Environment* |   | £864,396 | £1,057,865 | £1,252,964 | £993,934 | £1,122,057 |

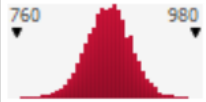
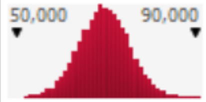
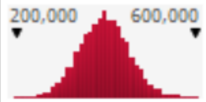
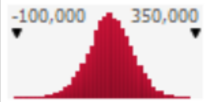
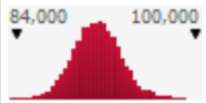
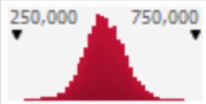
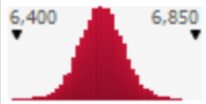
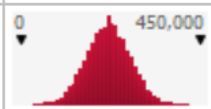
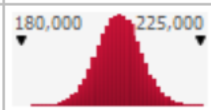
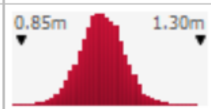
| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | */ Modal Change* |  | £591,907 | £788,973 | £966,465 | £723,878 | £853,250 |
| | ***End of Life Costs*** |  | £120,449 | £160,000 | £199,058 | £147,181 | £172,816 |
| | ***Construction Costs*** |  | £227,577 | £603,083 | £982,422 | £474,889 | £731,210 |
| | ***Maintenance Costs*** |  | £871,626 | £1,259,363 | £1,670,395 | £1,121,603 | £1,394,501 |
| | ***Track Use Costs*** |  | £1,968,458 | £2,284,089 | £2,612,336 | £2,172,367 | £2,396,246 |
| | ***Total Transport Costs*** |  | £3,172,144 | £4,306,535 | £5,541,474 | £3,917,831 | £4,694,639 |
| | ***Net Present Value*** |  | £2,439,049 | £3,384,418 | £4,444,291 | £3,062,333 | £3,710,524 |

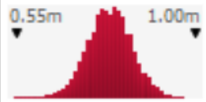
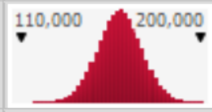
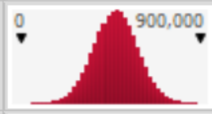
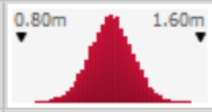
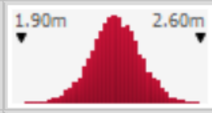
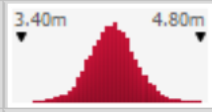
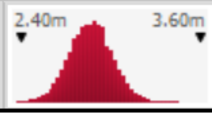
| SD (in mm) | Cost Element | Graph | Min | Mean | Max | 10% Confidence | 90% Confidence |
|---|---|---|---|---|---|---|---|
| **1.9** | */ Inspection* |  | £787 | £875 | £966 | £842 | £907 |
| | */ Track Realignment* |  | £101,279 | £120,000 | £142,761 | £113,521 | £126,498 |
| | */ Ballast Renewal* |  | £227,833 | £399,998 | £603,319 | £335,273 | £464,887 |
| | */ Ballast Cleaning* |  | £8,588 | £10,462 | £13,629 | £9,455 | £11,564 |
| | */ Capacity Lost* |  | £84,090 | £91,404 | £99,312 | £88,980 | £93,797 |
| | */ Routine Maintenance* |  | £310,212 | £500,000 | £701,114 | £436,630 | £564,455 |
| | */ Spillage* |  | £6,434 | £6,619 | £6,823 | £6,554 | £6,683 |
| | */ Derailment Risk* |  | £45,161 | £232,830 | £411,496 | £168,563 | £297,108 |
| | */ Train Operation* |  | £182,501 | £204,550 | £224,142 | £198,174 | £210,913 |
| | */ Environment* |  | £868,851 | £1,057,867 | £1,250,534 | £994,179 | £1,120,933 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | */ Modal Change* |  0.55m 1.00m | £586,726 | £788,967 | £985,993 | £725,473 | £852,959 |
| | *End of Life Costs* |  120,000 200,000 | £122,564 | £160,000 | £199,133 | £147,183 | £172,813 |
| | *Construction Costs* |  0.10m 1.00m | £162,013 | £562,499 | £958,172 | £434,326 | £690,612 |
| | *Maintenance Costs* |  1.00m 1.80m | £771,617 | £1,169,361 | £1,606,471 | £1,030,675 | £1,305,705 |
| | *Track Use Costs* |  1.90m 2.60m | £1,931,501 | £2,284,214 | £2,592,578 | £2,172,824 | £2,396,377 |
| | *Total Transport Costs* |  3.40m 5.00m | £2,778,782 | £4,176,073 | £5,390,497 | £3,784,955 | £4,560,658 |
| | *Net Present Value* |  2.40m 3.80m | £2,152,957 | £3,265,465 | £4,278,974 | £2,940,102 | £3,591,439 |

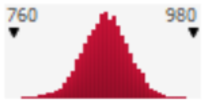
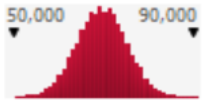
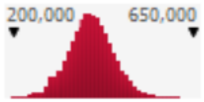
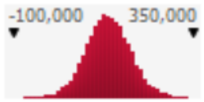
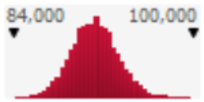
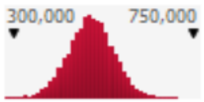
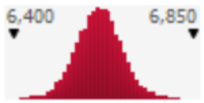
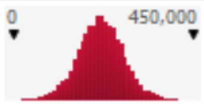
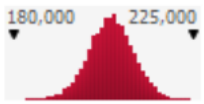
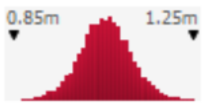
| SD (in mm) | Cost Element | Graph | Min | Mean | Max | 10% Confidence | 90% Confidence |
|---|---|---|---|---|---|---|---|
| **2.1** | */ Inspection* |  | £783 | £875 | £965 | £843 | £907 |
| | */ Track Realignment* |  | £83,296 | £100,000 | £118,559 | £93,509 | £106,350 |
| | */ Ballast Renewal* |  | £205,430 | £400,001 | £605,316 | £335,353 | £465,806 |
| | */ Ballast Cleaning* |  | £8,588 | £10,462 | £13,629 | £9,455 | £11,564 |
| | */ Capacity Lost* |  | £84,780 | £91,404 | £98,654 | £89,005 | £93,865 |
| | */ Routine Maintenance* |  | £301,509 | £500,001 | £694,520 | £436,307 | £564,098 |
| | */ Spillage* |  | £6,435 | £6,619 | £6,821 | £6,554 | £6,683 |
| | */ Derailment Risk* |  | £24,896 | £223,519 | £407,423 | £159,631 | £287,546 |
| | */ Train Operation* |  | £186,620 | £204,648 | £223,235 | £198,072 | £211,134 |
| | */ Environment* |  | £871,746 | £1,057,867 | £1,240,317 | £994,256 | £1,121,269 |

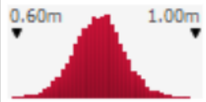
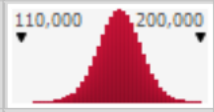
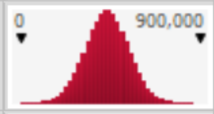
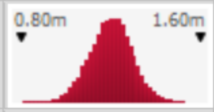
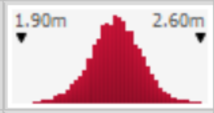
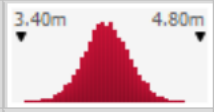
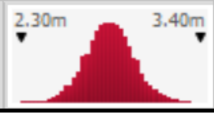
| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | / Modal Change |   | £597,686 | £788,968 | £1,007,353 | £724,603 | £853,355 |
| | End of Life Costs |   | £120,077 | £160,000 | £198,420 | £147,183 | £172,812 |
| | Construction Costs |   | £125,585 | £521,915 | £899,118 | £393,742 | £650,019 |
| | Maintenance Costs |   | £685,698 | £1,109,364 | £1,533,934 | £969,061 | £1,247,447 |
| | Track Use Costs |   | £1,931,391 | £2,275,003 | £2,596,633 | £2,162,473 | £2,388,296 |
| | Total Transport Costs |   | £2,827,777 | £4,066,282 | £5,307,228 | £3,672,402 | £4,455,919 |
| | Net Present Value |   | £2,189,910 | £3,165,435 | £4,214,120 | £2,840,531 | £3,492,284 |

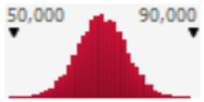
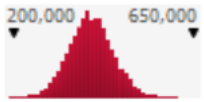
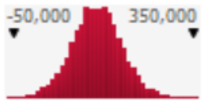
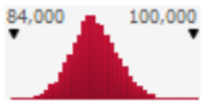
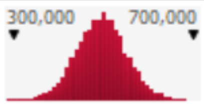
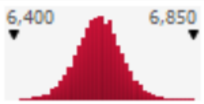
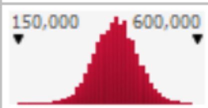
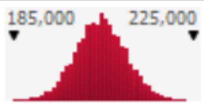
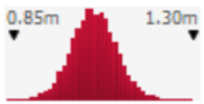
| SD (in mm) | Cost Element | Graph | Min | Mean | Max | 10% Confidence | 90% Confidence |
|---|---|---|---|---|---|---|---|
| **2.3** | */ Inspection* |   | £775 | £875 | £965 | £843 | £907 |
| | */ Track Realignment* |   | £53,263 | £70,000 | £89,907 | £63,497 | £76,497 |
| | */ Ballast Renewal* |   | £212,754 | £399,999 | £597,080 | £335,563 | £463,852 |
| | */ Ballast Cleaning* |   | £8,588 | £10,462 | £13,629 | £9,455 | £11,564 |
| | */ Capacity Lost* |   | £84,246 | £91,404 | £98,741 | £89,009 | £93,861 |
| | */ Routine Maintenance* |   | £293,782 | £499,999 | £708,095 | £435,926 | £563,834 |
| | */ Spillage* |   | £6,409 | £6,619 | £6,808 | £6,555 | £6,682 |
| | */ Derailment Risk* |   | £45,560 | £223,517 | £409,779 | £159,215 | £287,626 |
| | */ Train Operation* |   | £184,273 | £204,758 | £224,721 | £198,332 | £211,218 |
| | */ Environment* |   | £851,235 | £1,057,868 | £1,278,788 | £993,740 | £1,121,683 |

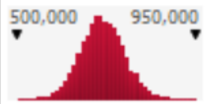
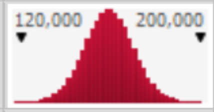
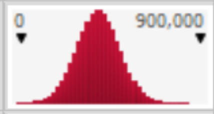
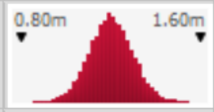
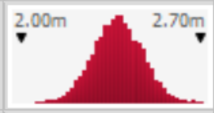
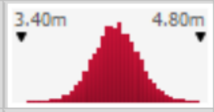
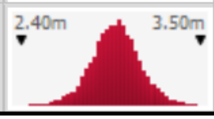
| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | / Modal Change |  | £564,910 | £788,971 | £963,114 | £724,983 | £852,418 |
| | End of Life Costs |  | £120,009 | £160,000 | £199,468 | £147,180 | £172,814 |
| | Construction Costs |  | £86,856 | £481,332 | £862,328 | £353,147 | £609,485 |
| | Maintenance Costs |  | £631,212 | £1,019,365 | £1,435,034 | £880,969 | £1,155,455 |
| | Track Use Costs |  | £1,945,587 | £2,275,113 | £2,576,261 | £2,164,732 | £2,385,147 |
| | Total Transport Costs |  | £2,784,227 | £3,935,811 | £5,236,374 | £3,545,829 | £4,324,421 |
| | Net Present Value |  | £2,082,544 | £3,013,811 | £4,077,054 | £2,698,360 | £3,329,649 |

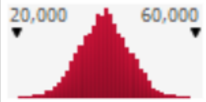
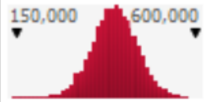
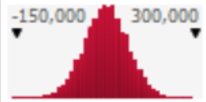
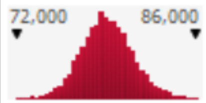
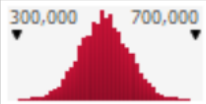
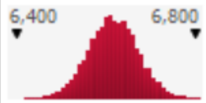
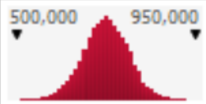
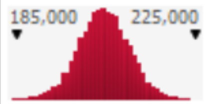
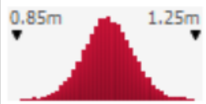
CV

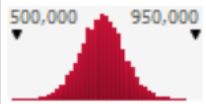
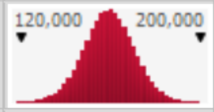
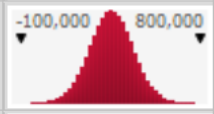
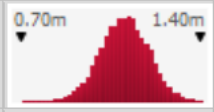
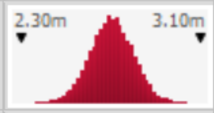
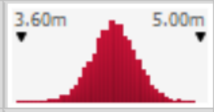
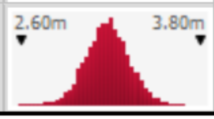
| SD (in mm) | Cost Element | Graph | Min | Mean | Max | 10% Confidence | 90% Confidence |
|---|---|---|---|---|---|---|---|
| **2.4** | */ Inspection* |   | £779 | £875 | £967 | £843 | £907 |
| | */ Track Realignment* |   | £52,323 | £70,000 | £89,920 | £63,461 | £76,527 |
| | */ Ballast Renewal* |   | £214,027 | £399,999 | £606,535 | £336,009 | £464,676 |
| | */ Ballast Cleaning* |   | £8,588 | £10,462 | £13,629 | £9,455 | £11,564 |
| | */ Capacity Lost* |   | £84,916 | £91,404 | £99,305 | £89,011 | £93,867 |
| | */ Routine Maintenance* |   | £302,041 | £499,999 | £701,446 | £435,223 | £563,801 |
| | */ Spillage* |   | £6,432 | £6,619 | £6,805 | £6,554 | £6,682 |
| | */ Derailment Risk* |   | £37,769 | £223,515 | £403,558 | £159,925 | £287,773 |
| | */ Train Operation* |   | £184,863 | £204,817 | £223,321 | £198,381 | £211,297 |
| | */ Environment* |   | £883,506 | £1,057,870 | £1,239,462 | £993,445 | £1,122,311 |

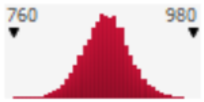
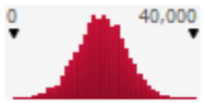
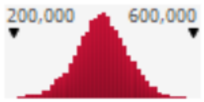
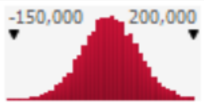
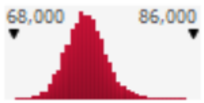
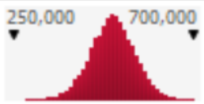
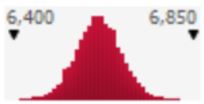
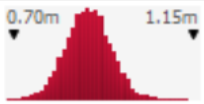
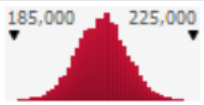
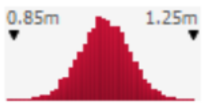
| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | / Modal Change |   | £606,547 | £788,972 | £977,723 | £724,530 | £852,919 |
| | End of Life Costs |   | £119,707 | £160,000 | £197,808 | £147,180 | £172,813 |
| | Construction Costs |   | £36,882 | £440,748 | £846,078 | £312,574 | £568,851 |
| | Maintenance Costs |   | £583,963 | £1,019,359 | £1,416,118 | £878,235 | £1,154,522 |
| | Track Use Costs |   | £1,973,066 | £2,275,173 | £2,583,743 | £2,165,040 | £2,386,568 |
| | Total Transport Costs |   | £2,720,119 | £3,895,280 | £5,116,648 | £3,507,143 | £4,284,126 |
| | Net Present Value |   | £2,013,249 | £2,979,689 | £3,965,092 | £2,667,621 | £3,297,225 |

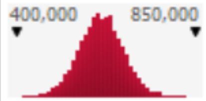
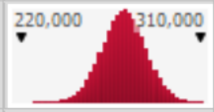
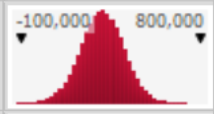
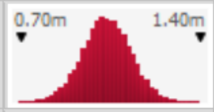
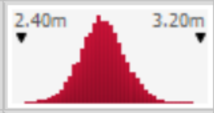
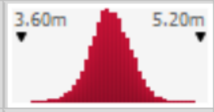
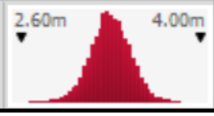
| SD (in mm) | Cost Element | Graph | Min | Mean | Max | 10% Confidence | 90% Confidence |
|---|---|---|---|---|---|---|---|
| **2.5** | */ Inspection* |  | £778 | £875 | £981 | £843 | £907 |
| | */ Track Realignment* |  | £50,658 | £70,000 | £88,136 | £63,575 | £76,346 |
| | */ Ballast Renewal* |  | £211,479 | £400,001 | £602,407 | £335,637 | £464,124 |
| | */ Ballast Cleaning* |  | £8,588 | £10,462 | £13,629 | £9,455 | £11,564 |
| | */ Capacity Lost* |  | £84,536 | £91,404 | £99,951 | £89,040 | £93,819 |
| | */ Routine Maintenance* |  | £304,886 | £500,000 | £672,721 | £436,536 | £563,906 |
| | */ Spillage* |  | £6,434 | £6,619 | £6,842 | £6,555 | £6,682 |
| | */ Derailment Risk* |  | £170,367 | £398,098 | £575,339 | £335,023 | £460,792 |
| | */ Train Operation* |  | £186,696 | £204,878 | £222,254 | £198,323 | £211,333 |
| | */ Environment* |  | £853,401 | £1,057,870 | £1,284,316 | £993,866 | £1,122,467 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | */ Modal Change* |   | £526,119 | £720,481 | £938,788 | £657,377 | £783,872 |
| | *End of Life Costs* |   | £121,050 | £160,000 | £198,666 | £147,184 | £172,813 |
| | *Construction Costs* |   | £18,847 | £400,168 | £820,442 | £271,992 | £528,276 |
| | *Maintenance Costs* |   | £623,834 | £1,019,367 | £1,428,280 | £880,499 | £1,155,829 |
| | *Track Use Costs* |   | £2,085,209 | £2,381,327 | £2,694,102 | £2,269,645 | £2,492,339 |
| | *Total Transport Costs* |   | £2,740,531 | £3,960,862 | £5,214,937 | £3,572,371 | £4,347,904 |
| | *Net Present Value* |   | £2,153,509 | £3,114,266 | £4,100,348 | £2,798,851 | £3,427,842 |

| SD (in mm) | Cost Element | Graph | Min | Mean | Max | 10% Confidence | 90% Confidence |
|---|---|---|---|---|---|---|---|
| **2.6** | */ Inspection* |  | £772 | £875 | £980 | £843 | £907 |
| | */ Track Realignment* |  | £22,284 | £40,000 | £57,683 | £33,598 | £46,474 |
| | */ Ballast Renewal* |  | £161,220 | £400,003 | £572,895 | £335,007 | £464,394 |
| | */ Ballast Cleaning* |  | £8,588 | £10,462 | £13,629 | £9,455 | £11,564 |
| | */ Capacity Lost* |  | £72,649 | £79,217 | £85,892 | £76,906 | £81,573 |
| | */ Routine Maintenance* |  | £320,975 | £500,000 | £677,986 | £436,029 | £564,485 |
| | */ Spillage* |  | £6,436 | £6,619 | £6,799 | £6,554 | £6,683 |
| | */ Derailment Risk* |  | £529,734 | £728,637 | £916,222 | £664,083 | £792,492 |
| | */ Train Operation* |  | £185,685 | £204,942 | £222,979 | £198,457 | £211,479 |
| | */ Environment* |  | £874,561 | £1,057,869 | £1,236,767 | £993,939 | £1,122,291 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | */ Modal Change* |  500,000 950,000 | £509,659 | £720,483 | £917,554 | £655,582 | £784,367 |
| | *End of Life Costs* |  120,000 200,000 | £121,489 | £160,000 | £197,839 | £147,182 | £172,812 |
| | *Construction Costs* |  -100,000 800,000 | -£17,398 | £359,582 | £748,134 | £231,410 | £487,688 |
| | *Maintenance Costs* |  0.70m 1.40m | £477,468 | £917,179 | £1,291,806 | £779,764 | £1,051,143 |
| | *Track Use Costs* |  2.30m 3.10m | £2,390,656 | £2,711,931 | £3,023,550 | £2,600,145 | £2,822,966 |
| | *Total Transport Costs* |  3.60m 5.00m | £2,854,073 | £4,148,692 | £5,386,360 | £3,759,088 | £4,536,779 |
| | *Net Present Value* |  2.60m 3.80m | £2,295,360 | £3,316,384 | £4,316,029 | £3,001,424 | £3,631,054 |

| SD (in mm) | Cost Element | Graph | Min | Mean | Max | 10% Confidence | 90% Confidence |
|---|---|---|---|---|---|---|---|
| **2.7** | */ Inspection* |  | £770 | £875 | £964 | £843 | £907 |
| | */ Track Realignment* |  | £1,898 | £20,000 | £39,680 | £13,565 | £26,384 |
| | */ Ballast Renewal* |  | £224,689 | £400,001 | £575,739 | £336,673 | £464,230 |
| | */ Ballast Cleaning* |  | £8,588 | £10,462 | £13,629 | £9,455 | £11,564 |
| | */ Capacity Lost* |  | £68,867 | £75,560 | £84,771 | £73,396 | £77,804 |
| | */ Routine Maintenance* |  | £298,942 | £500,002 | £688,063 | £435,040 | £564,990 |
| | */ Spillage* |  | £6,433 | £6,619 | £6,808 | £6,554 | £6,683 |
| | */ Derailment Risk* |  | £706,041 | £893,904 | £1,127,903 | £829,296 | £958,955 |
| | */ Train Operation* |  | £187,403 | £205,009 | £222,129 | £198,688 | £211,405 |
| | */ Environment* |  | £856,249 | £1,056,407 | £1,239,563 | £991,281 | £1,121,324 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | */ Modal Change* |   | £431,942 | £617,749 | £817,650 | £553,591 | £682,162 |
| | *End of Life Costs* |   | £229,881 | £271,999 | £309,386 | £259,182 | £284,815 |
| | *Construction Costs* |   | -£84,177 | £318,995 | £713,127 | £190,795 | £447,142 |
| | *Maintenance Costs* |   | £460,639 | £853,520 | £1,276,231 | £715,260 | £988,072 |
| | *Track Use Costs* |   | £2,453,297 | £2,773,070 | £3,150,813 | £2,659,391 | £2,887,066 |
| | *Total Transport Costs* |   | £2,981,411 | £4,217,585 | £5,572,745 | £3,827,669 | £4,607,843 |
| | *Net Present Value* |   | £2,385,480 | £3,436,781 | £4,469,289 | £3,111,256 | £3,764,821 |

| | |
|---|---|
| **Route** | Mixed Freight-Passenger |
| **Line** | Birmingham-Coventry |
| **Analysis Time Period** | 25 Years |

| SD (in mm) | | Whole Life Cycle Costs | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Inspection | Track Realignment | Ballast Renewal | Ballast Cleaning | Capacity Lost | Routine Maintenance | Spillage | Derailment Risk | Train Operation | Environmental Impacts | Mode Change |
| 1.2 | £971 | £168,502 | £1,198,233 | £13,629 | £100,697 | £706,833 | £6,807 | £421,228 | £222,110 | £1,252,361 | £978,755 |
| 1.4 | £973 | £217,900 | £584,099 | £13,629 | £100,092 | £688,695 | £6,811 | £418,385 | £225,369 | £1,237,831 | £972,432 |
| 1.6 | £976 | £167,794 | £586,565 | £13,629 | £98,687 | £675,801 | £6,804 | £427,814 | £221,885 | £1,252,964 | £966,465 |
| 1.9 | £966 | £142,761 | £603,319 | £13,629 | £99,312 | £701,114 | £6,823 | £411,496 | £224,142 | £1,250,534 | £985,993 |
| 2.1 | £965 | £118,559 | £605,316 | £13,629 | £98,654 | £694,520 | £6,821 | £407,423 | £223,235 | £1,240,317 | £994,256 |
| 2.3 | £965 | £89,907 | £597,080 | £13,629 | £98,741 | £708,095 | £6,808 | £409,779 | £224,721 | £1,278,788 | £963,114 |
| 2.4 | £967 | £89,920 | £606,535 | £13,629 | £99,305 | £701,446 | £6,805 | £403,558 | £223,321 | £1,239,462 | £977,763 |
| 2.5 | £981 | £88,136 | £602,407 | £13,629 | £99,951 | £672,721 | £6,842 | £575,339 | £222,254 | £1,284,316 | £938,788 |
| 2.6 | £980 | £57,683 | £572,895 | £13,629 | £85,892 | £677,986 | £6,799 | £916,222 | £222,929 | £1,236,767 | £917,554 |
| 2.7 | £964 | £39,680 | £575,739 | £13,629 | £84,771 | £688,063 | £6,808 | £1,127,903 | £222,129 | £1,239,563 | £817,650 |

# Appendix C Expert responses

Expert 1

**Case Study 1**

| | |
|---|---|
| Location of the track section | London Euston - Birmingham New Street |
| Route type | High Speed Passenger Route |
| Typical Usage | approximately 19,000 passenger trips annually |

Please consider the above-mentioned details of route and details in Table 1.

*Note: The questionnaire focuses on **derailment caused due to track geometry related faults only**.*

If the track is maintained at 'Poor' quality, what could be the **minimum** severity of a potential derailment?

| Severity | Description | Choice |
|---|---|---|
| Minor | Derailment is PHRTA with less than 30 minutes delay to the train services on the affected route | ☐ |
| Major | Derailment is PHRTA and causes majority of train services on the route to be delayed over 30 minutes | ☒ |

If the track is maintained at 'Poor' quality, what could be the **maximum** severity of a potential derailment?

| Severity | Description | Choice |
|---|---|---|
| Minor | Derailment is PHRTA with less than 30 minutes delay to the train services on the affected route | ☐ |
| Major | Derailment is PHRTA and causes majority of train services on the route to be delayed over 30 minutes | ☒ |

If the track is maintained at 'Medium' quality, what could be the **minimum** severity of a potential derailment?

| Severity | Description | Choice |
|---|---|---|
| Minor | Derailment is PHRTA with less than 30 minutes delay to the train services on the affected route | ☐ |
| Major | Derailment is PHRTA and causes majority of train services on the route to be delayed over 30 minutes | ☒ |

If the track is maintained at 'Medium' quality, what could be the **maximum** severity of a potential derailment?

| Severity | Description | Choice |
|---|---|---|
| Minor | Derailment is PHRTA with less than 30 minutes delay to the train services on the affected route | ☐ |
| Major | Derailment is PHRTA and causes majority of train services on the route to be delayed over 30 minutes | ☒ |

If the track is maintained at 'Good' quality, what could be the **minimum** severity of a potential derailment?

| Severity | Description | Choice |
|---|---|---|
| Minor | Derailment is PHRTA with less than 30 minutes delay to the train services on the affected route | ☒ |
| Major | Derailment is PHRTA and causes majority of train services on the route to be delayed over 30 minutes | ☐ |

If the track is maintained at 'Good' quality, what could be the **maximum** severity of a potential derailment?

| Severity | Description | Choice |
|---|---|---|
| Minor | Derailment is PHRTA with less than 30 minutes delay to the train services on the affected route | ☐ |
| Major | Derailment is PHRTA and causes majority of train services on the route to be delayed over 30 minutes | ☒ |

**Case Study 2**

| | |
|---|---|
| Location of the track section | Coventry - Birmingham |
| Route type | Mixed Freight-Passenger Route |
| Typical Usage | approximately 19,000 passenger trips and 2,000 freight trips annually |

Please consider the above-mentioned details of route and details in Table 1.

*Note: The questionnaire focuses on **derailment caused due to track geometry related faults only**.*

If the track is maintained at 'Poor' quality, what could be the **minimum** severity of a potential derailment?

| Severity | Description | Choice |
|---|---|---|
| Minor | Derailment is PHRTA with less than 30 minutes delay to the train services on the affected route | ☐ |
| Major | Derailment is PHRTA and causes majority of train services on the route to be delayed over 30 minutes | ☒ |

If the track is maintained at 'Poor' quality, what could be the **maximum** severity of a potential derailment?

| Severity | Description | Choice |
|---|---|---|
| Minor | Derailment is PHRTA with less than 30 minutes delay to the train services on the affected route | ☐ |
| Major | Derailment is PHRTA and causes majority of train services on the route to be delayed over 30 minutes | ☒ |

If the track is maintained at 'Medium' quality, what could be the **minimum** severity of a potential derailment?

| Severity | Description | Choice |
|---|---|---|
| Minor | Derailment is PHRTA with less than 30 minutes delay to the train services on the affected route | ☒ |
| Major | Derailment is PHRTA and causes majority of train services on the route to be delayed over 30 minutes | ☐ |

If the track is maintained at ‘Medium’ quality, what could be the **maximum** severity of a potential derailment?

| Severity | Description | Choice |
|---|---|---|
| Minor | Derailment is PHRTA with less than 30 minutes delay to the train services on the affected route | ☐ |
| Major | Derailment is PHRTA and causes majority of train services on the route to be delayed over 30 minutes | ☒ |

If the track is maintained at ‘Good’ quality, what could be the **minimum** severity of a potential derailment?

| Severity | Description | Choice |
|---|---|---|
| Minor | Derailment is PHRTA with less than 30 minutes delay to the train services on the affected route | ☒ |
| Major | Derailment is PHRTA and causes majority of train services on the route to be delayed over 30 minutes | ☐ |

If the track is maintained at ‘Good’ quality, what could be the **maximum** severity of a potential derailment?

| Severity | Description | Choice |
|---|---|---|
| Minor | Derailment is PHRTA with less than 30 minutes delay to the train services on the affected route | ☒ |
| Major | Derailment is PHRTA and causes majority of train services on the route to be delayed over 30 minutes | ☐ |

**Case Study 3**

| | |
|---|---|
| Location of the track section | Sutton Coldfield - Lichfield |
| Route type | Commuter Route |
| Typical usage | approximately 35,000 passenger trips annually |

Please consider the above-mentioned details of route and details in Table 1.

*Note: The questionnaire focuses on **derailment caused due to track geometry related faults only**.*

If the track is maintained at 'Poor' quality, what could be the **minimum** severity of a potential derailment?

| Severity | Description | Choice |
|---|---|---|
| Minor | Derailment is PHRTA with less than 30 minutes delay to the train services on the affected route | ☒ |
| Major | Derailment is PHRTA and causes majority of train services on the route to be delayed over 30 minutes | ☐ |

If the track is maintained at 'Poor' quality, what could be the **maximum** severity of a potential derailment?

| Severity | Description | Choice |
|---|---|---|
| Minor | Derailment is PHRTA with less than 30 minutes delay to the train services on the affected route | ☐ |
| Major | Derailment is PHRTA and causes majority of train services on the route to be delayed over 30 minutes | ☒ |

If the track is maintained at 'Medium' quality, what could be the **minimum** severity of a potential derailment?

| Severity | Description | Choice |
|---|---|---|
| Minor | Derailment is PHRTA with less than 30 minutes delay to the train services on the affected route | ☒ |
| Major | Derailment is PHRTA and causes majority of train services on the route to be delayed over 30 minutes | ☐ |

If the track is maintained at ‘Medium’ quality, what could be the **maximum** severity of a potential derailment?

| Severity | Description | Choice |
|---|---|---|
| Minor | Derailment is PHRTA with less than 30 minutes delay to the train services on the affected route | ☒ |
| Major | Derailment is PHRTA and causes majority of train services on the route to be delayed over 30 minutes | ☐ |

If the track is maintained at ‘Good’ quality, what could be the **minimum** severity of a potential derailment?

| Severity | Description | Choice |
|---|---|---|
| Minor | Derailment is PHRTA with less than 30 minutes delay to the train services on the affected route | ☒ |
| Major | Derailment is PHRTA and causes majority of train services on the route to be delayed over 30 minutes | ☐ |

If the track is maintained at ‘Good’ quality, what could be the **maximum** severity of a potential derailment?

| Severity | Description | Choice |
|---|---|---|
| Minor | Derailment is PHRTA with less than 30 minutes delay to the train services on the affected route | ☒ |
| Major | Derailment is PHRTA and causes majority of train services on the route to be delayed over 30 minutes | ☐ |

Expert 2

**Case Study 1**

| | |
|---|---|
| Location of the track section | London Euston - Birmingham New Street |
| Route type | High Speed Passenger Route |
| Typical Usage | approximately 19,000 passenger trips annually |

Please consider the above-mentioned details of route and details in Table 1.

*Note: The questionnaire focuses on* ***derailment caused due to track geometry related faults only****.*

If the track is maintained at 'Poor' quality, what could be the **minimum** severity of a potential derailment?

| Severity | Description | Choice |
|---|---|---|
| Minor | Derailment is PHRTA with less than 30 minutes delay to the train services on the affected route | ☐ |
| Major | Derailment is PHRTA and causes majority of train services on the route to be delayed over 30 minutes | ☒ |

If the track is maintained at 'Poor' quality, what could be the **maximum** severity of a potential derailment?

| Severity | Description | Choice |
|---|---|---|
| Minor | Derailment is PHRTA with less than 30 minutes delay to the train services on the affected route | ☐ |
| Major | Derailment is PHRTA and causes majority of train services on the route to be delayed over 30 minutes | ☒ |

If the track is maintained at 'Medium' quality, what could be the **minimum** severity of a potential derailment?

| Severity | Description | Choice |
|---|---|---|
| Minor | Derailment is PHRTA with less than 30 minutes delay to the train services on the affected route | ☐ |
| Major | Derailment is PHRTA and causes majority of train services on the route to be delayed over 30 minutes | ☒ |

If the track is maintained at 'Medium' quality, what could be the **maximum** severity of a potential derailment?

| Severity | Description | Choice |
|---|---|---|
| Minor | Derailment is PHRTA with less than 30 minutes delay to the train services on the affected route | ☐ |
| Major | Derailment is PHRTA and causes majority of train services on the route to be delayed over 30 minutes | ☒ |

If the track is maintained at 'Good' quality, what could be the **minimum** severity of a potential derailment?

| Severity | Description | Choice |
|---|---|---|
| Minor | Derailment is PHRTA with less than 30 minutes delay to the train services on the affected route | ☐ |
| Major | Derailment is PHRTA and causes majority of train services on the route to be delayed over 30 minutes | ☒ |

If the track is maintained at 'Good' quality, what could be the **maximum** severity of a potential derailment?

| Severity | Description | Choice |
|---|---|---|
| Minor | Derailment is PHRTA with less than 30 minutes delay to the train services on the affected route | ☐ |
| Major | Derailment is PHRTA and causes majority of train services on the route to be delayed over 30 minutes | ☒ |

**Case Study 2**

| | |
|---|---|
| Location of the track section | Coventry - Birmingham |
| Route type | Mixed Freight-Passenger Route |
| Typical Usage | approximately 19,000 passenger trips and 2,000 freight trips annually |

Please consider the above-mentioned details of route and details in Table 1.

*Note: The questionnaire focuses on **derailment caused due to track geometry related faults only**.*

If the track is maintained at ‘Poor’ quality, what could be the **minimum** severity of a potential derailment?

| Severity | Description | Choice |
|---|---|---|
| Minor | Derailment is PHRTA with less than 30 minutes delay to the train services on the affected route | ☐ |
| Major | Derailment is PHRTA and causes majority of train services on the route to be delayed over 30 minutes | ☒ |

If the track is maintained at ‘Poor’ quality, what could be the **maximum** severity of a potential derailment?

| Severity | Description | Choice |
|---|---|---|
| Minor | Derailment is PHRTA with less than 30 minutes delay to the train services on the affected route | ☐ |
| Major | Derailment is PHRTA and causes majority of train services on the route to be delayed over 30 minutes | ☒ |

If the track is maintained at ‘Medium’ quality, what could be the **minimum** severity of a potential derailment?

| Severity | Description | Choice |
|---|---|---|
| Minor | Derailment is PHRTA with less than 30 minutes delay to the train services on the affected route | ☒ |
| Major | Derailment is PHRTA and causes majority of train services on the route to be delayed over 30 minutes | ☐ |

If the track is maintained at 'Medium' quality, what could be the **maximum** severity of a potential derailment?

| Severity | Description | Choice |
|---|---|---|
| Minor | Derailment is PHRTA with less than 30 minutes delay to the train services on the affected route | ☐ |
| Major | Derailment is PHRTA and causes majority of train services on the route to be delayed over 30 minutes | ☒ |

If the track is maintained at 'Good' quality, what could be the **minimum** severity of a potential derailment?

| Severity | Description | Choice |
|---|---|---|
| Minor | Derailment is PHRTA with less than 30 minutes delay to the train services on the affected route | ☐ |
| Major | Derailment is PHRTA and causes majority of train services on the route to be delayed over 30 minutes | ☒ |

If the track is maintained at 'Good' quality, what could be the **maximum** severity of a potential derailment?

| Severity | Description | Choice |
|---|---|---|
| Minor | Derailment is PHRTA with less than 30 minutes delay to the train services on the affected route | ☐ |
| Major | Derailment is PHRTA and causes majority of train services on the route to be delayed over 30 minutes | ☒ |

**Case Study 3**

| | |
|---|---|
| Location of the track section | Sutton Coldfield - Lichfield |
| Route type | Commuter Route |
| Typical usage | approximately 35,000 passenger trips annually |

Please consider the above-mentioned details of route and details in Table 1.

*Note: The questionnaire focuses on **derailment caused due to track geometry related faults only**.*

If the track is maintained at 'Poor' quality, what could be the **minimum** severity of a potential derailment?

| Severity | Description | Choice |
|---|---|---|
| Minor | Derailment is PHRTA with less than 30 minutes delay to the train services on the affected route | ☐ |
| Major | Derailment is PHRTA and causes majority of train services on the route to be delayed over 30 minutes | ☒ |

If the track is maintained at 'Poor' quality, what could be the **maximum** severity of a potential derailment?

| Severity | Description | Choice |
|---|---|---|
| Minor | Derailment is PHRTA with less than 30 minutes delay to the train services on the affected route | ☐ |
| Major | Derailment is PHRTA and causes majority of train services on the route to be delayed over 30 minutes | ☒ |

If the track is maintained at 'Medium' quality, what could be the **minimum** severity of a potential derailment?

| Severity | Description | Choice |
|---|---|---|
| Minor | Derailment is PHRTA with less than 30 minutes delay to the train services on the affected route | ☒ |
| Major | Derailment is PHRTA and causes majority of train services on the route to be delayed over 30 minutes | ☐ |

If the track is maintained at 'Medium' quality, what could be the **maximum** severity of a potential derailment?

| Severity | Description | Choice |
|---|---|---|
| Minor | Derailment is PHRTA with less than 30 minutes delay to the train services on the affected route | ☒ |
| Major | Derailment is PHRTA and causes majority of train services on the route to be delayed over 30 minutes | ☐ |

If the track is maintained at 'Good' quality, what could be the **minimum** severity of a potential derailment?

| Severity | Description | Choice |
|---|---|---|
| Minor | Derailment is PHRTA with less than 30 minutes delay to the train services on the affected route | ☒ |
| Major | Derailment is PHRTA and causes majority of train services on the route to be delayed over 30 minutes | ☐ |

If the track is maintained at 'Good' quality, what could be the **maximum** severity of a potential derailment?

| Severity | Description | Choice |
|---|---|---|
| Minor | Derailment is PHRTA with less than 30 minutes delay to the train services on the affected route | ☒ |
| Major | Derailment is PHRTA and causes majority of train services on the route to be delayed over 30 minutes | ☐ |

**Case Study 1**

| | |
|---|---|
| Location of the track section | London Euston - Birmingham New Street |
| Route type | High Speed Passenger Route |
| Typical Usage | approximately 19,000 passenger trips annually |

Please consider the above-mentioned details of route and details in Table 1.

*Note: The questionnaire focuses on* ***derailment caused due to track geometry related faults only****.*

If the track is maintained at 'Poor' quality, what could be the **minimum** severity of a potential derailment?

| Severity | Description | Choice |
|---|---|---|
| Minor | Derailment is PHRTA with less than 30 minutes delay to the train services on the affected route | ☐ |
| Major | Derailment is PHRTA and causes majority of train services on the route to be delayed over 30 minutes | ☒ |

If the track is maintained at 'Poor' quality, what could be the **maximum** severity of a potential derailment?

| Severity | Description | Choice |
|---|---|---|
| Minor | Derailment is PHRTA with less than 30 minutes delay to the train services on the affected route | ☐ |
| Major | Derailment is PHRTA and causes majority of train services on the route to be delayed over 30 minutes | ☒ |

If the track is maintained at 'Medium' quality, what could be the **minimum** severity of a potential derailment?

| Severity | Description | Choice |
|---|---|---|
| Minor | Derailment is PHRTA with less than 30 minutes delay to the train services on the affected route | ☐ |
| Major | Derailment is PHRTA and causes majority of train services on the route to be delayed over 30 minutes | ☒ |

If the track is maintained at 'Medium' quality, what could be the **maximum** severity of a potential derailment?

| Severity | Description | Choice |
|---|---|---|
| Minor | Derailment is PHRTA with less than 30 minutes delay to the train services on the affected route | ☐ |
| Major | Derailment is PHRTA and causes majority of train services on the route to be delayed over 30 minutes | ☒ |

If the track is maintained at 'Good' quality, what could be the **minimum** severity of a potential derailment?

| Severity | Description | Choice |
|---|---|---|
| Minor | Derailment is PHRTA with less than 30 minutes delay to the train services on the affected route | ☐ |
| Major | Derailment is PHRTA and causes majority of train services on the route to be delayed over 30 minutes | ☒ |

If the track is maintained at 'Good' quality, what could be the **maximum** severity of a potential derailment?

| Severity | Description | Choice |
|---|---|---|
| Minor | Derailment is PHRTA with less than 30 minutes delay to the train services on the affected route | ☐ |
| Major | Derailment is PHRTA and causes majority of train services on the route to be delayed over 30 minutes | ☒ |

## Case Study 2

| | |
|---|---|
| Location of the track section | Coventry - Birmingham |
| Route type | Mixed Freight-Passenger Route |
| Typical Usage | approximately 19,000 passenger trips and 2,000 freight trips annually |

Please consider the above-mentioned details of route and details in Table 1.

*Note: The questionnaire focuses on **derailment caused due to track geometry related faults only**.*

If the track is maintained at 'Poor' quality, what could be the **minimum** severity of a potential derailment?

| Severity | Description | Choice |
|---|---|---|
| Minor | Derailment is PHRTA with less than 30 minutes delay to the train services on the affected route | ☐ |
| Major | Derailment is PHRTA and causes majority of train services on the route to be delayed over 30 minutes | ☒ |

If the track is maintained at 'Poor' quality, what could be the **maximum** severity of a potential derailment?

| Severity | Description | Choice |
|---|---|---|
| Minor | Derailment is PHRTA with less than 30 minutes delay to the train services on the affected route | ☐ |
| Major | Derailment is PHRTA and causes majority of train services on the route to be delayed over 30 minutes | ☒ |

If the track is maintained at 'Medium' quality, what could be the **minimum** severity of a potential derailment?

| Severity | Description | Choice |
|---|---|---|
| Minor | Derailment is PHRTA with less than 30 minutes delay to the train services on the affected route | ☒ |
| Major | Derailment is PHRTA and causes majority of train services on the route to be delayed over 30 minutes | ☐ |

If the track is maintained at ‘Medium’ quality, what could be the **maximum** severity of a potential derailment?

| Severity | Description | Choice |
| --- | --- | --- |
| Minor | Derailment is PHRTA with less than 30 minutes delay to the train services on the affected route | ☐ |
| Major | Derailment is PHRTA and causes majority of train services on the route to be delayed over 30 minutes | ☒ |

If the track is maintained at ‘Good’ quality, what could be the **minimum** severity of a potential derailment?

| Severity | Description | Choice |
| --- | --- | --- |
| Minor | Derailment is PHRTA with less than 30 minutes delay to the train services on the affected route | ☐ |
| Major | Derailment is PHRTA and causes majority of train services on the route to be delayed over 30 minutes | ☒ |

If the track is maintained at ‘Good’ quality, what could be the **maximum** severity of a potential derailment?

| Severity | Description | Choice |
| --- | --- | --- |
| Minor | Derailment is PHRTA with less than 30 minutes delay to the train services on the affected route | ☐ |
| Major | Derailment is PHRTA and causes majority of train services on the route to be delayed over 30 minutes | ☒ |

**Case Study 3**

| | |
|---|---|
| Location of the track section | Sutton Coldfield - Lichfield |
| Route type | Commuter Route |
| Typical usage | approximately 35,000 passenger trips annually |

Please consider the above-mentioned details of route and details in Table 1.

*Note: The questionnaire focuses on **derailment caused due to track geometry related faults only**.*

If the track is maintained at 'Poor' quality, what could be the **minimum** severity of a potential derailment?

| Severity | Description | Choice |
|---|---|---|
| Minor | Derailment is PHRTA with less than 30 minutes delay to the train services on the affected route | ☐ |
| Major | Derailment is PHRTA and causes majority of train services on the route to be delayed over 30 minutes | ☒ |

If the track is maintained at 'Poor' quality, what could be the **maximum** severity of a potential derailment?

| Severity | Description | Choice |
|---|---|---|
| Minor | Derailment is PHRTA with less than 30 minutes delay to the train services on the affected route | ☐ |
| Major | Derailment is PHRTA and causes majority of train services on the route to be delayed over 30 minutes | ☒ |

If the track is maintained at 'Medium' quality, what could be the **minimum** severity of a potential derailment?

| Severity | Description | Choice |
|---|---|---|
| Minor | Derailment is PHRTA with less than 30 minutes delay to the train services on the affected route | ☒ |
| Major | Derailment is PHRTA and causes majority of train services on the route to be delayed over 30 minutes | ☐ |

If the track is maintained at 'Medium' quality, what could be the **maximum** severity of a potential derailment?

| Severity | Description | Choice |
|---|---|---|
| Minor | Derailment is PHRTA with less than 30 minutes delay to the train services on the affected route | ☒ |
| Major | Derailment is PHRTA and causes majority of train services on the route to be delayed over 30 minutes | ☐ |

If the track is maintained at 'Good' quality, what could be the **minimum** severity of a potential derailment?

| Severity | Description | Choice |
|---|---|---|
| Minor | Derailment is PHRTA with less than 30 minutes delay to the train services on the affected route | ☒ |
| Major | Derailment is PHRTA and causes majority of train services on the route to be delayed over 30 minutes | ☐ |

If the track is maintained at 'Good' quality, what could be the **maximum** severity of a potential derailment?

| Severity | Description | Choice |
|---|---|---|
| Minor | Derailment is PHRTA with less than 30 minutes delay to the train services on the affected route | ☒ |
| Major | Derailment is PHRTA and causes majority of train services on the route to be delayed over 30 minutes | ☐ |

Expert 4

**Case Study 1**

| | |
|---|---|
| Location of the track section | London Euston - Birmingham New Street |
| Route type | High Speed Passenger Route |
| Typical Usage | approximately 19,000 passenger trips annually |

Please consider the above-mentioned details of route and details in Table 1.

*Note: The questionnaire focuses on* ***derailment caused due to track geometry related faults only****.*

If the track is maintained at 'Poor' quality, what could be the **minimum** severity of a potential derailment?

| Severity | Description | Choice |
|---|---|---|
| Minor | Derailment is PHRTA with less than 30 minutes delay to the train services on the affected route | ☐ |
| Major | Derailment is PHRTA and causes majority of train services on the route to be delayed over 30 minutes | ☒ |

If the track is maintained at 'Poor' quality, what could be the **maximum** severity of a potential derailment?

| Severity | Description | Choice |
|---|---|---|
| Minor | Derailment is PHRTA with less than 30 minutes delay to the train services on the affected route | ☐ |
| Major | Derailment is PHRTA and causes majority of train services on the route to be delayed over 30 minutes | ☒ |

If the track is maintained at 'Medium' quality, what could be the **minimum** severity of a potential derailment?

| Severity | Description | Choice |
|---|---|---|
| Minor | Derailment is PHRTA with less than 30 minutes delay to the train services on the affected route | ☐ |
| Major | Derailment is PHRTA and causes majority of train services on the route to be delayed over 30 minutes | ☒ |

If the track is maintained at 'Medium' quality, what could be the **maximum** severity of a potential derailment?

| Severity | Description | Choice |
|---|---|---|
| Minor | Derailment is PHRTA with less than 30 minutes delay to the train services on the affected route | ☐ |
| Major | Derailment is PHRTA and causes majority of train services on the route to be delayed over 30 minutes | ☒ |

If the track is maintained at 'Good' quality, what could be the **minimum** severity of a potential derailment?

| Severity | Description | Choice |
|---|---|---|
| Minor | Derailment is PHRTA with less than 30 minutes delay to the train services on the affected route | ☒ |
| Major | Derailment is PHRTA and causes majority of train services on the route to be delayed over 30 minutes | ☐ |

If the track is maintained at 'Good' quality, what could be the **maximum** severity of a potential derailment?

| Severity | Description | Choice |
|---|---|---|
| Minor | Derailment is PHRTA with less than 30 minutes delay to the train services on the affected route | ☐ |
| Major | Derailment is PHRTA and causes majority of train services on the route to be delayed over 30 minutes | ☒ |

**Case Study 2**

| | |
|---|---|
| Location of the track section | Coventry - Birmingham |
| Route type | Mixed Freight-Passenger Route |
| Typical Usage | approximately 19,000 passenger trips and 2,000 freight trips annually |

Please consider the above-mentioned details of route and details in Table 1.

*Note: The questionnaire focuses on **derailment caused due to track geometry related faults only**.*

If the track is maintained at 'Poor' quality, what could be the **minimum** severity of a potential derailment?

| Severity | Description | Choice |
|---|---|---|
| Minor | Derailment is PHRTA with less than 30 minutes delay to the train services on the affected route | ☐ |
| Major | Derailment is PHRTA and causes majority of train services on the route to be delayed over 30 minutes | ☒ |

If the track is maintained at 'Poor' quality, what could be the **maximum** severity of a potential derailment?

| Severity | Description | Choice |
|---|---|---|
| Minor | Derailment is PHRTA with less than 30 minutes delay to the train services on the affected route | ☐ |
| Major | Derailment is PHRTA and causes majority of train services on the route to be delayed over 30 minutes | ☒ |

If the track is maintained at 'Medium' quality, what could be the **minimum** severity of a potential derailment?

| Severity | Description | Choice |
|---|---|---|
| Minor | Derailment is PHRTA with less than 30 minutes delay to the train services on the affected route | ☒ |
| Major | Derailment is PHRTA and causes majority of train services on the route to be delayed over 30 minutes | ☐ |

If the track is maintained at ‘Medium’ quality, what could be the **maximum** severity of a potential derailment?

| **Severity** | **Description** | **Choice** |
|---|---|---|
| Minor | Derailment is PHRTA with less than 30 minutes delay to the train services on the affected route | ☐ |
| Major | Derailment is PHRTA and causes majority of train services on the route to be delayed over 30 minutes | ☒ |

If the track is maintained at ‘Good’ quality, what could be the **minimum** severity of a potential derailment?

| **Severity** | **Description** | **Choice** |
|---|---|---|
| Minor | Derailment is PHRTA with less than 30 minutes delay to the train services on the affected route | ☐ |
| Major | Derailment is PHRTA and causes majority of train services on the route to be delayed over 30 minutes | ☒ |

If the track is maintained at ‘Good’ quality, what could be the **maximum** severity of a potential derailment?

| **Severity** | **Description** | **Choice** |
|---|---|---|
| Minor | Derailment is PHRTA with less than 30 minutes delay to the train services on the affected route | ☐ |
| Major | Derailment is PHRTA and causes majority of train services on the route to be delayed over 30 minutes | ☒ |

**Case Study 3**

| | |
|---|---|
| Location of the track section | Sutton Coldfield - Lichfield |
| Route type | Commuter Route |
| Typical usage | approximately 35,000 passenger trips annually |

Please consider the above-mentioned details of route and details in Table 1.

*Note: The questionnaire focuses on **derailment caused due to track geometry related faults only**.*

If the track is maintained at 'Poor' quality, what could be the **minimum** severity of a potential derailment?

| Severity | Description | Choice |
|---|---|---|
| Minor | Derailment is PHRTA with less than 30 minutes delay to the train services on the affected route | ☐ |
| Major | Derailment is PHRTA and causes majority of train services on the route to be delayed over 30 minutes | ☒ |

If the track is maintained at 'Poor' quality, what could be the **maximum** severity of a potential derailment?

| Severity | Description | Choice |
|---|---|---|
| Minor | Derailment is PHRTA with less than 30 minutes delay to the train services on the affected route | ☐ |
| Major | Derailment is PHRTA and causes majority of train services on the route to be delayed over 30 minutes | ☒ |

If the track is maintained at 'Medium' quality, what could be the **minimum** severity of a potential derailment?

| Severity | Description | Choice |
|---|---|---|
| Minor | Derailment is PHRTA with less than 30 minutes delay to the train services on the affected route | ☒ |
| Major | Derailment is PHRTA and causes majority of train services on the route to be delayed over 30 minutes | ☐ |

If the track is maintained at 'Medium' quality, what could be the **maximum** severity of a potential derailment?

| Severity | Description | Choice |
|---|---|---|
| Minor | Derailment is PHRTA with less than 30 minutes delay to the train services on the affected route | ☒ |
| Major | Derailment is PHRTA and causes majority of train services on the route to be delayed over 30 minutes | ☐ |

If the track is maintained at ‘Good’ quality, what could be the **minimum** severity of a potential derailment?

| Severity | Description | Choice |
|---|---|---|
| Minor | Derailment is PHRTA with less than 30 minutes delay to the train services on the affected route | ☒ |
| Major | Derailment is PHRTA and causes majority of train services on the route to be delayed over 30 minutes | ☐ |

If the track is maintained at ‘Good’ quality, what could be the **maximum** severity of a potential derailment?

| Severity | Description | Choice |
|---|---|---|
| Minor | Derailment is PHRTA with less than 30 minutes delay to the train services on the affected route | ☒ |
| Major | Derailment is PHRTA and causes majority of train services on the route to be delayed over 30 minutes | ☐ |

# Appendix D Least Square Method

The least square method is explained below:

**Step 1**: Minimise squared distance between observed $y_i$ and fitted $\acute{y}_i$

$$L(a,b) = \sum_{i=1}^{n}(y_i - \acute{y}_i)^2 = \sum_{i=1}^{n}(\acute{y}_i - b - ax_i)^2 \quad \text{(D.1)}$$

**Step 2**: Set partial derivative to zero:

$$\frac{\partial L}{\partial a} = 0 \leftrightarrow \sum_{i=1}^{n}(\acute{y}_i - b - ax_i) = 0 \quad \text{(D.2)}$$

$$\frac{\partial L}{\partial b} = 0 \leftrightarrow \sum_{i=1}^{n}(\acute{y}_i - b - ax_i) = 0 \quad \text{(D.3)}$$

**Step 3**: Calculate the lease squares estimators

$$\hat{b} = \bar{y} - \frac{S_{xy}}{S_{xx}}.\bar{x} \quad \text{(D.4)}$$

$$\hat{a} = \frac{s_{xy}}{s_{xx}} \quad \text{(D.5)}$$

**Step 4**: Calculate the Sum of Squares in equation 3.8 and 3.9

$$S_{xy} = \sum_{n=1}^{n}(\acute{y}_i - \bar{y})(x_i - \bar{x}) \quad \text{(D.6)}$$

$$S_{xx} = \sum_{n=1}^{n}(x_i - \bar{x})^2 \quad \text{(D.7)}$$

**Step 5**: Calculate the least square predictor $\acute{y}_i$

$$\hat{y}_i = \hat{a}x_i + \hat{b} \quad \text{(D.8)}$$

$$\text{Errors } \hat{e}_i = y_i - \widehat{y}_i = y_i - \hat{a}x_i - \hat{b} \quad \text{(D.9)}$$

Hence, the Sum of Errors ($SS_{Errors}$) can be calculated as

$$SS_{Errors} = \sum_{i=1}^{n} \hat{e}_i^{\,2} = \sum_{i=1}^{n}(y_i - \acute{y}_i)^2 \quad \text{(D.10)}$$

**Step 6**: Calculate average Standard Deviation

$$\hat{\sigma}^2 = \frac{1}{n-2}\sum_{i=1}^{n}(y_i - \acute{y}_i)^2 = \frac{1}{n-2}SS_{Errors} \quad \text{(D.11)}$$

**Step 7**: Thus, the regression standard error can be calculated as:

$$s_e = \hat{\sigma} = \sqrt{SS_{Residual}/(n-2)} \quad \text{(D.12)}$$

**Step 8**: Calculate the variation in the linear model

$$SS_{Model} = \sum_{i=1}^{n}(y_i - \acute{y}_i)^2 \quad \text{(D.13)}$$