Network Level Decision Support System to Assess Railway Track Maintenance Needs

(Doctorate Thesis)

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Abstract

Maintenance management decision-support systems are needed to help senior decision-makers and asset managers to better plan timely and efficient maintenance. Within the railway industry, several maintenance management decision-support systems have been developed. However, most these operate at project level where decisions are limited to short sections of track. Network level maintenance management systems enable future prediction of the condition of the railway network under different allocation of resources in a manner to provide acceptable levels of safety, reliability and cost. This project describes the development of a theoretical framework for the strategic assessment of network level railway maintenance funding and policy decisions. The model is designed to aid railway asset managers in planning medium to long-term maintenance investment requirements for the railway network. The model is based on stochastic processes which are capable of determining the effects of traffic, maintenance and climate on network condition under any budget scenario.

Table of Contents

Table of Figures

Table of Tables

Chapter One

1. INTRODUCTION

1.1 Background of the Research

The UK has one of the oldest and yet busiest railway networks in Europe. Annually, the railway system contributes to 1.3 billion journeys. It is anticipated that over the next thirty years passenger demand for railways will double and freight growth will increase by around 140% (Network Rail, 2014). The increased demand for railway transportation is creating a need for increased frequency, higher train speeds and axle loads which, in turn, increases the rate of track degradation. This will require increased railway track maintenance. In addition, climate change predictions suggest that there will be a general trend towards more extreme weather where winters will become warmer and wetter, whereas summers will be hotter and drier (RSSB, 2016). These weather extremes have the potential to cause significant service interruptions because of increases in buckling of the railway track; increased ground swelling and shrinkage; more surface water and flooding events and increase in frequency of landslip (Baker, 2007). For instance, due to high temperatures, in July 2016, rail temperature reached more than 50˚C and resulted in imposition of speed restrictions to prevent buckling and service disruptions (Telegraph, 2016). There are also likely to be associated weather induced increases in track and earthworks deterioration. The adverse impact of climate can be controlled through achieving sufficient level of preparedness for the effects of climate change which requires understanding the correlation between weather and track (Network Rail, 2015) (RSSB, 2016).

With global average temperature and precipitation continuing to rise and being higher than they were in the past, together with increase in infrastructure requirements in terms of axle load, gross tonnage and speed, rates of railway asset deterioration are set to increase with corresponding increases in maintenance requirements (Patra, 2009). To create a sustainable railway system, maintenance must be efficient and provided at low cost. However, due to the large variety of infrastructure assets which comprise the railway system, the governance of resources and the allocation and prioritisation of maintenance resources within and across asset types is complex (Macchi, et al., 2010). Maintaining such a system requires a well-developed capability in asset management to enable assets to perform optimally for the level of funding available (Network Rail, 2014). Thus, in order to manage assets effectively and efficiently there is a need for suitable decision support systems which can aid the asset manager in making informed decisions (Farreira & Murray, 2016).

Indeed, railway companies are dedicating significant effort to develop decision-making tools to improve their maintenance management, with the aim of optimising maintenance expenditure while maintaining high standards of safety. To this date, varieties of maintenance management systems have been developed so that senior decision-makers can determine timely and efficient maintenance (see Section 4.7). However, most of the existing systems only consider the effects of traffic and operate at a project level with decisions being made on short sections of track. Long-term planning of maintenance expenditure should be determined using network level management approaches which involve the analysis of the railway system in its entirety, using suitable data sets. It is at this level of management where the effects of change in maintenance investments on maintenance policies and budget requirements is determined and funds argued for (Burrow, et al., 2009). Due to the varieties of track composition, geology and climate over any given railway network, developing a network level decision-making support tool is challenging since it requires the collection and analysis of large data sets. To address this, this thesis focuses on developing a system which utilises real data sets of railway track components and combines it with weather data to predict and quantify current and future maintenance and renewal needs of the railway network as a function of available maintenance budgets.

1.2 Aim of Research

This research project describes the development of a network level maintenance management system which utilizes data sets of track condition collected periodically, and combines these with climate change, traffic and maintenance data and maintenance standards in a planning tool to predict future maintenance and renewal requirements. The system incorporates railway track degradation models as a function of maintenance history, traffic, speed and construction type to identify and quantify the predicted changes in climate in terms of parameters influencing track degradation. Hence, the aim of the project is to develop a strategic-planning tool which can be used to predict the network level rail track condition over time as a function of maintenance expenditure.

1.3 Objectives of Research

To address the aim, this research project has the following objectives:

1. Explore the asset management literature to identify the required components of the proposed decision-support system.
2. Investigate suitable deterioration models for the major structural components of the railway track which require routine and periodic maintenance (i.e. rails, sleepers, ballast, switches, crossings and subgrade) as a function of traffic, railway track construction, maintenance history and climate.
3. Explore how railway track maintenance affects the condition of the railway track components identified in objective two and investigate suitable means of modelling these changes in condition over time.
4. Develop a number of indices of overall railway network condition as a function of the condition of the major structural components of the railway track system.
5. Utilise the outputs of objectives 2 - 4 to develop a fully working prototype system which can predict future railway network condition as a function of maintenance expenditure.
6. Demonstrate the prototype system under a variety of budget scenarios.

1.4 Novelty of Research

A novel maintenance management tool is proposed and developed which, unlike present management systems, it is able to undertake appropriate network level analysis on the condition of railway track taking into account budget levels and the deleterious effects of traffic, climate and maintenance (as stipulated in objective number two). The majority of current management systems solely analyse the condition of rails and ballast as a function of traffic to determine the overall condition of the track. The developed tool in this research allows asset managers and senior engineers to simulate and manipulate different scenarios to evaluate the effects of present and future traffic, climate and maintenance activities on the condition of track infrastructure components over time, under different funding mechanisms in order to support strategic maintenance decision-making.

The current gap of knowledge in the existing railway decision support tools is a lack of consideration of the effects of climate induced deterioration on the condition of track components. The general warming of the global climate is unequivocal and therefore maintenance planning over the medium and long term needs to take into account the effects of future climatic conditions on changes in the condition and rates of deterioration of track components. This project introduces two novel measures which quantifies the effects of temperature and precipitation on the degradation and condition of track infrastructure. This is achieved through establishing a relationship between temperature and precipitation variables and track condition parameters.

The system not only predicts the level of improvements and effectiveness of maintenance treatments; in particular stoneblowing, tamping and grinding on track condition, but also it calculates the extent in which different maintenance treatments and histories affect the current and future deterioration rates of track components.

Finally, in almost all maintenance management tools, the condition of ballast in determined using the irregularities in track geometry and yet less attention has been given to the rate of by which the track geometry deteriorates. It is necessary to consider such a measure whilst planning for future maintenance actions because, inappropriate decisions can cause faster deterioration of track which may reduce the safety of operation and waste the maintenance budget.

1.5 Structure of the Thesis

In this chapter, the need for a network level management maintenance management tool which illustrates the effect on track condition as a result of investment decisions was illustrated. The outline of the subsequent chapters of the thesis is as follows:

- In Chapter Two, the predominant structural components of the railway track are described together with their main traffic, climate and maintenance induced deterioration mechanisms. Moreover, various inspection and maintenance techniques used in the industry are also presented.
- Different methods described in the literature to model the deterioration and maintenance processes of track components are discussed in Chapter Three.

- Chapter Four discusses the concept of maintenance management of the railway system together with current maintenance practice carried out within the UK. Furthermore, a review of existing maintenance management tools available in the literature is given.
- The methodology and approach taken to fulfil the aim and objectives of the research is given in Chapter Five.
- Chapter Six, illustrates the logical design of the system.
- A fully working prototype system is developed and described in Chapter Seven. Number of case studies are presented to illustrate the tool under different budget scenarios and maintenance strategies.
- A discussion regarding the calculated results and the application of the tool for maintenance management is incorporated in Chapter Eight.
- The conclusions from the research and recommendations for further research to improve the system are summarised in Chapter Nine.

Chapter Two

2. LITERATURE REVIEW

2.1 Introduction

As stated in Chapter One, there is a need for a maintenance management decision-making tool to aid railway asset managers plan and argue for funds for maintaining railway infrastructure. Such a tool should consider the major assets which form the infrastructure, their long-term deterioration behaviour over time and the effect and cost of maintenance. In this Chapter, first, the function of the railway infrastructure is described, and secondly track infrastructure components and their deterioration modes caused by traffic, climate, environment and maintenance activities are reviewed. The Chapter then explores typical inspection methods used to monitor the condition of track infrastructure components, the range of defects affecting the major components and conventional maintenance activities. The manner in which some treatment types change the deterioration of components are discussed.

2.1.1 Background

The railway track is a structural system designed to withstand the combined deterioration effects of railway traffic and the environment so that the subgrade is adequately protected, and train operating costs, passenger comfort and safety are at appropriate levels (Burrow, et al., 2004). Traditional ballasted railway track infrastructure consists of two parts, the track superstructure and substructure as illustrated in Figure 2.1. Both elements are to be considered in this research.

Rails, rail fastenings, sleepers and switches and crossings (S&Cs) units are the components forming the track superstructure. The substructure consists of ballast underlain by the sub-ballast which sits on the subgrade. In some cases, a sand blanket or geotextile is sandwiched between the subgrade and the granular layers (i.e. ballast and sub-ballast). The rail supports and guides the train, and these are attached to the sleepers by means of fastening system. S&Cs are junctions which create a multi-route rail network and are used to guide trains from one track to another (Hassankiadeh, 2011). Sleepers support the rail and maintain the track gauge. They deflect elasticity into the ballast to distribute the load to layers underneath and theoretically return to the same position after the passage of the train (Dahlberg, 2004). The purpose of the ballast layer is to secure track stability and transfer the load from sleepers to the subgrade. It also drains water away from the bottom of the sleeper (Lim, 2004). Typically, a sub-ballast layer separates the subgrade from the ballast and prevents subgrade particles penetrating the ballast layer (Shi, 2009), however, it is not always present. The purpose of the substructure is to prevent damage to the subgrade. The natural ground, or subgrade, provides track foundation. Ideally it should provide uniform and adequate support without excessive deformation (Li, et al., 2016). Overtime, due to the combined effects of traffic and the environment, (see Section 2.3) the track structure deteriorates, thereby, maintenance is needed to make sure that the condition of track infrastructure components is kept at acceptable levels to control the level of load imposed onto the subgrade so that the latter is adequately protected and does not deteriorate faster than the rate at which it was designed. To ensure that such maintenance is cost effective, appropriate and timely maintenance needs to be carried out.

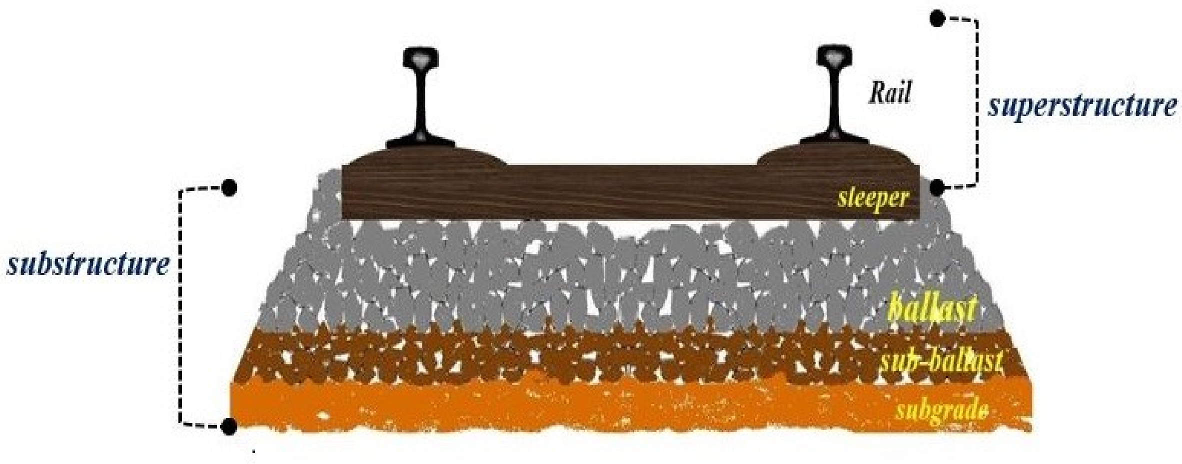

Figure 2-1Track infrastructure components

The functional and structural properties of track infrastructure components, their modes of deterioration, inspection techniques and maintenance activities used to remedy their defects and extend their useful life are explained in Sections 2.2, 2.3, 2.4 and 2.5 respectively.

2.2 Track Infrastructure Components

2.2.1 Rails

Rails are typically constructed from steel and are subject to very high stresses due to direct rail-wheel contact. Due to repeated loading and rail-wheel contact, rails deteriorate overtime. Therefore, as traffic and speed increases, there is a likelihood that the level of deterioration of the rails will increase. Traditionally, rails were connected together using fishplates. In such jointed rails (JRs), gaps are left in between rail pieces to allow the expansion of the rail due to thermal forces in order to decrease the effect of buckling (see Section 2.3.1). However, due to the gaps JRs are not suitable for high speed trains (Zhu, et al., 2016) because frequent maintenance is required to ensure fasteners and fishplates are secure enough to provide safety for passage of trains. Therefore, JRs may be inappropriate for railways, such as the UK, where the trend is towards increased traffic density and speed. An alternative to JR are Continuous Welded Rails (CWR) where rails are welded together using flash-butt welding which provides a better ride quality. Due to the welding process, the construction of CWRs is more expensive than JRs, but they have lower maintenance costs (Ahmed, et al., 2016) since they require less maintenance compared to JRs. Therefore, the long-term maintenance costs of JR will become more expansive because of frequent maintenance requirements and the associated delays that might occur.

Rails are designed to tolerate certain temperature ranges. When a new piece of rail is installed it is pulled by hydraulic tensors or heated along its length in a manner that it experiences zero longitudinal force (Kish, 2013). The temperature at which the rail is in such a stress-free state is known as the Stress Free Temperature (SFT) or neutral temperature. Within the UK, SFT of CWR is set to be between 21°C to 27°C (Dobney, 2010). SFT varies over time and can decrease because of the welding process in maintenance and replacement of rails, rail longitudinal movements, track lateral shift, or track settlement. Maintaining stable SFT is necessary because, the generation of high thermal forces in CWR, when the rail temperature is high, makes the track more prone to buckling during hot and cold weather. Based on the range of SFT determined for the UK railways, and the fact that the average global temperature is higher compared to previous decades, it is anticipated that buckling occurrence will be more recurrent in the future (Dobney, 2010) .

2.2.2 Switches and Crossings

S&Cs vary by shape and size and are designed based on the requirements of specific locations. They are typically in the form of turnouts, diamonds, crossovers and slip diamonds

(RAILTRACK, 1990). The type used is determined by number of factors including the number of lines involved, tonnage, frequency, and running line speed. For high speed trains, longer S&C systems are used since it is more difficult for trains to make tighter turns at high speeds. (MAINLINE, 2013). Research indicates that within the UK, in general, S&C units can be classified into seven groups according to the length of turnout and radius of switch (see Table 2.1). Since the length of S&C varies as a function of speed, category G+ relates to highspeed tracks. A schematic of a typical S&C unit is given in Figure 2.2.

Category	Turnout Length (m)	Switch radius (m)
A	7.3	141.1
B	8.7	184
C	11.9	245.8
D	12.4	332.7
E	17.3	645.1
F	20.8	980.9
G+	24.4	1264

Table 2-1 S&C categories (Cornish, 2014)

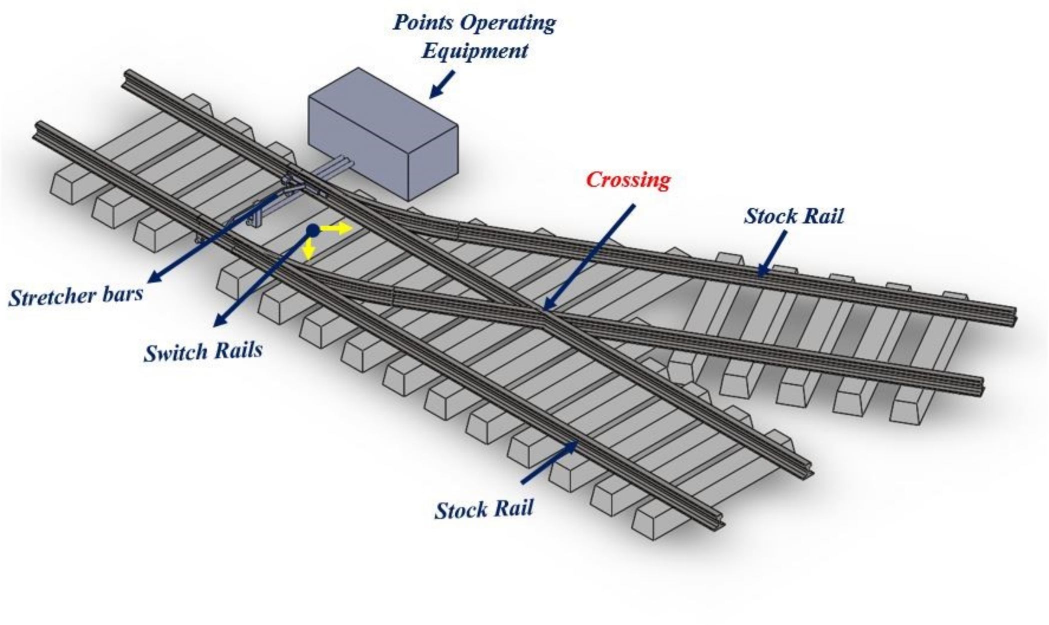

Figure 2-2 Schematic of typical switch and crossing unit

2.2.2.1 Switches

Switch rail is a moving part of S&Cs layout and is made by two long blades which move and guide the train. The two switch rails, which are fixed to the sleeper using slide chairs, are made to move at the same time by a series of stretcher bars. The non-moving component of the switch is the stock rail (Hassankiadeh, 2011). The two switch blades are fixed to each other by stretcher bars to make sure when one is against the stock rail the other is fully clear from the rail to allow the train to pass through. Movement of the stretcher bars is achieved by a point mechanism and other supplementary drives. Point operating equipment (POE) is an electro-mechanical device which ensures locking occurs using a clamp-lock by directly fastening the switch to the stock rail. Heaters, ensure reliable operation of S&C units in cold weather (Rama & Anderws, 2013). The temperatures at which the heaters operate vary amongst countries since the weather conditions are significantly different. Within the UK, heaters ideally maintain the rail temperature at +3$°C$ against a minimum air temperature of -25$°C$, and can cope with a maximum precipitation rate of approximately 150 $mm/hour$ (The Heat Tracing Authority, 2004).

2.2.2.2 Crossings

A crossing creates a gap in the rail for a flange to cross through. It is a non-moving part of the S&C layout. This allows the train to either pass in any direction once the switch has been set. The structure of the crossing contains few elements. Nose of the crossing and check rails either side of the crossing area are provided to assist the guidance of the wheelset through the crossing. The nose of the crossing is designed to resist high impact loads from train wheels (Zwanenburg, 2009).

Due to effects of traffic and aging the condition of the components deteriorate and maintenance must be carried out to keep the unit reliable to operate since failure of the unit might cause derailment. The deterioration and maintenance of S&Cs are further described in detail in Sections 2.3.2 and 2.5.2 respectively.

2.2.3 Sleepers

Rails are fastened to sleepers so that the latter prevents the track from moving sideways. Therefore, sleepers keep correct track geometry, and propagate the load imposed from the rail to the ballast. They also support the rail to resist thermal forces and buckling (Network Rail, 2017). Sleepers are classified into three general categories as timber (either hardwood or softwood), concrete and steel sleepers (Ferdous & Mana, 2014). The usage of each type of sleeper varies with respect to traffic, speed and the surrounding environment. The spacing between sleepers differs according to their type, line speed and tonnage, and is usually between 600 to 750 mm, based on the UK engineering standards (Whitmore, 2014). Within the UK concrete sleepers are most commonly used. Each type of sleeper deteriorates differently with respect to traffic and environmental conditions as explained in Section 2.3.3.

2.2.4 Trackbed

2.2.4.1 Ballast

The ballast forms the upper part of the substructure (Figure 2.1). Ballast consists of uniformly graded granular materials usually sourced from granite, basalt or hard limestone (Office of Rail Regulation, 2008). It supports sleepers through providing adequate vertical and longitudinal support. Thus, the upper portion of the ballast suffers from high stress levels induced by traffic load. The angular shape of the newly laid ballast particles maximises inter-particle void volume to provide drainage for water and space for fouling materials (Lim, 2004). Therefore, the primary functions of ballast are to withstand and distribute train induced loads to the subgrade and enable the superstructure to drain water away from the bottom of the sleepers to side drains (Li, et al., 2016).

2.2.4.2 Sub-ballast

The sub-ballast, or blanket, is a layer of granular materials, usually sand, which is located between the ballast and the subgrade (Burrow, et al., 2011). Its function is to further reduce and spread the imposed load onto the subgrade and provide a filter between the ballast and subgrade and by so doing helps to prevent the upward migration of subgrade soils into void spaces between ballast particles. Sometimes, a geotextile separator is placed on top of a sand layer. This creates increased resistance to abrasion between the sand layer and sub-ballast and helps to prevent the upward migration of fines. The sub-ballast also provides frost protection to the subgrade in cold climates. In addition, the sub-ballast provides drainage out of the track away from subgrade (Shi, 2009).

2.2.4.3 Trackbed Design

The trackbed layers are designed to protect the subgrade from different types of failure (see Section 2.2.5) and whilst the trackbed layers can be relatively easily maintained, failure of the subgrade is costly and requires significant maintenance (Li, et al., 2016). If the thickness is insufficient, the repetitive cyclic stress induced by trains causes excessive deformation of subgrade. In addition, a reduced ballast thickness requires more frequent renewal. Taking into account the costs of construction and maintenance of ballast should be considered in thickness design of trackbed because, if a trackbed is unnecessarily thick it would be unnecessarily expensive to build and maintain.

To address this, many railway organisations have developed standards which specify the required thicknesses of the substructure layers. In some, but not all cases, these are defined as a function of strength of the subgrade and the level of traffic and speed (Burrow, et al., 2006). In general, the thickness for the individual trackbed layers is not specified, albeit a minimum thickness of ballast of 300 mm (in the UK) is usually specified to enable ease of maintenance (see below) (Network Rail, 2003).

2.2.5 Subgrade

Subgrade is the natural ground and soil stratum on which the trackbed and superstructure is constructed. Subgrade must be stiff enough to resist the level of applied stresses, otherwise it will settle. To this end, the thickness of the ballast and sub-ballast layers are designed such that the magnitude of the intended design loads do not exceed the ability of the subgrade to carry these loads over the life of the track (Burrow, et al., 2006).

Within the UK, the required depth of trackbed is determined as a function of the modulus of the subgrade and the minimum requirements for the dynamic sleeper support stiffness and is specified in Network Rail's standard (Network Rail, 2003) and is shown in Figure 2.3.

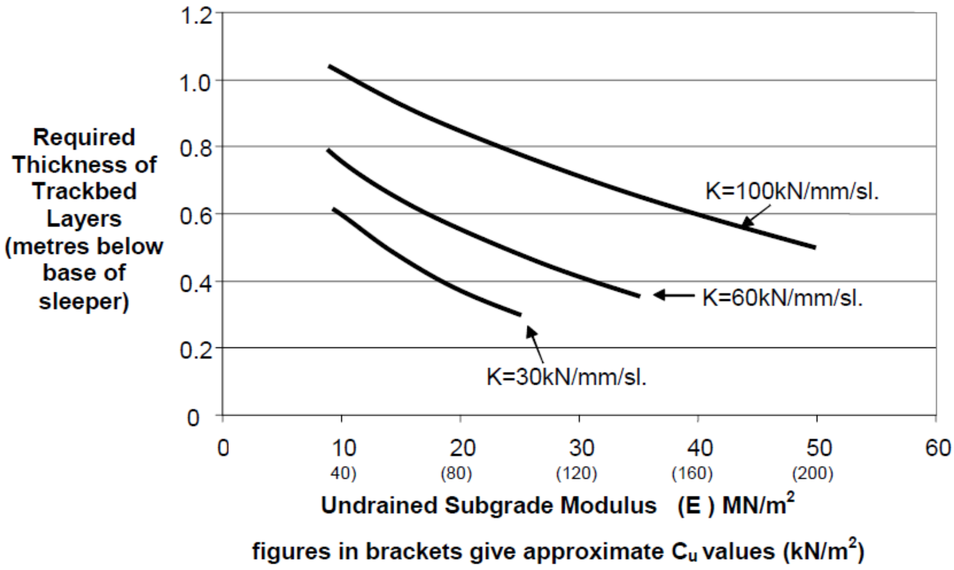

Figure 2-3 Required thickness of trackbed layers (after Network Rail, 2003)

In Figure 2.3 three curves are shown. These relate to the minimum required dynamic sleeper support stiffness, K, that is to be achieved for railway lines with a geogrid (i.e. 30 $kN/mm/sleeper$), without geogrid reinforcement (i.e. 60 $kN/mm/sleeper$), or new railway lines with a speed of up to 100 mph (i.e. 60 $kN/mm/sleeper$) and for new railway lines with a line speed above 100 mph (i.e. 100 $kN/mm/sleeper$). The required thickness of the trackbed layers is determined by selecting the type of track (e.g. a new line with a line speed greater than 100 mph) and the modulus of the subgrade. For example, for a highspeed line if the subgrade modulus is around 50 MN/m^2, the minimum trackbed layer depth of 0.5 m should be used.

A number of other railway operating companies specify different standards based on a variety of criteria including line speed, cumulative tonnage, axle loads and subgrade strength. A useful summary of these is provided by (Burrow, et al., 2006).

2.3 Deterioration of Track Infrastructure Components

In Section 2.2, the major types of track infrastructure assets and their functions were described. There are several influencing factors which cause deterioration of these assets. Effectively and efficiently controlling their deterioration is the key element in sustaining a safe and reliable railway network. In general, parameters influencing track deterioration are related to traffic, speed, historical maintenance activities and climate (Esveld, 2001) (Kumar, 2008) (Network Rail, 2015). The effects of these influencing parameters are different for each infrastructure asset and vary according to their type, material and the surrounding environmental conditions.

2.3.1 Rail

2.3.1.1 Traffic Induced Deterioration

Corrugation

Due to the effects of repetitive train loads, rails may develop quasi-sinusoidal irregularities known as corrugation. Corrugation types are classified according their wavelengths which range typically between 20 mm to 80 mm, for shortwave, and to more than 80 mm, for longwave (Afferrante & Ciavarella, 2008). Pinned-pinned corrugation and rutting are examples of shortwave corrugation. The former is caused by the rapid deterioration of ballast and sleepers on light axle load straight tracks. Longwave corrugation occurs due to the fundamental torsional resonance of the wheelset in heavy haul and light rails. Based on the wavelength of corrugation standards are set to determine the corresponding permissible values (see Section 5.3.4) (Grassie, 2008).

Wear

Direct rail-wheel contact of the passing train wears out the railhead which creates variations in gauge. The contact usually occurs between the leading outer wheel of the train and the outer rail of the curve. Based on the effects of wearing, deterioration is typically defined as headwear, sidewear or plastic-flow (Whitmore, 2014). In fact, the long-term damage mechanism of shortwave corrugation is headwear and sidewear whereas damage mechanism of a fully developed longwave corrugation is plastic-flow. Headwear is the loss in depth of the railhead which damages the crown. Increase in headwear increases the likelihood of flange more frequently hitting the rail causing sidewear. Plastic-flow occurs at the contact between the flange and the gauge corner of the rail where high stresses to which the rail is subject causes metal to flow along the rail. This can result in cracking, such as gauge corner cracking (Bower & Johnson, 1991).

Cracks

Loss of material caused by wear and plastic-flow corrodes the rail and reduces its stiffness and initiates cracks. The types of cracks developing under traffic include squats, caused by wheel and rail contact forces, wheel burns, due to friction caused by breaks, and rolling contact fatigue (RCF) which relates to creep and plastic-flow (Whitmore, 2014). Abrasive effects of wear and plastic-flow overtime if not maintained cause the rail to age and break and can result in severe consequences such as derailment. For example, the Hatfield incident which occurred in the UK in October 2000, was due to cracks originating from RCF, where the rail broke and caused derailment and the loss of four lives (Guardian, 2005).

Welding of rails can also leave inherent defects that develop into cracks such as alumino-thermic welds. Other defects originating from poor manufacturing of rails are tache ovales, which occur at the production stage as a consequence of excessive hydrogen in the metal or boltholes cracks. Cracks not maintained frequently eventually can cause the rail to break (Kumar, 2008).

2.3.1.2 Effects of Temperature on Rail Buckling

The propensity of a rail to buckle depends on many factors including the traffic volume and speed, axle loads, rail temperature, the condition of ballast, maintenance history and SFT (Bae, et al., 2014). Extreme low temperatures can cause the rail to contract resulting in tension cracks which can then cause the rail to break (Whitmore, 2014). Moreover, because the ends of CWRs are fixed, at high temperatures rails can experience compressive stress which could cause buckling. However. it is rare for rails to buckle spontaneously. The occurrence of buckling is highly correlated with ballast condition as the ballast provides track stability. Because railway track is laid on ballast, movements of the rail as a result of settlement or tamping operation, which requires lifting the track, causes a decrease in a rail's SFT or neutral temperature (Kish & Samavandam, 2013). When a track and the ballast are of poor condition, under extreme heat, the thermal forces within the rail increases and causes the metal to expand and creating normal forces acting in the direction of the rail. In this situation, the disturbance and stresses of the passing train might create buckling.

The propensity for buckling to occur can be reduced via the imposition of speed restrictions since the stress applied to rails is a function of train speed and track condition (Figure 2.4) (Burrow, et al., 2009). Lower train speeds induce lower stresses (Chen, et al., 2013) and therefore reduce the likelihood of buckling.

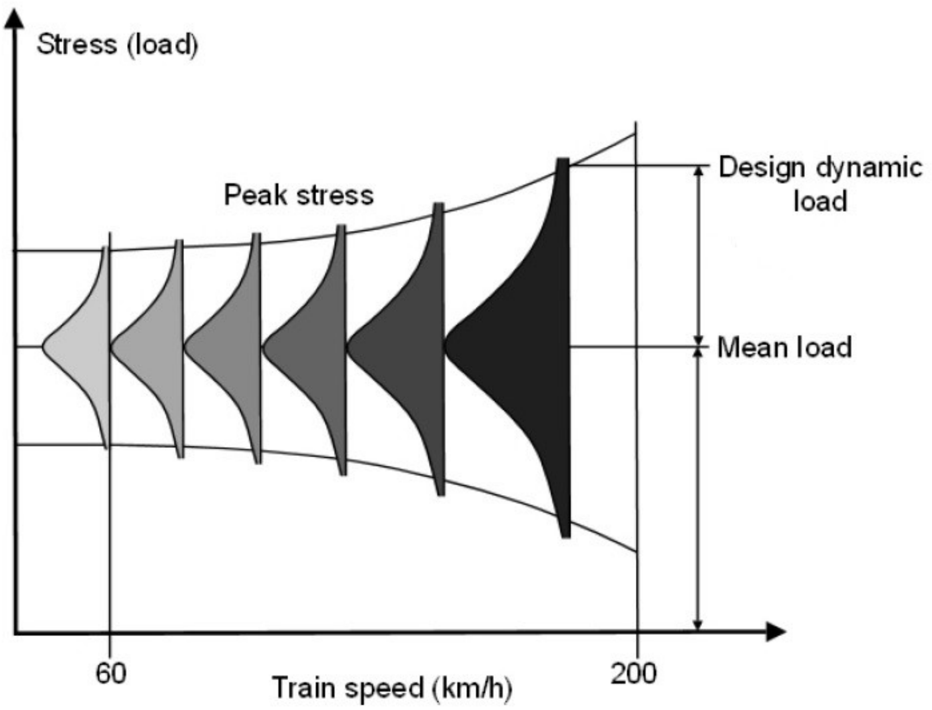

Figure 2-4 Train induces stresses as a function of train speed (Burrow, et al., 2009)

For this reason, research has been carried out to determine rail soffit temperature from the ambient air temperature under different weather conditions (Chapman, et al., 2007). Based on experiments carried out at Winterbourne and Leominster in the UK, the following Equation has been suggested to estimate the relationship between air and rail temperature (Chapman, et al., 2007).

(2.1)

$$T_{rail} \approx 3/2 \times T_{air}$$

$$T_{rail} = T_{air} + 17$$

Where T_{air} is the air temperature and T_{rail} is the rail temperature in $°C$. This is mainly used to infer high T_{rail} from T_{air}. Suitable standards which determine suitable speed restrictions are stated in Table 2.2

Track Condition	On Standby	30/60 mph speed	20 mph speed
Good Condition	SFT+32	SFT+37	SFT+42
Poor Condition	SFT+10	SFT+13	SFT+15

Table 2-2 Speed restrictions based on critical rail temperature and condition of track (Dobney, 2010)

According to Table 2.2 and Equation 2.1, Dobney (2010) suggests that in the UK, lines in good condition, in terms of having stable ballast shoulder at both sides of sleeper, will not buckle when the air temperature is less than 39°C or the rail temperature at 58°C. For railway lines with poor ballast condition the temperature at which buckling is likely to occur is 25°C. For this reason, when the air temperature is approximately 28°C a speed restriction of 20 mph is imposed on line with poor condition to prevent buckling. Other methods used to calibrate rail temperature is explained in detail in Section 2.4.1.4

Buckling may occur more frequently in the future due to increasing average global temperatures (Dobney, et al., 2009). Adhering to standards and utilizing efficient maintenance is likely to reduce the probability of buckling (Kish & Samavandam, 2013).

2.3.2 Switches and Crossings

Large lateral forces caused by passage of trains changing direction creates significant wear and deformation on rails at S&C points. The amount of such deterioration is a function of traffic, axle load and speed of trains where the magnitude of their impact varies according to the radius of curve and the existing sub-soil (Zhu, 2005). Moreover, poor quality track in terms of ballast condition can also increase the impact of train dynamic loads at S&C units (see Section 2.3.4).

Usually the slide plate under the switch rail is welded to two pieces of steel plates and therefore there is no elasticity in this section. Due to unevenness in geometry irregularities and stiffness along the track, when a train passes over the stock rail and the switch rail the vertical impact load creates unequal vertical stiffness of the two rails (Wan, et al., 2014). This in turn creates higher dynamic force on the track. Furthermore, at the crossing nose the vertical level of the inner rail is discontinuous. As a result, a train travelling from the wing rails to the crossing nose generates high impact force on the crossing. Since most crossings have a curved structure, corrugation, wear and plastic-flow defects tend to occur more frequently than on plain line

(Hassankiadeh, 2011) (Karttunen, 2012). Overtime, due to RCF, cracks can initiate and propagate at the crossings nose.

2.3.2.1 Deterioration of Switch Components

The mechanical and electrical components of switches are designed to last for a particular length of time, or undergo a specified number of train passages of a given load. Thereby, the life of S&Cs is affected by the age of switch components which wear through friction between moving parts and passage of trains. Severe wear causes major changes in rail profile and significantly impacts the level of dynamic train force (Xu, et al., 2016). High frequency of vibrations on track can damage electrical components such as POEs. Although components are tested, sometime faults in manufacturing process of the components can cause early malfunctioning. For instance, poor manufacturing can create improper seating of the rail at S&C points which can cause vertical and longitudinal fractures on rails. Continuously monitoring the constituent components of S&C is essential because, failure of a single element might render the whole unit as failed and cause derailment.

2.3.2.2 Temperature Related Problems

S&Cs are sensitive to temperature. The rails in S&C units when installed are stressed to the SFT so that they can operate within a given temperature range, in the same way as plain line is as described in Section 2.3.1 (Zwanenburg, 2009). In very cold weather, snow and formation of ice on switches can disrupt the operating of the unit and can potentially cause delays. Therefore, heaters are installed to increase the temperature of the unit to keep it from freezing (see Section 2.2.2) (Rama & Anderws, 2013). It is however envisioned that cold temperature related failures of S&C units will become less frequent in the future based on UKCP09 climate projections models, which predict that the average minimum temperature in the UK is rising (Met Office, 2017).

2.3.3 Sleepers

When a train passes over the track the elastic motion of the rail applies stress to the supporting sleepers. When sleepers fail, the adjacent sleepers carry the corresponding additional train induced load and overtime this can result in uneven settlement of the ballast and subgrade. In addition, as the number of consecutive unsupported sleepers increases the maximum displacement between the rail and sleepers increases. As a result, the level of imposed force from unsupported sleepers to the ballast increases thereby reducing the fatigue life of sleepers (Shi, et al., 2013). This issue is more common in heavy haul railway lines. In regions with unsupported sleepers, more load propagates to local areas of ballast and the resistance required for the frictional interlock decreases and the magnitude of the propagated load increases which increases ballast settlement. If ballast is in poor condition, the forced imposed from wheel/rail interaction to the sleeper becomes more significant, leading to faster differential settlement (Varandas, et al., 2012). Additional factors influencing the level of wheel/rail contact force are sleeper spacing and sleeper support stiffness (Shi, et al., 2013).

2.3.3.1 Traffic Related Deterioration

The imposed force of the train creates a large transverse shear load on sleepers. For timber sleepers end splitting might occur which reduces the support provided to the rail. Concrete sleepers are also subject to rail-seat abrasion due to the relative movement between the rail-pad and concrete rail-seat under repeated loading cycles. These movements create frictional forces which gradually wear the rail-seat and create small gaps which allows water to penetrate. Shear forces on the rail-pad interface increase the frictional force and creates movement (Zakeri & Rezvani, 2012). Therefore, as the loading cycle increases, the amount of force applied onto the sleepers increases. These defects also appear on steel sleepers resulting in fatigue cracks in the rail-seat region due to repeated cyclic loading. This decreases the stiffness of the sleeper and initiates cracks. In addition, rail abnormalities can adversely affect the rate of this process (Ferdous & Mana, 2014).

2.3.3.2 Effects of Surrounding Environment on Sleeper Deterioration

<u>Timber Sleepers</u>

Environmental effects that affect the deterioration of timber sleepers include fungal decay and termite attack (Ferdous & Mana, 2014). Fungal decay is classified as bio-deterioration of the timber sleeper and mainly occurs in environments containing moisture. For such reasons, this type of sleeper is not often used anymore within the UK. Termite attack permanently damages timber sleepers because termites consume the cellulose materials of the timber.

<u>Concrete Sleepers</u>

For concrete sleepers, the contact between cement and sulphates of sodium, potassium, calcium and magnesium on soil and groundwater creates a chemical reaction leading to deterioration. In addition, acid rains can deteriorate concrete sleepers which mainly consist of Portland cement (Ferdous & Mana, 2014).

Steel Sleepers

Steel sleepers are subject to corrosion in places where the ballast under the sleeper has a high salt content. Although rail and steel sleepers are made of similar material, the corrosion in steel sleepers is much faster than in the rail because of the latter's direct contact with the ballast (Townsend, et al., 2002).

2.3.4 Ballast

Train induced static and dynamic loads transmitted to the ballast create high stress levels. When a train passes, due to the weight and high frequency of load vibrations, the ballast undergoes elastic and plastic deformation. After the passage of a train, the track does not necessarily return to its exact original position (Dahlberg, 2004). Repeated cyclic loading causes the ballast and the foundation underneath to settle. This creates plastic deformation of the ballast and degradation of its component particles.

2.3.4.1 Ballast Fouling

Traffic and contamination from the surrounding environment cause ballast fouling which adversely impacts drainage. The main source of contamination originates from ballast breakdown whereas other sources of fouling materials relate to underlying granular layers, subgrade and sleeper surface materials (Lim, 2004). Fouling materials can negatively affect the rate of settlement of the ballast. Depending on the type and degree of fouled materials the rate of settlement differs. For example, research by Lim (2004) suggests that if the percentage of fouling is less than 20% and the fouling materials are moist silt, the ballast settles less, compared to fouling materials of moist clay. However, he found that if the degree of fouling is greater than 20%, due to the cohesiveness of fouling materials the reserve action is observed. If fouling material is dry clay, due to its high strength and stiffness the ballast settles less. Yet, if water is present in the layer, it will act as a lubricant and causes ballast particles to slide which increases the settlement. Similar reaction is expected in situations with wet silt if the percentage of fouling material is greater than 30% (see Section 2.4.4.3 for fouling index calculation).

2.3.4.2 Effects of Precipitation on Fouled Ballast

The presence of fouling materials in the ballast result in insufficient permeability of the ballast and the subsequent possibility of saturation of the subgrade soil. Overtime excessive deformation of the ballast leads to voids being created under the sleepers resulting in a lack of support for the sleepers (Paderno, 2009). Furthermore, at locations with highly fouled ballast there is a possibility of fouling materials in the presence of water resulting in slurry being formed. This process can cause excessive subgrade deterioration.

2.3.4.3 Effects of Maintenance Activities on Ballast Degradation

The ballast deterioration is not solely caused by traffic loads. Some maintenance activities tend to increase the rate of ballast deterioration. In the case of tamping, when ballast stones are squeezed together using tamping tines, breakage in particles produces fouling materials and particle rearrangement occurs, which impacts deterioration and stiffness (see Section 2.5.4) (Audley & Andrews, 2013). To this end, the main factors contributing to ballast degradation are train induced loads accompanied by some maintenance activities which foul the ballast. The deterioration and settlement of ballast creates deviations in railway track geometry and the main method, therefore, of determining the condition of ballast is via analysing track geometry irregularities (see Section 2.4.5) (Li, et al., 2016) (Esveld, 2001).

2.3.5 Sub-ballast

The sub-ballast is prone to degrade due to repeated traffic loads. The ability of the sub-ballast to spread load evenly depends on its compacted density which is controlled by its gradation and shape. A well graded sub-ballast has high stiffness. As a result of repeated load cycles, the sub-ballast gradually undergoes plastic deformation which decreases its stiffness. The degradation of the sub-ballast reduces the space between the ballast and subgrade and results in subgrade being subject to higher loads. It also gradually allows mixing of materials of the two layers. Where drainage is poor in the sub-ballast layer due to, for example, the upward migration of fines from the subgrade under loading, water can get trapped within sub-ballast and decreases its stiffness, leading to permanent plastic deformation of subgrade (Li, et al., 2016).

2.3.6 Subgrade

2.3.6.1 Combined Effects of Traffic and Precipitation on Subgrade Degradation

The major types of subgrade deterioration due to traffic loads are attrition by ballast, progressive shear failure, and excessive rate of settlement. Settlement occurs as a result of repeated loading cycles and accumulation of plastic strain and massive shear failure (Burrow, et al., 2006). Research suggests that soils have a threshold level of deviator stress above which plastic deformation increases rapidly with cyclic loading. Shear failure, as shown in Figure 2.5, occurs when cyclic stresses are very high, and the stiffness of the subgrade is not adequate (Burrow, et al., 2006). In addition, as stated in Section 2.3.5 due to ballast attrition, ballast is pushed in to the subgrade, as in Figure 2.6 and if there is water in the soil, it can get trapped in the pockets and decreases the stiffness of the subgrade.

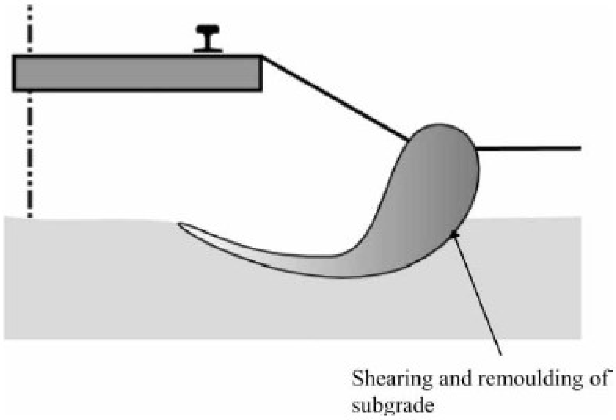

Figure 2-5 Progressive shear failure (Burrow, et al., 2006)

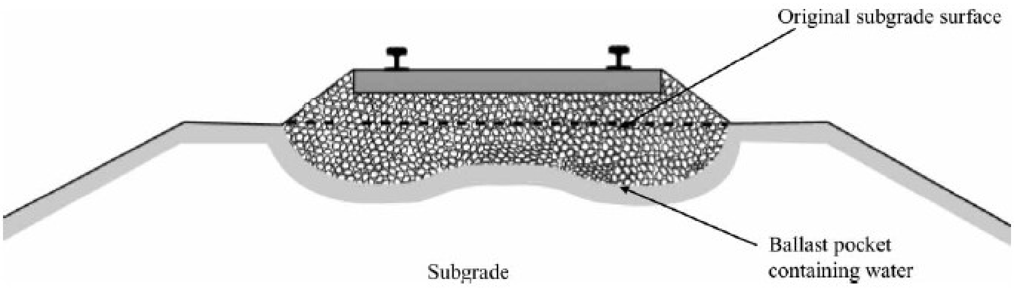

Figure 2-6 Plastic deformation (Burrow, et al., 2006)

In saturated and overloaded subgrade, the migration of fines creates wet spots in ballast via process known as mud pumping (Usman, et al., 2005).. As a result of overstressing, fine-grained soils or soils with high water content can cause progressive shear failure. This mainly occurs when the vertical stress of loaded layers is greater than horizontal stress and is usually manifested near the subgrade surface, heave in shoulders or depression under sleepers, known as cess heave can also occur (Hassankiadeh, 2011) (Li, et al., 2016).

2.3.6.2 Effects of Physical State of Subgrade on Its Degradation

Subgrade soil strength depends on the soil type, drainage condition and the stress history and depending on the soil type, repeated loading may decrease or increase soils resistance to deformation. For example, in the case of normally consolidated clay repeated loading causes consolidation and thus settlement. But for normally consolidated soil this phenomenon can make the soil stiffer (Li, et al., 2016). For over consolidated soils, repeated loading and poor drainage have a deteriorating effect because excess pore water pressure and deformation increases under repetitive loading. In a study of the factors which influence subgrade plastic strain, Li and Selig (1996) found that cumulative plastic strain is a function of the soil type and its stress and physical states. These parameters are affected by loading levels and the prevailing environment. The physical state of the soil depends on its moisture content and dry density whereby an increase in moisture content increases the plastic deformation. Therefore, the behaviour of the soil under loading could be expected to change seasonally. In order to take into account these factors, Li and Selig (1996) developed a relationship between the cumulative plastic deformation, ϵ_p, of the number, N of repeated loads as follows:

$$\epsilon_p = a\left(\frac{\sigma_d}{\sigma_s}\right)^m N^b \tag{2.2}$$

Where a, m and b are determined based on soil material, σ_d and σ_s are respectively deviator stress and soil static strength. In general, an increase in clay content increases a, m and b and thus plasticity.

2.3.6.3 Deterioration Caused by Extreme Low Temperatures

When water is trapped in the soil, depending on the soil type, in extreme low temperatures ice lenses can be developed due to capillary rise of water. In this situation, frost heave of the soil can occur which deteriorates track geometry. This occurs in soils that are high in capillary rise and low in plasticity such as, silt, sand and clay. When the ground water freezes below the ice lenses, due to permeability of frozen soil, the capillary rise stops. In addition, new ice lenses might develop. When temperature rises, causing the thawing of ice lenses the stiffness of soil decreases and causes accelerated damage to track geometry (Li, et al., 2016). Repeated loading imposes significant stresses on the subgrade which overtime causes settlement and subgrade soils subject to high precipitation are more prone to settle in sections with poor drainage conditions.

2.4 Condition Inspections and Measuring Techniques

The condition of track infrastructure components must be monitored and recorded overtime in order to enforce effective asset management (see Section 4.3.2). To measure track components' condition several methods and inspection techniques are used to identify and determine the severity of defects. Because, deterioration is directly related to the amount of traffic and speed, in practice, tracks in higher categories in terms of traffic and speed are inspected more frequently. Inspection methods for each component are described below.

2.4.1 Rail

2.4.1.1 Rail Wear Measurement

Ultrasonic examination is used on a regular basis to identify internal defects of rails. By analysing the behaviour of the ultrasonic signal, rail abnormalities such as headwear and sidewear can be determined (Podofillini, et al., 2006). In this inspection technique, ultrasonic signals are recorded over a length of track using devices fitted to trains moving at speeds up to 70 km/h on CWR and good quality JR. Portable devices are also available which allows the operator to interpret the signals over a smaller track sections to find defects in rails mainly relating to squats and tache ovales (Whitmore, 2014).

2.4.1.2 Corrugation Measurement

In the UK, corrugation measurements are obtained commonly from the Corrugation Analysis Trolley (CAT) which is used on Mainline and Metro railway systems. Furthermore, the Highspeed Track Recording Coaches (HTRCs), owned by Network Rail, are instrumented trains which are used to record periodically a variety of measures of condition at speeds up to 125 mph. Such trains measure rail top, cant, twist, level and alignment of track geometry (Presle, 2000).

2.4.1.3 Visual Inspection

Visual inspections are also carried out by track engineers to identify defects visible by the naked eye. Although this is time consuming, during emergencies when other sorts of inspections are not available visual inspection can be beneficial (Whitmore, 2014).

2.4.1.4 Rail Temperature Measurement

The effects of air temperature on rail temperature is triggered by factors such as exposure to the sun, track orientation, humidity, wind speed, precipitation and shadow caused by cloud cover. Experiments by Rail Safety Standards Board (RSSB, 2014) indicate that during high temperatures the soffit and the web is warmest compared to the head of the rail since the polishing effects of the rolling stock on railhead creates higher reflective properties. For this reason, RSSB recommends that because rail surface temperature varies across the rail, rail temperature measurements should be obtained from either the soffit or the shaded side of the rail web. This is done using mercury or digital thermometers. The device used is equipped with three-type magnetic thermocouples located on the head, web and soffit of the rail and connected to a four-channel data logging thermometer and a standard probe to measure rail temperature (RSSB, 2014). Rail temperature can also be estimated empirically using Equation 2.1 as stated in Section 2.3.1.

2.4.1.5 Measurement of Stress Free Temperature of Rails

The traditional practice of determining SFT involves the measurement of longitudinal rail load stress, longitudinal rail force and measurement of static dilatation (Wegner, 2013). These can be measured via contact or contactless technologies. For example, for measuring longitudinal rail load stress either the x-ray stress determination method which measures the lattice strains, or a hole drilling method where the stress is determined by the change in level of stress caused by a small borehole and measured by a strain gauge in a circular configuration mounted on the drilled hole can be used (Schajer, 2013). Ultrasonic methods determine the level of stress by measuring and analysing the stress sensitive sound velocity (Kish, 2013). Whereas, to measure longitudinal rail force a more complicated technique which measures the rail vibrations in order to analyse the harmonics for stress determination is used. In this type of measurement, longitudinal rail force is calculated using elasticity theory by applying a vertical lifting force on the rails unfastened from the sleepers on a specified length of track. The disadvantage of this approach is the fact that rails are unfastened and therefore, a more significant reaction force is generated from the rail as a result of the vertical lifting force (Wegner, 2013). For static dilatation measurement a traditional destructive method, which requires rail cutting to measure the gap size or strain change due to rail's contraction and expansion after the cut, is used to analyse SFT (Schajer, 2013). The mathematical methods and modelling techniques used to estimate rails' SFT are described in Section 3.3.1.

2.4.2 Switches and Crossing

The inspections used for rail related internal defects (see Section 2.4.1) are applicable for measuring rail defects of S&Cs. As the condition of the ballast plays an important role in supporting the superstructure (see Section 2.2.4), the measurement techniques undertaken to determine the ballast condition are very useful in identifying the condition of S&C units (see Section 2.4.5). Inspection of switch components are mainly conducted by track engineers using manual means and can be very time consuming and subject to human error. To address this, number of automated methods are being researched and developed (Silmon & Roberts, 2010) (Halcrow Group Ltd, 2007).

Switch Inspection and Measurement (SIM) is a vehicle that carries switch and rail inspections at speeds up to 40 km/h. Seven cameras are used which record the switch in a synchronised manner, whilst rail profile is measured by a laser. The varying angle of the camera and its ability to capture high-quality images allows the engineers to accurately analyse the condition of the switch components (EURAILSCOUT, 2017).

2.4.3 Sleepers

Sleeper inspections are undertaken visually in the field or from photographs and videos of the track to identify the number and location of defective sleepers. In the UK, this is done routinely. The frequency of inspection is a function of traffic, speed and tonnage with greater inspection frequencies taking place on more highly trafficked lines (Whitmore, 2014). Upon inspection, if one or more sleepers have been found to have failed consecutively, the situation must be dealt with immediately. Otherwise, the replacement of failed sleepers is postponed until the end of their service time (Zhao, et al., 2007). It should be stated that inspecting track drainage is also necessary. Poor drainage and settlement of the subgrade increases the deflection imposed from rail-wheel contact and results in sleepers being unsupported (see Section 2.3.3) (Lundqvist & Dahlberg, 2005).

2.4.4 Ballast

2.4.4.1 Track Geometry Measurement

For ballast the measurement of track geometry parameters is primarily achieved through inspection trains equipped with number of devices to measure track geometry at line speed such as HTRC (see Section 2.4.1). In the UK, geometry measurements are recorded at frequencies given in line standards which relates the frequency of measurement to the track category. The lower the track category the more frequent the inspection. In the other words, higher speed and more heavily trafficked lines are required to be assessed more often. Measured values are manipulated and reported in terms of the standard deviation (SD) of measurements for each $1/8^{th}$ of a mile track section. The measurements of vertical and horizontal alignments are passed through a filter of 35m or 70m wavelengths (Andrews, 2012). 35m wavelength readings are used primarily to assess ballast quality. The 70m wavelength filter has a wider bandwidth and it therefore covers and measures wider geometry alignment and is more useful in determining the condition near transition points such as approaches to embankment, bridges, slab-track or level crossings where there is more significant variation of stiffness (Varandas, et al., 2012).

Track Geometry Parameters

Essential parameters considered in identifying track geometry irregularities are shown in Figure 2.7.

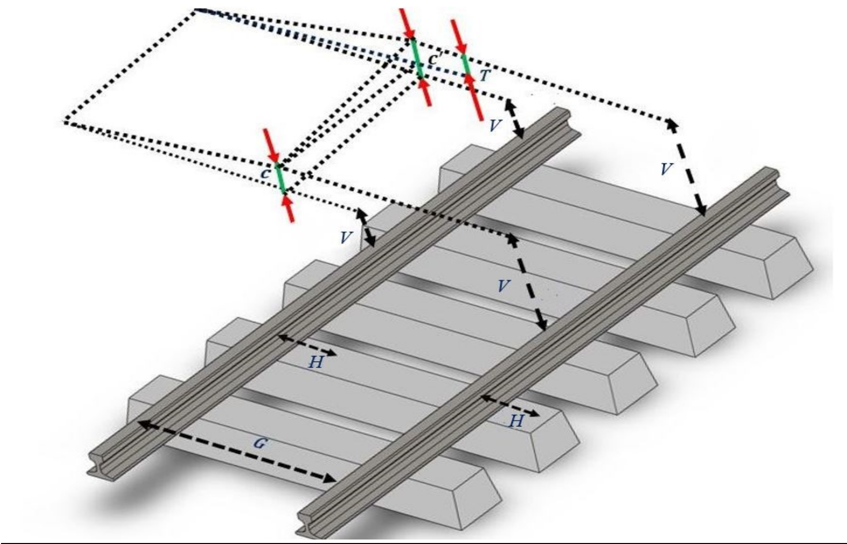

Figure 2-7 Track geometry parameters (Andrade & Teixeira, 2013)

As it can be seen from Figure 2.7, V, H, T, G and C represent vertical profile, horizontal alignment, twist and gauge and cant deviations respectively. A geometry irregularity of each rail projected onto the longitudinal vertical plain, is known as the vertical profile of the track.

The vertical profile is considered to be the most significant indicator of ride quality in many countries including the UK, USA and most of Middle East (Sadeghi & Askarinejad, 2009). Limits for Standard Deviation (SD) values of vertical and horizontal profile are set in design standards to indicate when maintenance is required. For example, in the UK if the value of SD of vertical alignment of ballast is greater than 3.4 mm the ballast requires maintenance (Network Rail, 2013).

The horizontal alignment is the horizontal positioning measurement of the rail against each other (Andrade & Teixeira, 2013). The angle between the two rails at a given distance is known as the gauge. In the UK standards, gauge is measured 16mm below the top surface of the railhead (Whitmore, 2014). Cant is the deviation between the top surface of two rails. Usually in curves the outside rail is higher than the inside rail (i.e. superelevation) to compensate for the applied centrifugal force. The positive values of cant cause superelevation of the track whereas negative values indicate reverse cross-level. Twist specifies the elevation of cant between the top surface of the two rails. Tangential forces imposed on the low rail at curves are reduced by decreasing cant and typically results in less corrugation (Sadeghi & Askarinejad, 2007).

2.4.4.2 Ground Penetrating Radar

Ground Penetrating Radar (GPR) is a non-destructive test used for determining the condition of various layers of the substructure. GPR uses horn antennas to radiate electromagnetic energy into the structure which is reflected back to the source where it is processed. The resulting images obtained from GPR, as shown in Figure 2.8, are used to determine the thickness of layers and the amount of clean and fouled ballast. It also identifies the presence of wet spots. Therefore, the use of GPR is very beneficial to railway industries for determining drainage conditions (Anbaxhagan, et al., 2010) (US department of transport, 2009).

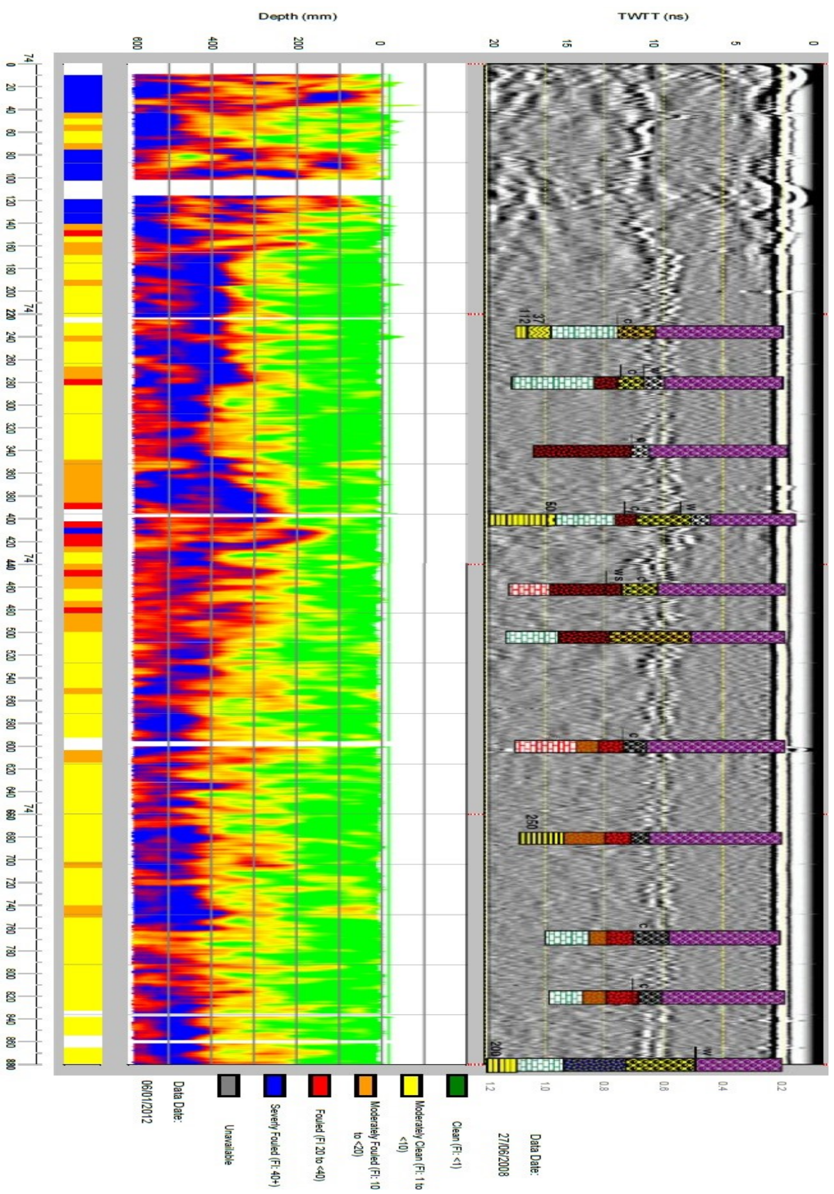

Figure 2-8 GPR measurements. Top: Thickness of material type Bottom: Fouling Index (Network Rail, 2013)

2.4.4.3 Manual Inspection and Particle Size Distribution Tests

Ballast is also inspected manually by investigating the distribution of its particle size. In its clean original state ballast consists of similarly sized aggregates of granite, basalt or limestone. In particle size distribution tests various meshed sized sieves are used to indicate the amount of fines, or fouling in the ballast. Fouling index, fouling ratio or percentage of void contamination index (VCI) are examples of ways to measure of the amount of fouling (Selig, et al., 1993).

Fouling Index and Fouling Ratio

In general, the fouling index is calculated by the summation of the percentage (by weight) passing a 4.75 mm sieve and 0.075 mm sieve (Tannakoon, et al., 2012). The fouling ratio is the ratio of dry weight of materials passing a 9.5 mm sieve with respect to the total weight of the dry sample (Haung, et al., 2009). As the amount of fouling increases, the ballast becomes more contaminated and results in reduced permeability suggesting poor drainage (see Section 2.3.4). Fouled ballast can create lower strength values since the presence of fouled materials can reduce the interlock between ballast particles and therefore its frictional properties. This reduces the ability of the ballast to carry and spread train induced load. According to fouling index different fouling categories are specified (see Figure 2.8). In addition, research determined that hydraulic conductivity of the ballast reduces considerably with increasing degree of fouling. Selig, *et al* (1993) showed that if the amount of fouling material increases, hydraulic conductivity correlates with how the voids are filled. Table 2.3 shows the hydraulic conductivity of ballast with respect to different fouling indices.

Fouling Category	Fouling Index	Hydraulic Conductivity (mm/sec)
Clean	<1	25 – 50
Moderately Clean	1 – 9	2.5 – 25
Moderately fouled	10 – 19	1.5 – 2.5
Fouled	20 – 39	0.005 – 1.5
Severely Fouled	>39	0.005 – 1.5

Table 2-3 Hydraulic conductivity of ballast based on fouling index (Lim, 2004)

Void Contamination Index

VCI is defined as the ratio between the bulk volume of fouling material to the initial volume of ballast voids as calculated by Equation 2.3 (Tannakoon, et al., 2012).

(2.3)

$$VCI = \frac{V_{f'}}{V_{vb}} \times 100$$

Where $V_{f'}$ represents the actual volume of fouling material within the ballast void, V_{vb}.

To include the effects of soil properties on fouling a more detailed equation can be used based on the work of Tannakoon, *et al.* (2012) as follows:

(2.4)

$$VCI = \frac{1 + e_f}{e_b} \times \frac{G_{sb}}{G_{sf}} \times \frac{M_f}{M_b} \times 100$$

Where e_b and e_f are the void ratio of clean ballast and void ratio of fouling materials respectively. G_{sb} and G_{sf} are specific gravity of clean ballast and fouling materials respectively. M_B is the dry mass of clean ballast and M_f is the dry mass of fouling materials. For instance, a VCI of 30% indicates that 30% of the ballast voids are contaminated by fouling materials.

To determine drainage using VCI research by Tannakoon, *et al* (2012) states that to have free or acceptable drainage in the upper part of the ballast the VCI needs to be less than 25%. Whereas, VCI greater or equal to 50% suggests that the ballast has poor drainage. In Australia, drainage classification is carried out per traffic volume, the capacity of drainage and the corresponding intensity of rainfall. Based on calculated flow rates and the maximum rainfall, in millimetre per hour, the drainage condition is categorised into different categories, namely: free drainage, good drainage, acceptable drainage, poor drainage, very poor drainage and impervious (Tannakoon, et al., 2012).

2.4.5 Subgrade

Usually the condition of the subgrade is inspected in sections where the track geometry is excessive. In the UK, GPR is often used in such locations to assess the water content and depths of ballast and sub-ballast to determine if the track geometry problems are associated with softening of the subgrade. From the resulting analysis where the cause of the poor track geometry has not been identified as being due to the ballast and sub-ballast layers, the stiffness of the trackbed layers and the subgrade is often assessed to aid the diagnoses as described below.

2.4.5.1 Static Stiffness Measurement

Falling Weight Deflectometer

The Falling Weight Deflectometer (FWD) device is used in the UK to measure the stiffness of the railway track. The FWD is placed on a sleeper which is unclipped from the rail. It is designed to apply 125 kN force on to a sleeper using a mass which is dropped from a predefined height on to rubber buffers located on the footplate of the device (see Figure 2.9). Geophones are placed at different distances from the footplate on both sides of sleepers and along the track to measure the surface velocity resulting from the dropped weight. The velocities are then integrated to determine vertical displacements (Burrow, et al., 2009).

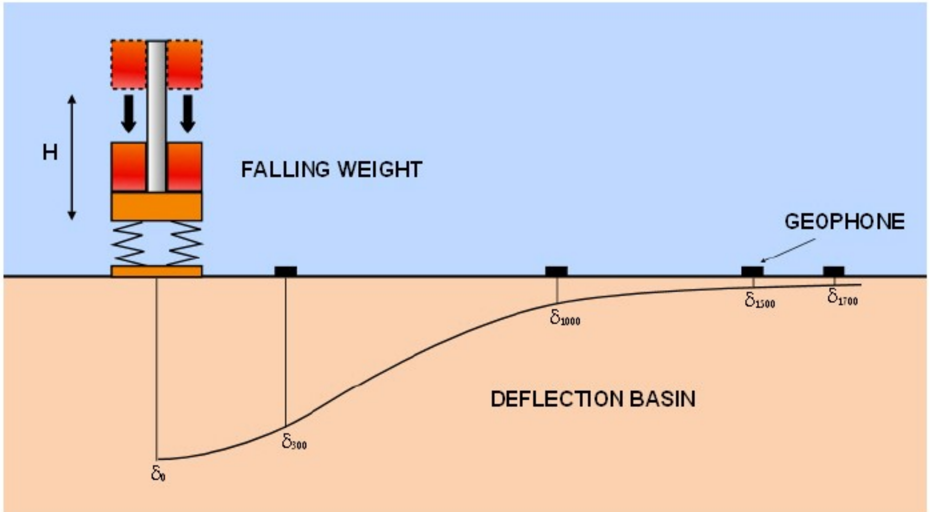

Figure 2-9 Schematic of FWD (Burrow, et al., 2009)

The values of d_0, d_{300}, d_{1000} and d_{1500} on opposite sides of sleeper, determine the defection below the track at different depths. The values determine the deflection measured on the loaded sleeper, d_0, on top of the ballast, d_{300} which is 300 mm away from FWD load and so on. Stiffness is calculated as the deflection divided by the magnitude of the imposed load (see Equation 2.5) (Burrow, et al., 2007).

(2.5)

$$K(t) = \frac{F(t)}{d(t)}$$

In practice, because existing voids beneath the sleepers cause great deflection at small load intensities as shown in Figure 2.10, secant stiffness is sometimes calculated using Equation 2.6 (Burrow, et al., 2009).

(2.6)

$$K_{x-t} = \frac{F_y - F_x}{Z_y - Z_x}$$

Where F_x an z_x are seating load and the resulting deflection. F_y and z_y are respectively load and deflection after which there are no voids beneath the sleepers.

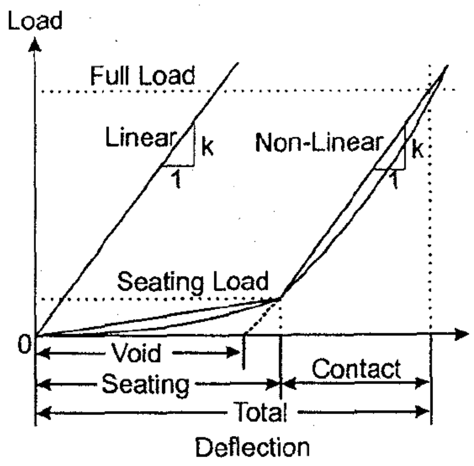

Figure 2-10 Load – deflection diagram to represent effects of voids (Burrow, et al., 2009)

The stiffness of different layers is calculated by determining the relative deflection of the layer. For example, to determine the stiffness of trackbed layers the deflection at the footplate (d_0) and at geophone located 1000 mm (d_{1000}) away from d_0 are used:

(2.7)

$$k_{trackbed} = \frac{62.5}{d_0 - d_{1000}}$$

Where the value 62.5 represents the load distributed on both ends of the sleeper. Equation 2.7 assumes that the deflection below 1000 mm is due solely to the subgrade.

The stiffness value of ballast is therefore:

(2.8)

$$k_{ballast} = \frac{62.5}{d_0 - d_{300}}$$

As discussed in Section 2.2.5, based on subgrade stiffness the required trackbed thickness is determined at the design stage. The overall stiffness of the system, is determined as (Powrie & Le Pen, 2016):

$$\frac{1}{k_{system}} = \frac{1}{k_{railpad}} + \frac{1}{k_{ballast}} + \frac{1}{k_{subballast}} + \frac{1}{k_{subgrade}} \tag{2.9}$$

Where $k_{railpad}$ is usually around 60 kN/mm.

Impact Hammer

The impact hammer is a handheld device equipped with a force transducer measurement. An accelerometer is attached to the sleeper. When the hammer hits the sleepers, the impulse force and its acceleration are calculated, and a transfer function is used to determine deflection. Subsequently the value of stiffness is calculated using Equation 2.3 (Li, et al., 2016).

2.4.5.2 Continuous Stiffness Measurement

Although standstill measurements are useful to determine stiffness variations, data obtained from continuous and rolling measurements have the potential to be more useful for maintenance purposes because the stiffness of more track sections can be monitored regularly overtime. Swedish railways use an oscillating mass on a vehicle, known as Rolling Stiffness Measurement Vehicle (RSMV), to load the railway axle. The vehicle loads the track and track dynamic stiffness is measured from oscillations while vehicle is moving (Dahlberg, 2004). The speed of the vehicle can be up to 30 km/h. Because the effects of rail bending stiffness (EL) are included in the stiffness calculation, the corresponding track modulus is calculated to determine track stiffness. Based on track stiffness, the corresponding track modulus, u, is determined from (Burrow, et al., 2009)

$$u = \frac{k^{4/3}}{(64EL)^{1/3}} \tag{2.10}$$

One drawback of this method is the lack of reference to the unloaded position of the track to obtain an approximate overall track deflection (INNOTRACK, 2006)

2.5 Track Infrastructure Maintenance

2.5.1 Rail

2.5.1.1 Lubrication

Rail maintenance tends to be proactive in its nature so that potentially catastrophic breaks do not occur. Lubrication, in form of grease applied by rail lubricators, is frequently used to reduce the friction between train wheels and the rail and by so doing it helps to prevent the occurrence of wear.

2.5.1.2 Grinding

Rail grinding is typically used to remove corrugation and in many countries, including the UK, it is carried out routinely as part of a preventative maintenance regime (Grassie, 2008). A grinding train consists of number of vehicles, coupled together, supplying power to drive both the train and the grinding stone. Grinding re-profiles the rail by modifying the shape of the railhead which has been deformed. In addition to removing corrugation, grinding can also be used to remove surface defects such wear and the effects of plastic-flow to some extent depending on the severity of defects (Whitmore, 2014). Although grinding removes rail internal defects, it can reduce the fatigue life of the rail since it is removes material from the railhead (Sawler & Reiff, 2000).

2.5.1.3 Rail Renewal

In case of buckling or a rail break, deformed rails are replaced. When a piece of rail is replaced in cold days of winter due to the difference between the ambient air and SFT it is difficult to maintain the correct welding temperature. In practice, to replace the rail fishplates are attached and replaced by welding in summer (Kish, 2013). Rails which passed their useful life and are not fit to be used for operation are also replaced with new pieces of rail.

2.5.2 Switches and Crossings

Maintaining S&C assets is a complex challenge to railway operators and often accounts for a disproportionate part of the maintenance and renewal budget. For example, in the UK, less than 5% of track miles are made up of S&C but they account for 19% of the maintenance budget (Silmon & Roberts, 2010). According to NR approximately 340 units are renewed per annum.

2.5.2.1 Common Rail and Ballast Maintenance to Rehabilitate Switches and Crossings

Maintenance of internal rail defects of S&Cs include, lubrication, grinding and rail re-profiling. As the majority of S&C are located on curves, correcting the elevation of track by fixing cant results in more support. By maintaining the correct track geometry, the gauge and cant are kept at correct levels creating lateral stability of the track.

2.5.2.2 Component Replacement

Renewal must be done when switch components fail. Before installing new components on the track, they ought to be checked and tested by manufacturers to guarantee that they are free from any early age defects (Nicklisch, et al., 2010).

2.5.3 Sleeper

2.5.3.1 Sleeper Renewal

When sleepers fail, or reach the end of their lifespan, they are replaced. Despite recently introduced automated sleeper laying technologies, sleeper renewal is time consuming and leads to the temporarily closure of the line (Ferdous & Mana, 2014). If sleepers are not maintained regularly, the increase number of failed sleepers causes extra delays and costs. Sleepers are not always replaced with new pieces. On some occasions, used sleepers in good condition might be considered as replacements.

2.5.3.2 Alternative Methods to Control Sleeper Degradation

Apart from renewal, other methods exist to increase the lifespan of sleepers by decreasing their rates of deterioration. For concrete sleepers, to control longitudinal cracks transverse reinforced bars are placed in sleepers enabling them to sustain more pressure and to redirect the cracking planes. Applying epoxy coating over the rail-seat as well decreases the rate of deterioration. However, epoxy coating is mainly effective if cracks are small (Whitmore, 2014). Splits in timber sleepers are treated by applying metal bands to close the open split and prevent it from propagating. Synthetic chemicals and biological methods are most common means of preventing fungal decay and termite attack in timber sleepers (Ferdous & Mana, 2014).

2.5.4 Ballast

Irregularities in railway track longitudinal profile arises from differential settlement (Dahlberg, 2004). Maintenance activities fix these settlements through machines which lift the track to level the profile. Tamping and stoneblowing techniques are examples of such machines.

2.5.4.1 Tamping

A tamping machine lifts the track to create a void between the sleeper and the ballast. The tines of the tamping machine are inserted into the ballast, on either side of the sleepers, and are squeezed together to remove and fill the crib area under the sleeper. Tamping is usually very easy to perform and is carried out regularly. Despite the advantages of tamping, the ballast condition does not return to the “good as new” condition. This is because pushing the ballast particles together can cause particle breakage (see Section 2.3.4.3) and whilst the process results in the temporary improvement of geometry it has been shown to increase the rate of track deterioration after each intervention cycle. The rate at which ballast deterioration changes is therefore, based on maintenance history (see Section 6.4.3) (Audley & Andrews, 2013) (Shi, 2009).

2.5.4.2 Stoneblowing

Stoneblowing corrects track profile error by raising the rail and blowing stones into the voids between the sleepers using injection tubes. The amount of stone to be injected depends of the design and rail elevation. The stone is added on top of the compacted ballast and is disturbed by tubes which creates more stability and less settlement in the aftermath of the intervention. In this process, it is important to use high quality granular material which are small enough to fill the void but large enough to create interlocking (Li, et al., 2016).

2.5.4.3 Ballast Cleaning and Replacement

Like any other component of the track structure ballast also has a finite life and when reached it must be replaced. In this situation ballast is cleaned using an under-cutter machine that is equipped with a continuous chain which excavates the fouled ballast underneath the sleepers (Lim, 2004). This machine is equipped with several sieves that are used to remove the fouled materials. The large ballast particles are conveyed back to the track and new ballast is used to replace the ballast which has been fouled.

2.5.4.4 Other Methods to Control Ballast Deterioration

To improve drainage shoulder cleaning, which removes fouled materials from ballast shoulder and improves drainage from the crib area, is used. This treatment is useful when fouling index is less than 30 (Li, et al., 2016).

Ditching is also used to provide rapid external drainage by removing water laterally from the track. Ditches must have adequate lateral and longitudinal slope and an invert elevation of sufficient depth below the subgrade so that water does not return back to the track (Li, et al., 2016).

2.5.5 Sub-ballast

If sub-ballast is installed with adequate thickness and gradation to carry the train loads to which it is subjected and provides adequate drainage, it should not require maintenance during its life (Li, et al., 2016). However, where drainage conditions are poor the sub-ballast can deteriorate rapidly leading to unplanned maintenance. For this reason, geosynthetic material, such as geogrid and geotextiles, are often placed on top of sand layer to reduce the vertical stress on the subgrade layer. Sometimes, a layer of concrete is placed within the sub-ballast to act as a stabiliser layer to reduce stress. However, bending fatigue in concrete is not strong and excess pressure can break the layer (Choi, 2014).

2.5.6 Subgrade

2.5.6.1 Useful Sleeper and Trackbed Maintenance to Protect Subgrade

The deterioration of the subgrade depends on the transfer of the imposed load and the strength properties of the subgrade. The load transference is greatly affected by the number of defective sleepers and the condition of ballast and sub-ballast (see Section 2.3.6). If the trackbed does not have adequate stiffness, and the problem cannot be remedied using ballast maintenance techniques, the trackbed is removed and reconstructed (Network Rail, 2003). In the UK, according to Figure 2.3, based on the subgrade modulus and track speed the thickness of trackbed layers can be determined.

2.5.6.2 Ground Improvements

Ground improvement treatments are used to improve soil gradation and reduce the plastic deformation of the subgrade by increasing its strength. Sometimes soil stabilisation is used by adding materials such as bitumen and lime. These products are blended into the soil to improve the strength and plasticity of the subgrade. The selection of type of additive is depended on soil type (Li, et al., 2016) . Ground improvement can also be achieved using compaction grouting. Compaction grout is a blend of cement, sand, clay and water in a stiff state. This method is used to replace the soil with a grout bulb to increase stiffness locally. Alternatively, penetration grouting such as slurry injection or injecting cement or chemical grout into the soil can be used. Although, this technique increases the stiffness, penetrating grout fills the void space and decreases permeability (Li, et al., 2016).

2.5.6.3 Vegetation Control

In some circumstances, controlling vegetation can be considered, to improve subgrade performance. Vegetation growing near the track can absorb large amounts of water which removes water from the track sub-structure (Hashiba & Ishida, 2015). In dry summers, vegetation can suck moisture out from the substructure system and can cause differential settlement specially at embankments. Therefore, controlling vegetation is important (Gunn, et al., 2017).

2.6 Summary

This Chapter has identified and described the major components of the railway track which account for the majority of maintenance cost. The functional and structural properties of these components were described, and it was shown that, overtime, repetitive traffic loads, maintenance activities and environmental conditions adversely affect the rate of track deterioration (see Section 2.3). It was illustrated that maintenance is necessary to be undertaken to provide safety of operation. For this reason, the inspection of all the major components is carried to monitor and record their condition periodically (see Section 2.4). Different maintenance treatments are undertaken to maintain the condition of track although some types of maintenance, such as tamping, can result in increased rates of deterioration (see Section 2.5). The next Chapter discusses how maintenance can be scheduled appropriately via the processes of railway maintenance, or asset management.

Chapter Three

3. MODELLING TRACK DETERIORATION AND RESTORATION

3.1 Introduction

Over a railway network it might be expected that the track will deteriorate at different rates and by different modes due to variations in soil types, track geometry (i.e. slope and curvature), train loads, speeds, climate, maintenance history and material used for track components (see Section 2.3). Efficient and timely maintenance necessitates analysing and predicting the effects of these influencing variables on condition and deterioration of track overtime. Different modelling methods have been proposed to this end and this Chapter presents and classifies the most widely used methods. Since the aim of this research is to develop a network level maintenance management decision-making system (see Section 1.2), the challenge is to determine appropriate models that can consider the variety of factors affecting the condition of the railway components to satisfy the requirements for network level analysis (see Section 4.3.1 for management levels).

3.2 Track Indices

Section 2.5 indicated that decisions regarding the type of treatments to be used to remedy track components condition are according to the type and progression of their defects. For this reason, indices are often used to represent the condition of infrastructure assets to enable efficient maintenance management. For the majority of defect types, which are recorded periodically, such as track geometry irregularities, gauge, rail profile and corrugation, indices are used to classify the condition of components into different categories based on the severity of the deterioration present. For the purposes of track maintenance, maximum permitted values, or intervention levels are set which when exceeded trigger maintenance.

In general, track degradation can be considered to be a function of time or traffic and space as follows (Soleimanmeigouni, *et al* (2016)):

$$Q_i = f_i(t, s) \tag{3.1}$$

Where Q_i is the deterioration according to measure of condition i, such as, corrugation.

Values of Q are commonly known as Track Quality Indices (TQIs). In general, the TQI associated with track geometry is known as the Track Geometry Index (TGI), and it mainly represents the condition of ballast. For other structural defects relating to the superstructure i.e. rails, sleepers, S&Cs or subgrade, the Track Structural Index (TSI) is commonly used (Soleimanmeigouni, et al., 2016). Section 2.3 described that, track assets belonging to different track categories deteriorate at different rates. Therefore, usually different limits of TQIs are set for each component as a function of the asset type and track category. For instance, for the condition of ballast, Sadeghi and Askarinejad (2007) proposed three values of TGI for each track category. Prescott and Andrews (2013) used the range of SD values of 35m vertical alignment of track geometry over 1/8th of a mile distance of track as a representor of ballast condition of that line. Based on the range of measured SD values, critical values were selected and used as indices to determine different condition states. In their work, for SD values between 3.5 and 4.5 track was assumed to be in a state requiring maintenance, whereas for values between 4.5 and 5 and any value above 5, track was considered to be in a condition that required a speed restriction and line closure respectively, if maintenance was not carried. Naito (2007) used the UK standards to determine ballast intervention levels based on SD of 35m vertical and horizontal alignment of track geometry. Four condition states namely, ‘very good’, ‘good’, ’poor’ and ‘very poor’ were suggested in his work. He also determined separate TSIs based on the type of rail and sleeper as a function of track categories. Bai *et al.*, (2014) proposed TQIs based on Chinese standards of track geometry and classified the condition of ballast into four states namely ‘qualified’, ’bad’, ’worse’ and ‘worst’. EL-Sibaie and Zhang (2004) classified the tracks within each track category with respect to curvature and determined TQIs according to Federal of Track Safety Standards (FTSS) as indices for surface geometry abnormalities.

In the work of Shafahani and Hakhamaneshi (2009), in order to determine TQI, Track Geometry Parameters (TGP) (see Section 2.4.4.1) where analysed. TGP, in their research, included unevenness, twist, alignment and gauge of track geometry. The values of TGP were combined into a single index known as the Combined Track Record (CTR). They defined five states on a scale of 0 to 100. For example, CRT between 80-100 indicated excellent condition, whereas between 0-50 was used to represent a failure state, meaning track has reached the end of its useful life. Hamid and Gross (1981) used a similar approach and determined five TQI values to represent the combined effects of TGP which included SD of gauge, superelevation (cant) and horizontal alignment per defined length of track in inches. Corriere and Vincenzo (2012) used the Italian Rail Quality Index (IQB) to evaluate the condition of rails as a function of cumulative tonnage (Million Gross Tonnes (MGT)), and the amount of wear. To define the overall condition of the rail and determine suitable treatments, Corriere and Vincenzo (2012) suggested four states representing 'level of safety', 'level of intervention', 'level of attention', and 'optimal level'.

Sadeghi and Askarinejad (2009) developed both a TQI and a TGI to indicate the condition of the substructure and superstructure respectively according to the type of rail and track category. TQI was defined to be between 1 to 10 where 1 represented the 'excellent' condition and 10 the 'poorest' condition. Karttunen (2012) used TQI to define the condition of rail as result of wear and RCF. Track was classified into five categories by speed, where each comprised of five states representing different severity levels of wear. Zakeri and Shahriari (2012) established TQI based on cumulative tonnage and wear. Accordingly, three condition states were defined as 'good', 'average' and 'weak'. Lyngby (2009) used variations of twist over time of a section of track to determine its condition. In his research 50 states were developed based on changes in twist (from 1 – 50 mm). Sadeghi and Askarinejad (2009) combined track geometry profile and alignment of numbers of small track sections within each track category to determine the ballast condition. Variations of geometry irregularities for aggregated track sections were modelled using a Normal distribution. They determined that values falling within three standard deviations from the mean value of the probability distribution represented a good condition.

Thus, to measure the condition of track, TQIs can be specified based on individual or combined influencing variables. TQIs so developed can be used to specify appropriate maintenance decisions (see Section 3.4).

3.3 Modelling Track Asset Deterioration

In general, prediction models are either based on deterministic or stochastic approaches. The former considers the mechanistic behaviour of track components under different operating conditions such as traffic, speed and climate to model the deterioration behaviour of track. This approach needs both theory, site and laboratory testing to assess how components respond under different conditions (Soleimanmeigouni, et al., 2016). In addition, expert opinion is sometimes used in cases where laboratory experiments cannot be undertaken (Kumar, 2008). Stochastic approaches, on the other hand, are statistical models which use recorded historical data of the actual behaviour of the track components to provide estimates of their future condition using probabilistic theories (Audley & Andrews, 2013). In the following subsections, both approaches are described along with their advantages and disadvantages.

3.3.1 Deterministic Modelling Approach

In this method, the mechanical properties of railway track components and their interactions are analysed under different operating conditions (influencing factors) such as traffic, speed or precipitation using experiments and tests. This approach is also known as engineering driven approach. Using the combined effects of defects, deterministic models determine relationships between track condition and influencing factors.

Ferreira and Murray (1997) used deterministic modelling to evaluate the effect of train dynamic force on track deterioration and concluded that the severity of the impact dynamic force on track depends on the axle load, train speed, ballast type along with its quality and level of fouling, the geometry of sleepers, and rail pads stiffness. Zhang *et al.,* (1997) used a deterministic modelling approach to further enhance the work of Ferreira and Murray (1997) by considering the subgrade stiffness in analysing the mechanical properties of track components and their interactions under dynamic load. Accordingly, an Integrated Track Degradation Model (ITDM) was established by Zhang *et al.*, (2000), which determined the integrated mechanistic deterioration of the track. Three sub-models were developed known as, rail sub-model, sleeper sub-model and ballast-subgrade sub-model. The rail sub-model was developed based on laboratory studies. Different equations were defined to predict the effects of wear, corrugation and fatigue under different loading cycles using variations in top of the high and low rail and gauge face of the high rail and the friction between the train wheel and the rail. The deterioration of sleepers was determined under the application of different bending moments, whereas, the ballast-subgrade sub-model was defined as a function of track geometry irregularities and subgrade stiffness. The models evaluated the effects of deterioration of one component on others. They concluded that as the roughness of rail increases, the depth of ballast and subgrade stiffness decreases and settlement increases.

Oberg and Andersson (2008) developed a track degradation model for rails with curves considering four factors; track settlement, component fatigue, abrasive wear and RCF of rails. They determined that the impact of vertical imposed load on RCF correlates with settlement of track. To determine a relationship between settlement and component fatigue, Oberg and Andersson (2008) adapted the model developed by UIC/Office of Research and Experiments (ORE). The wear model was defined according to the Railway Safety Directive (RSD) enforced by RSSB which uses the wear number as an input to calculate the lifecycle of rail. Wear number is the product of total creep force and total creepage which determines the frictional energy dissipation in the wheel-rail contact. For instance, a wear number between 0 to 5 N indicated no RCF and wear, whereas a wear number between 15 to 65 N, suggests that RCF could occur and that maintenance is therefore required.

Valente (2009) developed a methodology to predict the amount of wear and failures due to inadequate welds in UIC60 and UIC54 rail types. Track categories based on equal curvature, traffic and maintenance history were defined and for each category rail failure data due to squats and poor alumina-thermic welds were obtained and analysed. The ORE model was used in rail deterioration modelling. Using maintenance history data, the effects of lubrication on the wearing process was analysed for each lubrication interval and compared to assess the effects of lubrication of deterioration. He showed that lubrication decreases the friction, as a result of direct rail-wheel contact, and the rate of wear declines. Wear was found to be more common at curves than tangent track. However, a limitation of his model was not taking into account the effects of grinding which significantly increases the service life of the rail but changes the deterioration rate due to removing rail materials from its surface (see Section 2.5.1).

A number of researchers have developed deterioration models based on numerical simulation. For example, Karttunen (2012) used GENSYS, a dynamic simulation package, to determine the effects on RCF and wear of rail-wheel interaction under different rail curvatures and ballast condition. Based on the simulated vehicle model, individual numerical models for ballast and rail were developed and it was concluded that geometry irregularities of track at larger curvature is more severe, and longer length of rail is affected by RCF. However, RCF on plain tracks effects a smaller length of rail.

Dahlberg (2004) defined a numerical relationship between the dynamic train and track interaction, using a Finite Element Model (FEM), to analyse ballast and subgrade settlement.

He argued that ballast density and inelasticity of ballast and subgrade overtime causes ballast settlement. Moreover, he argued that models such as that developed by ORE, are inaccurate since they do not consider the effects of the structural properties of track and for this reason in those models deterioration is same for soft and stiff soils. Rhayma *et al.*, (2013) established a FEM model to assess the changes in track geometry as a result of MGT and speed for different types of soil. It was concluded that since soils have different properties in terms of grain size, saturation level and moisture content, their stiffness behaviour differs under different climate and track geometry and is highly influenced by drainage conditions and soil saturation.

Chen and McDowell (2014) used FEM to analyse the dynamic behaviour of track at transition zones, such as bridges, and stated that dynamic vehicle interaction increases when there is an abrupt change in stiffness. This creates uneven forces to be applied to the track. Thereby, ballast sections in the vicinity of the transition zones tend to settle more and cause uneven geometry. He further emphasised that settlement of the ballast is highly dependent on the strength of the subgrade and in sections with low soil stiffness and drainage, ballast settlement is higher.

Lundqvist and Dahlberg (2005) modelled train track interactions to determine the effect of unsupported sleepers on ballast deterioration. They showed that when sleepers are completely unsupported a gap appears between the sleeper and the ballast. As a result, when track geometry is deteriorating, train/track interactions increases the deterioration of ballast. Shi *et al.*, (2013) used a FEM to investigate the impact of unsupported sleepers on dynamic behaviour of embankments based on rail/wheel interactions. They stated that displacement of rails and sleepers increase significantly with the number of unsupported sleepers. In addition, the degree of displacement between sleeper and ballast is correlated with ballast and sleeper attrition. Furthermore, they concluded that because adjacent sleepers carry more load their fatigue life reduces.

Ballast deterioration under different dynamic forces, rail shape, and sleeper support and spacing was investigated by Shenton (1997), whom developed a deterministic model to determine the mechanistic behaviour of ballast as a function of ballast materials, axle load, sleeper type and subgrade conditions. It was concluded that axle load had the most impact on ballast settlement. Moreover, he concluded that the initial condition of the ballast is a prerequisite factor to be considered when determining its lifespan and rate of degradation because, if the original ballast has internal defects it cannot be rehabilitated by tamping or stoneblowing. He developed a model of track settlement as follows:

$$S_N = \frac{K_s A_{eq}}{20}(K_1 N^{0.2} + K_2 N) \tag{3.2}$$

Where S_N is the total settlement, N is number of loading cycles, A_{eq} is the equivalent axle load, K_s is a factor function depending on sleeper type and size, ballast and subgrade type. K_1 is a factor associated with the lift given to the track during tamping and K_2 is constant value.

Shenton's model was applied to Japanese railways by Sato (2007) whom investigated the effects of track structural condition, loading cycles and initial condition of ballast on geometry irregularities. He postulated that irregularities in geometry follow an exponential function as follows:

$$S_N = \gamma(1 - e^{-\alpha N}) + \beta N \tag{3.3}$$

Where N is loading cycle and α, β and γ are parameters derived from tests.

In the mechanistic model described by Soleimanmeigouni *et al.*, (2016) the effects of the number of loading cycles, the amount of ballast fouling (represented by the fouling index), tamping and rail wear on settlement of ballast, sub-ballast and subgrade was evaluated. They concluded that settlement of ballast is faster than in the underlying layers and that tamping significantly increases the rate of ballast settlement due to particle breakage and movement. Varandas *et al.*, (2012) developed a settlement model to evaluate track settlement. Two phases of settlement were defined. The initial phase relates to the rapid settlement rate as a result of tamping, whereas the second phase is where rate of settlement is almost constant with time. A logarithmic model was therefore used as follows:

$$\epsilon_N = \epsilon_1(1 + Clog(N)) \tag{3.4}$$

Where ϵ_N is the total permanent strain after load cycle N, ϵ_1 is permanent strain after first load cycle and C is the parameter of the model.

The parameters were determined from triaxial tests and accumulated settlement after N cycles calculated from the product of ϵ_N and thickness of the ballast. Lou *et al.*, (1997) used cumulative plastic deformation model using Equation 2.2 (see Section 2.3.6) and applied a sinusoidal train load using multivariate regression analyses on the cyclic triaxial test data. They found that long-term deformation is dependent on the compaction of the subgrade soil, the number of loading cycles and the ratio of deviatoric stress over confining stress.

3.3.2 Combined Deterministic and Stochastic Models

To capture the randomness of influencing variables on track deterioration using deterministic models, the mechanistic approach has been combined with stochastic methods. Using such an approach a probabilistic distribution of influencing factors after each maintenance intervention can be included in the model. For instance, Sadeghi and Askarinejad (2008) used regression analysis to define the relationship between track geometry and track condition data. The regression coefficients were then included in their mechanical deterioration model so that the effects of maintenance on track condition can be calculated. An exponential function was defined between degradation coefficients and MGT and speed. After the initial condition of track, the MGT was considered to be the second most influencing factor affecting deterioration.

Bae *et al.,* (2014) used the combined mechanistic-statistical approach to predict the probability of buckling. They found that buckling is affected by rail temperature, rail's neutral temperature (i.e. SFT), train speed and load, track geometry and maintenance of track. Two processes were developed. The first process related to the calculation of load demand and buckling resistance, which assumes that temperature variation acts as a load and the probability distribution of temperature loads was determined. In this stage the temperature load, T_L, was defined based on the difference between current rail temperature, T_R, and neutral temperature, T_N (see Equation 3.5). Rail temperature was determined based on air temperature, relative humidity and solar radiations. It was assumed that rail temperature follows a Normal distribution. To determine the distribution of T_N, a small database was obtained that included T_N values of number of tracks and a Normal distribution was used to model the frequency of data. In this manner,

$$T_L = T_R - T_N \tag{3.5}$$

In the second stage, buckling probability was determined using a limit state equation (Equation 3.7). In this stage, allowable buckling temperature of the rail was determined according to buckling theory based on the principle of virtual work. Initially, Miura (1991) determined this theory. Based on this approach, the type of energy accumulated into the track is of interest. It is assumed that strain energy is generated from the change in longitudinal force and rail bend, whereas internal energy is developed by ballast resistance. Based on these elements, the following expression was derived (Miura, 1991)

(3.6)

$$P_t = P + \left\{\frac{\gamma^2 r^2}{p} + \frac{\alpha r}{P^3\sqrt{P}}\left[\left(g - \frac{\xi P}{R}\right)^2 + k\left(g - \frac{\xi P}{R}\right)\frac{P}{R}\right]\right\}^{1/2} - \left(\frac{\gamma r}{\sqrt{P}}\right)$$

Where P_t is buckling strength, P is longitudinal rail force balanced after buckling, g is longitudinal ballast resistance, r is lateral ballast resistance, R is radius of track curvature and γ, α, ξ and k are constants depending on track structure.

Bae *et al.*, (2014) used a similar approach and evaluated the effects of track radius, amplitude of misalignment, vertical ballast stiffness, lateral ballast resistance and the velocity of the train on buckling strength. The probability distributions of influencing parameters were used as an input. Multivariate regression analysis was performed to develop an equilibrium equation as follows:

(3.7)

$$g = T_a - T_L$$

Based on Equation 3.7, buckling occurs when g is less than zero. Advance First Order Second Moment (AFOSM) method was used to solve the equation.

Similar approach was used by Kish and Samavandam (2013) to predict the probability of buckling using rail neutral temperature data obtained from the American Railway Engineering and Maintenance-of-way Association (AREMA), database. The variation of rail neutral temperature was found to be between $0°C$ to $6°C$ depending on climate and followed a Normal distribution. The lateral resistance of length of track was determined based on the ballast type using a mechanistic approach and experiments. It was assumed that maintenance history reduces the lateral resistance of the track. Further, track geometry irregularities were also evaluated. Data are evaluated using a computer programme known as CWR-SAFE to determine the strength of the track as a function track modulus, rail type, axle load, lateral and longitudinal resistance. Nonlinear differential equations were used using lateral deflection in the buckled zone and longitudinal displacement in the adjoining zone (Federal Railroad administration, 2013). Thereafter, based on the total distribution of T_L and T_a, Monte Carlo simulation was applied to calculate the convolution integral of the two distributions based on suitable T_N to predict the probability of buckling occurrence.

In general, AREMA developed five software programs which carry out the process of predicting the buckling probability. CWR-BUCKLE is a program which calculates the buckling response of tangent and curved tracks using thermal forces and train load. CWR-INDY is used at the design stage of track and determines the buckling strength and safety based on track structural design parameters. CWR-RISK(GAU) predicts the probability of buckling as a function of combined track lateral resistance and misalignment amplitude and the amount by which rail temperature increases above the neutral temperature. In addition, information of track stiffness, curvature and train type are imported to the system. The output illustrates the probability of buckling with respect to rail temperature. The last program is similar to CWR-RISK(GAU) except that the input variables are in a form of statistical distributions derived from numerical models(Kish & Samavandam, 2013).

In summary, mechanistic models combined with statistical processes have been developed to formulate the behaviour of track under different conditions based on dependent influencing parameters with consideration for random variation. In the majority of studies found, the random variables were used to determine the variation of temperature and track geometry. These models require large amounts of data of dependent parameters, operational conditions and train design parameters related to track. The models are not able to consider the cases where despite homogenous track condition parameters such as, traffic and speed, deterioration might occur at different rates (Andrews, 2012) (Audley & Andrews, 2013). Although stochasticity can be added to deterministic models, maintenance and degradation effects are directly determined by influencing variables which are constant. These models are useful when the uncertainty is low but are not effective in cases with a high degree of uncertainty.

3.3.3 Stochastic Modelling Approach

Stochastic processes are statistical approaches based on probability theories and are more widely used than deterministic models within maintenance decision-making tools especially at network level management. Probabilistic models use historical data to reflect track condition considering its random behaviour. The models are based on set of inputs, which are recorded measurements of track components' condition, and processes which facilitate the degradation and maintenance procedures (Soleimanmeigouni, et al., 2016). Although these models generally do not consider the interactions between track components, research suggests that when sufficient data is available statistical approaches are more accurate in modelling deterioration processes compared to deterministic approaches (Yousefikia, et al., 2014). Track condition measurement are used in statistical models to determine a relationship with track performance. Different methods can be used to determine this relationship such as, regression, correlation, curve fitting and other stochastic processes. Because there is a direct relationship between input and output parameters, the influence of the former on the latter can be accurately estimated using this approach.

Rama and Andrews (2013) evaluated the lifespan of switch components. Based on Network Rail's Fault Management System (FMS) database, switch failures were obtained. The data included the equipment type, location, time, mileage and failure description of switch components. The measurements were over a period of ten years. In this work based on the turnout speed and type of switch element, the FMS database was classified. Failure of each switch element was modelled individually using a three parameter Weibull probability function. In this manner, the reliability of components was modelled as follows:

(3.8)

$$R(t) = e^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}}$$

Where β, η and γ are shape factor, characteristic life, and failure free life parameters respectively.

Zwanenburg (2009) used regression analysis to model the progression over time of wear on S&Cs. He found that the angle of crossings has a significant effect on wear and the life expectancy of S&Cs. Although train speed is lower at S&Cs, the large angle switches are more exposed to higher creeping forces as the train passes (see Section 2.3.2). In his analysis, S&C units were categorised according to traffic, speed, frog angle and switch curvature. He found that as traffic, switch angle and curvature increase, the deterioration due to wear increases. He also found that deterioration is highly dependent on soil quality.

Meier-Hirmer *et al.*, (2006) developed a statistical deterioration model for a track section based on variations in tonnage, maximum speed, ballast type, curvature of track and their influence on longitudinal level of track geometry. A gamma process was used to facilitate this process. Based on the gamma process for any time, t, and s, given $s, t \geq 0$, $X_{t+s} - X_t$ has a gamma distribution with parameters αs and β where its density function is given by:

(3.9)

$$f_{X_{t+s}-X_t}(x) = \frac{1}{\Gamma(\alpha s)} \beta^{\alpha s} x^{\alpha s-1} \exp(-\beta x), x > 0$$

Where $X(t)$ is the gamma process and t is independent time variable. α is shape parameter and β is the scale parameter. The gamma process has constant degradation rate of $(\frac{\alpha}{\beta})$ and degradation variance of $(\frac{\alpha}{\beta^2})$. Usually when there is a monotonic increasing function such as cumulative tonnage, the gamma process is useful.

Zhu *et al,* (2013) used the recorded track geometry data on Chinese railways to build a stochastic model to analyse the changes in vertical and horizontal alignment of track geometry of both rails over 1 km sections of track. Zhu *et al,* (2013) used the Gaussian prosses to sample data and used the power spectral density of the two parameters to determine the randomness of track irregularities.

Vale and Lurdes (2013) investigated the rate of deterioration of the Portuguese Northern-line over a section of approximately 336 km in length. Because the track had different curves and layout, three speed categories where defined and the track was classified accordingly. They determined that the variations of longitudinal level of left and right tracks are similar for fixed speed categories. Whereas, the variations of longitudinal level were significantly different for each speed category. Variations of longitudinal level was determined using a Dagum distribution as follows: (Vale & Lurdes, 2013)

(3.10)

$$f(x) = \frac{\alpha k x^{\alpha k-1}}{\beta^{\alpha k\left[1+\left(\frac{x}{\beta}\right)^{\alpha}\right]^{k+1}}}, x > 0$$

Where β is scale parameter, α and k are shape parameters and x is a random number following a Dagum distribution.

Although statistical models are not suitable in providing information regarding components interaction, they are capable of using the combination effects of influencing factors such as, tonnage, speed, axle load, maintenance and curvature on deterioration (Soleimanmeigouni, et al., 2016). Therefore, multivariate regression analysis can be used to measure the combined effects of the influencing variables on degradation. Lyngby (2009) used the values of vertical and horizontal alignments and cant for a length of track and applied multivariate regression to determine their variations over time. A quality indicator MDZ was developed which is similar to the CTR index (see Section 3.2), to determine the quality of track based on combined effects of influencing variables. The deterioration was found to follow an exponential function and that track sections with different maintenance history, curvature, axle load, type of soil and weather condition deteriorate at different rates. Therefore, Lyngby (2009) suggested that determining the effects of multiple influencing factors on track condition requires the classification of track based on similar characteristics because, sections of track having same traffic, track composition, maintenance history, subgrade material and other environmental characteristics deteriorate in the same manner. This was also addressed by Zhang *et al.*, (2000) whom stated that based on structural properties of track the deterioration rate varies. A similar approach based on homogenous section of track has been adopted in this research (see Section 5.3.1).

Hamid and Gross (1981) investigated the deterioration rate of track segments with the same track structure i.e. rail type and weight, ballast condition, curvature, and traffic (cumulative tonnage and speed). They used multivariate linear regression to determine the condition of track, using TQIs as follows:

(3.11)

$$Y = a_0 + bY' + \sum_{i=1}^{n} a_i X_i$$

Where Y' is the previous TQI, X_i is physical measurement of track condition, $a_i = 1, .., n$ and b are constants. Developing artificial TQI in this manner, provides a simple indication of the state of track. However, there is no relationship between track condition and maintenance. Berawi *et al.,* (2010) suggested that to determine the condition using TGI it is necessary to include the effects of maintenance on deterioration.

Based on the measured geometry irregularities and some rail defects over a length of track, He *et al.,* (2014) developed a deterioration model to determine the effects of MGT on the severity of defects. The measured values of cant, gauge, vertical and horizontal alignment, twist and wear defects were classified according to their derailment risk. Multivariate regression was applied to all defect types to determine the relationship between monthly MGT and values of defect measures. A Gaussian distribution was used to model the distribution of values of each measured defect recorded overtime. Based on suitable TQI values the condition of track with respect to each defect was determined. They concluded that for a same section of track the progression rate of each defect differs.

Berggren (2010) evaluated track condition using data originating from geometry conditions, dynamic stiffness, and GPR. The stiffness data overtime for a track section was analysed using measurements of RSMV (see Section 2.4.5). Based on GPR, track sections were classified according to their fouling index and materials. Track stiffness data for each track category was determined over different times. Geometry measurements were also obtained on the same sections over a period of four years. Track condition was determined using Key Performance Indicators (KPI). Pattern recognition was applied to determine the deterioration rate of each category of track between every maintenance interval. Berggren (2010) found that track deterioration was a function of soil type and defects associated with the ballast and the rail. This was also reiterated by a study by Sadeghi and Askarinejad (2009) whom determined that the age of rail, ballast fouling index, traffic and speed are necessary factors to be considered whilst analysing the long-term settlement of track using TQIs.

Quiroga and Schnieder (2010) studied geometry variations of highspeed French railway track over a length of 120 km (in both directions). The entire track was classified into eight categories each containing 30 km of track. Based on date and type of maintenance activities, deterioration rates were classified and analysed. A curve fitting method was used to determine a relationship between measured geometry and time. Monte Carlo simulation was used to calculate the deterioration behaviour using the following formula:

(3.12)

$$Q = Ae^{B(t-t_0)} + \epsilon(\mathrm{t})$$

Where Q is TQI, and A, B and ϵ are parameters that are assumed to have Lognormal, Normal and Normal distributions. t_0 is the time of tamping to determine maintenance intervention. In general, Lognormal distribution has two parameters known as the logarithmic mean, μ and standard deviation, σ. The former is the location parameter and the latter the scale parameter. The probability density function of the Lognormal is given by Equation 3.13 (The Mathworks Inc, 2017):

(3.13)

$$f(x|\mu,\sigma) = \frac{1}{x\sigma\sqrt{2\pi}} e^{\left\{\frac{-(lnx-\mu)^2}{2\sigma^2}\right\}} \ ,x > 0$$

$$\mu = e^{(\mu + \frac{\sigma^2}{2})} \qquad -\infty < \mu < \infty$$

$$var = e^{(2\mu + \sigma^2)}(e^{\sigma^2} - 1)$$

Where var is variance. The CDF, of Lognormal distribution is

(3.14)

$$F(x) = \phi\left(\frac{\ln(x)}{\sigma}\right) \; x \geq 0, \sigma > 0$$

Where ϕ is the cumulative distribution function of the Gaussian distribution.

Similarly, Cheng *et al.,* (2010) assessed the irregularities on the rail surface, vertical and horizontal alignment, cant, twist and gauge for a Beijing-Jiulong railway track. Track was divided into 100 m length sections and different measures of condition parameters were combined to determine TQIs. In this manner, the deterioration of the track was defined according to multiple linear equations relating to each 100 m sections.

A hierarchical Bayesian approach was utilised by Andrade and Teixeira (2013) on a Portuguese railway line to determine the deterioration of track geometry parameters with respect to time. The track was divided into smaller sections, and five categories based on variations of speed was established. Suitable TQIs for geometry parameters were defined. The uncertainty in randomness of the process was included in the model based on the combination of prior and likelihood distributions ($p(\theta)$ and $p(y|\theta)$ respectively) to obtain parameters of interest using posterior distribution ($p(\theta|y)$). According to Bayes rule the posterior distribution based on observed θ is (Andrade & Teixeira, 2013):

(3.15)

$$p(\theta|y) = \frac{p(y|\theta) \times p(\theta)}{\int p(y|\theta') \times P(\theta')d\theta'} \propto p(y|\theta) \times p(\theta)$$

Bai *et al.,* (2014) used track irregularities over a 200-m section of track between two maintenance interventions. He analysed the deterioration trend of track geometry based on Chinese TQIs. Bayes model was used to determine the effects of maintenance on the deterioration rate by comparing the posterior and prior distributions. In their research, Markov Chain Monte Carlo (MCMC) sampling was applied to ensure that when the condition state changes it does not return to its previous quality. By determining an equation which best fitted the distribution of measures of condition, the effects of maintenance on deterioration were analysed between each maintenance interval. Although the effects of maintenance were determined, the deterioration rate remained constant between each maintenance intervention. It was claimed that separately analysing the vertical and horizontal alignment of track geometry is more useful in determining maintenance actions since maintenance of horizontal alignment is usually unplanned.

Kumar *et al.*, (2008) used Bayes approach and analysed the effects of wear and RCF on rails. Data obtained included the amount of wear and failures due to RCF with respect to MGT. Based on the posterior and prior distributions of defects between two maintenance interventions, the effects of maintenance on condition of rails were determined using the rate of deterioration of track.

Audley and Andrews (2013) modelled the deterioration of track geometry using its vertical profile. Based on suitable condition indicators, different stages of deterioration were defined. The objective was to determine the effects of tamping cycles on the deterioration rate. For this reason, relationships between time and changes in vertical profile of track geometry were established using a linear equation. To determine deterioration, for every state, the time that track spends at each state was calculated. The trend of distribution of times followed a Weibull distribution. It was shown that after each tamping the deterioration rate in the majority of cases increases. In general, a two parameter Weibull function consists of a scale parameter, η, indicating characteristic life, and a slope or shape parameter β. The Probability Density Function (PDF) of a Weibull distribution is (Abernethy, 2001)

$$f(t) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} . e^{\left(-\left(\frac{t}{\eta}\right)^{\beta}\right)} \tag{3.16}$$

Where t is time and $f(t) \geq 0, \beta > 0, \eta > 0$.

The Weibull cumulative distribution function (CDF) has an explicit equation of

$$F(t) = 1 - e^{-\left(\frac{t}{\eta}\right)^{\beta}} \tag{3.17}$$

Where $F(t)$ is the fraction failing CDF.

Markov chains are also a popular stochastic process used to model deterioration. To facilitate deterioration analysis, transition probabilities are developed according to condition states (Taylor & Karlin, 1998). The condition states are determined using suitable ranges of TQI for either individual or combined effects of components' defects. For example, Bai *et al.*, (2014) classified track into different categories according to homogeneous characteristic defined by train speed and accumulated tonnage. Based on changes in vertical and horizontal track geometry alignments, transition matrices were developed and used to predict the condition of track geometry at different times.

A rail failure model which considered two types of failure was proposed by Hokstad and Langseth (2005). Failures considered were divided into two classes of shock failures (i.e. immediate critical failures) and failures due to cracking. Asymptotic distributions were used to model the failure times for each failure type. A Markov chain was developed which used the failure rate to generate transition matrices to determine the probability of track being in a particular state at particular. However, this model was limited to rail failure prediction since only times to failure were considered. The model does not take into account the degradation stages of rail (i.e. the progression of wear or plastic-flow which overtime initiate cracks). It is more beneficial to consider the wearing process of the rail in order to perform preventive maintenance to mitigate failures.

Another Markov deterioration model was developed by Yousefikia *et al.*, (2014) whom modelled the tram line of the Melbourne railway. Track geometry was analysed, and different condition states were defined based on TQIs. A hazard rate function was calculated using a Gamma process, and the time that track has different critical TQIs were determined. Thereafter, a Markov chain was used to predict the future deterioration stages of track geometry using transition matrices.

Prescott and Andrews (2013) used the values of track geometry, in particular SD of vertical and horizontal alignment, to determine the condition of ballast between two tamping interventions. UK standards were used to determine TQIs and accordingly four states were developed. The time that track geometry changes condition and degrades to a poorer state was modelled using Weibull distribution function and Markov chain was used to model the deterioration using transition matrices.

Shafahani and Hakhamaneshi (2009) developed five condition states based on CTR index and used a Markov model for degradation prediction. Initially, tracks were classified based on traffic and topology (Table-3.1). Six categories were established, and it was assumed that tracks in the same category deteriorate in the same manner.

`Traffic	**Topology condition**		
	Plain areas	Hilly areas	Mountainous Areas
Light	1	2	3
Heavy	4	5	6

Table 3-1 Track classification based on traffic and topology (Shafahani & Hakhamaneshi, 2009)

Transition probabilities were calculated based on the average mean value of probability distribution of track sections at each category. It was assumed that tracks at each state will either stay in the same state each year or will jump to the next subsequent state. The deterioration results were compared with a refined ORE model which uses MGT and axle load to determine the CTR index. Shafahani and Hakhamaneshi (2009) concluded from the comparison that the Markov model provided more robust results.

Zakeri and Shahriari (2012) used Markov chains to predict the future condition of the rail based on the amount of wear. Rails were classified according to rail type and track category. The amount of wear was recorded over a period of six months. Based on TQI, the distribution of condition of rail at each time was modelled using a Weibull probability function. Accordingly, the hazard function was determined and the rate of wear of each state was calculated to determine transition matrices.

Because in Markov process, the deterioration rate between each analysis period is constant, by grouping track sections with same characteristics such as maintenance history, curves, traffic, speed, climate, soil type and track structure, a Markov chain can be successfully used to provide satisfactory results (Yousefikia, et al., 2014). For instance, Famurewa *et al.,* (2013) for the development of Markov chains, determined homogenous sections of track based on traffic, material of components and their age, and environmental condition.

Andrews (2012) developed a Petri Net model to analyse track deterioration over time. In his research, 35m SD of vertical track geometry data were obtained over predefined sections of track having the same traffic, speed and maintenance history. A linear equation was defined to determine a relationship between changes in SD of vertical alignment and the time between each tamping intervention. Based on pre-specified threshold values of SD, obtained from Network Rail standards, four condition states were developed. To develop a Petri Net model distribution for SD of track geometry to deteriorate from one state of condition to another was modelled. To achieve this, transition times from one threshold SD value ($S1$) to the next ($S2$) was modelled using a two parameter Weibull density function ($f_{S1}(t)$ and $f_{S2}(t)$). A differential equation was developed which determined the time for the track to deteriorate to $S2$ given that it has already deteriorated to $S1$. In this manner, the time taken for the track to reach $S2$ between time t to $t + dt$ requires the track to have already reached $S1$ between time $u + du$ and then degrade to $S2$ at time t'. Therefore,

(3.18)

$$f_{S2}(t)dt = \int_{u=0}^{t} f_{s1}(u)du \times f_{s2 \because S1}(t-u)dt$$

The convolution integral was calculated using Laplace transform functions and the deterioration between each maintenance intervention was calculated.

3.4 Track Maintenance Models

To account for this maintenance models have been developed to evaluate the effects of different maintenance strategies on subsequent track deterioration behaviour. As discussed in Section 3.2, TQIs are an effective means of determining the condition of components. Based on acceptable permissible values specified by TQIs maintenance can be planned. For instance, in the work of Corriere and Vincenzo (2012) (see Section 3.2) four critical degradation stages were identified, based on TQIs, and accordingly four maintenance treatments were allocated to each state.

In the work of Sadeghi and Askarinejad (2009), the condition states determined were labelled as ‘low’, ’moderate’, and ‘high’ which indicated different severity of defects. Accordingly, defects with ‘low’ severity did not affect the condition of track and therefore no maintenance was required, however, for ‘moderate’, and ‘high’ levels respectively, speed restrictions, and operating restrictions such as hauling the train operation was specified.

Based on European Standards, Soleimounmeigouni *et al*, (2016) determined three condition states as ‘immediate action limit’, ‘intervention limit’ and ‘alert limit’ using permissible values of geometry parameters. They assigned adequate maintenance activities to each state. For instance, when the condition of ballast was in ‘immediate action limit’ state it was suggested that speed restrictions needs to be enforced.

Within the UK, acceptable thresholds are defined to determine means of condition of the majority of track component using measure of conditions. For example, based on the values of SD of vertical and horizontal alignment of track geometry four condition states are derived (Network Rail, 2013). Prescott and Andrews (2013) used these states to determine different stages of deterioration for ballast to apply suitable speed restrictions or line closures.

A number of authors have suggested maintenance restoration models which return the condition of the track to a pre-defined condition. Often this condition is the as new state.

A maintenance model developed by Bai *et al.*, (2014) used Markov chains to determine the timing of maintenance. They used different condition states to determine the severity of geometry defects. Therefore, when track condition departs from one state and arrives at another such as from 'good' to a 'bad' state, adequate maintenance was assigned. When maintenance was performed, track condition moved to a 'qualified' state and deteriorated with a new rate. However, in Bai *et al's,* (2014) model they assumed that after each tamping cycle the condition of the track moves to the lowest state (i.e. new condition). Similarly, Shafiee *et al.*, (2014) developed a deterioration model based on Bayes theorem. Track geometry of small sections of track were analysed over time and the rate of deterioration between two consecutive maintenance operations was determined. In they work it was also assumed that the condition of the track will revert to its 'as-good-as new' condition.

However, it is accepted that track geometry maintenance changes the deterioration rates of components. i.e. track deteriorates at a different rate prior to maintenance than it does afterwards and also in some cases track geometry can worsen the state of the track. Indeed, the condition of components after maintenance, especially tamping, has a high degree of uncertainty Prescott and Andrews (2013).

Accordingly, Audley and Andrews (2013) established a method which aids in evaluating the randomness behaviour of the effects of tamping on the subsequent condition of ballast. Initially, tracks were classified based on maintenance history, and accordingly after each maintenance intervention, the distribution of SD of vertical profile of track geometry was modelled using a Lognormal distribution. In this manner, the probability of ballast reaching any condition after tamping was determined. In their work, the effects of tamping on the rate of deterioration of ballast were analysed using historical track data and indeed they found that some sections of track which had been tamped were in a worse condition after being tamped than before. They postulated that deterioration differs after each tamping cycle because of particle breakage of ballast and therefore, tamping will cease to be effective after a certain number of cycles.

However, the analysis was carried out irrespective of the physical condition of the ballast before maintenance. Research carried by Berggren (2010), Sadeghi and Askarinejad (2009) and Li and Selig (1996) s that the current physical condition of the ballast highly affects its deterioration rate.

Arasteh Khouy *et al.,* (2013) defined condition indices based on variations in SD of vertical and horizontal track geometry and cant. Three states as 'excellent', 'good' and 'bad' were defined. Accordingly, suitable maintenance activities were determined. To evaluate the effects of tamping on deterioration, they analysed data of 200 m section of track during the period of two consecutive tamping events. Further, Arasteh Khouy *et al.*, (2014) used exponential regression to calculate the deterioration rate of track geometry based on the slope of the line. By comparing the deteriorate rate before and after tamping events the usefulness of tamping on track condition was investigated.

Meier-Hirmer *et al.,* (2006) used a gamma process to model deterioration of longitudinal ballast geometry using suitable condition indices. To assess the effects of tamping linear regression was applied to the distribution of track geometry before and after maintenance and the rate of deterioration was compared for each maintenance intervention. Famurewa *et al.,* (2013) also used the same approach and applied linear regression to determine the effects of tamping.

3.5 Choosing a Method of Modelling for the Task at Hand

In Section 3.3, different techniques used to model the deterioration behaviour of track components were described. In this section the advantages and disadvantages of the three modelling techniques described are discussed so that the most appropriate method to be used for the purpose of this research can be selected.

In general, developing a decision-making tool compatible with network level analysis requires large amounts of data associated with the condition of track components. Track sections over the entire network comprise of different characteristics in terms of structure, material, traffic, speed, climate and maintenance history.

Although deterministic approaches are useful in predicting deformation and degradation, the majority of the models described above are either based on empiricism or utilise numerical models. For the former, they may not be relevant to consider conditions other than in which they were developed, or they require extensive data to calibrate under a variety of operating conditions. For the latter the numerical models used also require extensive characterisation and are time consuming to run. Since such models are also more suited to project level analysis (see Section 4.3.1) it was decided not to consider them further in the research.

Deterministic-stochastic models were also described. As explained in Section 3.3.2, this method was used to capture the random behaviour of mainly track geometry irregularities. However, because deterministic-stochastic models are partially based on deterministic approaches and the rate of deterioration is derived from coefficients of model parameters, the deterioration of track sections remains constant regardless of the type and frequency of maintenance. Accordingly, these types of models were not considered further in the foregoing.

Track deterioration and the effects of maintenance have been shown by a number of authors to exhibit a random behaviour (i.e. sections of track subject to the same loading and environmental conditions may not deteriorate at the same rate). It would therefore seem appropriate to utilize a stochastic model for this research, more so as the developed tool is for network level railway asset management. Although such an approach necessitates the use of large amounts of data so that predictions become accurate, data are more easily captured, and readily available, compared to deterministic methods. In particular data suitable for network level analysis can be obtained using automated inspection techniques, rather than via detailed laboratory or field investigations which are required to characterise many of the deterministic models identified. To effectively use a method based on stochastic processes the network need to be classified into homogenous sections with similar characteristics since several researches showed that tracks with similar properties deteriorate in a similar manner (see Section 3.3.3).

As explained in Section 3.2, to indicate the condition of components condition indices are used. Condition indices represent different stages of deterioration and based on their values suitable maintenance treatments are selected (see Section 3.4). The indices can be either based on single or combined effects of defect types. For the purpose of maintenance, it is more beneficial to define individual critical values for each defect type because if condition indices are based on the effects of multiple defects, it would be very difficult to determine the exact type of maintenance to rehabilitate the condition of track (Hassankiadeh, 2011) (Corriere & Vincenzo, 2012). For this reason, in this research, for majority of component defects' individual condition indices are defined. For some other defects such as buckling, the condition of several track components needs to be analysed (see Section 2.3.1 and 3.3.2) and thereby it is necessary to include multiple effects of defects in modelling such failures. The current buckling prediction models are derived based on theory which considers temperature as a load. Therefore, these models are not fit to be used for network level analysis. In this research suitable statistical processes are proposed which use the measured track condition data and combines it with temperature data to predict the occurrence of buckling (see Section 6.6.1).

Another, gap in existing models is that although the effects of maintenance on the deterioration rate is determined between each maintenance interval, in practice, the effects of maintenance on condition of tracks having same homogenous properties varies according to the physical condition of the track, type and volume of past maintenance. Moreover, the majority of maintenance models do not consider the change in rate of deterioration which can occur after maintenance.

Finally, it is also necessary to quantify the effects of a climate (and particularly precipitation and temperature) on the deterioration of components. Track sections with same homogenous properties but different precipitation and temperature deteriorate differently. Therefore, for a network level model which facilitates the long-term planning of maintenance it is necessary to be able to account for changes in climate which may occur

For this research the Markov chain was considered to be the most appropriate method for modelling the deterioration and restoration processes. The reason for selecting the Markov technique is twofold. One is because any form of statistical modelling method such as regression, pattern recognition or curve fitting can be used for modelling deterioration and the other is that different states can be developed using condition indicators for maintenance purposes and transition matrices are used to predict the probability of track moving from one state of deterioration to the other. However, a drawback of the Markov method is that deterioration remains constant over future period if no maintenance is carried. To address this, in this thesis suitable mathematical techniques are proposed and used (see Section 5.3.8) which includes the effects of precipitation and temperature on deterioration. Therefore, at every cycle within a Markov chain, the effects of these two climate variables alter the degradation rate of track and thus new transition matrices are generated every time that there is a change in these two climate parameters. It must be mentioned that although, Petri Nets use the same approach as Markov chains in calculating the transition times of track at each state, it is more beneficial to use Petri Nets to analyse smaller lengths track, since the model would be over complicated and time consuming to run network level analyses (Andrews, 2012).

3.6 Summary

Deterministic and statistical approaches are the predominant methods used for deterioration modelling. To this end, it was determined that condition indices can be defined to determine different deterioration stages for each track component. Accordingly, number of condition state can be developed, and based on the condition of components at each state suitable maintenance treatments can be identified. The challenge, is to incorporate and predict the effects of maintenance treatments such as grinding, tamping and stoneblowing on the deterioration rate of track. Therefore, it is necessary to analyse the measurements of condition of components between each intervention period, as it was shown (see Section 3.3.3) that such treatments impact the rate of track deterioration. It was found that the models lack predicting the level of improvements which is going to be achieved after maintenance. In addition, the effects of temperature and precipitation induced deterioration were not included in the models. Therefore, to develop a stochastic Markov process which takes into account the above factors to determine deterioration and restoration processes is one of the challenges of this project. To accomplish this, Chapter Four describes the current railway asset management systems utilised within the UK railway industry, and also focuses on the UK climate projection models which provide suitable information that are later used for developing a stochastic Markov process described in Chapter Five.

Chapter Four

4. MAINTENANCE MANAGEMENT

4.1 Introduction

Maintenance of the railway network is a complex process and represents a significant portion of the overall railway costs (Network Rail, 2014). To this end, Chapter Two determined different assets forming the railway infrastructure and examined the deterioration of asset as a result of traffic, maintenance and climate. Effective maintenance management in terms of railway includes controlling and improving the lifecycle of railway assets over time (Patra, 2009). In Chapter Three it was discussed that suitable condition indices are used to specify the condition of track components and accordingly maintenance requirements are identified. However, decisions to renew or keep assets maintained is a difficult task because it requires comprehensive analysis of the effects of maintenance actions on the condition and degradation of assets (see Sections 6.4 and 6.5). Implementing timely and effective maintenance under budget constraint is challenging task for asset managers (Espling, 2007).

This Chapter describes the concept of maintenance, which deals with maintenance planning of the UK railway network**.** The maintenance management is discussed at network level and project level. The requirements of maintenance management at both levels are discussed accompanied by the information needed to establish a network level maintenance management decision-making system. The UK Climate Projection 2009 (UKCP09) which provides a basis for studying of impacts and adaptation to climate change is described. Lastly, literature concerning the current maintenance management systems enforced in the UK is discussed.

4.2 Concept of Maintenance

After time railway assets start aging and deteriorating (see Section 2.3). The increased amount of traffic and speed on one hand, and the unexpected changes in climate towards more extreme weather on the other, are adversely affecting the rate of deterioration of these assets (RSSB, 2015). Since railway components are different in terms of structural and environmental characteristics, the effects of influencing factors vary amongst components and each asset deteriorates differently over time (see Section 2.3). If assets are not maintained properly and in a timely fashion the safety of the train operation decreases. In railways, proper maintenance planning rather than just reacting to malfunctions as they arise, reduces the in-service failures and service disruptions. Maintenance increases the life of assets, but it is important for maintenance to be cost-effective (Network Rail, 2013). If adequate maintenance is not undertaken, poor performance of some assets may impact the condition of the other assets. For example, the increase in the number of unsupported consecutive sleepers increases the deterioration of ballast (see Section 2.3.3). It is necessary to have a management system in place to assess the future condition of components to make strategic maintenance planning and to provide the required level of safety over the network. Such levels of service are defined in terms of maintenance standards for each asset. These levels are used to determine different treatment types required for track based on its condition and defect type (Network Rail, 2013). To achieve this, inventory of assets and condition reports including inspections and maintenance records accompanied by failure data and analyses of potential impacts of climate change on the railway network is necessary (Dobney, 2010) (Network Rail, 2014).

4.3 Maintenance Management

Maintenance of the railway is defined as a combination of all technical and associated administrative actions intended to retain the system in, or restore it to, a state in which it can perform its required function (Dekker, 1996). A maintenance management system can be thought of as a tool which facilitates this process (Frangopol, 2012). Any maintenance management system must allow the user to make strategic maintenance decisions in order to achieve the best use of assets over time. Determining cost-effective maintenance is complicated because it requires analyses of interrelated processes of deterioration and maintenance under limited financial resources (Andrews, 2012). To this end, decisions to maintain assets are determined using suitable intervention levels defined for each component by maintenance standards. Each of the railway assets have one or more measures of condition which by comparing them with standards the requirements of maintenance are identified (see Section 5.3.3). To conclude, standards determine the extent of permissible levels of deterioration of assets before requiring any sort of maintenance (RSSB, 2014). Therefore, developing a network level maintenance decision support system is difficult due to mixed traffic, speed and weather conditions over the network (The UK Rail Sector, 2014).

4.3.1 Maintenance Levels

In general, track maintenance management is carried out at two levels. These are network level and project level. The purpose of the former is determining the condition and maintenance costs for the entire network rather than focusing on individual sections of the network. In contrast, project level management operates at regional scale and for every region it assigns project priorities ideally appropriate with network level decisions since, any change at a network level funding can have impact on project level management (Pavement Interactive, 2007). The benefit of network level models is the ability of analysing the future performance of the railway system under varying levels of funding. These levels of management are described below.

4.3.1.1 Network Level Management

Network level management requires large amount of data and sophisticated models. Since network level management specifies maintenance and renewal requirements of the entire network, it can also be applied to individual projects level tasks. If analyses of network level are done in advance to project level, decisions regarding project level requirements are achieved more effectively considering network level targets (Gerke, et al., 1998).

At network level management different maintenance scenarios, using consistent assumptions, are considered to produce outcomes which reflect appropriate qualitative and comparative results regarding the condition of the network under different funding schemes (Pavement Interactive, 2007). In general, data for network level management is averaged over sections that are considered homogenous with respect to structure, traffic, previous maintenance and weather conditions (Costello, et al., 2005). Thus, network level management predicts the average degradation of the entire network which is dependent on the condition of all its consisting segments (Busch, 2010). Commonly, network condition is defined by statistical methods using condition indices (see Section 3.2). The indices represent the percentages of network having different conditions. Senior administrators and decision-makers who have responsibility to determine the required maintenance budget are responsible to undertake network level management (Costello, et al., 2005).

4.3.1.2 Project Level Management

Management at this level is limited to individual sections of the network. It determines the maintenance and renewal requirements for each region (Pavement Interactive, 2007). Thereby, regional engineers are responsible for maintaining the railway segments in each region. Engineers must specify the exact time and location of maintenance taking into account the availability of budget, labour and maintenance resources (Kumar, 2008). The process of determining the required maintenance is similar to that of network level management, however in a smaller scale, which is by comparing the condition of track with applicable standards.

If priorities of maintenance and renewal needs at project level are set in advance of network level decisions they potentially cause conflict with network level outcomes. Therefore, it is best that network level decisions determine project level priorities. Although management at a project level is less capable of producing solutions and conditional scenarios, it can deliver detailed information regarding regional decisions because it uses actual degradation of the components for a limited length of track (Busch, 2010). One drawback of management at this level is the high cost of detailed data collection. Thus, undertaking complete analysis of the network using project level management would be very expensive and impractical.

4.3.2 Maintenance Management Requirements

Maintenance at both levels of management comprises of common prerequisites that must be fulfilled to support managers in defining aims and asset needs by considering safety and degradation behaviour of assets and to better monitor and implement actions. These requirements are known as management cycles, and are used to plan and coordinate the operation of the system effectively and efficiently throughout its life (Naito, 2007). Although few details of management cycle may vary between the two levels of management, the overall concept is the same. The detail description of the above elements is discussed in detail below.

4.3.2.1 Defining Aims

The initial step in every management cycle is defining the total aim that needs to be achieved. The aim is determined by factors that provide safety of operations. As mentioned in Section 4.3, to obtain a reliable operation, intervention levels are used by maintenance standards to indicate the permissible level of progression of defect. The term “reliable” means the probability that assets perform their required function under given conditions for a predefined time interval (Kumar, 2008). Therefore, standards should entail all the corresponding operating conditions such as permitted axle load, speed and degradation levels at both levels of management.

4.3.2.2 Identifying Asset Needs

In the second phase of management cycle, the requirements of assets to operate reliably are must be specified. As mentioned in Section 4.3.1, at network level the condition of assets is determined by indices, which represent the overall condition in form of percentages at different condition bands. By comparing the current and future condition of assets with maintenance standards the overall volume of maintenance is determined based on percentages of network at each band. Whereas, at project level the total amount of maintenance treatments along with location and volume should be specified according to the condition of each section of track (Network Rail, 2016).

4.3.2.3 Determining and Implementing Actions

The total amount of maintenance is determined by defining asset needs. In practice budget is limited and the required maintenance cannot be entirely implemented. The budget of maintenance is determined at a network level. For this reason, the total amount of feasible maintenance under budget must be determined at network level. To identify feasible maintenance under budget restriction, maintenance prioritisation must be undertaken (Fwa, 2005). The decision is based on the overall effects and efficiency of treatments on the condition of the track taking into account the safety limits set by standards. Thus, at network level different maintenance strategies are analysed and the conditions of components are compared under different maintenance standards to define the most optimal maintenance solution under budget constraint. If under every scenario, the amount of feasible maintenance exceeds the budget limit, then this information must be fed back to network level management in order to revise the level of funding available.

4.3.2.4 Monitor

To determine improvements of maintenance on assets and to control their deterioration, it is necessary to monitor the behaviour of assets. This provides clue regarding the appropriateness of maintenance treatments considering the aim defined at the initial stage of the management cycle. The effectiveness of maintenance can be done by comparing the prior and post maintenance deterioration trends (Fair & Anderson, 2002). This process is the same at both levels of management. The only difference is at network level monitoring assets should be over a longer period such as ten or more years whereas, at a project level the time is limited to one year or less (Clarke, 2011).

4.3.3 Maintenance Management Information

To plan and deliver improvements in the quality of the assets, availability of sufficient and adequate information is necessary. Maintenance management information covers all meaningful data relating to assets and asset management which support maintenance cycles objectives. These include asset type, location, age, condition as well as maintenance work histories. This information is critical in maintenance and renewal decision-making at both levels of management. Information regarding maintenance management can be collected from sites, inspection vehicles or other related sorts of literature and research. Following is the list of maintenance management information (Office of Rail Regulation , 2011).

1. Asset data
2. Condition data
3. Maintenance history data
4. Traffic data
5. Climate data
6. Cost data

Detail description of the above elements are discussed below.

4.3.3.1 Asset Data

Asset data consist of all datasets that are accessed through information systems that record, process and transmit asset information. It refers to information regarding the type and behaviour of components forming the railway network such as track infrastructure components and signalling systems. At network level, asset data relates to all the railway lines within the network, which can be classified based on their characteristics in terms of traffic and speed. As an example, 1000 miles of tracks having a speed between 90 to 100 miles per hour can be known as asset data. At a project level asset data relates type, age, location and date of construction of a particular asset (Network Rail, 2010).

4.3.3.2 Condition Data

The condition data refers to the condition of the assets. Condition data at network level has a wider scope than that of project level. For the former, this includes the condition of the entire network or portions of the network. As stated in Section 4.3.1, condition data at this level is demonstrated in form of percentages of network having different conditions such as “good” or “fair”, which are achieved by comparing the condition with the standards. Conversely, at a project level the condition data are limited to a condition of each individual track component located at a specified region (Lewis, 1984). For example, the condition of ballast at project level is defined by variations of vertical and horizontal alignments of track geometry for a 1/8th mile of track in one particular region (Network Rail, 2013). Inspection methods mentioned in Section 2.4 are used to collect condition data.

4.3.3.3 Maintenance History Data

Maintenance history data relates to the previous maintenance work carried out on the railway system. Maintenance history data at network level include the overall maintenance work undertaken on the network or some portions of the network in the past few years. Whereas, at project level this refers to maintenance treatments that has been accomplished on a specific component located in a particular region during its previous year. Consideration of maintenance history data for maintenance management system is important because, after each maintenance cycle the condition of the components and their degradation rate varies (see Section 3.3.3). Thus, by combining the condition data with maintenance history data the level of improvements of a particular type of maintenance can be determined. Maintenance history data specially at network level are not yet very comprehensive. However, few detail of maintenance work on ballast can be found from the database of recorded track geometry data using IMPART, which contained few maintenance history data regarding rails and ballast, or Network Rail reports (Network Rail, 2013).

4.3.3.4 Traffic Data

Traffic data are used to indicate the aging of the railway system. Traffic data relates to the weight and number of passing trains over a particular network. The number of passing trains over a section of a network depends on the speed of the track. At network level traffic data are determined by the percentages of network having specific speed or traffic, and the condition is defined by percentages of the network exceeding certain level of traffic (Naito, 2007). However, at project level, traffic data are the total number of trains travelling on a particular region in the past year. Traffic data are known as Equivalent Million Gross Tonnes Per Annum (EMGTPA) which determines the yearly passing tonnage over tracks (Network Rail, 2013).

4.3.3.5 Climate Data

Similar to traffic data, climate data are important to be considered as it influences the degradation process of track (see Section 2.3). A common definition of climate is the average of the weather (UK Climate Projections, 2010). Since climate varies over the network time, at both levels of management data are limited to climate conditions at each region. Climate is defined by different variables such a temperature, precipitation, sunshine and humidity. At network level, based on regions of particular sections of track, relevant data are obtained from weather stations near to the locations of particular track sections. This way, average climate information for any region is determined. Whereas, at project level, based on the exact location of track segment, climate data for that specific location is determined (Met Office, 2017). In this project UKCP09 Weather Generator (WG) is used (see Section 4.4.2) to predict the future climate projections for different regions within the UK.

4.3.3.6 Cost Data

To determine maintenance activities under budget restrictions, the cost of portions of maintenance must be determined. The cost data include the costs to repair a predefined length of track, labour costs, and costs originating from delays in operation. (Kumar, 2008) At project level cost data are limited to costs of maintenance activities that is going to be carried out on a particular component for a section of track. However, since network level comprises the entire network or sections of network, which includes thousands of miles of track, the cost data should include the total cost of treatments which are going to be carried out on defined portions of the network (Butcher, 2010).

4.4 UK Climate Impact Programme

UK Climate Impact Programme (UKCIP), established in 1997, is a body of experts in producing climate predictions under different emission scenarios (Low, Medium and High) for adaptation and mitigation purposes (UK Climate Impact Programme, 2017). The emission scenarios are adopted from the global future predictions made by Inter-governmental Panel on Climate Change (IPCC) (see Section 4.4.1.3) (Dobney, 2010). In the UKCP09 temperature is based on mean daily temperature which is the average of the daily maximum and minimum temperatures. Whereas, precipitation is based on the rate of rainfall in millimetres per day. The changes of these two climate variables are averaged over the future overlapping time periods (stepped forward by a decade). The future time periods start from 2020s, which is from 2010-2039, and ends with 2080s, which is from 2070-2099. In this manner, climate data can be obtained for annual, seasonal or monthly temporal averages under each emission scenario. There are some uncertainties in these models that are explained below.

4.4.1 Uncertainly in Modelling Climate

In general, there are three sources of uncertainties in predicting the future climate. The uncertainties are due to (UK Climate Projections, 2009):

1. Natural variability
2. Incomplete representations in models, known as modelling uncertainty
3. Uncertainty in future emissions

These are in turn explained below.

4.4.1.1 Natural Variability

Even in the absence of manmade activities, the climate at both the global and local scale can change significantly from one period (decade or more) to the next. This is because of firstly, the variability as a consequence of chaotic nature of the climate system that ranges from individual storms which impacts the regional weather to larger scale variations over period of seasons to years. Secondly, because of human activities, the future internal variability changes and can significantly impact the overall climate change. If greenhouse gas emissions resulting from human activities increases the overall change will be much bigger. On the contrary, if it reduces the change would be much smaller (UK Climate Projections, 2009). The natural variability can be estimated using the climate model, by running the model many times with different initial conditions and thus quantify the uncertainty in projections (see Section 5.3.8)

4.4.1.2 Uncertainty Due to Climate Models

Uncertainly in climate models is due to lack of complete knowledge of the global climate system and the ability to model it flawlessly. In general, climate models estimate the change in climate as a result of human activities under different emissions (UK Climate Projections, 2009). These models use mathematical representation of many processes in the climate system and their interactions, such as atmosphere, ocean and land surface to determine how climate changes with respect to the speed of greenhouse gases emission. For example, the way the atmosphere moves horizontally and vertically and the processes occurring in it, such as formation of clouds and precipitation, can affect the climate. On the other hand, there is a continual exchange of heat and water vapour between the oceans and the atmosphere which can significantly influence the climate. In addition, changes in land surface, both naturally and human made, can impact the flow of air over land and affect the hydrological cycle. Thus, all these have the potential to impact how the climate changes (UK Climate Projections, 2009).

4.4.1.3 Uncertainty in Emissions

Special Report on Emission Scenarios (SRES) states that there are no fixed grounds in evaluating relative probability to determine future emissions (Dobney, 2010). In other words, uncertainty due to future emissions cannot be incorporated in future probabilistic projections. To address this issue, UKCP09 provides probabilistic projections of future climate under different emission scenarios (UK Climate Projections, 2009). Figure 4.1 illustrates the emission of CO_2 under three scenarios. Based on the graph, A1F1 indicates high emission, whereas A1B and B1 indicate medium and low emissions respectively. The dashed lines (A2 and B2) represent the emission scenarios in UKCIP02 which is the older version of UKCP09. A2 represents medium-high emission and B2 represents medium-low emission. Last but not least, human plans aiming to reduce the speed of global warming such as, the new plan for 2040 which aims to ban diesel and petrol cars, will significantly affect the trend of CO_2 emissions (Telegraph, 2017).

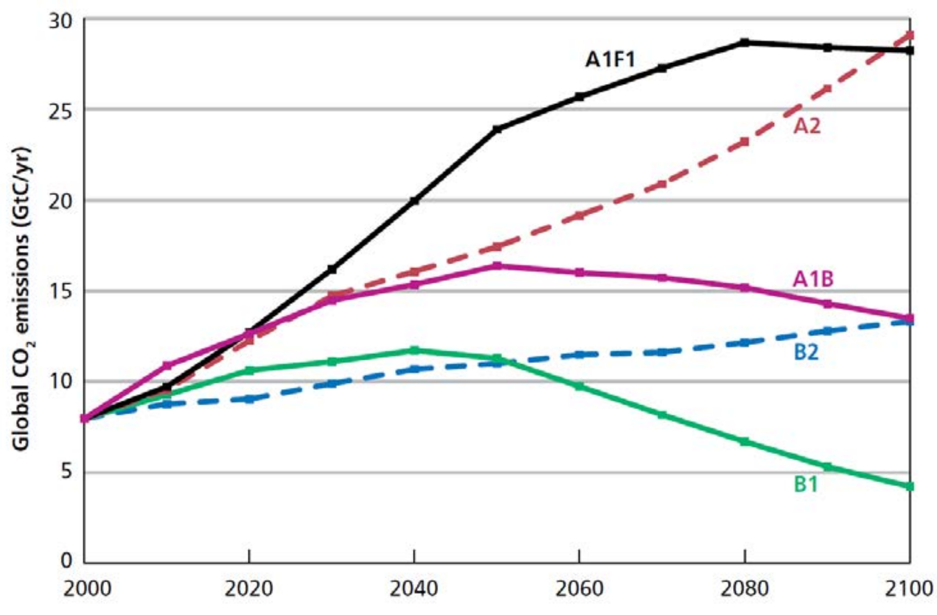

Figure 4-1 Emission scenarios used in UKCP09 projections (UK Climate Impact Programme, 2010)

4.4.2 UKCP09 Weather Generator

The Weather Generator (WG) was developed by the Universities of Newcastle and East Anglia based on previous version in use by the Environmental Agency (Dobney, 2010). WG does not provide weather forecast for a particular day in the future, rather it provides statistical representation of what is likely to happen in the future climate. Therefore, it generates synthetic daily time series of climate variables (i.e. temperature and precipitation) over land for the three emission scenarios for 30-year time period (overlapping every 10 years) of 2020s, 2050s and 2080s. For rainfall the observed data between the period of 1961-1990 is selected as a baseline, however, a longer period of 1961-1995 is used for temperature to allow for a small fraction of missing data in some series (UK Climate Projections, 2010).

The UKCP09 WG is based around a stochastic rainfall model that simulates future rainfall sequences. Accordingly, other climate variables, such as temperature, are generated using the state of the rainfall. For example, based on whether the day is wet or dry, daily temperature is modelled using mathematical relationships with rainfall and the weather on the previous day. This is achieved using intervariable relationships between rainfall and other climate variables (UK Climate Projections, 2010).

4.4.2.1 Producing Extremes Using Weather Generator

Extremes are infrequent events, such as flooding or drought, and only small historical data are available for most extremes. This limits the ability of WG to estimate extremes. Therefore, it requires the user to determine extremes using the confidence bounds around the estimates (see Section 5.3.8). These are changes in 1st and 99th percentile of daily distribution of each climate parameter over a month, season or year. For example, the 99th percentile for maximum temperature for summer months indicates the temperature of the hottest day in summer. Whereas, in case of precipitation for winter months, 99th percentile roughly estimates the wettest day in winter (UK Climate Projections, 2010).

4.5 Structure of UK Railway Industry

The UK railway network has undergone significant change since railway was privatised in 1996 and railway companies were split to provide transportation services and infrastructure services in a more effective manner. At that time, Railtrack was owner of infrastructure. But due to poor asset management skills such as Hatfield incident (see Section 2.3.1) the management of the infrastructure was appointed to Network Rail (NR) in 2002 (Office of Rail Regulation , 2015). NR builds, operates and maintains the railway infrastructure. Its tasks' include management of track, signalling infrastructure and bridges and implementing engineering work, setting speed restrictions and managing few stations (Office of Rail Regulation , 2015).

Department for Transport (DfT) is a government department and responsible for the transport network within the UK. DfT is accountable for sustaining economic growth and productivity of the network (Transport, 2017). Train Operating Companies (TOCs) are responsible for operation and running of train services. The management of most train stations on their routes is also TOCs' responsibility. Freight Operating Companies (FOCs) are responsible for freight services (Office of Rail Regulation , 2017). The Office of Rail Regulation (ORR) is an independent economic and safety regulator. ORR ensures that all railway organisations comply with health and safety regulations. One of the responsibilities of ORR is monitoring the performance of NR to ensure railway infrastructure is managed efficiently. Safety related issues such as setting minimum standards for the infrastructure is dealt with by RSSB. The standards set by RSSB in relation to technical and operational aspects must be considered within NR, TOCs and FOCs (Ling, 2005).

The income of railway industry in 2014 – 2015 was around £13.5 billion, where 71% was from passengers, with government contributing to 26% of its funding. The overall expenditures of running the railway network was £13.6 billion, where 54% was for train operating and 46% for infrastructure (Office of Rail Regulation , 2015).

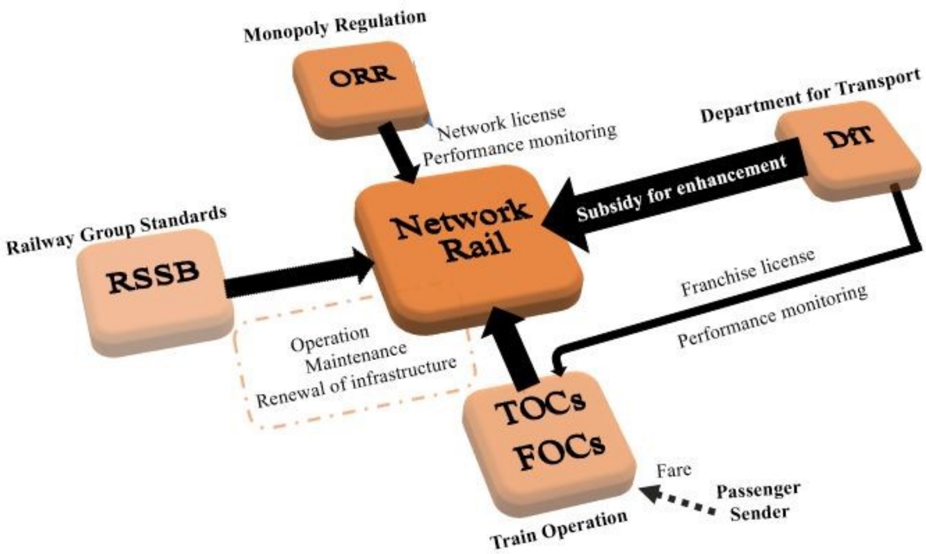

Figure 4-2 Structure of UK railway industries (Network Rail, 2010)

4.5.1 The Office of Rail Regulation

ORR must comply with UK and EU legislations. The members of ORR board are appointed by secretary of state for transport with maximum duration of five years. ORR is responsible to make sure NR is producing high levels of performance and service. Therefore, NR is responsible to report the annual performance and achievements to ORR. These are measured through a number of KPIs (see Section 3.3.3) such as portions of network with "very good" and "good" track geometry and total delay times (Office of Rail Regulation , 2017).

4.5.2 Department for Transport, Train and Freight Operation Companies

The strategic direction for the railway network is set by DfT. Dft is responsible for specifying and assigning contract to TOCs to run franchised passenger services. The contract between DfT and TOCs stipulates standards which ought to be complied by TOC. In this manner, DfT monitors the level of achievements of the TOCs. Same principals are held for FOCs as well (Office of Rail Regulation , 2015).

4.5.3 Rail Safety Standard Board

RSSB is responsible to set up-to-date operational standards to railway organisations to provide safety requirements. The standards are known as Railway Group Standards (RGS) and determine the minimum standards required. NR formulate these standards in a more rigid form known as desirable standards. If the RSSB standards and NR standard are not compatible which each other, NR has responsibility to report any issues regarding this matter to RSSB to set alternative measures to provide safety of train operation (RSSB, 2015).

4.5.4 Network Rail

NR operates under the licence issued by ORR. The licence includes regulations which NR must fulfil (Office of Rail Regulation , 2013). The primary objectives of NR are operational management, which deals with running the railway and asset management which deals with keeping the track reliable. Within the UK, according to NR's current classification system, the railway network is classified into a route-based system and accordingly ten regions are specified as Anglia, East Midlands, London North East (LNE), London North West (LNW), Scotland, Wales, Wessex, Sussex, Kent, and Western Regions (Network Rail, 2015). Accordingly, climate variables are determined for each region within the industry (Network Rail, 2015).

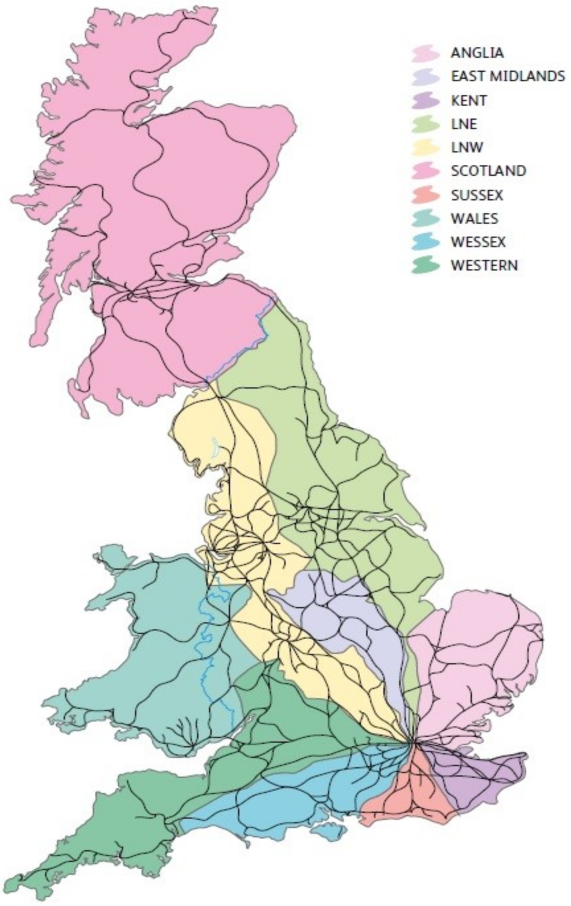

Figure 4-3 Network Rail route-based regions (Network Rail, 2015)

In this respect, local engineers will have better understanding of assets and climate induced deterioration at each region and a better of risk-based management can be established.

4.6 Track Maintenance Management in the UK

The government funds NR in a five-year block known as Control Period (CP) and sets the requirements for the railway system (Office of Rail Regulation , 2013). In addition. it specifies how much they can contribute to the maintenance expenditures. ORR evaluates how much NR's efficient level of expenditure needs to be in order to deliver regulated outputs. Thereby, NR must ensure the collection and use of asset information to better plan and manage the railway system to satisfy the present and future demands (Network Rail, 2014) (Network Rail, 2016).

Using good management skills during CP5 (i.e. between 2014 – 2019) the efficiency was increased by 18%. This comprises of £37.5 billion expenditures on running and expanding the railway. However, NR refinanced £7.4 billion of its debts along with another £16 billion during this period which is predicted that the total debt would be approximately £49 billion. Therefore, NR has been subjected to borrowing limits imposed by the treasury which ORR stated this is potential to cause financial problems in CP6 (i.e. between 2019 – 2024) (Network Rail, 2014).

The improvements made by NR originates from its asset management skills. Asset management requires understanding the degradation mechanism of the railway system. Setting intervention levels at an earlier stage of the planning process can also reduce the overall maintenance costs. Good asset management system will provide excellent benefits such as up to 50% reduction in costs (Office of Rail Regulation , 2013).

4.7 Existing Track Maintenance Management Systems

Maintenance management systems facilitates the decision-making process based on the level of data available. Due to huge amount of data required for maintenance management, decision-making tools are developed to ease and automate the management of such data. Several decision-making tools developed, which are appropriate to meet the objectives of this research, are illustrated below. These tools develop relationship between maintenance budget and the corresponding network condition.

4.7.1 Europe

4.7.1.1 ECOTRACK

This maintenance decision-making tool is developed by European Rail Research Institute (ERRI) (Bartram, 2005). The tool is used for plain track and optimises the repair and renewal needs of the sections of network to provide efficient maintenance planning. The system was developed under logical statements using a computer program to facilitate the decision-making process. For example, if the cumulative tonnage of particular rail type, reaches beyond the specified value set by standards, it determines that renewal is required. The system uses a database of track condition data and traffic data to operate (Jovanovic, 2000).

The user selects the specified location of the track which requires analyses and enters the asset information to the system. The system processes the data using degradation models and expresses the condition of the track in a graphical format. For each section of track the tool considers rails, sleepers and ballast as track components. For rails and sleepers, it uses the cumulative tonnage as a measure to define its condition. Whereas for ballast, it uses the standard deviation (SD) of track geometry. The deterioration model of all the components is determined using a linear equation. In Section 3.3.3, it was discussed that deterioration rate is not always linear with time. The tool uses graphs to determine the type of treatment, location and date as a function of distance along the track. For the costs, the budget is allocated and the system calculates the costs in a way to be within the level of funding available (Jovancovic, 2000).

Since ECOTRACK operates based on each individual section, in order to determine the condition of the railway network considerable amount of time is needed. In addition, the user need a comprehensive knowledge regarding each section of track to determine appropriate maintenance planning. However, it is difficult to determine the overall condition of the network under the given budget since budget analysis is at project level. Lastly, due to predefined deterioration patterns, the effects of maintenance on the rate of change in deterioration is not considered (Jovancovic, 2000).

4.7.1.2 RAMSYS

A more advance version of ECOTRACK is Railway Asset Management SYStem (RAMSYS). which was developed in Italy. RAMSYS is flexible in implementing different maintenance scenarios on the infrastructure. This system uses Life Cycle Costs (LCC) analysis to optimise the cost effectiveness of maintenance strategies at project level. For the system to make optimum maintenance strategy using LCC, detailed data are required. As for ECOTRACK, this system lacks a method to determine the condition after maintenance and its effects on subsequent change in deterioration rate (Patra, 2009) (Mirmahmoudsadeghi, 2012).

4.7.1.3 MARPAS

Maintenance And Renewal Planning Aid System (MARPAS) was one of the pioneers in launching maintenance management decision-making tools and was developed by British Rail Research group (Nash, 2002). The tool utilises track condition data and develops track deterioration models to produce outputs in a graphical format to the user. The system provides information regarding track condition and the required budget to keep the track at safe levels. One advantage of MARPAS is considering effects of vehicle type on deterioration of the track (Network Rail, 2008). In addition, as with ECOTRACK time and location of track requiring maintenance must be specified. MARPAS uses small sections of track, usually 200 metres to evaluate the overall condition using the aggregated condition of track sections. This makes the tool more suitable to be used at a network level, however, the system lacks the ability of considering budget constraints in reaching maintenance decisions (Nash, 2002).

4.7.1.4 TrackMaster

TrackMaster is the modified version of MARPAS (Grimes, 2006). To use TrackMaster, the user must enter detailed maintenance plans such as type, volume of maintenance and location. TrackMaster only considers the condition of ballast to determine the track condition. It uses SD value of track geometry over a 1/8th mile section (Grimes, 2006). Therefore, it can only determine the required amount of tamping or ballast renewal. One advantage of TrackMaster is prioritisation of sections requiring tamping. This is achieved by considering track geometry irregularities. There is an embedded toolbox within the model known as Track Quality Manager (TQM) which determines the efficiency of tamping on track sections. However, the change in rate of deterioration after tamping is not modelled in the system. Currently the tool is used within the UK to determine the amount of tamping required for every section of track at project level. Similar to other management systems the tool produces output in a graphical format to the user (Grimes, 2006).

4.7.1.5 T-SPA

Track Strategic Planning Application (T-SPA) is another decision-making tool which was commissioned by NR (Network Rail, 2013). The tool is developed to predict the renewal requirements of the entire UK railway network. The tool predicts the renewal requirement for as far as ten years into the future. As an input to the system, the user is required to import data regarding component type, construction date and history condition data of rail and track geometry. The deterioration of the track components considered in T-SPA are modelled using suitable processes (Naito, 2010). The rail module, determines the rail defects using local history of track sections. The sleeper module predicts sleeper renewal needs based on engineering judgement of age and tonnage of each track section. Finally, the ballast module predicts geometry irregularities considering deterioration of ballast with respect to void spaces filled with fouled materials. Because the modules are developed based on deterministic models (see Section 3.3.1) for each particular track section, the tool uses the project level analysis to determine the network renewal needs. Therefore, undertaking simulation to predict network level renewal requires a considerable amount of time (Bevan, 2012).

4.7.1.6 NETCOM

NETwork COndition Model (NETCOM) is a prototype computer model develop to facilitate network level analysis of roads (Kerali & Snaith, 1992). In principal, stochastic deterioration models are used to assess the effects of maintenance standards on budget and road condition. To carry network level analysis, the system uses different deterioration models for each homogenous sections of road. Homogenous road sections are sections same in terms of traffic and geographical location such as trunk or motorway road network. To represent the condition of the network, statistical distribution of defects such as wheel track rutting is used which represent the portions of track with different conditions. The system is able to predict the overall required budget as well as determining feasible maintenance under budget restrictions using priorities and intervention levels. The future condition of the network is demonstrated in a graphical format to the user. Overall the system provides suitable framework for asset managers to make decisions.

4.7.2 USA

4.7.2.1 RAILER

Railroad Maintenance Management System (RAILER) was developed by the US army to facilitate the network level management of railways (Mirmahmoudsadeghi, 2012). The system uses history and condition data to evaluate the required volume of maintenance. The modules within the tool use information from relevant database and surveys to perform network and project level analyses. The tool estimates the budget requirement and optimisation as well as priority of inspection scheduling at Network level. Whereas for the project level, it determines appropriate maintenance treatments based on project level data (Uzarski, 1988).

4.7.2.2 TRACS

Total Right-of-way Analysis and Costing System (TRACS) is a maintenance management system which not only determines maintenance scheduling to keep the track running, but also it determines the effects of maintenance treatments on the track to keep trains running reliably. TRACS is used by North American railroads for technology assessment, costing and budgeting. The system includes different deterioration and failure models to estimate the condition of track and to evaluate the required volume of maintenance. The models are based on engineering-based deterioration models (see Section 3.3.1) with LCC techniques to estimate track maintenance and renewal needs. Due to the type of models used in the system, the best use of the tool is at project level (Mirmahmoudsadeghi, 2012).

4.7.3 Asia

4.7.3.1 DTM

Direct Track Maintenance (DTM) is a management tool developed in India (Mirmahmoudsadeghi, 2012). The main purpose of the tool is to evaluate the future requirements of ballast renewal and maintenance. The tool operates at project level and is suitable to be used for particular track sections. Using different deterioration models the tool determines the required amount of maintenance expenditure to provide evidence of level of funding needed. The disadvantage of this tool is that data must be sampled and imported to the tool manually making it very time consuming. Moreover, the system does not take into account the effects of maintenance on ballast condition and its rate of deterioration. Lastly, since the system only determines costs of required maintenance, it is unable to set priorities to calculate feasible maintenance under budget constraints.

4.7.3.2 TOSMA

TOkaido Shinkansen track MAintenance system (TOSMA) is a maintenance decision-support tool made for Shinkansen highspeed lines in Japan (Reddy, 2004). The system uses track geometry data to calculate ballast condition over every 20 miles of track. The tool only determines the amount of tamping for that specific line making is limited to be used at project level scale. However, the tool not only determines the overall volume of required tamping, but also it is capable of estimating the condition of each section of track after every tamping cycle (Naito, 2007). As an output, the system illustrates the geometry irregularities in a graphical format to the user. It can be concluded that this tool as well follows the same principals as TrackMaster.

4.8 Summary

In this Chapter, the concept of maintenance and definition of maintenance management were explained in detail. Two distinct but related management levels, network level and project level, were illustrated. The management cycles and information used as requirements for both management levels were discussed. Maintenance standards and the methods used to determine the required maintenance were described in Section 4.3. Details of current climate modelling techniques used to determine future climate projections were explained in Section 4.4. It was discussed that the effects of climate on deterioration and condition of the railway tracks is not considered in the maintenance management systems developed to date, Furthermore, the degree of improvements of maintenance treatments on the condition of components and their deterioration rate were not considered in the existing maintenance management systems. To this end, to develop a maintenance management system it is required to have a detailed understanding of deterioration of assets and the effects of maintenance and climate on their condition and deterioration. In the next Chapter, the methodology used in this project to incorporate such important factors in developing a network level maintenance management tool for the railway track is demonstrated.

Chapter Five

5. METHODOLOGY

5.1 Introduction

Section 3.3.3 discussed that in order to develop a railway maintenance management decision-making system that considers the effects of network level investments on network level track condition, a statistical approach is a suitable approach since it is able to take into account the random behaviour of track components. In particular Markov modelling was identified as an appropriate method for the purpose of this research (see Section 3.5). In this chapter, the methodology and the necessary components of such a system are discussed in detail.

5.2 Outline of the System

As stated in Sections 1.2 and 1.3, the goal of this research is to develop a system that uses historical railway track component condition data to determine the future network level track condition considering the effects of traffic, maintenance and climate on railway track component degradation. To this end, it was decided to adapt a network level iterative system developed for roads, known as NETCOM (see Section 4.7) and to build further on a related system for railways proposed by Naito (2007). The significant innovations with respect to Naito's approach include the incorporation of an S&C module, a more realistic maintenance/restoration module which takes into account component damage during maintenance, more realistic and accurate deterioration models and the incorporation of the effects of climate induced deterioration. The latter allows for the effects of climate change to be studied, in particular changes in temperature and precipitation.

The conceptual model of the proposed system is shown in Figure 5.1 and Figure 5.2 depicts its logical design (Kerali & Snaith, 1992). With reference to Figure 5.1 the logical processes followed in order to determine the network level track condition after a time period T are as follows:

i. The extent of the conceptual network to be analysed is specified by the user (see Section 5.3.1)
ii. The major components of the railway track which are to be included in the analysis are specified, such as rails, sleepers and ballast (see Section 5.3.3)
iii. The minimum period of analysis, t, is specified. This is usually the minimum length of time between inspections of component condition
iv. The number of measures of condition of a particular component, to be used in the model, are identified (e.g. rail cracks and rail corrugation)
v. The initial condition of each component, at= 0, according to each measure of condition, is specified as a percentage of the total number of components in the network (see Figure 5.2).
vi. The length of analysis T, or number of iterations of the model N is specified (were $T = N \times t$)
vii. Maintenance standards are specified by the user in a format which allows comparison with the current condition to determine maintenance requirements (see Section 5.3.5). This includes specifying the priority order in which defects are to be treated and also the order in which maintenance treatments are to be applied under a constrained budget.
viii. Determining feasible maintenance under a constrained budget (see Section 5.3.5)
ix. Modelling the improvements in condition of the network after maintenance interventions (see Section 5.3.6)
x. Calculating cost of required and feasible maintenance at the end of each year for a duration of analysis (see Section 5.3.7)
xi. Predicting network level degradation as a result of traffic, climate and maintenance (see Sections 5.3.2 and 5.3.8)

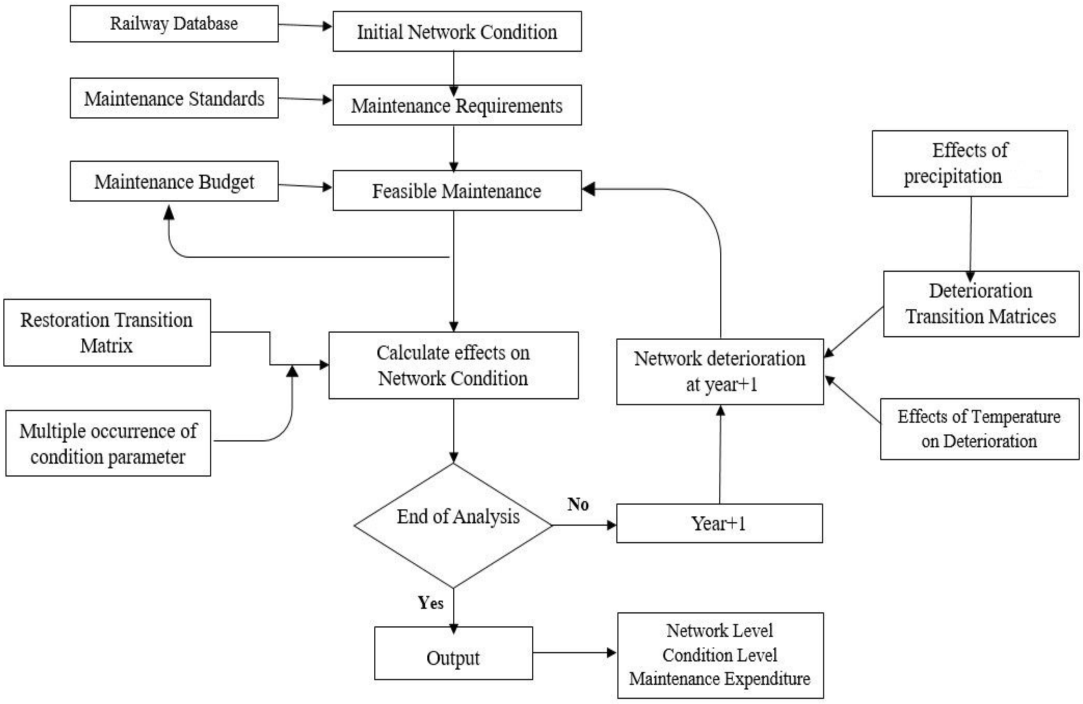

Figure 5-1 Flow chart of the system (Kerali & Snaith, 1992)

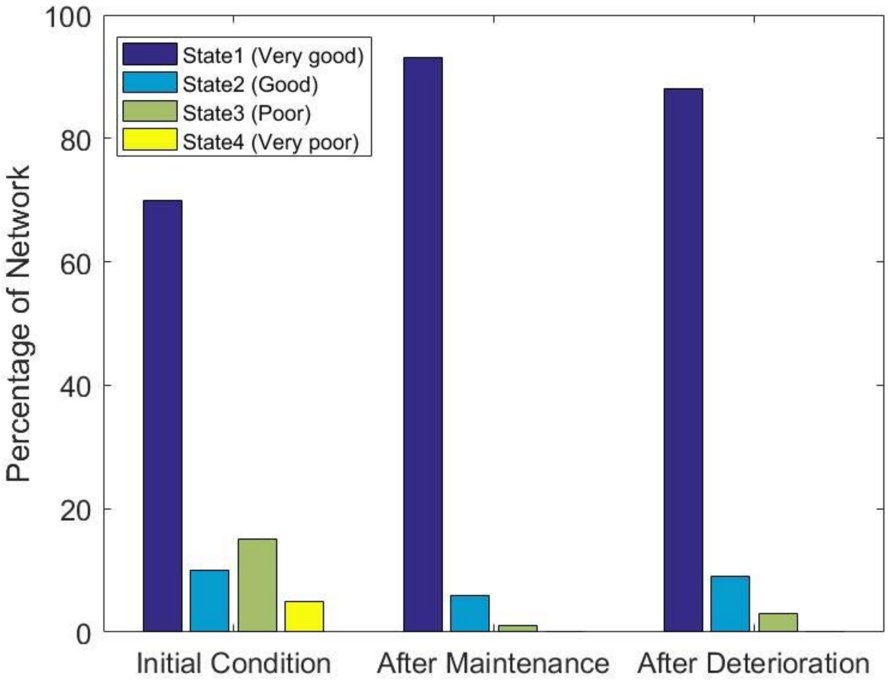

Figure 5-2 Transition histogram of standard deviation 35m vertical ballast profile

Figure 5.2 provides an example which illustrates the probability distribution of the conditions of the ballast before and after maintenance at time t as well as the condition of ballast after one year of degradation.

5.3 System Processes

5.3.1 Conceptual Railway Network

The proposed modelling approach is applied to homogeneous sections of railway track which may be considered to deteriorate at similar rates and therefore for which the same deterioration models may be used and for which the same maintenance standards are applicable. In order to determine the condition of the entire railway network, the model can be run separately for as many homogeneous sections as exist in the entire network and the results amalgamated. As discussed in Section 3.3.3, homogenous sections may be considered those with similar train speeds and tonnage, track composition, geometry, construction type. climate, drainage conditions and maintenance history. A group of homogenous track sections may not necessarily be physically connected and are referred herein as a conceptual railway network.

5.3.2 Deterioration Modelling

The tool developed herein may be regarded as a network level maintenance management system. Therefore, following the review of deterioration modelling carried out in Chapter Three which investigated a number of modelling approaches in similar fields it was decided to utilize a statistical approach. In particular, the Markov modelling approach was used (see Section 3.5). It uses the condition of a component as a random variable and determines the probability via transition matrices to determine the likelihood of a component transitioning from one condition state to another following the deterioration or restoration (maintenance) process. To develop the Markov model, or chain, for a particular component, regression analysis was used to determine the behaviour of the components in the conceptual network over time using historical condition and maintenance data (see Section 6.4.1). From these probability distributions were determined and used to ascertain the probability of a component transitioning from one condition state to another during a period of analysis, t (see Sections 6.4.2. and 6.5.1). In this manner, the probability of a component being in a given condition is defined by percentages of track in that condition at any point in time.

The Markov approach assumes that deterioration is discrete in time which is convenient to predict the condition of railway network at any point in time (Taylor & Karlin, 1998). Although there are many deterioration patterns, the Markov model used in this research uses finite states space which uses the possible range of different defects to determine the particular condition of track sections under consideration, to account for different track deteriorations. The Markov approach also assumes that the future condition depends on the current state and not the past and is independent of the time at which transition is made (Taylor & Karlin, 1998). To account for this in this research, where the deterioration trend of components changes due to maintenance and/or climate at certain point in time, different transition matrices were developed to reflect such changes (see Sections 6.4.4 and 6.6.1 and 6.6.2).

Following the Markov approach the condition of a particular type of component in a network is defined by a vector $p_{xy}(t_0) = [p_{y1}\, p_{y2}\, p_{y3} \dots p_{yn}]$ (see Figure 5.2). The vector represents the portions, p, in each condition state n of a track component x, when the condition of the component is measured by parameter y. To model the deterioration over time of a component transition probability matrices are used as follows:

(5.1)

$$P_{xy} = \begin{bmatrix} p_{11} & p_{12} & p_{13} & & p_{1n} \\ p_{21} & p_{22} & p_{23} & \cdots & p_{2n} \\ p_{31} & p_{32} & p_{33} & & p_{3n} \\ & \vdots & & \ddots & \vdots \\ p_{n1} & p_{n2} & p_{n3} & \cdots & p_{nn} \end{bmatrix}$$

P_{xy} is the transition probability matrix for component x where its condition is measured by y. p'_{12} determines the transition from current state 1 to state 2 in the next analysis time, t. The sum of every row of a transition matrix should be equal to unity and the element should be positive to satisfy Markov theorem.

To predict the future condition distribution of a component, the initial condition, is multiplied by the deterioration transition matrix, P_{xy}. Therefore,

(5.2)

$$p_{xy}(t_1) = p_{xy}(t_0)P_{xy}$$

$$p_{xy}(t_2) = p_{xy}(t_1)P_{xy} = p_{xy}(t_0)P_{xy}^2$$

$$p_{xy}(t) = p_{xy}(t_0)P_{xy}^t$$

Or in generalized form (Shafahani & Hakhamaneshi, 2009):

(5.3)

$$p_{xy}(i+t) = p_{xy}(i)P_{xy}^t$$

where $p_{xy}(i)$ is the distribution of condition y, for component x at time i, $p_{xy}(i+t)$ is the distribution of condition at time $i+t$, and P_{xy}^{t} is the transition matrix raised to the power of time elapsed.

Examples of how the deterioration transition matrices were developed for this research are given in Section 6.4.3 using real datasets.

To demonstrate this process, an example is shown in Table 5.1 of a renewal process of rails, assuming that no previous maintenance has been carried out and that the initial condition of the track, as measured by the cumulative EMGT (i.e. y), is $p_{xy}(t_0) = [50\ 35\ 8\ 7]$.

State	Cumulative Equivalent Million Gross Tonnes (EMGT)	Condition	Initial network condition	Post-treatment proportion	Post-deterioration proportions
1	0<, but< 334	Very good	50	61	58.6148
2	334<, but<668	Good	35	35	35.7539
3	668<, but<1000	Poor	8	4	5.4340
4	>1000	Very Poor	7	0	0.1972

Table 5-1 Distributions of condition for Rails

Assuming that there is sufficient funding to renew all of the rails in very poor condition and half of that in poor condition at time t_0 and that renewal restores the condition at any state to a very good condition, then 11% of rails are renewed and $p_{xy}(t_0) = [61\ 35\ 4\ 0]$

Assuming, from historical records, that the probability of the rail deterioration moving to each state is given by the following Table (using cumulative EMGT as a measure of condition):

Condition (Year N)	(Year N+1) State	Very Good 1	Good 2	Poor 3	Very Poor 4
Very Good	**1**	0.9783	0.0215	0.0002	0
Good	**2**	0	0.9771	0.0226	0.0003
Poor	**3**	0	0	0.9798	0.0202
Very Poor	**4**	0	0	0	1

Table 5-2 Transition Matrix P_{xy} for rail deterioration using cumulative EMGT

Table 5.2 indicates that at the next iteration, for a track in a very good state there is 0.9783 probability that the condition stays in very good state and 0.0215 probability that it moves to a good state. However, the track in a good state remains in the good state with probability 0.9771 and moves to poor and very poor states with probability of 0.0226 and 0.0003 respectively. In the same manner, the track in poor condition moves to a very poor condition with probability 0.0202, whereas with 0.9798 probability it remains in the same state. The tracks in very poor state remain in the very poor state since their cumulative EMGT is greater than 1000 and it is assumed that they have reached their useful life. To determine the future deterioration, therefore, 11% of tracks in very good state deteriorate using P_{xy} and the rest of tracks deterioration with P_{xy}^2, since they already deteriorated in a previous year. Thus,

$$p_{xy}(t+1)P_{xy} = [50\ 35\ 4\ 0] * P_{xy}^2 + [11\ 0\ 0\ 0] * P_{xy}$$
$$= [47.8535\ \ 35.5174\ \ 5.4318\ \ 0.1972] + [10.7613\ \ 0.2365\ \ 0.0022\ \ 0]$$
$$= [58.6148\ \ 35.7539\ \ 5.4340\ \ 0.1972]$$

5.3.3 Major Railway Track Components

The proposed tool aims to evaluate the change in condition of a conceptual network over time as a result of deterioration caused by traffic, the climate and maintenance. Since railway maintenance is related to individual track components (e.g. rail grinding, ballast cleaning, ballast tamping) it was decided to analyse the deterioration and restoration of individual component types and to establish the associated maintenance and renewal costs. This requires the choice of measures of deterioration for each component and the careful selection of associated deterioration models. Because the system's aim is to support the management of maintenance budgets at the network level, defects which account for the majority of maintenance expenditure were identified and considered for incorporation within the tool. Within the UK, the majority of the maintenance budget is dedicated to rails (i.e. renewal and grinding), S&Cs (renewal), sleepers (renewal), ballast (tamping, stoneblowing, cleaning and renewal) and as the subgrade (ground improvements) (Network Rail, 2012). Accordingly, following the literature review presented in Section 2.3 and from consultation with trackbed experts at Network Rail the measures of condition, and possible treatments, selected for the rail, S&Cs, sleepers, ballast and subgrade are those given in Table 5.3. These are those which in addition to capturing the deterioration of components adequately are also those which are currently, or can be, measured in practice.

Component	Measure of condition	Treatment Type
Rail	Age (EMGT)	Rail renewal
	Wear	Rail renewal, grinding
	Corrugation	Rail grinding
	Buckling	Rail renewal
Switches & Crossings	Age (EMGT)	Crossing renewal
	Corrugation, wear	Rail grinding, renewal
	Cant	Tamping
Sleeper	Age (EMGT)	Sleeper renewal
Ballast	SD of vertical and Horizontal alignment	Tamping, stoneblowing
	dSD/dt of vertical and horizontal alignment	Ballast Cleaning / Renewal
Subgrade	Absolute Stiffness Value (k)	Ground stabilisation & improvement
	Differential Stiffness Value (dk/ds)	

Table 5-3 Track's measure of condition and associated treatments (Burrow, et al., 2009)

It should be noted that applications of the proposed tool for railway networks in other countries could replace or supplement the above components.

5.3.3.1 Rails

Wear and Corrugation

Corrugation as a result of repetitive train load causes quasi-static waves and unevenness of the railhead which wears the rail (see Section 2.3.1.1). On the other hand, the direct rail-wheel contact causes the rail to wear over time (see Section 2.3.1.2). These defects are recorded regularly by Network Rail (see Section 2.4.1). Rail grinding is carried out routinely to remove corrugation (see Section 2.5.1.2). Grinding also affects the deterioration rate of wear. For this reason, corrugation and wear are chosen as measures of condition for rails. As a result of grinding, the effect of corrugation decreases, by removing the hardened surface of the rail, and the service life of the rail increases. Grinding might not always restore the condition of the rail to the 'as good as new' condition, however, it reduces the rate of deterioration of the rail in most cases and stops small cracks from getting larger (Grassie, 2008). The amount by which the lifecycle is increased, or the wear rate changes is not constant and depends on the past maintenance history (see Section 6.5).

Equivalent Million Gross Tonnes (EMGT)

The passage of railway vehicles (traffic) is the predominant cause of corrugation and wear which if excessive requires the rail to be renewed. Hence, the amount of traffic over the rail since its installation is considered as a measure triggering rail renewal. In the UK, the cumulative EMGT is used as a measure of the cumulative traffic. EMGT is used because it reflects and quantifies the service life of a rail (Sadeghi & Askarinejad, 2009). Accordingly, for the purposes of the incremental model developed herein, the Equivalent Million Gross Tonnes Per Annum (EMGTPA), is used as a measure of condition triggering rail renewal.

Buckling

When a rail buckles, it causes serious misalignment and requires the section of rail to be replaced (renewed). Buckling is dependent on the temperature of the rail and the condition of the underlying ballast layer (see Section 2.3.1). Although, the rail is pre-stressed to tolerate certain temperature ranges, in extreme heat, both JR and CWR become prone to buckle due to the thermal forces (Dobney, 2010). In addition, when the support from the ballast is poor, the imposed train load significantly contributes to the occurrence of buckling. Therefore, rail temperature under extreme temperatures, together with ballast condition were selected as measures of condition provoking rail renewal (see Section 5.3.3.3 for measures of condition of ballast).

5.3.3.2 Sleepers

EMGT

As discussed in Section 2.3.3 sleepers deteriorate under the combined effects of traffic and the environment. Measuring the progression of physical defects of individual sleepers using current inspection techniques is a difficult and expensive task. Therefore, since the proposed tool operates at the network level, the EMGT was selected as a measure of the effective life of sleepers (Zhang, et al., 1997). In the proposed tool, sleeper renewal is considered as a single treatment.

5.3.3.3 Ballast

Track Geometry

As stipulated in Section 2.4.4, the condition of the ballast is determined by measuring the irregularities in track geometry. In the UK, the SD of vertical profile and horizontal alignment are most commonly used as parameters specifying the range of deviations in the track geometry (Andrews, 2012). Typically track geometry is realigned using tamping or stoneblowing (see Section 2.5.4) and therefore for this research, the vertical profile and horizontal alignment measures of condition were selected as measures triggering tamping and stoneblowing.

Rate of Change of Geometry Deterioration

As described in Section 2.3.4, due to traffic and the aggregated effects of maintenance treatments, ballast particles break and create fouling materials which contaminates the ballast. This reduces the ability of the ballast to carry load (and can have other consequences such as reducing drainage). At this point, maintenance activities such as tamping or stoneblowing cease to be effective in improving geometry irregularities. For network level management, due to huge data requirement, it would be impractical to assess the physical properties of the ballast using, for example, the fouling index, moisture content and saturation level, since these measures are mainly estimated via field measurements on a project level by project basis and laboratory experiments. It was therefore decided to use the rate of change of SD of vertical and horizontal alignments over time, (dSD/dt), as a measure to indicate ballast renewal (Naito, 2007). Higher values of dSD/dt indicate a faster deterioration rate and at which it is considered that additional tamping and stoneblowing are ineffective and that ballast renewal is required (see Section 6.4.4).

5.3.3.4 Subgrade

Track Stiffness

The function of the ballast and sub-ballast is to reduce the load imposed on the subgrade to acceptable levels (see Section 2.2.4) and therefore the subgrade should rarely require maintenance. Within the UK, trackbed thickness is a function of subgrade stiffness as stated in Section 2.2.5 (Figure 2.3). Different stiffness values are needed from ballast and sub-ballast layers to reduce the load transferred to subgrade. For instance, if the stiffness of the sub-ballast is not adequate, the stresses imposed to the subgrade increases resulting potentially in subgrade failure (Burrow, et al., 2009). When insufficient stiffness is provided by trackbed layers and it is not possible to rehabilitated it using maintenance treatments, the track is reconstructed with a required level of thickness to restore the condition to the good as new. Thus, determining the variations of stiffness of each of these layers are important.

Therefore, stiffness of the trackbed, $k,$ and stiffness of the system, dk/ds were selected as measures of condition triggering subgrade/ ground improvement.

5.3.3.5 Switches and Crossings

S&Cs comprise of various components as explained in Section 2.2.2. The failure of these components can occur due to a number of different factors. Upon inspection, the failed units are replaced. However, currently there are no standards to specify the condition for S&C units. Therefore, for the purpose of this research it was decided to base the requirements of S&C maintenance on the condition of the rails and the ballast in a unit and to use cumulative traffic (EMGT) as a measure of the condition of the switches.

Wear and Corrugation

Rails located on S&C units, generally suffer from high impact loads from train transitions on curves which create a high amount of corrugation and wear especially on switch rails, wings and the nose of the crossing (see Section 2.3.2). Therefore, corrugation and wear were selected as measures of condition to determine the grinding requirements for S&C units. Furthermore, because of the superelevation at switch rails and crossings, ballast cant irregularities may also occur (see Section 2.4.4). Ballast cant deficiency was therefore chosen as a measure of condition which triggers S&C tamping.

EMGT

The service life of the switch components is affected by its usage and therefore its cumulative EMGT is used to determine its cumulative traffic (Rama & Anderws, 2013). When the permissible age of the component is reached, it becomes prone to in-service failure and must be renewed. Therefore, the age of switch components (i.e. cumulative EMGT) was considered as a measure of condition which triggers component renewal.

5.3.4 Condition Indices

Since the tool is designed for network level analysis it was decided to use condition indices to represent each measure of component condition (see Section 3.2 for a description condition indices). For each condition index, different ranges of condition, or severity bands, were established to represent components in very good, good, poor and very poor condition. The process of so doing is described below.

5.3.4.1 Rails

Wear

The UK standards define the permissible values of widths of the railhead. Using the standards four severity bands were determined as shown in Table 5.4. The minimum permissible value of the width of the railhead indicates the lower threshold of the fourth severity band. Rails with a head width equal or below this value were considered to be in a 'very poor' state (condition) which require renewal (Table 5.4). The upper bound of the third severity band was set to be equal to the lower bound of the fourth severity band. The lower limit of the first severity band was defined according to the head width of a new rail which is 70 mm in the UK. Rail having head width between 70 and 67 mm were considered to be in a 'very good' state (Naito, 2007).

Severity Band	**1**	**2**	**3**	**4**
Condition State	Very Good	Good	Poor	Very Poor
Head width (mm)	70 - 67	67 - 64	64 - 61	61 >

Table 5-4 Severity bands for wear for track category 1A (Naito, 2007)

Corrugation

Four severity bands were also established for rail corrugation according to the amplitude of corrugation as shown in Table 5.5. Grassie *et al*., (2008) suggest that if the amplitude of corrugation increases beyond 0.1mm, the rail is in a 'very poor' state. Therefore, this value was assigned to the lowest bound of fourth severity band. The upper bound of the third severity band was set to be equal to the lower value of the fourth severity band. The lowest value of first severity band was set to zero which indicates no corrugation.

Severity Band	1	2	3	4
Condition State	Very Good	Good	Poor	Very Poor
Corrugation (mm)	0.00 - 0.04	0.04 - 0.08	0.08 - 0.10	≥ 0.10

Table 5-5 Severity bands for corrugation for track category 1A (Naito, 2007)

<u>EMGT</u>

EMGT of the rail with respect to the time it first started service was used to determine a rail's severity bands (see Table 5.6). Based on rail type and track category different limits of EMGTPA were used according to the standards (Office of Rail Regulation, 2008). Tracks with higher EMGTPA and speed deteriorate at a faster rate (see Section 2.3.1). Therefore, the effective lifespan of track categories with higher EMGTPA and speed differ from the tracks with lower EMGTPA. The permissible service life according to EMGT, for all track categories, is set to be the lower limit of highest severity band. Table 5.6 is an example of the range of severity bands for JR and CWR belonging to the same track category.

Severity Band	1	2	3	4
Condition State	Very Good	Good	Poor	Very Poor
JR (EMGT)	0 - 267	267 - 534	534 - 800	800 <
CWR (EMGT)	0 - 334	334 - 668	668 - 1000	1000 <

Table 5-6 Severity bands for EMGT for JR and CWR for track category 1A (Naito, 2007)

5.3.4.2 Switches and Crossings

<u>EMGT</u>

Currently in the UK there are no standards which specify the effective operating age of switch components. Due to the fact that these components either operate or fail, two severity bands were defined based on the age of the components, which can be either be in days, months or years depending on the frequency of recorded data. Based on the useful life of switch components the value of the lower bound of the second severity band was defined. To make the unit of service life compatible with the system, the permissible age (EMGT) of the component is determined on a yearly basis. An example of the severity bands of switch components used in the research are shown in Table 5.7.

To better plan for maintenance (i.e. preventive maintenance) it would be more beneficial to specify more than two condition states so that different deterioration stages can be identified, and accordingly suitable treatment types can be assigned to inspect or maintain the condition of components before reaching failure. However, the information available to enable this was not available and so it was decided for the prototype system only to use two severity bands.

Severity Band	**1**	**2**
Condition State	OK	Failed
Clamp Lock (EMGT)	0 – 62.5	62.5<
Point Machine (EMGT)	0-70.7	70.7<
Stretcher Bars (EMGT)	0-162.5	162.5<
Supplementary Derives (EMGT)	0-112.5	112.5<
Slide Chairs (EMGT)	0-100	100<
Heaters (EMGT)	0-187.5	187.5<
Fastenings (EMGT)	0-131.25	131.25<

Table 5-7 Severity bands for switch components (Rama & Anderws, 2013)

<u>Wear and Corrugation</u>

Because the type of crossing varies according to its geographical location, suitable standards must be determined based on the type and curvature of crossings for each track category (see Section 2.2.2). In this research, on the assumption that the performance of crossings is affected by corrugation and wear, it was assumed that same set of standards used for rails are applicable for crossings. Therefore, adequate permissible values of corrugation, wear and EMGT can be specified to determine the number of severity bands for crossings (see Section 5.3.4.1).

5.3.4.3 Sleepers

<u>EMGT</u>

The service life of sleepers, defined in UK standards, is a function of the type of sleeper and the corresponding track category. Accordingly, the EMGT specified in standards as the maximum allowable before the sleeper must be replaced was set as the minimum threshold of the fourth severity band. The lower bound of the first severity band was set equal to zero indicating new a sleeper. The rest of the bands were assumed to be equal in size between the range of minimum and maximum values of EMGT. Table 5.8 represents the severity bands for concrete, timber and steel sleepers for a track category 1A.

Severity Band	1	2	3	4
Condition State	Very Good	Good	Poor	Very Poor
Concrete (EMGT)	0 - 350	350 - 700	700 - 1050	1050<
Timber (EMGT)	0 - 300	300 - 600	600 - 900	900 <
Steel (EMGT)	0 - 150	150 – 300	300 - 450	450 <

Table 5-8 Severity bands for concrete sleeper (Naito, 2007)

5.3.4.4 Ballast

Track geometry

Ranges of SD of track geometry are specified in NR standards to represent different conditions of ballast (Network Rail, 2013). Different permissible values are specified for vertical and horizontal alignments of track geometry and also according to the bandwidth associated with the measurement of track geometry, i.e. 35m or 70m (see Section 2.4.4). Four severity bands are specified in the standards to represent the condition of the ballast. Table 5.9 shows the range of SD values, considering 35m and 70m wavelength of vertical and horizontal alignment of track geometry as a measure of condition for ballast with the line speed of 100 – 110 mph. For the purpose of the research the values specified by Network Rail were adopted to represent ballast condition.

Severity Band	1	2	3	4
Condition State	Very Good	Good	Poor	Very Poor
SD of 35 m Vertical Profile (mm)	0.0 - 1.9	1.9 - 2.7	2.7 - 3.4	3.4 <
SD of 35 m Horizontal alignment (mm)	0.0 – 0.53	2.10 - 2.67	2.67 - 6	6 <
SD of 70 m vertical profile (mm)	0.0 – 3.28	3.28 – 5.09	5.09 – 6	5.66 <
SD of 70 m horizontal alignment (mm)	0.0 – 2.7	2.10 - 4.62	4.62 – 5.14	5.14<

Table 5-9 Severity band for 35 m vertical profile (Network Rail, 2013)

5.3.4.5 Subgrade

Track Stiffness

No standards were identified from the literature which could be directly used to specify subgrade condition for a network level analysis. However, track stiffness, which can be measured by a variety of technologies, is related to the condition of the subgrade (see Section 2.3.6). It is proposed therefore in this research to use track stiffness as a measure of subgrade condition. Burrow *et al.,* (2009) found that for a UIC60 rail type, track stiffness (dk/ds) of 55 kN/mm (one rail), or equivalently track modulus of 28 MPa (conversion done by Equation 2.10), measured from top of the rail is the minimum to provide good track performance. Whereas for highspeed lines, track stiffness values between 70 to 80 KN/mm (one rail) are optimal. In addition, it was stated that for highspeed lines track stiffness of 200 kN/mm is optimal stiffness measured from top of the sleeper, whereas for non-highspeed freight lines track stiffness value of 160 KN/mm was shown to be adequate in situations where the rail pad and sleeper stiffness are respectively 80 kN/mm and 200 kN/mm and sleeper spacing and ballast depth are respectively 0.6 m and 0.3 (see Section 2.2.5, Figure 2.3) (Burrow, et al., 2009).

5.3.5 Maintenance Standards, Budgets and Prioritisation

In the proposed model, the total required maintenance for the entire railway network is the cumulative maintenance requirements for the conceptual networks making up the network. For a conceptual network these are determined by comparing, for each component, the standards for each measure of condition with the measured condition of each of component. Standards are set by the user and an example of these is given in Table 5.10.

Component	Defect	Intervention level	Treatment
Rail	Wear (head width)	<61 mm	Grind or Renew
	Corrugation	>0.1 mm	Grind
	Wear and corrugation	Every 4 weeks	Grind
	Age	>1000 EMGT	Renew
Sleeper	Age	>1050 EMGT	Renew
S&C	Age	>62.5 EMGT	Renew
Ballast	Vertical profile of track geometry	35m SD>3.4	Tamp or Stoneblow
	Horizontal alignment of track geometry	35m SD >6	Tamp or Stoneblow
	Rate of change of vertical and horizontal track geometry	35m $\frac{dSD}{dt}$ > 3.4	Renewal

Table 5-10 Maintenance standards and intervention levels for track components

In Table 5.10, treatments are assigned by the user using intervention levels which are based on measures of condition as discussed above. However, in case of grinding, in practice, routine maintenance may be carried out on the rail of some sections of track regardless of the condition of the rail. In the UK, NR performs such operations to prevent cracks growing which may eventually result in rolling contact fatigue. To take into account this issue in the proposed model, it is important to, first, determine the track sections requiring routine grinding and then tracking the transition of those track sections to each state to ensure that maintenance is applied on correct sections.

In practice, the available maintenance budget is not always sufficient to perform all of the required maintenance. To take into account budget constraints the system allows the priority order of treatments and defects to be set. For example, see Table 5.11.

Component	Treatment	Treatment priority	Defect parameter	Intervention level	Defect priority	Severity band	Degree of improvement
Rail	Grinding	2	Wear	<64	4	3	50%
	Renewal	1		<61	1	4	100%
	Grinding	3	Corrugation	>0.08	5	3	60%
				>0.1	2	4	100%
	Renewal	1	EMGT	>668	3	3	5%
				>1000	1	4	100%
Sleeper	Renewal	1	EMGT	>700	2	3	0%
				>1050	1	4	100%
S&C	Renewal	1	Age (years)	>2.5	1	2	100%
Ballast	Tamping	2	SD of vertical profile	> 2.7	4	3	50%
				> 3.4	2	4	100%
	Stoneblowing	2	SD of horizontal alignment	>2.67	4	3	50%
				> 6	2	4	100%
	Renewal	1	$\frac{dSD}{dt}$ of vertical and horizontal alignment	> 2.5	3	3	30%
				> 3.1	1	4	100%

Table 5-11 Treatment priority based on defect type and treatment type

Using this approach, the system specifies the maintenance to be carried on defective sections of track according to firstly the priority of the required treatment and secondly the specified defect priority. Initially those sections of the network which require treatment with the highest priority are identified, the treatment is then allocated to those sections with the highest defect priority. Then, should there be sufficient budget remaining those sections with the next highest priority defects are remedied. If all defective sections which require the highest priority treatment have been remedied and there is sufficient budget remaining, the system then considers those sections requiring the treatment with the second highest priority and so on. This iterative process is repeated until the available budget has been exhausted.

When specifying the maintenance and treatment priorities it is important to consider number of factors. These include safety and the long-term effects of maintenance on the rate of deterioration of components. It would be expected that the user would set the priorities for mandatory maintenance at the highest level and use expert judgment to specify the priority levels for other types of maintenance. However, routine maintenance treatments performed regardless to the state of the component, such as grinding, needs to be given a high priority to ensure the system allocates suitable resource as envisioned. Alternatively, as happens in practice routine maintenance is given a separate budget.

In addition, some treatment types such as sleeper or S&C renewal, requires further tamping to level the track geometry. In case of S&C grinding, prior maintenance must be performed to make the track defect free. This necessitates the rational selection of treatment types to get more practical results.

5.3.6 Effects of Maintenance

After allocating the feasible maintenance, the system calculates the level of improvement on the condition of track (i.e. the condition state to which a section of track is transformed). The degree of improvement is specified by the user for many treatment types (see Table 5.11). For other treatment types, including tamping and stoneblowing the historical amount of maintenance carried out influences the level of improvement achieved (Andrews, 2012). For these types of maintenance, improvements are determined using transition matrices determined from an analysis of historical improvements (see Section 6.5.2). This makes it necessary to consider the deterioration following these maintenance activities.

Furthermore, some maintenance types remove multiple defects. For example, when ballast renewal is triggered for a section of track, the track geometry parameters are restored to a new condition, or when track is tamped both vertical and horizontal alignments are remedied. Similarly, when a rail section of a length of track is renewed, it is free from wear and corrugation. To model the rectification of multiple defects the user can specify the joint occurrence of defects on track portions. Examples are given in Tables 5.12 to 5.15.

For example, assume that 19.72% of the network requires rail renewal because its EMGT lies in the 'very poor' condition band. Also assume that 1% of these rails have wear associated defects, and 2% have corrugation. Accordingly, by renewing 19.72% of the rails in the network, 0.20 % (0.01 x 19.72%) of the rails in the network will have their wear set to zero and 0.39% (0,02 x 19.72) of the rails in network will have their corrugation removed.

		Corrugation			
	severity band	1	2	3	4
EMGT	1	35	3	3	3
	2	30	1	2	2
	3	6	2	4	1
	4	3	2	1	2

Table 5-12 Coexistence transition matrices for EMGT and corrugation

		Wear			
	severity band	1	2	3	4
Corrugation	1	30	7	2	4
	2	13	4	5	1
	3	12	2	3	1
	4	5	4	6	1

Table 5-13 Coexistence transition matrices for Corrugation and wear

		EMGT			
	severity band	1	2	3	4
Wear	1	37	5	2	1
	2	29	1	1	2
	3	8	4	0	1
	4	6	1	1	1

Table 5-14 Coexistence transition matrices for EMGT and wear

	Horizontal alignment				
	Severity band	1	2	3	4
Vertical profile	1	27	28	1	1
	2	18	3	3	2
	3	4	2	0	1
	4	3	3	1	3

Table 5-15 Coexistence transition matrices for vertical profile and horizontal alignment

5.3.7 Maintenance Costs

After each maintenance cycle (t), the system calculates the overall maintenance costs. In the proposed tool, costs are based on the type and volume of treatments and are specified by the user (see Section 7.3.7).

5.3.8 Climate-induced Deterioration

The deterioration rate of components over time is not constant and is dependent on variations in traffic load, climate and maintenance history (see Section 6.4.4 and 6.6). The condition of homogeneous track sections in the iteration of the model are determined from the current state of the track and the relevant transition matrix. This way, the time that track sections spend at each state is evaluated and transition matrices are developed (see Section 5.3.2).

As mentioned in Section 5.2, the tool has been developed to predict the future track condition over a user defined period of time. In order to be able to take into account the effects of climate change, it was considered necessary to take into account the effect on changes in component deterioration of changes of temperature and rainfall which may occur during the chosen period of analysis. The effects of these are considered for two components which are considered to be most affected, the rail (buckling) and the subgrade. For buckling, the effect of climate change is included by considering predicted temperature changes which may occur over the analysis period (see Section 6.6.1). For the subgrade, precipitation associated deterioration is firstly evaluated and used to determine future changes in deterioration due to climate change (see Section 6.6.2). To determine the effects of precipitation and temperature on subgrade deterioration and rail buckling, it is necessary to model the changes of these two climate variables over the future years under different CO_2 emission scenarios (see Section 4.4.1).

5.3.8.1 Methodology to Modelling Climate Variables

In general, changes in daily values of temperature and precipitation carry more significant information than changes in annual, monthly or seasonal averages. For this reason, UKCP09 WG (see Section 4.4.2) was used to provide plausible daily time series of maximum temperature and average precipitation projections. The method used is to run the WG for the control period (i.e. observed statistics) 100 times and generate an ensemble of 100 different time series each of 30 years duration (Jones, et al., 2010). Then the WG is run again for each of the future time series of 2020s and 2050s under different emission scenarios. The characteristics of daily time series are used to determine the changes in the future climate, such as determining monthly maximum temperature or average precipitation distributions. A sample of this data, for the first iteration for the baseline (see Section 4.4.2), is shown in Figures 5.3 and 5.4, starting from January for precipitation and temperature respectively.

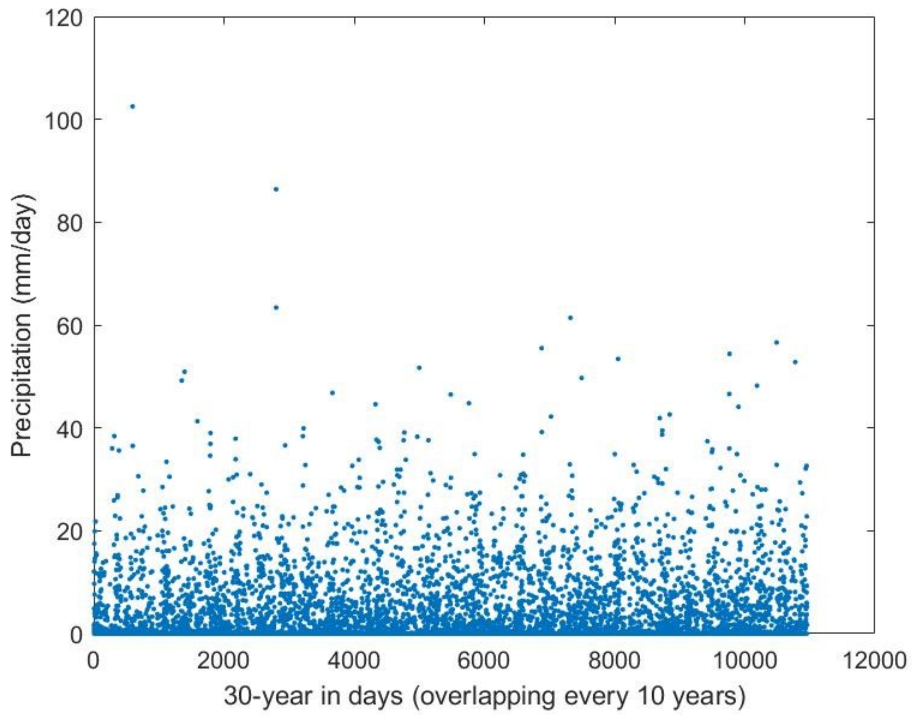

Figure 5-3 Daily average precipitation for the baseline 1960-1990 for the first iteration

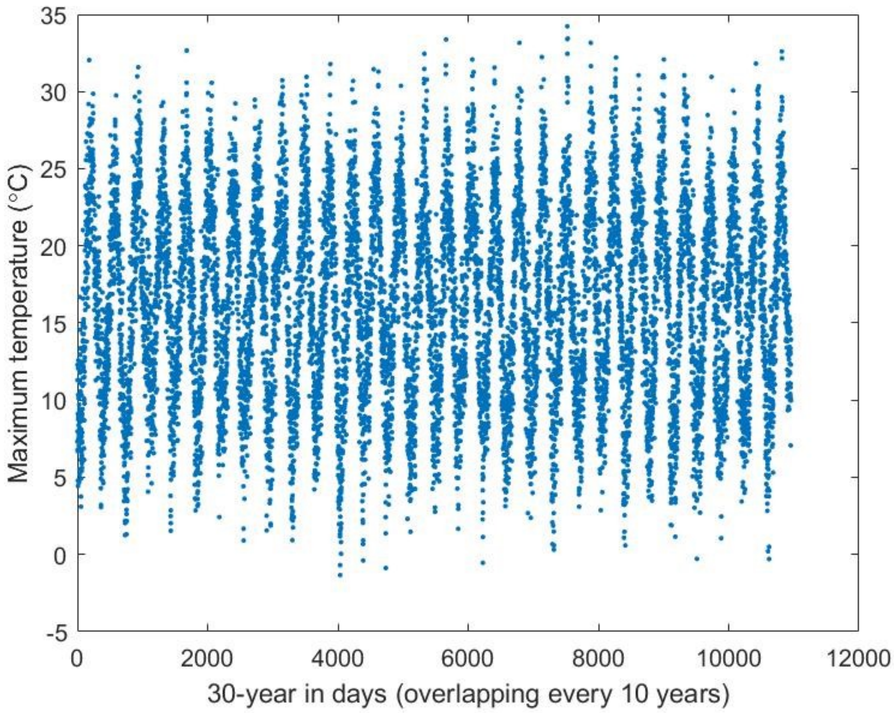

Figure 5-4 Daily maximum temperature for the baseline 1960-1995 for the first iteration

<u>Modelling the Precipitation Rate</u>

For each iteration the average of precipitation for each month is calculated and then amalgamated for 100 iterations. This means that for every month in each iteration there would be 30 averages of precipitation rates and when this is run for 100 iterations and the data is combined, there would be 3000 daily precipitation averages representing each month. After determining suitable probability distributions to represent the data of average daily precipitation for each month, the central estimate (median) of the average daily precipitation for each month is calculated. The reason for calculating the central estimate is because the effects of precipitation on subgrade deterioration depends on various factors such as drainage, the type of fouling materials and level of the fouling index (see Section 2.3.4). Usually for well-designed railway track in good condition, typical amounts of rainfall, in terms of volume and intensity, do not affect the condition of trackbed and subgrade assuming that sufficient voids exist in the ballast and sub-ballast and suitable drainage is provided (Lim, 2004). However, extreme rainfall amounts and intensities can adversely impact the railway track in good condition. Low degrees of saturation and moisture content have negligible effects on settlement. However, the stiffness of the subgrade decreases significantly with high degrees of saturation. Consequently, the intensity and duration of precipitation is a major contributor in impacting the condition of track. For a track in good condition with low level of saturation and adequate drainage there might be sufficient time for the water to drain away from the track. Therefore, to more accurately determine the impact of extremes the hourly rate of precipitation would be a more suitable option to use. The purpose of this project is developing a network level maintenance management system (see Section 1.2), thereby, analysing the hourly rate of precipitation for every track section within each conceptual network would be over complicated with low levels of precision. However, this could be very useful for the case of project level management (see Section 4.3.1). Therefore, the average amount of daily precipitation is considered reasonable to be used within the proposed system.

A sample histogram of the data for the month of January is shown in Figure 5.5. The central estimate is approximately 3 mm/day and using this value the total amount of precipitation in January is approximately 93 mm (i.e. 31 days x 3 mm).

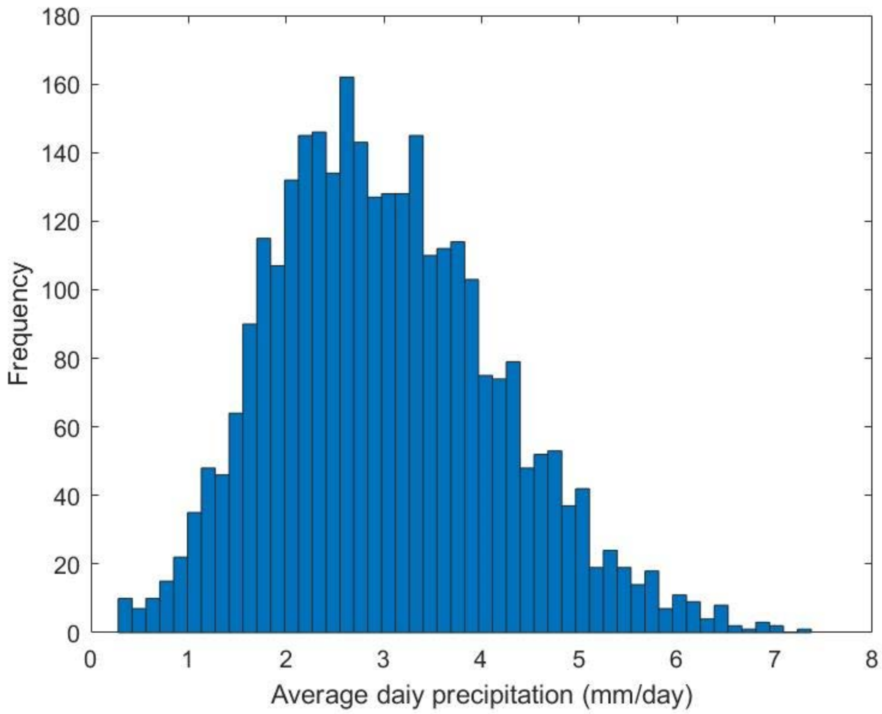

Figure 5-5 Histogram of average daily precipitation for January (baseline)

Thereafter, a suitable probability distribution is fitted to the histogram and based on the Log likelihood, the most suitable distribution is selected, where higher Log-likelihood indicates a better fit (see Table 5.16).

From Table 5.16 it can be seen that the Normal distribution provided the best fit for the data. This process is undertaken for all the months and the results are shown in Figure 5.6.

Distribution	Log likelihood	Mean	Variance	parameters
Exponential	-6316.62	3.02085	9.12554	$\mu = 3.02$
Gamma	-4679.87	3.02085	1.48434	$a = 6.14\ b = 0.491$
Inverse Gaussian	-4885.12	3.02085	1.95316	$\mu = 0.0006\ \lambda = 4.6 \times 10^{-10}$
Logistic	-4734.6	2.9677	1.45273	$\mu = 2.96\ \sigma = 0.664$
Log-Logistic	-4752.98	3.1419	2.3718	$\mu = 1.049\ \sigma = 0.238$
Lognormal	-4813.53	3.0523	1.92437	$\mu = 1.022\ \sigma = 0.433$
Normal	-4706.44	3.02085	1.34997	$\mu = 0.0004\ \sigma = 9.6 \times 10^{-16}$
Weibull	-4661.6	3.02155	1.37399	$\alpha = 3.39\ \beta = 2.78$

Table 5-16 Fitted results and parameters for different probability distributions

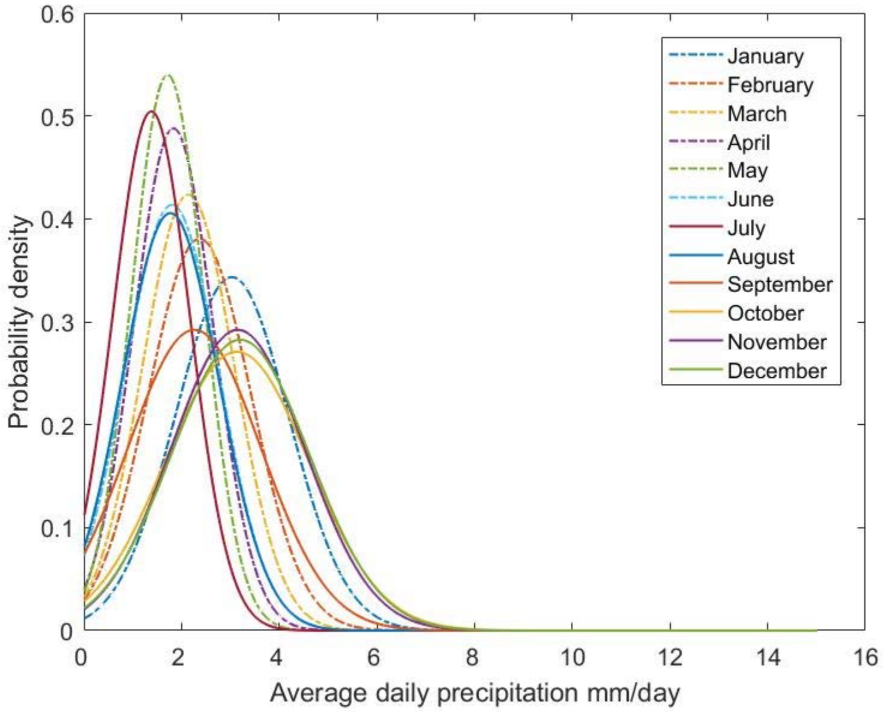

Figure 5-6 Baseline probability density function for different months of year under medium emission scenario

Since it is impossible to determine the absolute value of precipitation, using the Cumulative Distribution function (CDF) plots, the probability of precipitation being less or greater than some specific value can be determined using percentiles.

For example, considering the month of January using Figure 5.7, the central estimate (precipitation at 50% probability level) is 3.04 mm/day. In the same way, there is a 10% probability that precipitation is less than 1.54 mm/day and 90% probability that precipitation is less than 4.52 mm/day or greater than 1.54 mm/day.

This procedure is carried out for the years 2020 and 2050 under the medium and high emission scenarios and an example of the results for January are shown in Figures 5.8 and 5.9.

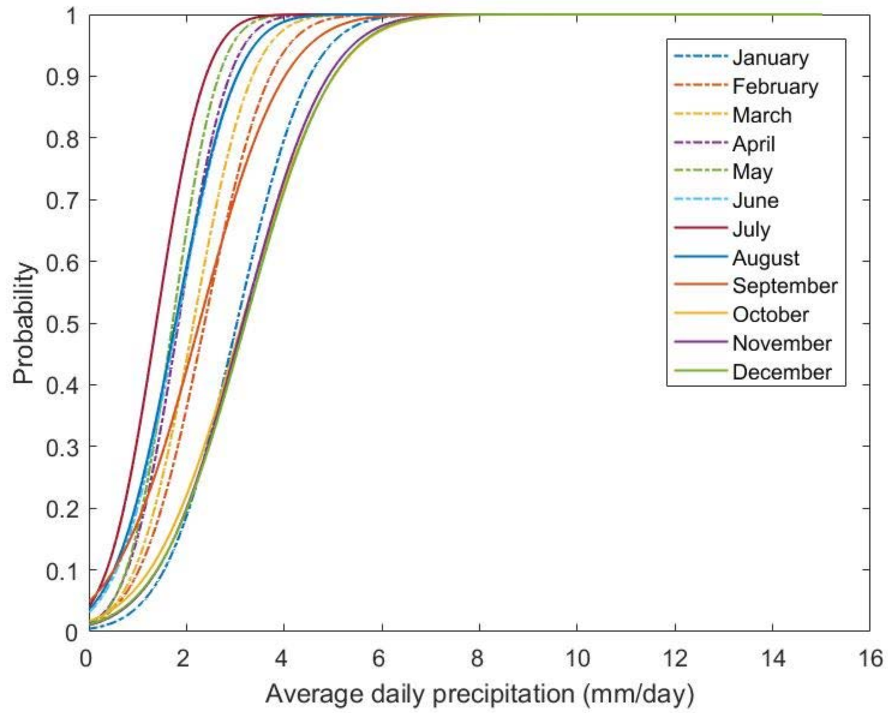

Figure 5-7 Baseline cumulative distribution functions for different months of year under medium emission scenario

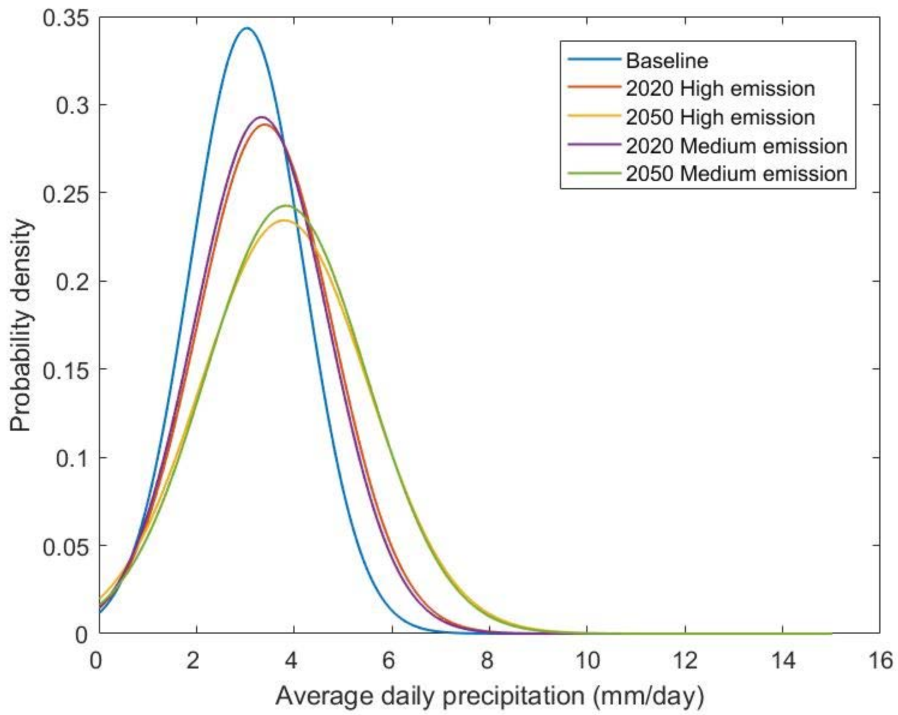

Figure 5-8 Probability density for average daily precipitation for January using the baseline, 2020s and 2050s under medium and high emissions

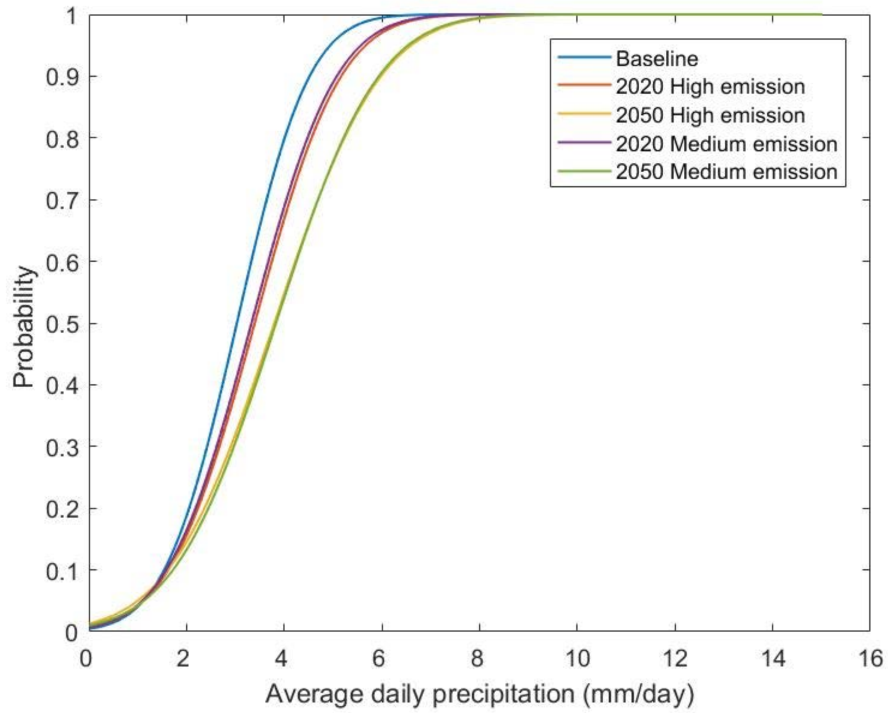

Figure 5-9 Cumulative probability of average daily precipitation for January using the baseline, 2020s and 2050s under medium and high emissions

Modelling Temperature Changes

The same approach used in the above section was also applied to model the variations of monthly temperature using daily values of maximum temperature. Because buckling occurs at high temperatures, instead of using the average of maximum temperature for individual months at each iteration, the maximum of maximum daily temperature for each month was used (see Section 5.3.3). This procedure is continued until the iteration is exhausted and data for each month is integrated to determine the distribution of maximum daily temperatures. Based on Section 2.3.1, it was determined that buckling occurs due to extremes in temperature. Thereafter, for the probability of buckling calculation, according to Section 4.4.2, the 90th percentile was used to represent the extreme temperature for each month.

An example of a histogram of baseline (see Section 4.4.2) data relating to the month August is shown in Figure 5.10.

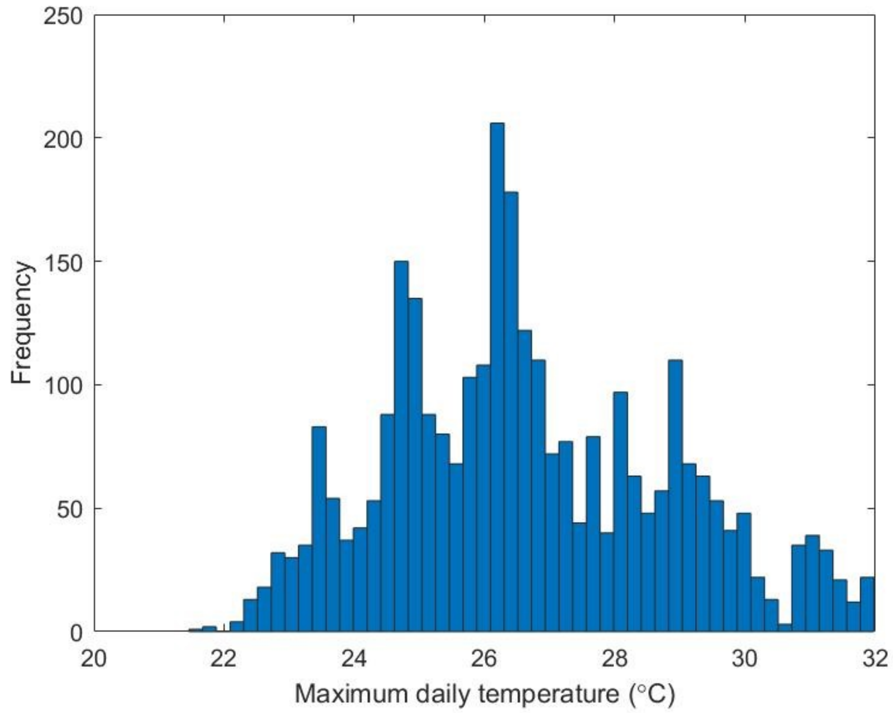

Figure 5-10 Histogram of maximum daily precipitation for August (baseline)

As for the analysis of rainfall data, different probability functions were applied to the histogram of maximum daily temperature and the most suitable distribution was selected to represent the data. The results for the histogram shown in Figure 5-10 are illustrated in Table 5.17.

Distribution	Log likelihood	Mean	Variance	parameters
Exponential	-12849.8	26.6626	710.887	$\mu = 0.2369$
Gamma	-6524.77	26.6625	4.55	$a = 156.06\ b = 0.1708$
Inverse Gaussian	-6516.56	26.66	4.55	$\mu = 0.001\ \lambda = 1.11 \times 10^{-6}$
Logistic	-6609.39	26.56	5.12	$\mu = 0.0016\ \sigma = 3.11 \times 10^{-5}$
Log-Logistic	-6585.63	26.61	5.11	$\mu = 2.24\ \sigma = 5.11$
Lognormal	-6517.06	26.66	4.55	$\mu = 2.1 \times 10^{-6} \sigma = 1.3 \times 10^{-20}$
Normal	-6512	26.66	4.60	$\mu = 0.001\ \sigma = -1.44 \times 10^{-17}$
Weibull	-6759	26.57	6.48	$\alpha = 0.001\ \beta = 0.0024$

Table 5-17 Fitted results and parameters for different probability distributions

Again, the Normal distribution provided the best fit using the Log-likelihood value. The procedure is carried for all the months and the results of their PDF and CDF are shown in Figure 5.11 and 5.12 respectively.

The procedure was completed for data relating to years 2020 and 2050. Examples for the maximum temperatures in the month of August are shown in Figures 5.13 and 5.14 from the baseline and years 2020 and 2050 under medium and high emission scenarios.

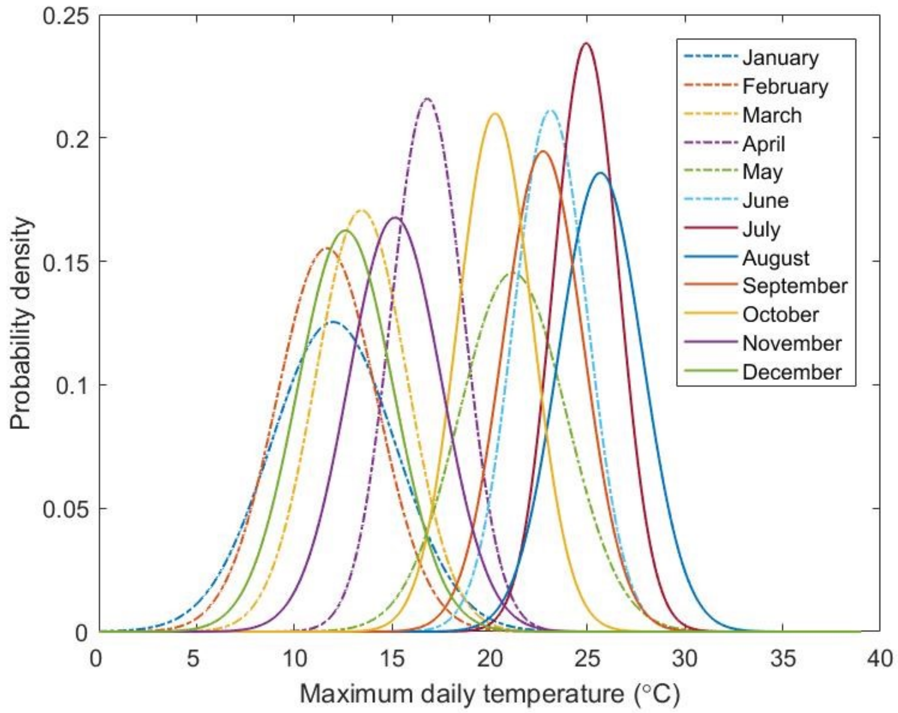

Figure 5-11 Baseline probability density of maximum daily temperature for different month of year

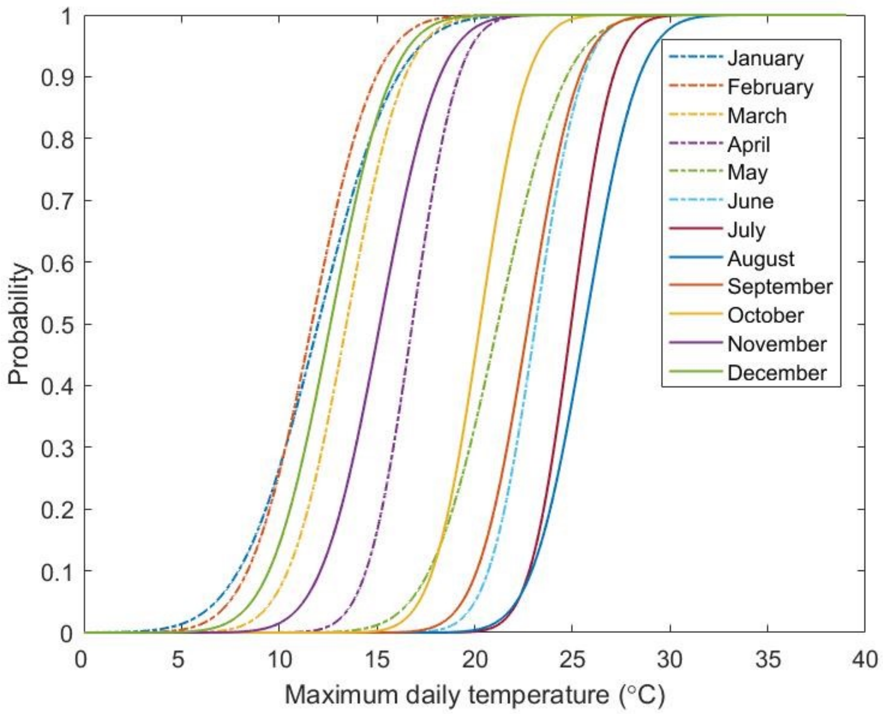

Figure 5-12 Baseline cumulative distribution of maximum daily temperature for different months of year

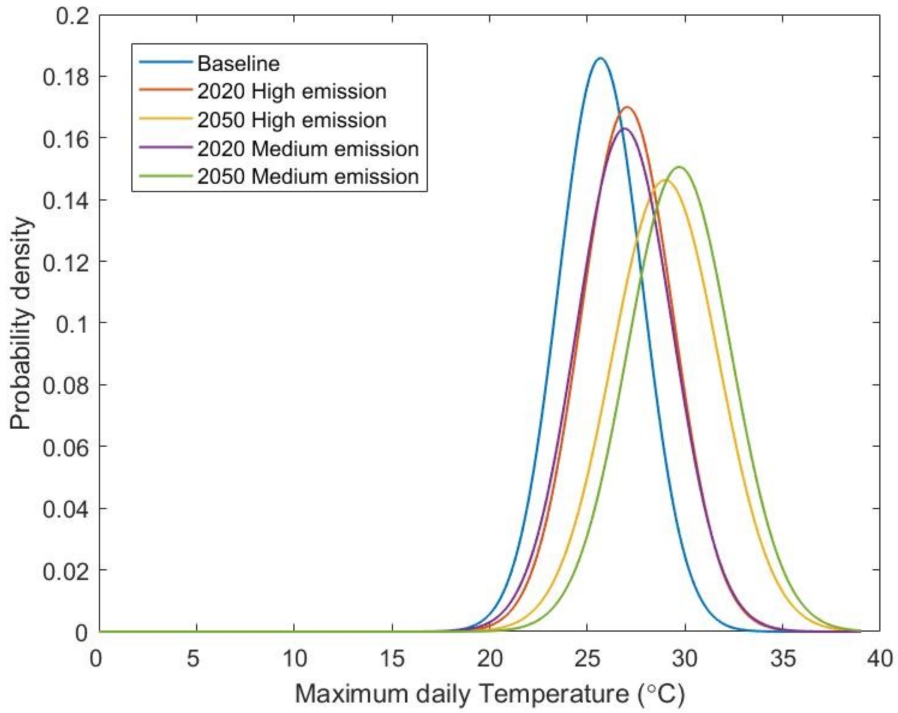

Figure 5-13 Probability density for maximum daily temperature for August using the baseline, 2020s and 2050s under medium and high emissions

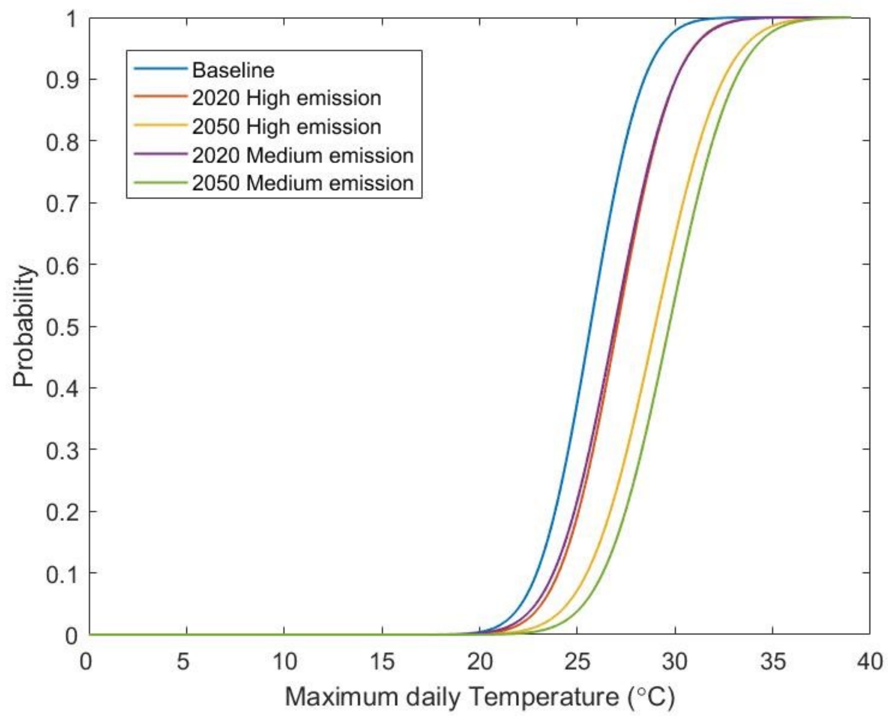

Figure 5-14 Cumulative probability for maximum daily temperature for August using baseline, 2020s and 2050s under medium and high emissions

5.3.8.2 Estimation of the Amount of Precipitation and Temperature at Different Years

As mentioned in Section 5.3.8.1 using UKCP09 WG the values of daily maximum temperature and average precipitation are determined for the baseline and also for the years 2020 and 2050. However, the WG does not provide any information (climate projections) for these two variables for the years within each decade. Because the aim is to calculate the condition and deterioration as a function of maintenance expenditure on an annual basis, it is necessary to estimate and define the daily average precipitation and maximum temperature values for each individual year. From Figures 5.8 and 5.13 it can be observed that values of precipitation and temperature are both increasing from the baseline toward years 2020 and 2050 under both high and medium emissions. Given that there are no other information to be extracted from the WG simulations, for the purpose of this research, it was assumed that the trend of increasing precipitation and temperature values for each month follows a linear function. Consequently, for every month, the range of daily average precipitation and maximum temperature values from year 2020 to 2050 was divided equally according to the number of years in between 2020 and 2050 (i.e. 30 years). In this manner, the distribution of these two climate variables were estimated for every month for each year (see Figures 5.15).

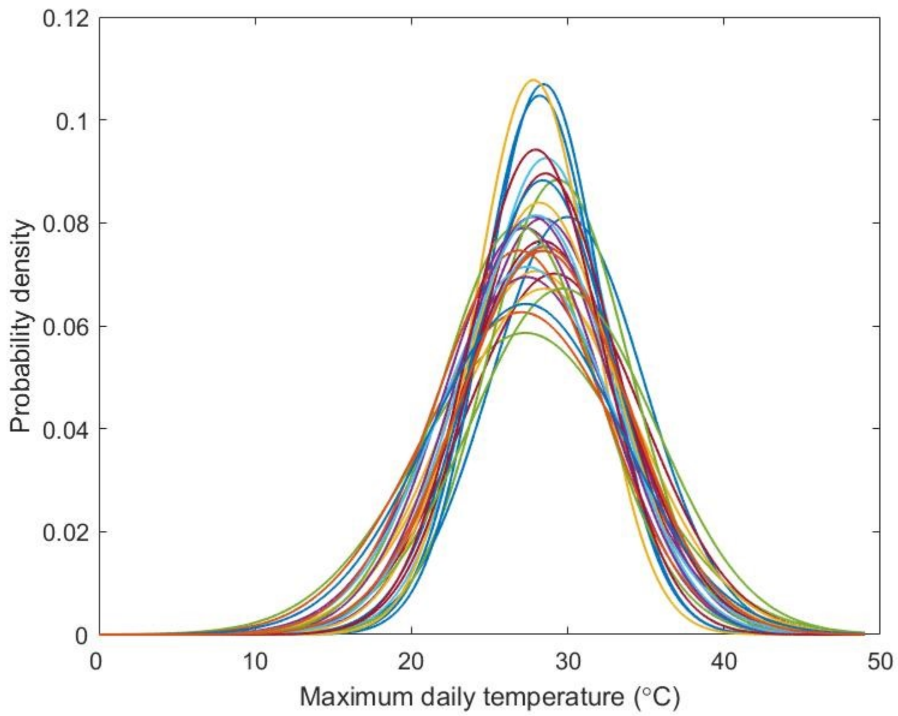

Figure 5-15 Probability density of maximum daily temperature for August for years in between 2020 to 2050 under high emission

For clarity, a cumulative distribution function (CDF) of maximum daily temperature for August from 2020 to 2030 is shown in Figure 5.16 below.

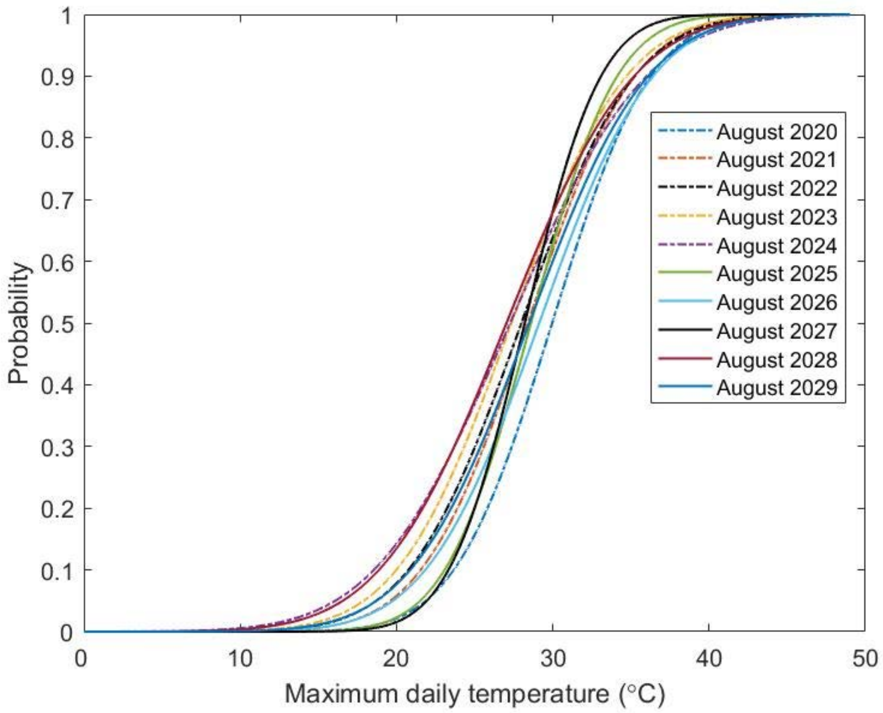

Figure 5-16 Cumulative distribution of maximum daily temperature for August from year 2020 to 2025 under high emission

The CDF plots so calculated are used to calculate the extremes in maximum daily temperatures for each month under different emission scenarios between 2020 to 2050. An example is shown in Figure 5.17 which indicates the maximum daily temperature for August under the high emission scenario using different confidence bounds.

The above process is carried out for all the months and accordingly for every month of a particular year the daily maximum temperature is determined. A sample of a probability density plot for each individual month for the year 2025 is shown in Figure 5.18.

This procedure is carried for all the months and the data is sorted according to the order of the months and year. This way the variations in temperature was estimated (see Figure 5.19). In Figure 5.19 a change in colour determines a change in a year.

Figure 5.20 illustrates the maximum temperature for each month using a 90% confidence level, between years 2020 to 2050 under the high emission scenario.

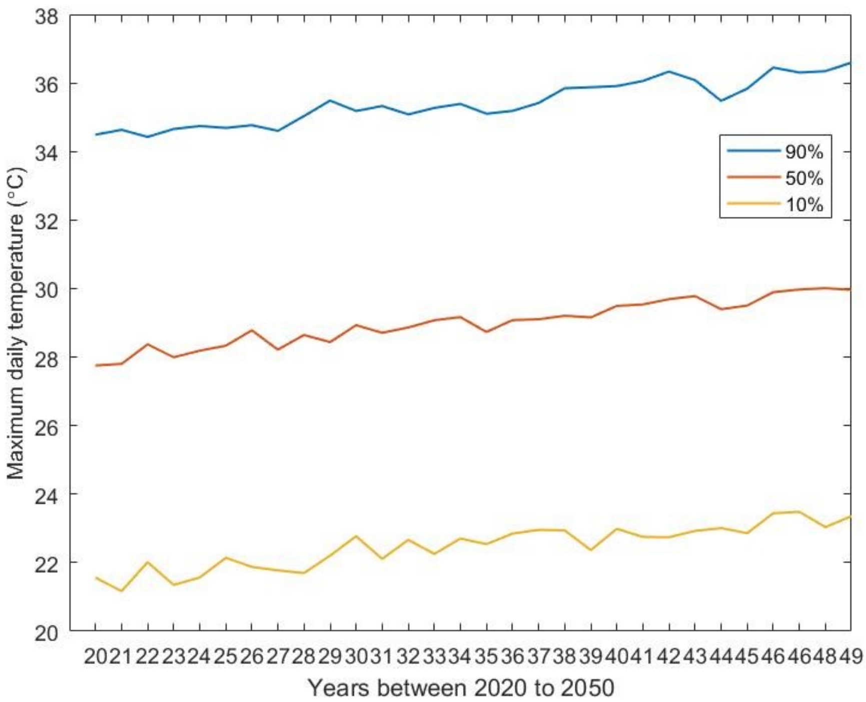

Figure 5-17 Maximum daily temperature for August between years 2020 to 2050 using different confidence bounds under high emission

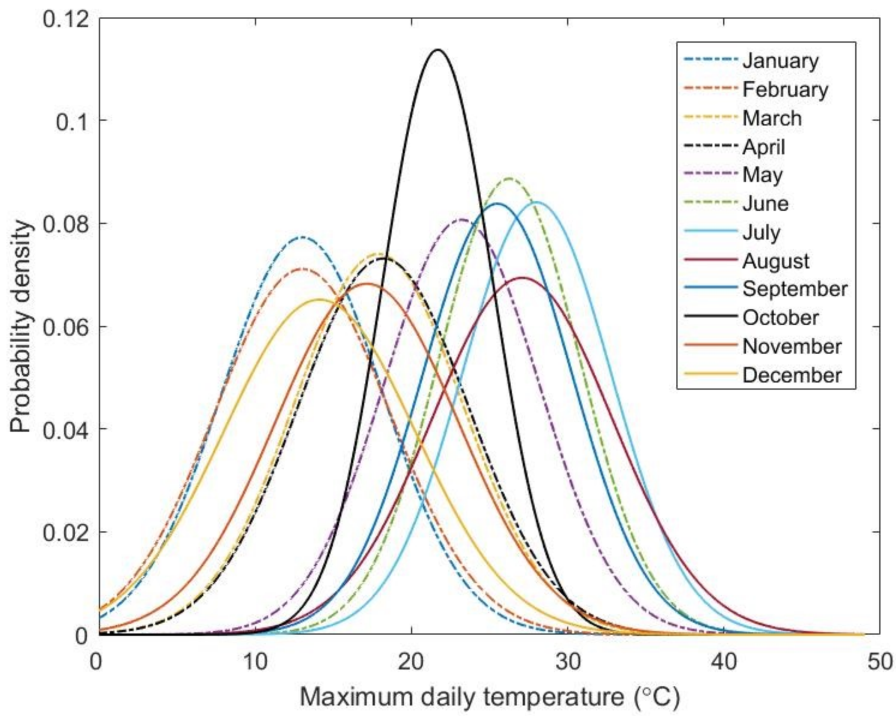

Figure 5-18 Probability density of maximum daily temperature for every month in year 2025

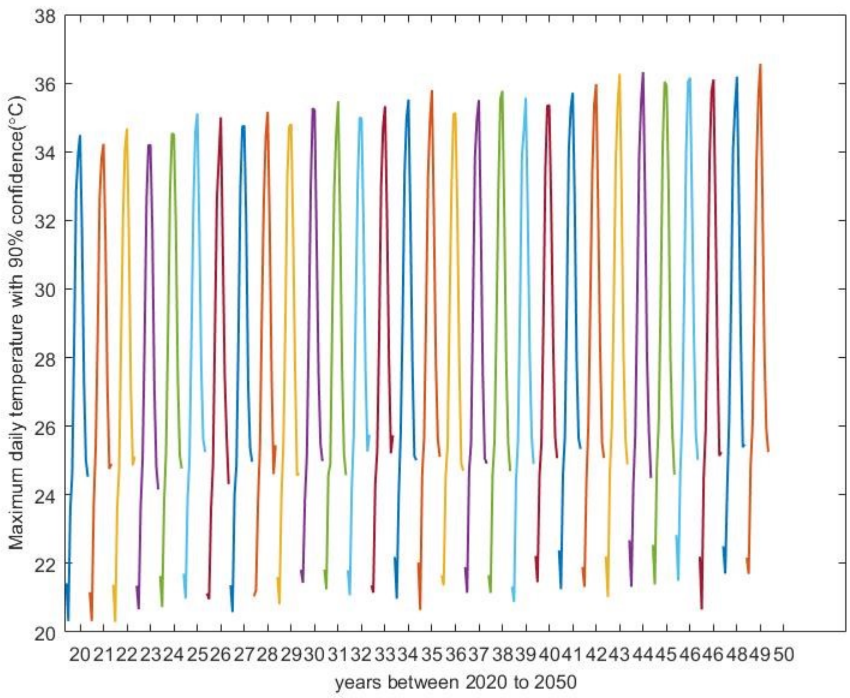

Figure 5-19 90% confidence of maximum daily temperature from 2020 to 2050

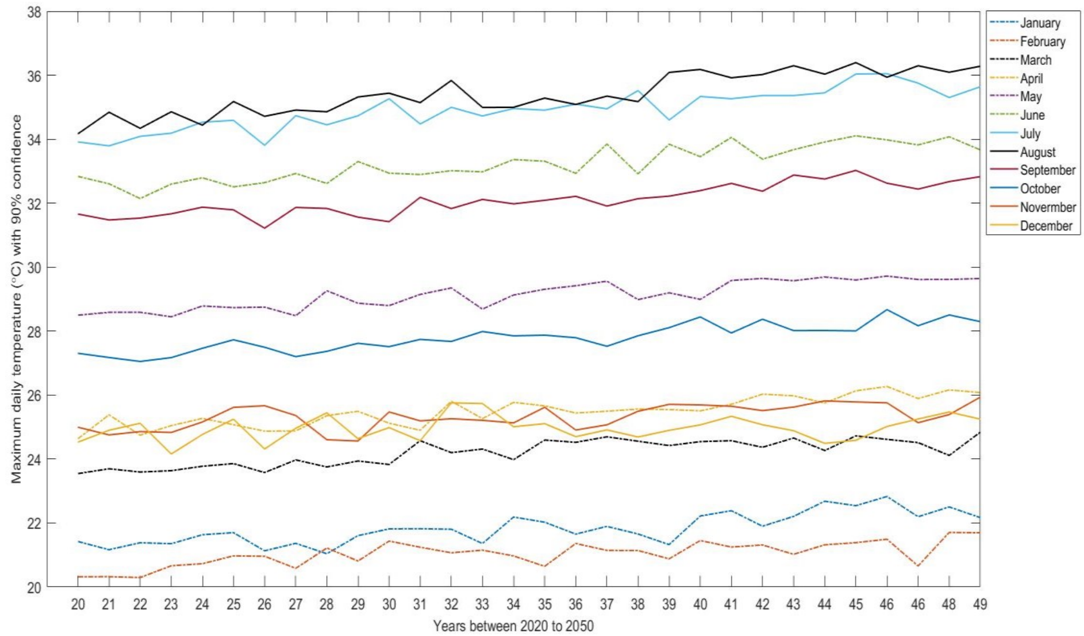

Figure 5-20 Maximum daily temperature for each month over the years 2020 to 2050 using 90% confidence

The same methodology was applied to determine the average precipitation for each month for the years 2020 to 2050. An example of the results of daily average precipitation for January between 2020s and 2029 is illustrated in Figure 5.21. As an example, with reference to Figure-

5.21, the average daily precipitation for January is calculated for 50% and 90% confidence levels and the results are shown in Figure 5.22 for the period 2020 to 2050.

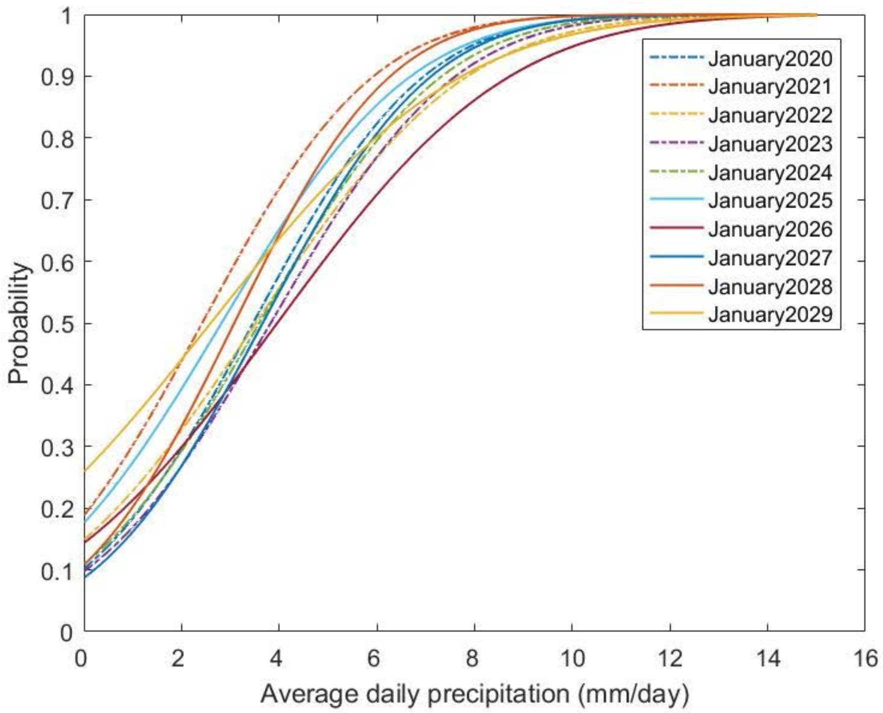

Figure 5-21 Cumulative distribution of average daily precipitation for January from year 2020 to 2025 under high emission

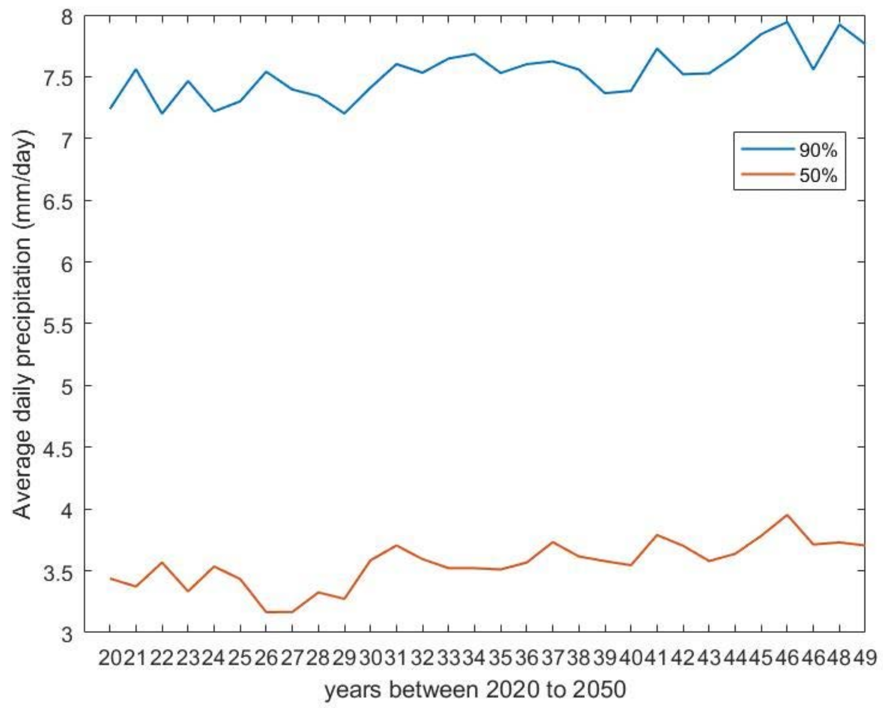

Figure 5-22 Average daily precipitation for January between years 2020 to 2050 using 50% and 90% confidence bound under high emission

To determine the average daily precipitation for every month between years 2020 and 2050 the same procedure was carried out. An example of the probability density plot of the average daily precipitation for different months within 2025 under high emission scenario is illustrated in Figure 5.23.

Figure 5.24 illustrates the average daily precipitation for every month from 2020 to 2050 using the central estimate.

An example of the average daily precipitation for each month within the 30-year time period using a 50% confidence level is depicted in Figure 5.25.

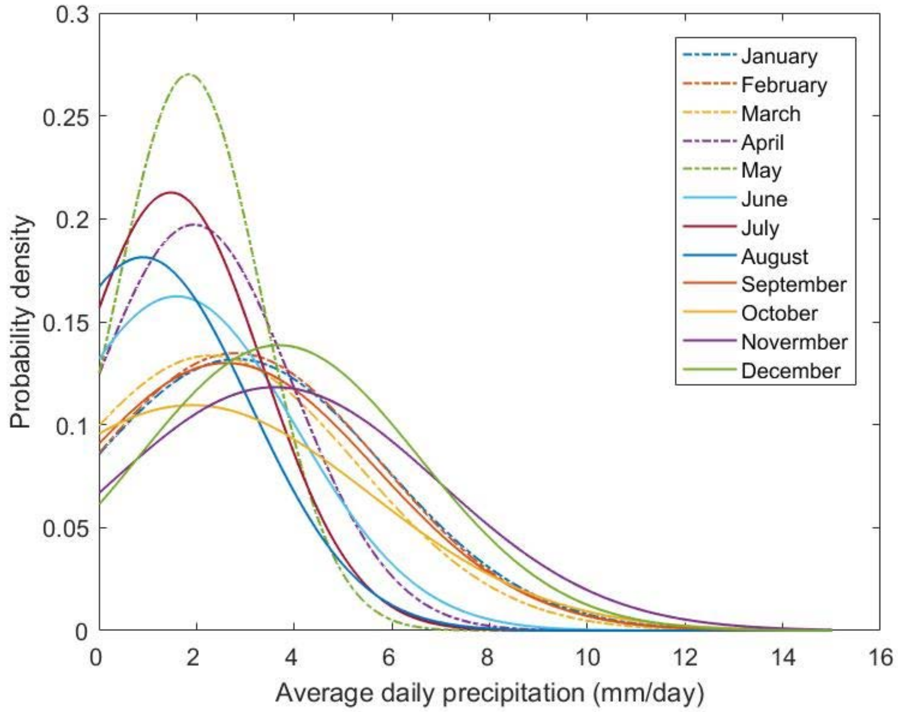

Figure 5-23 probability density of average daily precipitation for each month of year 2025 under high emission scenario

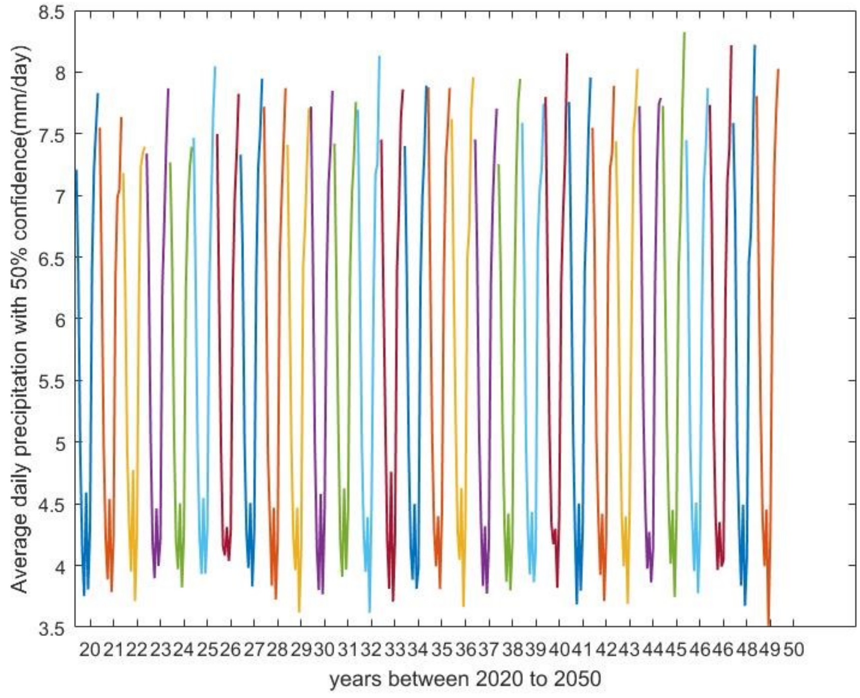

Figure 5-24 50% confidence of average daily precipitation from 2020 to 2050 (when there is change in colour there is a change in year)

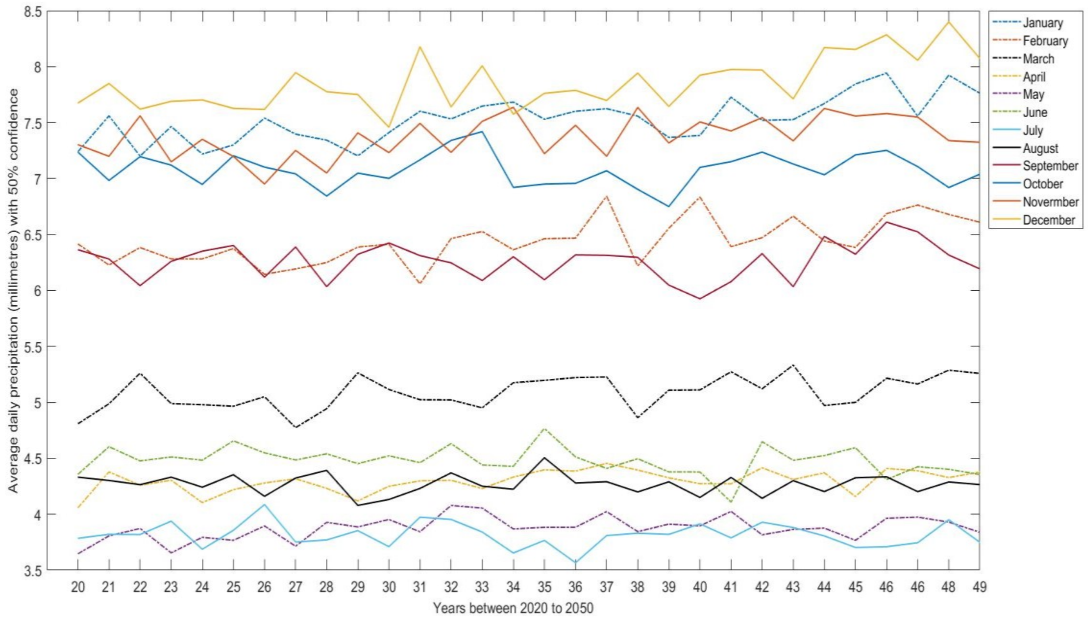

Figure 5-25 Average daily precipitation for each month over the years 2020 to 2050 using 50% confidence under high emission

5.3.8.3 Modelling the Probability of Buckling Occurrence

In extreme temperatures, rail temperature can exceed its SFT and may result in the rail buckling. In addition, the condition of the ballast significantly contributes to buckling. To account for this, a relationship between the probability of buckling, rail temperature (see Section 2.3.1.4 for the calculation of rail temperature), and track geometry was determined using multivariate regression analysis (see Section 6.6.1.1). As part of this process the number of buckling at different time, mainly in months, along with the corresponding maximum daily temperature for each month and the condition of the track geometry for the sections of track which buckled must be determined.

In addition, as described in Section 2.3.1, maintenance interventions such as tamping and stoneblowing may alter the SFT of rails. Therefore, rails in the same condition state with the same temperature could be prone to buckle depending on their previous maintenance regimes. Thus, to calculate more accurate results, it is important to include the past maintenance activities when determining the probability of buckling.

Accordingly, in order to determine a probability of buckling it is necessary to combine both the distribution of measures of ballast condition (SD of vertical track geometry), and the distribution of maximum rail temperatures for each month. This was achieved using a Monte Carlo simulation which is further described and illustrated in Section 6.6.1.

5.3.8.4 Modelling the Effects of Precipitation on Degradation

For the purposes of determining changes of future subgrade deterioration rates which may occur because of precipitation induced deterioration, a precipitation deterioration factor was developed. This was determined by comparing the deterioration of different track sections, with the same homogenous characteristics, other than climate. It was assumed that any difference in the deterioration rates between homogenous track sections was related to the difference in the amount of precipitation.

The precipitation degradation factor was determined using the following steps:

1. The amount of monthly precipitation of two regions is determined (see Section 5.3.8.2) and any changes in precipitation is calculated for different emission scenarios (see Section 6.6.2)
2. The difference between subgrade deterioration of the conceptual networks of two different regions are analysed and precipitation deterioration factor is calculated as the ratio of the deterioration of the networks per millimetre rainfall (Equation 5.4). Using

this ratio, the amount by which the deterioration of conceptual network differs is calculated.

(5.4)

$$PF = \frac{D_a - D_b}{D_b} \times 100$$

(Where D_a and D_b indicate the deterioration rate of conceptual networks per millimetre rainfall, considering subgrade stiffness as measure of condition, at regions a, and b respectively).

3. After completing the procedure for all the conceptual networks, a sensitivity analysis was undertaken to define a relationship between the change in precipitation deterioration factor and the change in precipitation.
4. Based on step 3 above, the future deterioration rate of the conceptual networks was estimated using the future changes of precipitation rate for each conceptual network in different regions and accordingly new transition matrices were developed to reflect the effects of precipitation on track condition.

This process is demonstrated using real datasets in Section 6.6.2.

5.3.9 Overall Network Condition

One of the objectives of the asset management tool developed in this research is to be able to convey the overall (conceptual) network condition in a straight forward manner (see Section 1.3 Objective 4). To achieve this, five Track Condition Indices (TCI) were developed to indicate the overall condition of the network. These are defined in Equations 5.5 to 5.7 below. TCI1 is the cost to repair one-kilometre of track and determines the overall efficiency of maintenance, for each analysis year. Whereas, TCI2 and TCI3 indicate the overall condition of the network using track geometry and its variation over time, respectively. (Burrow, et al., 2009). TCI4 determines the condition of the network with respect to track stiffness and its special variations. The overall probability of buckling occurrence for the network is determined by TCI5.

(5.5)

$$TCI1 = \frac{\sum_{j=1}^{n} \sum_{i=1}^{m} MV_{ij} \times MC_i}{L}$$

Where m, n are the number of maintenance treatments and conceptual networks respectively. MV is the volume of maintenance type i for subnetwork j. MC is the cost of maintenance type i and L is the total length of the network (Burrow, et al., 2009).

TCI2 and TCI3 are defined as:

(5.6)

$$TCI2, TCI3 = \frac{\sum_{j=1}^{n} p_j \times d_j}{L}$$

Where, p is the percentage of network j that has a very good or good track geometry and d and L respectively represent the length of network j and total length of the whole network in kilometres. TCI4 is determined same as TCI2 and TCI3, however, instead of track geometry subgrade stiffness is used. High values of TCI2, TCI3 and TCI4 indicates good network quality.

TCI5 is defined as:

(5.7)

$$TCI5 = \sum_{i=1}^{n} \sum_{j=1}^{j} N_{buckle(i,j)}$$

Where j is the total number of severity bands, i is the number of conceptual networks and N_{buckle} is the probability of buckling (see Section 6.6.1) High values of TCI5 indicated higher likelihood of buckling occurrence.

5.4 Summary

In this chapter, the elements of an iterative model to analyse the effects of maintenance, and predict the changes in defect distribution over the network were discussed. The described model requires the initial condition of a number of track components to be specified by the user in the form of probability distributions of measures of condition. By means of user specified maintenance standards, for each measure of component condition, the percentage of track sections requiring maintenance is determined by comparing the standards with the distributions of condition. These when aggregated over the network for each component are used to determine the total maintenance costs for the maintenance period. In order to take into account budget constraints a process was developed which allows treatments of defects to be prioritised by the user. The effects of maintenance on the subsequent track condition and the subsequent deterioration due to the combined effects of train loads and the environment were modelled using Markov chains. The distributions of condition for each component so determined was used as the input into the next iteration of the model (see Section 5.3.5).

The effects of climate induced deterioration on railway track components were taken into account using a novel methodology to analyse and model the future temperature and precipitation variables along with their deteriorating effects on the rail and subgrade respectively.

The following chapter explains the logical design of the system based on the methodology developed in this Chapter.

Chapter Six

6. THE LOGICAL DESIGN OF THE SYSTEM

6.1 Introduction

Chapter Five provided the research methodology undertaken in this work to develop a prototype system capable of determining network level railway track quality as a function of component deterioration and maintenance expenditure. It was proposed to use condition indices to represent the condition of individual components of the railway track structure (see Section 5.3.4). Markov chains which are determined from historical rates of deterioration and maintenance restoration effects were proposed to determine the future network condition (see Section 5.3.2 and 5.3.6).

In this Chapter, the logical design of the system developed according to the methodology described in Chapter Five is further elaborated. The processes and algorithms used to calculate the deterioration and restoration transition matrices are explained in detail and illustrated using real datasets (see Sections 6.4 and 6.5). Furthermore, the logical design associated with modelling temperature and precipitation induced deterioration is fully described (see Section 6.6).

6.2 Design of the System

According to the methodology (see Section 5.2 and Figure 5.1), the system consists of number of inputs, processes and outputs as described below.

6.2.1 Inputs

The following inputs are required to be given by the user for each conceptual rail network (see Section 7.3):

1. Probabilistic distributions of measures of condition for the rail, sleepers, S&Cs, ballast and subgrade (Section 5.3.3)

2. A set of relevant standards by which the condition of components is compared to determine maintenance requirements. This should include the priority order of treatments and defects (Section 5.3.4 and 5.3.5)
3. The minimum analysis period, t
4. The number of years of analysis, T (see Equation 5.3)
5. The annual maintenance budget for each year of the period of analysis
6. Historical data (such as Figure 6.1) are required for the system to develop transition matrices (Markov models) representing the deterioration and restoration of each component (see Sections 5.3.2 and 5.3.6)
7. The amount of maximum daily temperature and average rainfall for each month for the period of analysis (Section 5.3.8)

6.2.2 Processes

The developed system uses the following processes to determine the effects of deterioration and maintenance.

1. The prediction of the future condition of track components using a Markov chain requires transition matrices to be developed which indicate the probability of portions of track transiting from one condition to another at each iteration (Section 6.4.2)
2. The change in deterioration rate after maintenance is determined using transition matrices (see Section 6.4.3)
3. Restoration transition matrices are required to determine the change in track condition with respect to maintenance history and user specified standards (see Section 6.5.2)
4. The probability of buckling occurring is calculated using the relationships between the rail temperature and track geometry (see Section 6.6.1)
5. The effects of precipitation on subgrade deterioration and the associated transition matrices are calculated using a precipitation deterioration factor (see Section 6.6.2)

6.2.3 Outputs

Based on the inputs and processes a number of outputs are given by the system in graphical and tabular format. These are as follows:

1. The feasible maintenance under budget constraints and the maintenance required to keep the track at acceptable levels, according to standards, are provided for each component over the specified analysis period (see Section 7.4)

2. The overall condition (according to five TCIs, suggested in Section 5.3.9) of the railway network is specified as a function of maintenance expenditure (see Section 7.4)

6.3 Data

To illustrate the main processes of the developed system track component data were collected from various sources. These sources are summarised below and the data itself are described in more detail in the relevant sections of this Chapter. Other data and information such as costs of maintenance used to run the prototype system are described in Section 7.3.

6.3.1 Track Geometry

The geometry condition data in the form of SD of vertical and horizontal track geometry alignment was obtained from Network Rail reports (Network Rail, 2013). These data relate to St Pancras to Chesterfield Line (SPC), Bournemouth Main Line (BML) and East Coast Mainline (ECM). In general, BML is classified into three sections as BML1 (Waterloo to Northam Short Mile), BML2 (Northam Short Mile to Dorchester Junction) and BML3 (Dorchester to Weymouth). Whereas, based on available data, SPC was divided into two sections of SPC1 (St Pancras to Bedford) and SPC3 (Wellingborough to Wigston South Junction). For ECM only ECM1 (King's Cross to Shaftholme Junction) was available. A sample of condition of 1/8th mile track section over time is shown in Figure 6.1. However, data were not available for the entire routes explained above. Information regarding the type and installation date of components and S&C locations and curvature were available for some sections of track and subgrade materials were only available for a few small sections. For some track sections the time and type of maintenance was often included in the data. For sections of track were this information was unavailable maintenance was assumed to have taken place where there is a drop in the SD value (see Figure 6.1). After discussing this with NR engineers it was decided to assume that tamping was most likely to have been carried out at these points. In addition, at some points (red circles in Figure 6.1) the value of SD suddenly increases and then decreases. This is due to dynamic stabilisation of the track by the passage of trains after maintenance (Audley & Andrews, 2013). This might also be due to frequency of inspection at same date on different times. Consequently, it was considered necessary to remove these phenomena points from samples (however, the distribution of points is modelled and explained in Section 6.4.1).

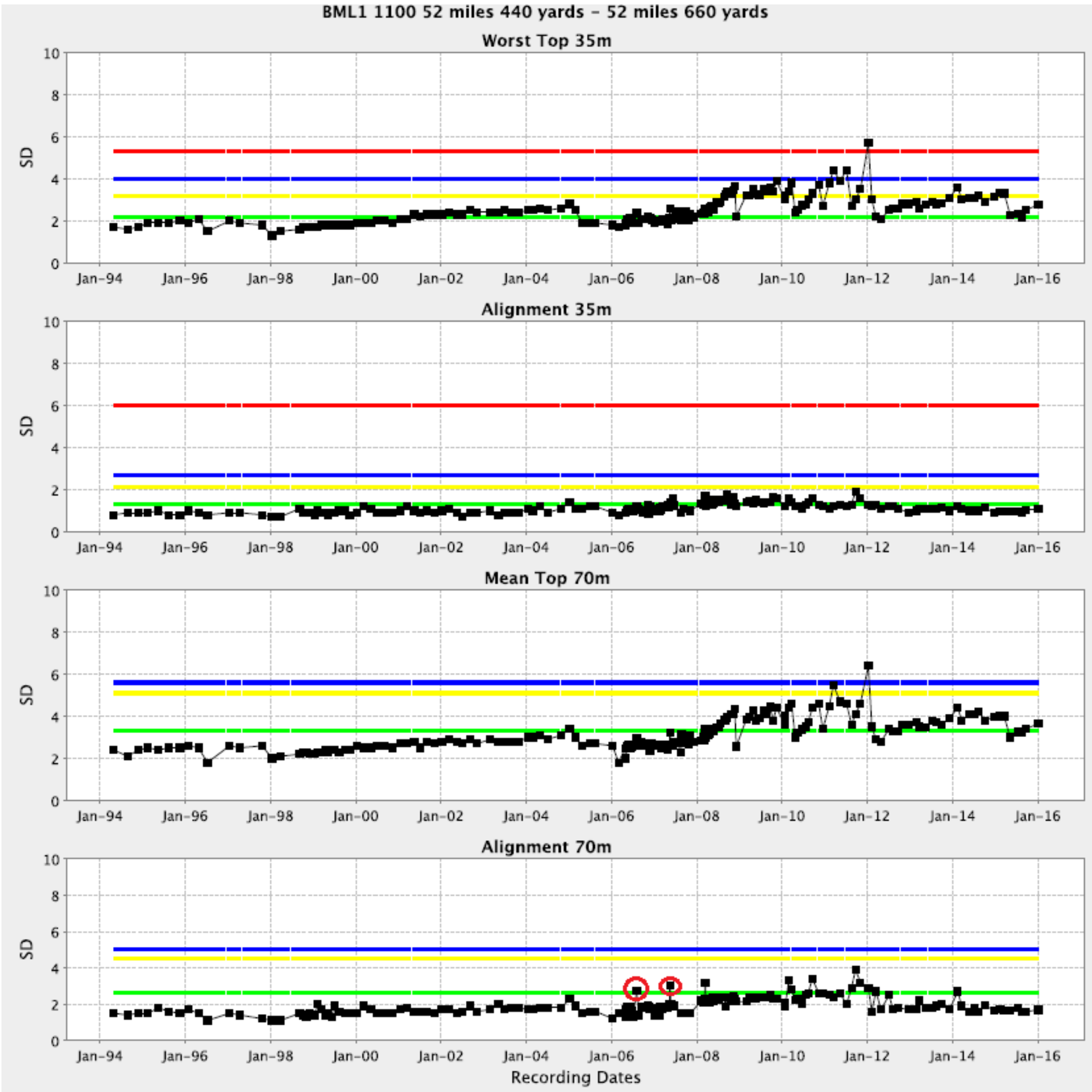

Figure 6-1 Raw data of change in track geometry over time (measured monthly) (Network Rail, 2013)

6.3.2 Rail, Sleepers and Switches and Crossing

Ideally rail, sleeper and S&C condition data, measured at the same time as the track geometry data described above, would have been obtained for the SPC, BML and ECM. However, this data were not available. Therefore, alternative sources for the data were used as summarised in Section 7.3.

6.3.3 Climate Data

The climate data, was obtained from UKCP09 WG simulations and were modelled based on the work carried in Section 5.3.8. The buckling data were obtained from Network Rail reports (Network Rail, 2015) which include the number of track related failures with respect to maximum daily temperature and from information provided by Dobney (2010).

6.4 Markov Model Development

This section describes how the Markov models were developed from historical component condition data. Ballast deterioration and restoration is used as an example, since a more complete data set was available and also because the development of the associated transition matrices are the most complex compared to the other components.

Transition matrices specify, for a particular measure of condition for a track component, the percentage of all components transitioning from one condition state to another (see Section 5.3.2). In order to develop these matrices, track component condition data need to be analysed. It is also necessary to take into account the fact that the deterioration of a component (and therefore its transition matrix) is dependent on its maintenance history (Andrews, 2012). For example, the ballast on a section of newly laid track will deteriorate at a different rate compared to a section which has recently been tamped (see Section 6.4.2). Therefore, the first step in the process is to classify the data for each track section based on its history of maintenance (see Section 6.4.1). The rest of the analysis consists of number of processes as follows:

1. Determining an equation defining the underlying deterioration trend
2. Determining the probability distribution of the condition of components of sections of track
3. Developing the transition matrix

6.4.1 Determining an Equation of the Underlying Deterioration Trend

The process of determining the underlying deterioration trend consists of the following aspects:

1. Preliminary analysis of data: Available condition data (such as Figure 6.1) are scrutinised to identify and classify physical 1/8th mile sections of track which have similar maintenance histories (e.g. tamping followed by stoneblowing followed by tamping). An example using a real data set is shown in Figure 6.2 from which it can be seen that whenever maintenance is undertaken track geometry does not necessarily return to its previous condition, and if it does, it subsequently has a different deterioration pattern. With reference Figure 6.2, occasionally, there is a small period of time after a maintenance intervention when the condition of the track improves. Such apparent anomalies were excluded from the analysis.
2. Determining the relationship defining the underlying trend of variations in track geometry with time: Section 3.3.3 described different methods which can be used to model the deterioration patterns. In this research regression analysis was chosen to

determine the distribution of the measure of condition at each time. As shown in the example of Figure 6.3, between each maintenance intervention, various functions were fitted to the time history data of sections of track to determine the functional relationship between the dependent random variable (measure of condition) and to the independent variable (time).

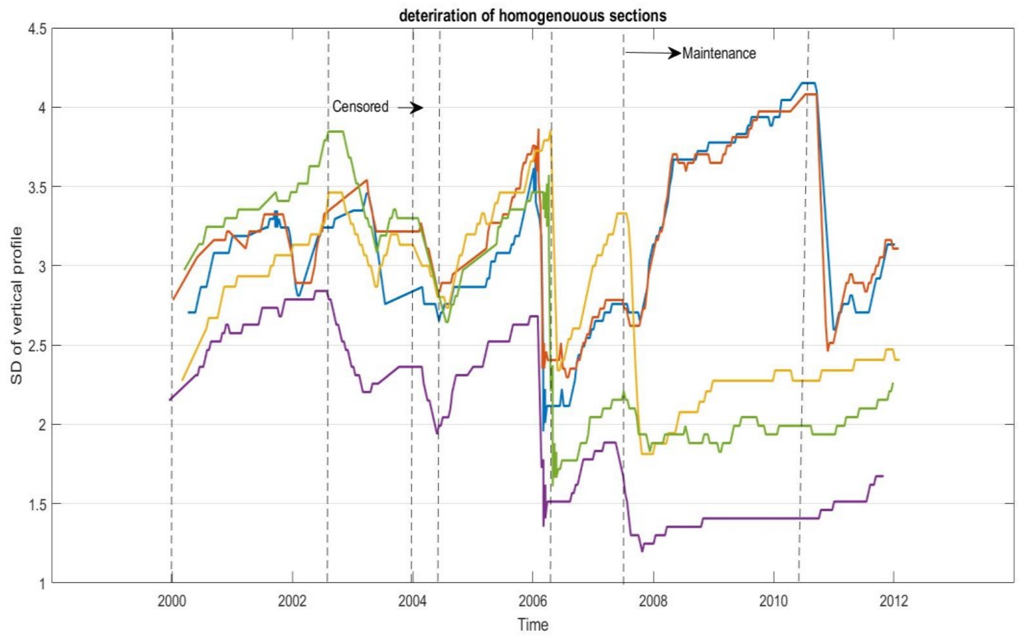

Figure 6-2 Schematic of sampled data of 35m vertical profile of track geometry

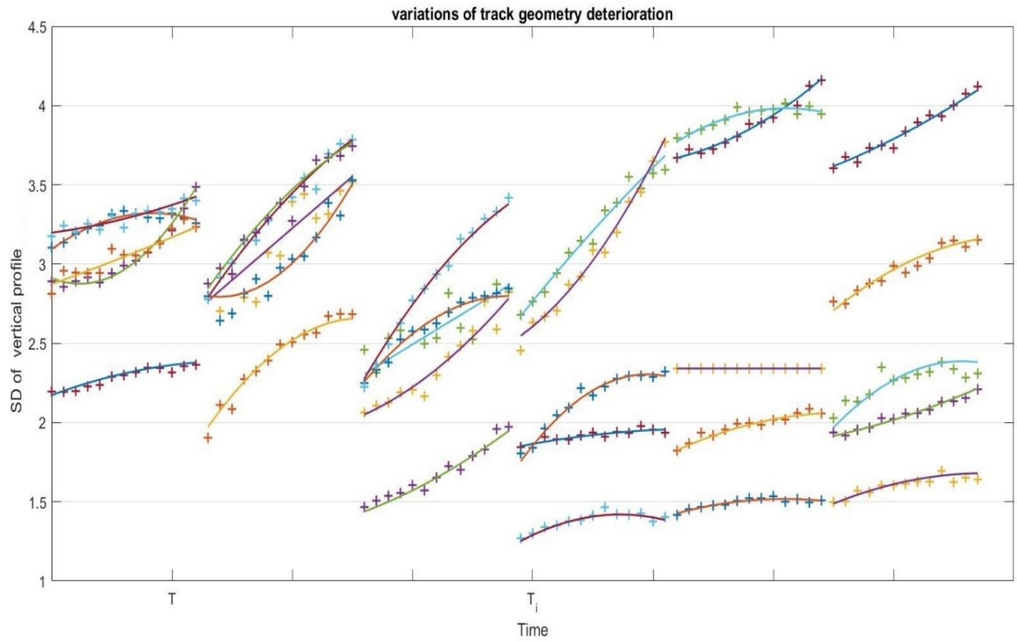

Figure 6-3 Models fitted to determine the deterioration trend of track geometry

The procedure is demonstrated using, a simple linear regression defined as $Y_i = \beta_0 + x_i\beta_1 + \epsilon_i$ fitted to the recorded geometry variations, where Y is the random variable representing the dependent observed values y_i for the independent predictor values x_i and is distributed as $f_{Y_i}(y)$. β_0 and β_1 are the intercept and the slope respectively, and ϵ_i is the error term with zero mean $E[\epsilon_i] = 0$, variance $\mathsf{V}[\epsilon_i] = \sigma^2$, and $\mathsf{V}[\epsilon_i\epsilon_j] = 0$ for $i \neq j$. With these assumptions the following can be derived (Marques de Sa, 2007):

- ϵ_i are independent and identically distributed with $E[Y_i] = \beta_0 + \beta_1 x_i$. Therefore, $E[Y] = \beta_0 + \beta_1 X$ expresses the regression of Y dependent on X. The density of the observed values $f_{Y_i}(y)$ is the density of errors, $f_\epsilon(\epsilon)$, with mean $E[Y_i]$.
- $\mathsf{V}[\epsilon_i] = \sigma^2$ therefore, $\mathsf{V}[Y_i] = \sigma^2$.
- Y_i and Y_j are uncorrelated.

To estimate the regression function Least Squared Errors (LSE) is used to minimise the total sums of the squared errors (deviations) between the observed values and the estimated $\hat{y} = b_0 + b_1 x_i$, where b_0 and b_1 are estimates of β_0 and β_1 respectively (Marques de Sa, 2007).

(6.1)

$$E = \sum_{i=1}^{n} \epsilon_i^2 = \sum_{i=1}^{n} (y_i - b_0 - b_1 x_i)^2$$

Using LSE, the following normal equation is derived:

(6.2)

$$\begin{cases} \sum y_i = nb_0 + b_0 \sum x_i \\ \sum x_i y_i = b_0 \sum x_i + b_1 \sum x_i^2 \end{cases}$$

Therefore, $b_1 = \frac{\sum(x_i - \bar{x})(y_i - \bar{y})}{\sum(x_i - \bar{x})}$, and $b_0 = \bar{y} - b_1\bar{x}$.

The coefficient determination or goodness-of-fit variable, R^2, is (Marques de Sa, 2007):

(6.3)

$$R^2 = \frac{SSR}{SST} = 1 - \frac{SSE}{SST},$$

where $SSE = \sum(y_i - \hat{y}_i)^2$ is the sum of squared errors which determines the total residual values obtained from the fit. The total sum of the squares is $SST = \sum(y_i - \bar{y})^2$, and sum of squared to the regression is $SSR = \sum(\hat{y}_i - \bar{y})^2$.

To determine the difference between observed values and predicted values of the model the root-mean-square error, RSME, was used:

$$RSME = \sqrt{SSE}. \tag{6.4}$$

To defined how well the model predicts new observation with different number of predictors the following equation was used:

$$AdjR^2 = 1 - \left(\frac{n-1}{n-p}\right)\frac{SSE}{SST} \tag{6.5}$$

where n is the number of samples and p is the total number of predictors.

To make the system flexible, when data is entered into the prototype system by the user, the system automatically applies eight different functions, specified in Table 6.1, to the average values of the data sets. Based on the resulting goodness-of-fit the most appropriate function is selected by the system automatically. Table 6.1 describes the models. The numerical values of the coefficients, R^2, $adjR^2$, RSME and SSE shown in Table 6.1 were obtained by fitting the models to the sample data sets described in Section 6.3.1.

Higher than 4th degree polynomial equations were not considered to be suitable because the size of data between each intervention is small and the equation would be badly fitted and results in poor prediction values.

For the data set considered, the quadratic function provided was selected as it had highest mean R^2 and $adjR^2$ for the majority of the track sections (see Table 6.1). Similar equations were determined for each measure of condition for each component for each homogenous conceptual network.

Model	Equation	Coefficients	R^2	$Adj\ R^2$	RSME	SSE
Exponential	$f(x) = a * exp(b * x) + c * exp(d * x)$	$a = 388.8$ $b = -0.665$ $c = 2.913$ $d = 0.0062$	0.8379	0.7839	0.0339	0.0103
Gaussian	$f(x) = a_1 * exp(-\left(\frac{x - b_1}{c_1}\right)^2) + a_2 * exp(-\left(\frac{x - b_2}{c_2}\right)^2 + a_3 * exp(-\left(\frac{x - b_3}{c_3}\right)^2 + +a_4 * exp(-\left(\frac{x - b_4}{c_4}\right)^2)$	$a_1 = 3.272$ $b_1 = 26.48$ $c_1 = 7.29$ $a_2 = 3.09$ $b_2 = 13.03$ $c_2 = 6.92$ $a_3 = 0.469$ $b_3 = 17.5$ $c_3 = 0.378$ $a_4 = 0.708$ $b_4 = 20.09$ $c_4 = 3.53$	0.9539	9.4471	0.0542	0.0029
Linear Fit	$f(x) = a * (\sin(x - \pi)) + b * ((x - 10)^2 + c$	$a = -0.017$ $b = 0.0009$ $c = 3.199$	0.8429	0.8115	0.0316	0.0100
Power	$f(x) = a * x^b + c$	$a = 0.0001$ $b = 2.383$ $c = 3.151$	0.8158	0.7789	0.0343	0.0117
Linear	$f(x) = p_1 * x + p_2$	$p_1 = 1.42$ $p_2 = 2.4$	0.9238	0.9169	0.0525	0.0303
Quadratic	$f(x) = p_1 * x^2 + p_2 * x + p_3$	$p_1 = -0.0008$ $p_2 = 0.094$ $p_3 = 2.672$	0.987	0.985	0.0506	0.0009
Cubic	$f(x) = p_1 * x^3 + p_2 * x^2 + p_3 * x + p_4$	$p_1 = -0.0003$ $p_2 = 0.019$ $p_3 = -0.03$ $p_4 = 2.4$	0.8513	0.8017	0.0325	0.0095
4^{th} degree polynomial	$f(x) = p_1 * x^4 + p_2 * x^3 + p_3 * x^2 + p_4 * x + p_5$	$p_1 = 3.193$ $p_2 = -0.002$ $p_3 = 0.087$ $p_4 = -1.18$ $p_5 = 9.06$	0.8545	0.7817	0.0340	0.0093

Table 6-1 Fitted model to deterioration trends

6.4.2 Probability Distribution Selection

The equations developed showing the rates of deterioration for each measure of condition for each component are used to determine the time, T_i, taken for track sections to reach given levels of condition (Jackson & Andrews, 2013). By so doing the probability (i.e. distribution) of any track section reaching a particular condition were then determined as described below:

1. Determine the levels of condition which define when a component is considered to move from one condition band to the next (e.g. from good to poor). These are determined from the condition indices (see Section 5.3.4). For the example, for the standard deviation (SD) measure of ballast condition (35m vertical profile) these values are 1.9 (severity band/ State one), 2.7 (severity band two) and 3.4 (severity band three). Any value greater than 3.4 is considered to be in severity band four which indicates 'very poor' condition from which the track cannot degrade further. Hence, it is not necessary to determine the average time to failure of values in band four. However, the distribution of T_i within severity band four was used to model the changes in deterioration after maintenance (see Section 6.5).
2. Use the deterioration equation identified (see Section 6.4.1 and Table 6.1), together with the critical levels determined above, to compute the time for the condition of each individual component/ section of track to reach the next severity band. For example, the time to reach a good state, j and poor state k, from a very good state i is given as $T_{i,j}$ and $T_{i,k}$ respectively. In this way distributions of the times to reach the next condition state can be built up.
3. Thereafter the system determines the most appropriate mathematical probability distribution function for the distribution of times in each state. To do this, a routine was developed (described in detail below) which compares the fit of number of mathematical distributions commonly used for component life analysis on data (O'Connor, et al., 2016).

6.4.2.1 Mathematical Probability Distribution Function

The routine developed to determine the most appropriate mathematical probability distribution function for the distribution of times in each state, determines a parameter known as the Log-likelihood (Edwards, 1984). The Log-likelihood parameter is a measure of the goodness-of-fit between the histogram and the mathematical distribution. The higher the value of Log-likelihood the better the fit. Each distribution has a number of parameters which need to be defined (see Table 6.2). These are determined by Maximum Likelihood Estimation (MLE) (Edwards, 1984).

In general, MLE uses the distribution of measures of condition to determine a suitable probability function for the data. In this case, ballast geometry data comes from Weibull distribution (see Table 6.2) with probability function of $f(x_1, x_2, \dots, x_n|\theta)$ where x_n is the number of observations for a given θ which represents the Weibull parameters. This is achieved using the following equation based on probability theorem (Edwards, 1984):

(6.6)

$$f(x_1|\theta) \times f(x_2|\theta) \times \dots f(x_n|\theta) = \prod f(x_i|\theta)$$

Where $f(x_i)$ is the probability of observing each data point given the parameters. Because the likelihood function is the inverse of probability distribution function, the likelihood function is $L = L(\theta|x_i) = \prod f(x_i|\theta)$ which means that likelihood of variable θ given data x_i is the same as probability of given data x given true probability values. By maximising the Log-likelihood functions the probability function parameters are calculated (Edwards, 1984).

(6.7)

$$L(\theta|x_i) = \prod f(x_i|\theta) \rightarrow lnL(\theta|x_i) = \sum lnf(x_i|\theta)$$

Distribution	Log likelihood	Mean	Variance	parameters
Exponential	-478.847	48.35	2337	$\mu = 23.37$
Gamma	-484.183	48.35	1623.11	$a = 0.034, b = -0.7964$
Inverse Gaussian	-497.599	48.35	3909.67	$\mu = 39.096, \lambda = 16.716$
Logistic	-503.581	44.017	20.81	$\mu = 13.14, \sigma = 0.56$
Log-Logistic	-491.25	64.96	∞	$\mu = 3.583, \sigma = 0.563$
Lognormal	-490.933	54.34	51117.64	$\mu = 3.49, \sigma = 1.002$
Normal	-504.84	48.35	1435.09	$\mu = 48.35, \sigma = 37.88$
Weibull	-480.813	48.33	1472.62	$\eta = 52.05, \beta = 1.26$

Table 6-2 Fitted results and parameters of different probability distribution

Table 6.2 shows the results for eight different probability distributions of applying the above process on the track geometry data described in Section 6.4.1. From Table 6.2 it can be seen that the Weibull probability distribution provides the best fit amongst the rest of the distributions (c.f. Section 3.3.3).

For the example of ballast deterioration, Figures 6.4 to 6.7 show the track sections (crosses) plotted together with the theoretical Weibull probability distribution (red line) of the times required to reach the next critical SD value (i.e. the condition index for the next state). It can be observed that the data for this example has a good fit. The Weibull plot provides information regarding the failure mode, since η is the time when 63.2% of the components fail (by setting $t = \eta$ in Equation 3.17) (Abernethy, 2001). Different slopes of β imply different classes of failure mechanism. $\beta < 1$ gives as decreasing deterioration rate. $\beta = 1$ implies a constant degradation rate meaning that failures are independent of time. However, $\beta > 1$ implies wearout due to failure. The higher the value of β the faster the deterioration rate.

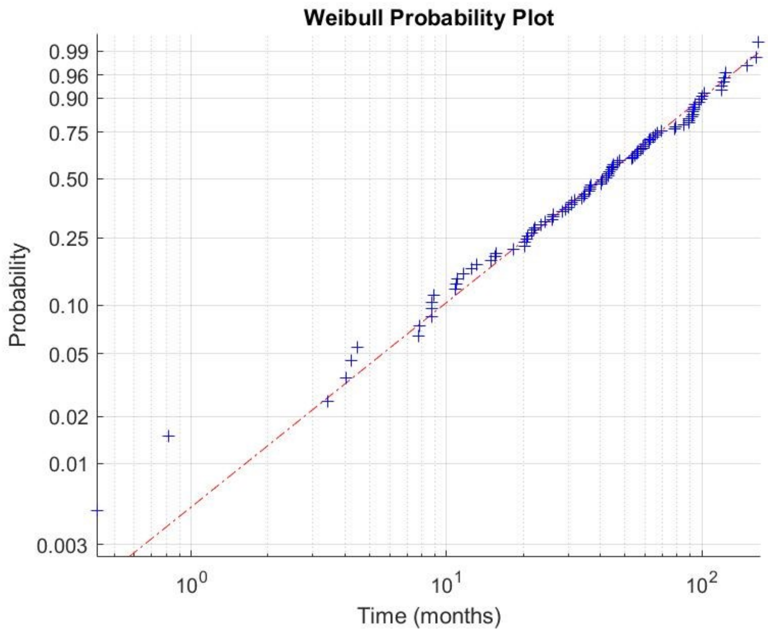

Figure 6-4 Distribution of times for a very good state for sample of homogenous ballast

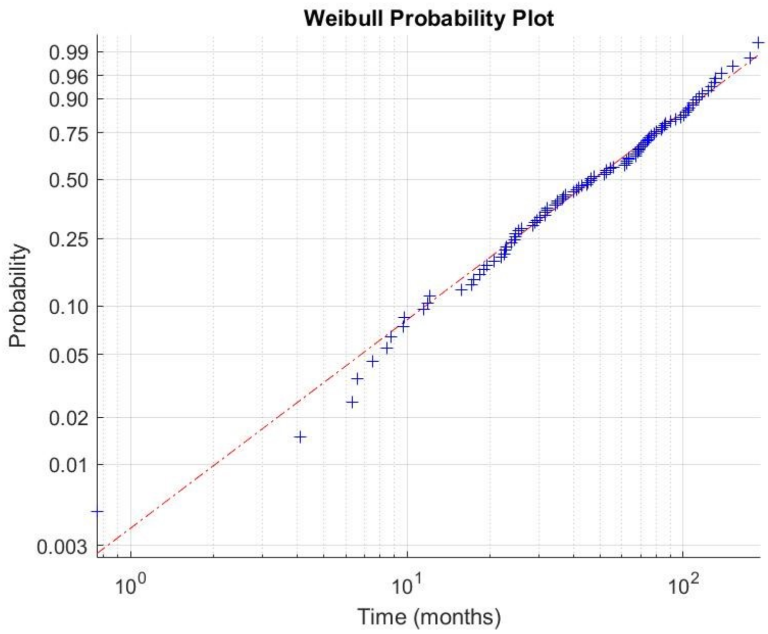

Figure 6-5 Distribution of times for a good state for sample of homogenous ballast

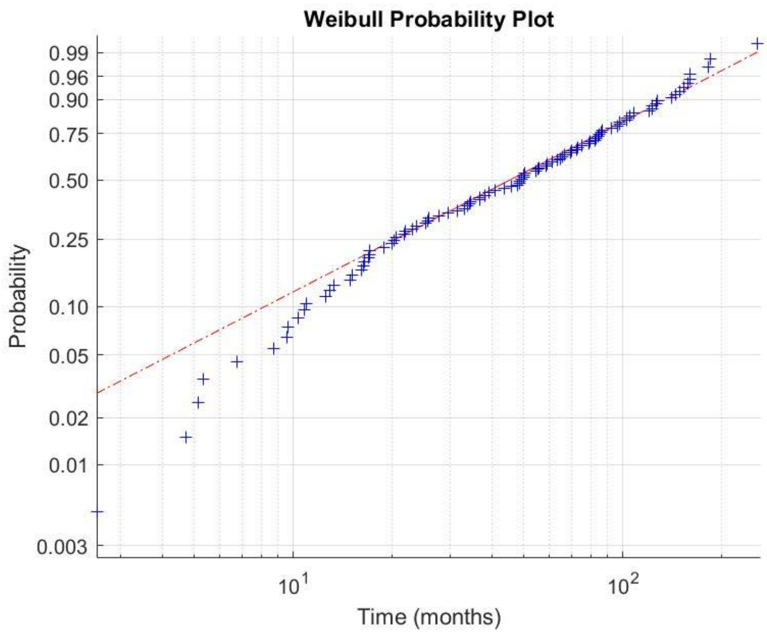

Figure 6-6 Distribution of times for a poor state for sample of homogenous ballast

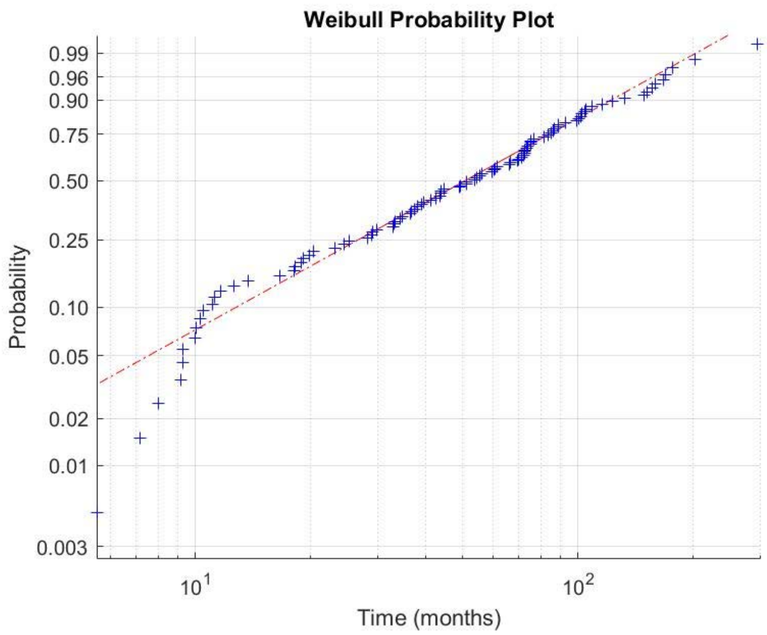

Figure 6-7 Distribution of times for a very poor state for sample of homogenous ballast

6.4.3 Transition Probability Matrix

The distribution of times for a particular type of component to progress from one condition state to another ($T_{i,j}$), are used to calculate the length of time that the component spends at each state before moving to another state (see Section 6.4.2). This is known as the sojourn time or holding time (Rausant, 2004). According to the Markov property, when a component of the track is in state i, independent of the past state, the length of time, t, spent in state i is a continuous and positive random variable in state i (Taylor & Karlin, 1998). To calculate the sojourn times for each state the infinitesimal generator matrix, Q, is established in which its diagonal elements are defined as (Rausant, 2004):

(6.8)

$$\lambda(i,i) = -\sum_{i \neq j} \lambda(i,j)$$

The elements of the Q matrix, λ_{ij}, for $i \neq j$ denotes the departing rate from condition state i and arriving rate in condition state j and must satisfy the following terms

- $0 \leq -\lambda_{ii} < \infty$
- $0 \leq \lambda_{ij} \; for \; i \neq j$
- $\sum_i \lambda_{ij} = 0 \;\; for \; all \; i$

In this manner, the Qmatrix is defined as

(6.9)

$$Q = \begin{bmatrix} -\lambda_{11} & \lambda_{12} & 0 & & 0 \\ 0 & -\lambda_{22} & \lambda_{23} & \cdots & 0 \\ 0 & 0 & -\lambda_{33} & & 0 \\ \vdots & \vdots & & \ddots & \vdots \\ 0 & \ldots & -\lambda_{(i-1)(j-1)} & & -\lambda_{(i-1)j} \\ 0 & \ldots & 0 & & 0 \end{bmatrix}$$

To determine the transition rate, λ, the time of transiting from one state to another is calculated using the Mean Time To Failure (MTTF) of components at each condition state. MTTF of the Weibull distribution is defined by a Gamma function of β as (Abernethy, 2001)

(6.10)

$$MTTF = \eta\Gamma[1 + \frac{1}{\beta}])$$

Accordingly, the transition rate λ is the inverse of $MTTF$ defined as

(6.11)

$$\lambda = \frac{1}{MTTF}$$

Based on Markov theorem, the probability that the condition of any component is in condition state i an infinitesimal time after time t, $p_i(t + dt)$ is calculated from the probability that the component's condition is in state i at time t minus the probability that the component leaves the state with rate λ and plus the probability that the component enters state i with rate λ from some other state, j. This is mathematically represented as (Norris, 1998).

(6.12)

$$p_i(t + dt) = p_i(t) - p_i(t)\lambda_i dt + \sum_{i \neq j} p_j(t)\lambda_{ji} dt$$

In matrix form this is represented as:

(6.13)

$$p(t + dt) = p(t) + p(t)Qdt$$

Where according to Equation 6.8, $Q = \{\lambda_{ij}\}$ and $\lambda_{ii} = -\lambda_i$, thereby:

(6.14)

$$p'(t) = \lim_{t \to 0} \frac{p(t + dt) - p(t)}{dt} = p(t)Q$$

Based on the Markov property, by substituting $p(t)$ with $p(0)P(t)$ (see Section 5.3.2 Equation 5.2)

(6.15)

$$p(0)P'(t) = p(0)P(t)Q$$

The Kolmogorov backward equation (Taylor & Karlin, 1998) states that with transition rate matrix $Q = P'(0)$, $\{P(t)\}$ satisfies the following linear differential equation.

(6.16)

$$P'(t) = QP(t), t \geq 0\ , P(0) = I$$

Thereby, the sojourn times follows an exponential function in a form of

(6.17)

$$P(t) = e^{Qt}, t \geq 0$$

Since the unique solution is $P(t) = e^{Qt}$, it can explicitly be concluded that the infinite sum in the solution is (Haggstrom, 2002):

$$P(t) = e^{Qt} = \sum_{n=0}^{\infty} \frac{(Qt)^n}{n!} \tag{6.18}$$

Accordingly, the deterioration transition matrix $P(t)$, for a particular condition parameter x represents the progression of track from state i to state j at time t.

From the above, the general form of the Markov chain for the deterioration process is given as:

$$\begin{aligned} [P_{bx1y}\ P_{bx2y}\ P_{bx3y}\ P_{bx4y} \dots P_{bxny}] \times P^{y+T} \\ = \sum_{m} [\rho_{xm1y}\ \rho_{xm2y}\ \rho_{xm3y}\ \rho_{xm4y} \cdots \rho_{xmny}] \times P_m^{y+T} \\ = [P_{ax1y+T}\ P_{ax2y+T}\ P_{ax3y+T}\ P_{ax4y+T} \dots P_{axny+T}] \end{aligned} \tag{6.19}$$

Where P_{bxny} indicates the probability of component with condition x at severity band n, at time y before maintenance. Because portions of track at each band contain different maintenance histories, they deteriorate differently. Therefore, ρ_{xmn} is the percentage of the conceptual network with defect x, at severity band n with maintenance history m and P_m^{y+T} is the transition matrix developed based on maintenance history (m) where, $\sum^m \sum_{i=1}^n \rho_{xmi} = 1$.

Tables 6.3 to 6.6 show the Weibull parameters, MTTF and the corresponding λ for each state as a function of maintenance history (i.e. renewal only, renewal followed by stoneblowing, renewal followed two stoneblowings, and renewal followed by two stoneblowing activities and a tamp) for a conceptual network consisting of two UK railway lines (i.e. SPC1 and BML1) and with ballast renewal dates of 2000, 2007, 2009.

State	SD	Intervention history	**η [95% confidence bound]**	**β [95% confidence bound]**	MTTF	**λ**
Very good	1.9	Renewal	55.3915 [53.9659, 56.8548]	1.11912 [1.09515, 1.14361]	53.1524	0.0188
		+ stoneblowing	58.7778 [57.4213, 60.1662]	1.25014 [1.22344, 1.27742]	54.7432	0.0183
		+ stoneblowing	60.9802 [59.6542, 62.3357]	1.3276 [1.29913, 1.35669]	56.0898	0.0178
		+tamping	63.1291 [61.8593, 64.425]	1.43687 [1.4062, 1.46821]	57.3136	0.0174
Good	2.7	Renewal	59.52 [58.0141, 61.0651]	1.13853 [1.11418, 1.16342]	56.8133	0.0176
		+ stoneblowing	60.9581 [59.6247, 62.3213]	1.31978 [1.29162, 1.34855]	56.1325	0.0178
		+ stoneblowing	66.2829 [64.9229, 67.6715]	1.40773 [1.37765, 1.43847]	60.3601	0.0166
		+tamping	69.3879 [68.0281, 70.7749]	1.4747 [1.44307, 1.50702]	62.7733	0.0159
Poor	3.4	Renewal	65.253 [63.6226, 66.9252]	1.15332 [1.1286, 1.17858]	62.0495	0.0161
		+ stoneblowing	68.7311 [67.3473, 70.1434]	1.43407 [1.40323, 1.46558]	62.4170	0.0160
		+ stoneblowing	72.5834 [71.1816, 74.0127]	1.49709 [1.46504, 1.52984]	65.5398	0.0153
		+tamping	82.304 [80.7965, 83.8396]	1.57926 [1.54555, 1.61371]	73.8830	0.0135
Very poor	>3.5	Renewal	67.6278 [66.091, 69.2004]	1.26899 [1.24168, 1.2969]	62.7762	0.0159
		+ stoneblowing	72.3521 [70.947, 73.7849]	1.48808 [1.45627, 1.52058]	65.3797	0.0153
		+ stoneblowing	75.392 [73.99, 76.8205]	1.55534 [1.52219, 1.58922]	67.7825	0.0148
		+tamping	83.1074 [81.6773, 84.5626]	1.68146 [1.64557, 1.71813]	74.2093	0.0135

Table 6-3 Fitted Weibull parameter for SPC1 Ballast age 2009

State	SD	Intervention history	**η [95% confidence bound]**	**β [95% confidence bound]**	MTTF	**λ**
Very good	1.9	Renewal	49.4656 [48.0677, 50.9041]	1.01858 [0.996892, 1.04075]	49.0908	0.0204
		+ stoneblowing	54.2663 [52.7917, 55.7821]	1.05959 [1.03702, 1.08265]	53.0459	0.0189
		+ tamping	56.2664 [55.0726, 57.4861]	1.36033 [1.33117, 1.39014]	51.5266	0.0194
		+tamping	62.0577 [60.7856, 63.3564]	1.40849 [1.37814, 1.4395]	56.5077	0.0177
Good	2.7	Renewal	57.755 [56.3059, 59.2414]	1.1484 [1.12377, 1.17356]	54.9879	0.0182
		+ stoneblowing	58.6212 [57.1575, 60.1225]	1.15418 [1.12946, 1.17945]	55.7312	0.0179
		+ tamping	61.4506 [60.156, 62.773]	1.37039 [1.34104, 1.40039]	56.2030	0.0178
		+tamping	68.0085 [66.914, 69.1209]	1.79798 [1.75953, 1.83726]	60.4824	0.0165
Poor	3.4	Renewal	59.4827 [58.0989, 60.8994]	1.23936 [1.21288, 1.26642]	55.5107	0.0180
		+ stoneblowing	64.4314 [62.9517, 65.9459]	1.25587 [1.22895, 1.28338]	59.9467	0.0167
		+ tamping	63.0483 [61.6715, 64.4558]	1.32154 [1.2932, 1.35049]	58.0424	0.0172
		+tamping	69.3785 [68.3157, 70.4577]	1.89019 [1.84971, 1.93156]	61.5743	0.0162
Very poor	>3.5	Renewal	60.2092 [59.3363, 61.0949]	1.99914 [1.95653, 2.04268]	53.3594	0.0187
		+ stoneblowing	66.7829 [65.4146, 68.1797]	1.40936 [1.37916, 1.44022]	60.8046	0.0164
		+ tamping	70.1773 [69.1627, 71.2067]	2.00407 [1.96123, 2.04784]	62.1907	0.0161
		+tamping	71.9444 [71.0128, 72.8883]	2.24007 [2.19221, 2.28898]	63.7214	0.0157

Table 6-4 SC1 Fitted Weibull parameter for SPC1 Ballast age 2007

State	SD	Intervention history	**η [95% confidence bound]**	**β [95% confidence bound]**	MTTF	**λ**
Very good	1.9	Renewal	60.1463 [58.8697, 61.4506]	1.36103 [1.33194, 1.39075]	55.0748	0.0182
		+ tamping	64.5689 [62.9428, 66.237]	1.14384 [1.1194, 1.16881]	61.5473	0.0162
		+ tamping	63.2917 [61.849, 64.7681]	1.26562 [1.23846, 1.29337]	58.7854	0.0170
		+tamping	65.3551 [64.1663, 66.5659]	1.58972 [1.55577, 1.62441]	58.6310	0.0171
Good	2.7	Renewal	59.8154 [58.6953, 60.9568]	1.54432 [1.51126, 1.57811]	53.8186	0.0186
		+ tamping	68.2487 [66.5756, 69.9639]	1.1756 [1.15047, 1.20128]	64.5499	0.0155
		+ tamping	69.5164 [68.311, 70.743]	1.66881 [1.63325, 1.70514]	62.1079	0.0161
		+tamping	75.2805 [73.9659, 76.6184]	1.65726 [1.62191, 1.69338]	67.2935	0.0149
Poor	3.4	Renewal	69.2758 [67.9759, 70.6006]	1.54217 [1.5094, 1.57565]	62.3400	0.0160
		+ tamping	69.1214 [67.5962, 70.681]	1.30778 [1.27973, 1.33646]	63.7629	0.0157
		+ tamping	74.8345 [73.7173, 75.9687]	1.94077 [1.89934, 1.98311]	66.3645	0.0151
		+tamping	76.3082 [75.0449, 77.5928]	1.7482 [1.71073, 1.7865]	67.9655	0.0147
Very poor	>3.5	Renewal	69.6949 [68.6548, 70.7506]	1.94085 [1.89915, 1.98347]	61.8065	0.0162
		+ tamping	71.2181 [70.1677, 72.2843]	1.96522 [1.92333, 2.00802]	63.1381	0.0158
		+ tamping	78.494 [77.4542, 79.5478]	2.18871 [2.14198, 2.23646]	69.5153	0.0144
		+tamping	79.3072 [78.5263, 80.0958]	2.94955 [2.88663, 3.01383]	70.7677	0.0141

Table 6-5 Fitted Weibull parameters for BML1 Ballast age 2000

State	SD	Intervention history	η [95% confidence bound]	β [95% confidence bound]	MTTF	λ
Very good	1.9	Renewal	48.8915 [47.7247, 50.0869]	1.20827 [1.18239, 1.23471]	45.9096	0.0218
		+ tamping	54.6391 [53.4223, 55.8836]	1.29524 [1.26753, 1.32356]	50.5009	0.0198
		+ tamping	57.4329 [56.5097, 58.3711]	1.80183 [1.76341, 1.8411]	51.0718	0.0196
		+tamping	63.4825 [62.8597, 64.1116]	2.95976 [2.89651, 3.02439]	56.6553	0.0177
Good	2.7	Renewal	53.0875 [51.9868, 54.2114]	1.39269 [1.36282, 1.42322]	48.4253	0.0207
		+ tamping	56.2018 [55.2123, 57.209]	1.6429 [1.60773, 1.67884]	50.2737	0.0199
		+ tamping	63.8016 [62.8781, 64.7386]	2.00241 [1.95958, 2.04619]	56.5414	0.0177
		+tamping	68.9147 [68.083, 69.7565]	2.40488 [2.35367, 2.4572]	61.0940	0.0164
Poor	3.4	Renewal	58.3228 [57.3245, 59.3385]	1.69163 [1.65557, 1.72848]	52.0559	0.0192
		+ tamping	62.1266 [61.2094, 63.0575]	1.96114 [1.9192, 2.00399]	55.0807	0.0182
		+ tamping	65.3099 [64.4101, 66.2222]	2.10547 [2.06082, 2.15109]	57.8436	0.0173
		+tamping	73.6887 [72.7997, 74.5885]	2.4058 [2.35444, 2.45828]	65.3266	0.0153
Very poor	>3.5	Renewal	59.8074 [58.8121, 60.8197]	1.73883 [1.70164, 1.77684]	53.2857	0.0188
		+ stoneblowing	64.4832 [63.4959, 65.486]	1.89077 [1.85021, 1.93221]	57.2292	0.0175
		+ stoneblowing	69.5289 [68.7181, 70.3494]	2.48796 [2.43469, 2.54238]	61.6833	0.0162
		+tamping	73.6505 [72.8616, 74.4479]	2.70913 [2.65123, 2.7683]	65.5037	0.0153

Table 6-6 Fitted Weibull parameter for SPC1 Ballast age 2000

With reference to Equations 6.9 and 6.18, transition matrices using the values of λ can be developed. For example, for SPC1 track with a ballast renewal date of 2009, the Q matix and transition matrix, P, immediately following renewal are as follows:

(6.20)

$$Q = \begin{bmatrix} -0.0188 & 0.0188 & 0 & 0 \\ 0 & -0.0176 & 0.0176 & 0 \\ 0 & 0 & -0.0161 & 0.0161 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

(6.21)

$$P = e^{Qt} = \begin{bmatrix} 0.9814 & 0.0185 & 0 & 0 \\ 0 & 0.9826 & 0.0173 & 0.0001 \\ 0 & 0 & 0.9840 & 0.0160 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Then by using the transition matrices and the initial condition (see Figure 6.8), Equation 6.19 is used to determine the deterioration after one year, in terms of standard deviation of 35m vertical profile, of the conceptual network. The initial condition of the conceptual network analysed is shown in Figure 6.8 and its subsequent condition following deterioration in Figure 6.9.

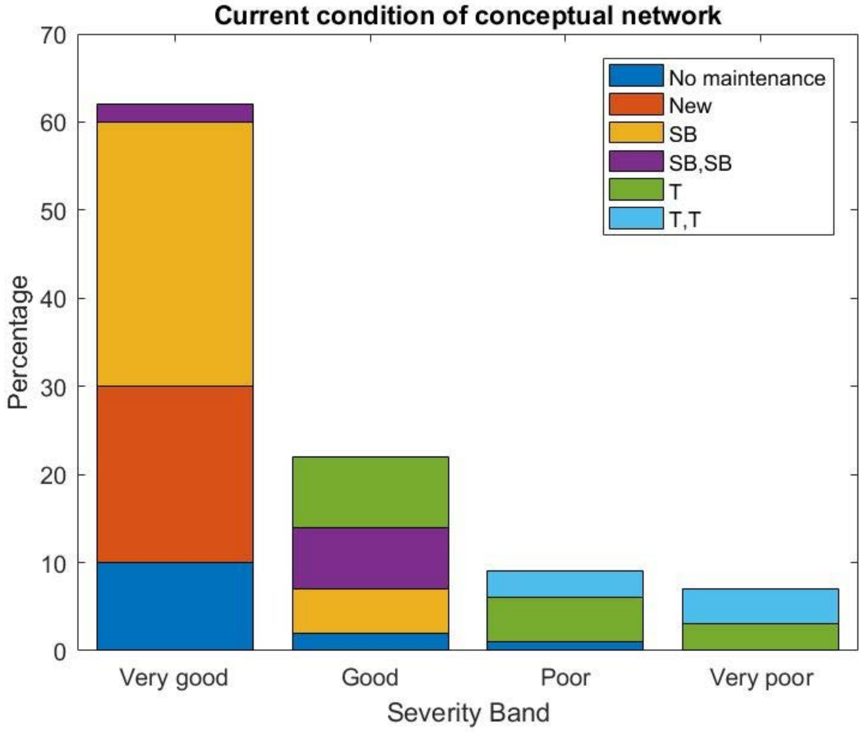

Figure 6-8 Initial condition of a conceptual network at each severity band together with maintenance histories (StoneBlowing (SB), followed by another StoneBlowing (SB, SB), and Tamping (T), followed by another Tamping (T, T))

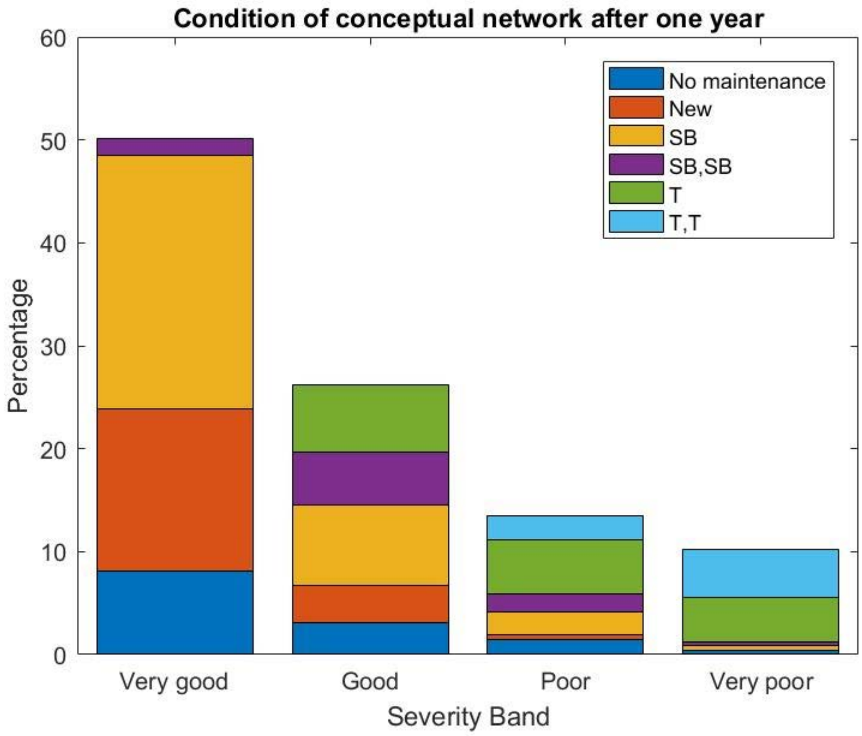

Figure 6-9 Condition of conceptual network after one-year deterioration calculated using specific transition matrices calculated for each treatment type based on maintenance history (SB, SBSB, T and TT)

6.4.4 Effects of Maintenance on Subsequent Ballast Deterioration

Section 5.3.6 suggests that tamping and stoneblowing maintenance may lead to both accelerated deterioration after maintenance and indeed in some cases for the condition of sections of track to be worse after maintenance (Lim, 2004).

Indeed after scrutinising the data in Tables 6.3 to 6.6, after each maintenance activity, it can be seen that although the useful life of ballast, η, mainly increases for the sections of track considered, there are times that depending on the condition and maintenance history, the condition of some sections decrease. In addition, it can be seen that after each maintenance activity, β increases which implies faster subsequent deterioration. To investigate the effects of η and β on deterioration, regression analysis was used to determine a relationship between the Weibull parameters and SD measure of ballast condition for the conceptual network described above. Via this procedure, a quadratic equation, Equation 6.22, was found to give the best fit and the resulting plots are shown in Figures 6.10 and 6.11 for η and β respectively.

$$y = p_1 SD^2 + p_2 SD + p_3 \tag{6.22}$$

Where y determines η or β, and p_1, p_2 and p_3 are coefficients and SD is standard deviation measure of ballast condition. The coefficients determined for the example data set are given in Table 6.7.

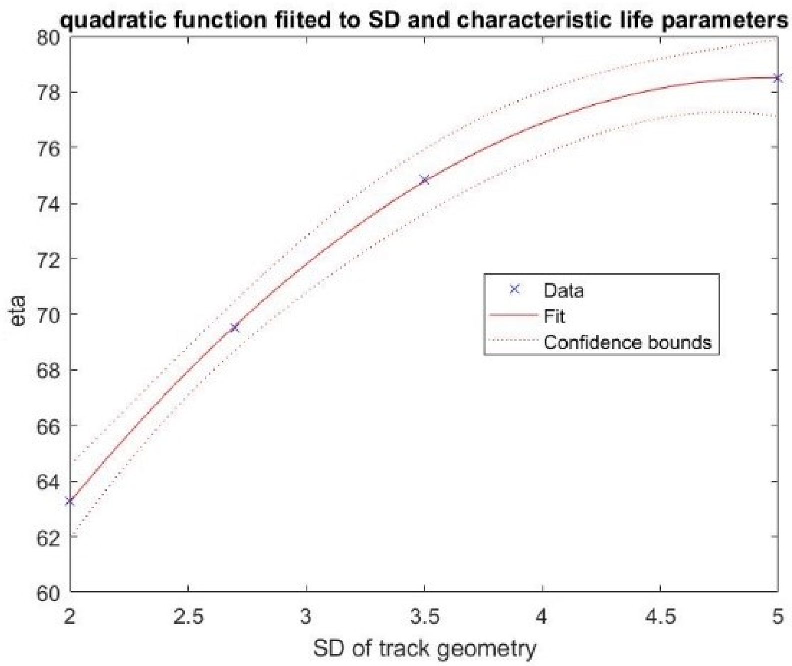

Figure 6-10 Relationship between η and standard deviation of measure of ballast condition

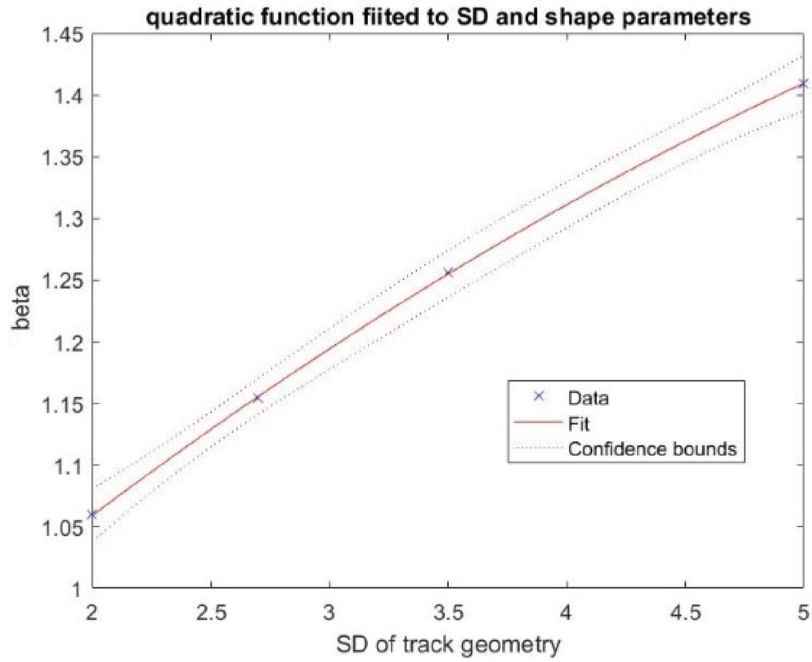

Figure 6-11 Relationship between β and standard deviation of measure of ballast condition

Ballast	Intervention	Coefficient	η	β	Ballast	Intervention	Coefficient	η	β
SCP1 (est. 2009)	Renewal	p_1	−1.45	0.005	SPC1 (est. 2007)	Renewal	p_1	−0.02	0.005
		p_2	14.39	0.25			p_2	2.53	0.25
		p_3	32.076	0.42			p_3	1.18	0.42
	+Stoneblowing	p_1	−0.112	−0.014		+Stoneblowing	p_1	−0.112	−0.014
		p_2	1.15	0.48			p_2	1.15	0.48
		p_3	5.21	0.132			p_3	5.21	0.132
	+Stoneblowing	p_1	−0.15	0.04		+Tamping	p_1	−0.15	0.04
		p_2	1.62	−0.117			p_2	1.62	−0.117
		p_3	3.95	1.2			p_3	3.95	1.2
	+Tamping	p_1	−0.215	−0.113		+Tamping	p_1	−0.215	−0.113
		p_2	1.62	1.115			p_2	1.62	1.115
		p_3	3.53	−0.42			p_3	3.53	−0.42
BML1 (est. 2000)	Renewal	p_1	−1.45	0.005	SPC1 (est. 2000)	Renewal	p_1	−0.02	0.005
		p_2	14.39	0.25			p_2	2.53	0.25
		p_3	32.076	0.42			p_3	1.18	0.42
	+Tamping	p_1	−0.112	−0.014		+Tamping	p_1	−0.112	−0.014
		p_2	1.15	0.48			p_2	1.15	0.48
		p_3	5.21	0.132			p_3	5.21	0.132
	+Tamping	p_1	−0.15	0.04		+Tamping	p_1	−0.15	0.04
		p_2	1.62	−0.117			p_2	1.62	−0.117
		p_3	3.95	1.2			p_3	3.95	1.2
	+Tamping	p_1	−0.215	−0.113		+Tamping	p_1	−0.215	−0.113
		p_2	1.62	1.115			p_2	1.62	1.115
		p_3	3.53	−0.42			p_3	3.53	− 0.42

Table 6-7 Calculated coefficients of quadratic function on Weibull parameters

Using Equation 6.22, the predicted η and β values with respect to maintenance history are shown in Figures 6.12 to 6.19.

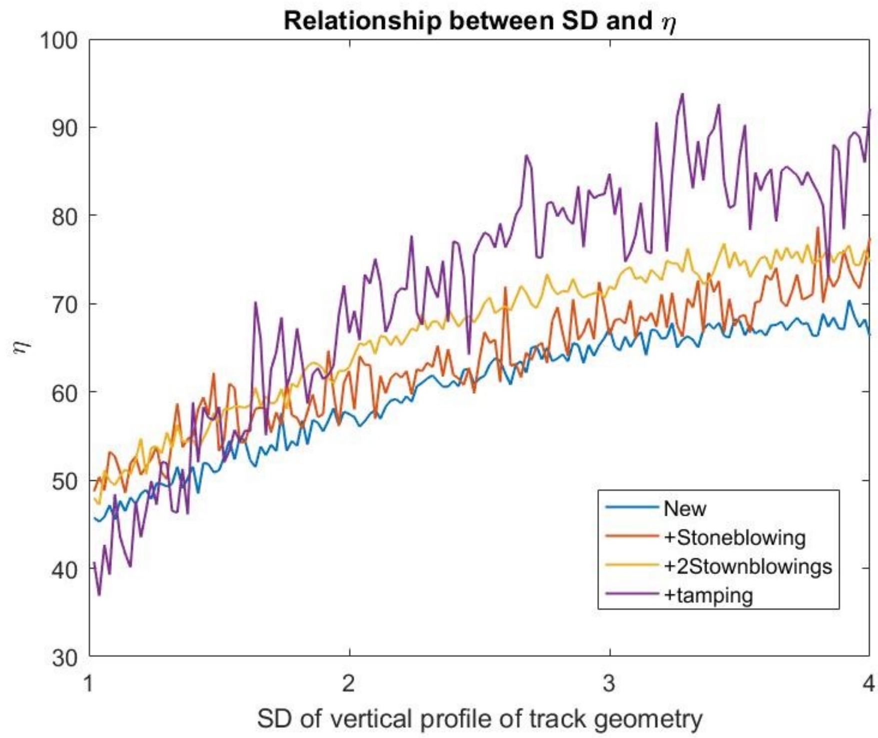

Figure 6-12 Relationship between η and standard deviation of measure of ballast condition for SPC1 track (ballast est. 2009)

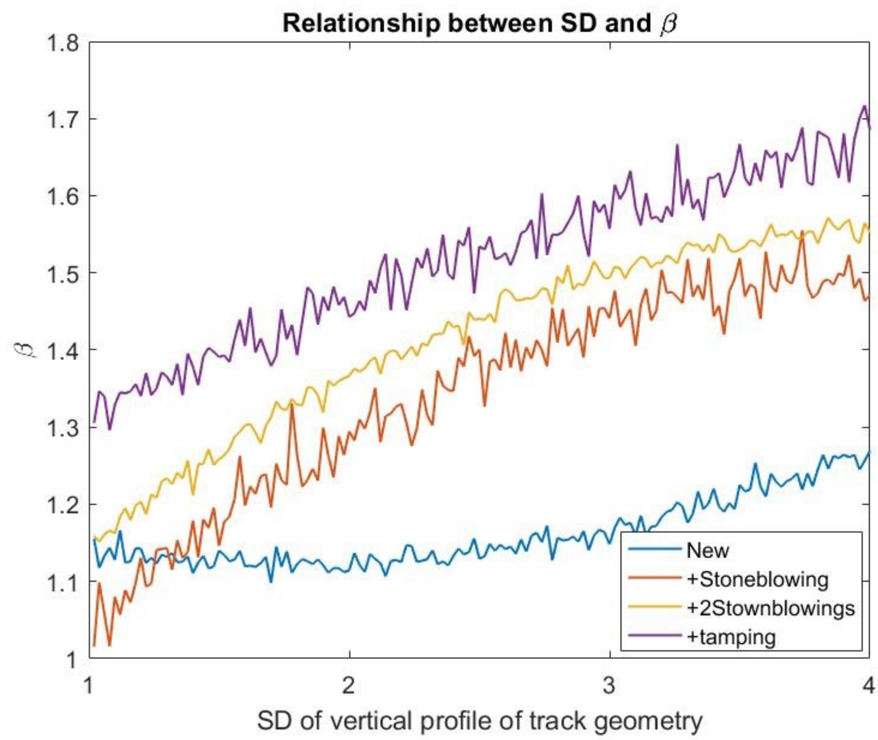

Figure 6-13 Relationship between β and standard deviation of measure of ballast condition for SPC1 track (ballast est. 2009)

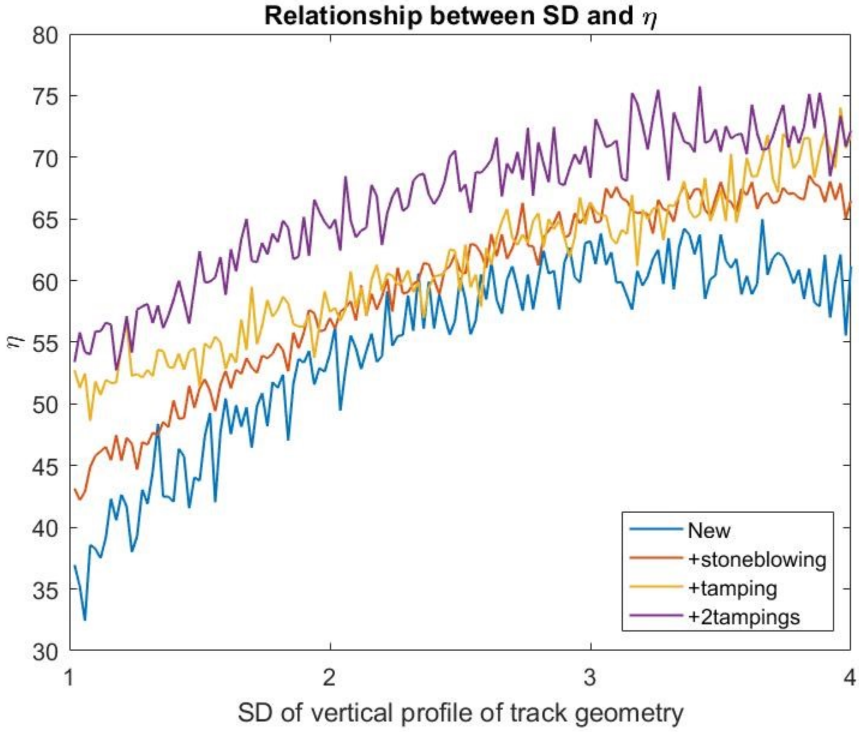

Figure 6-14 Relationship between η and standard deviation of measure of ballast condition for SPC1 (ballast est. 2007)

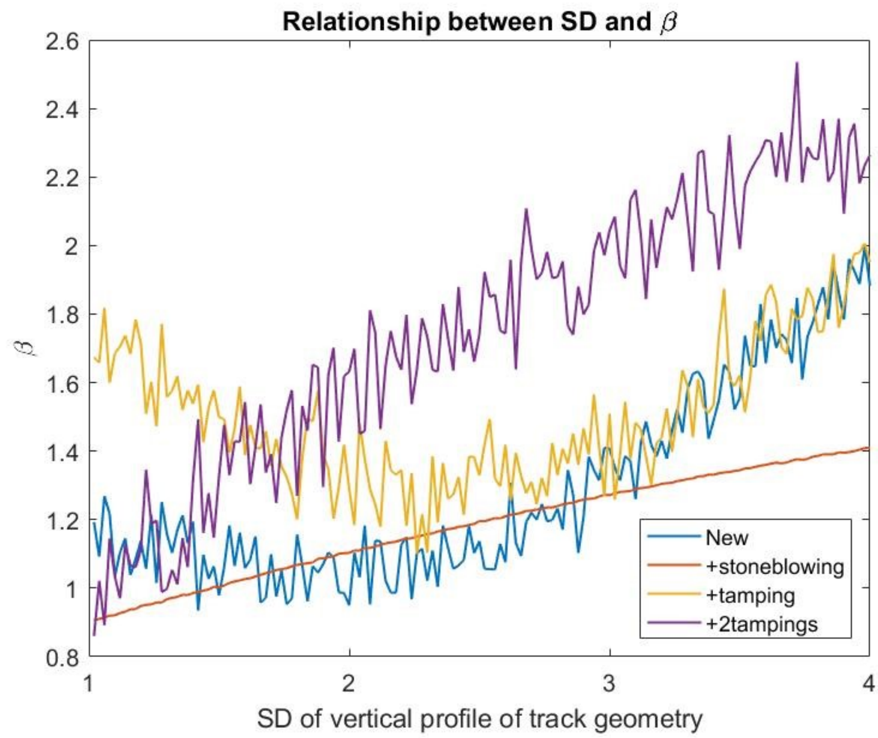

Figure 6-15 Relationship between β and standard deviation of measure of ballast condition for SPC1 (ballast est. 2007)

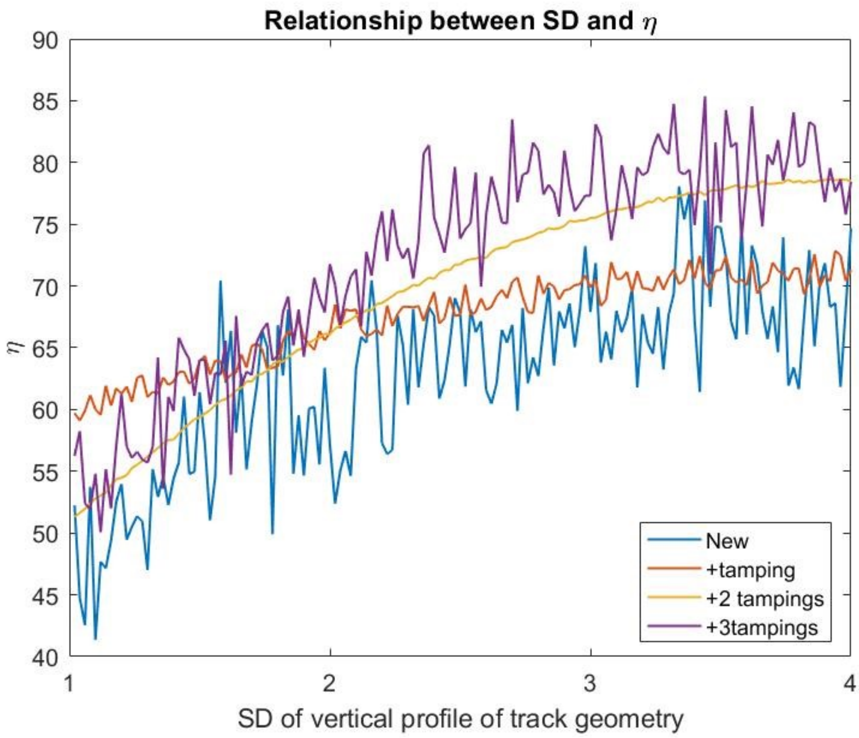

Figure 6-16 Relationship between η and standard deviation of measure of ballast condition for BML1 (ballast est. 2000)

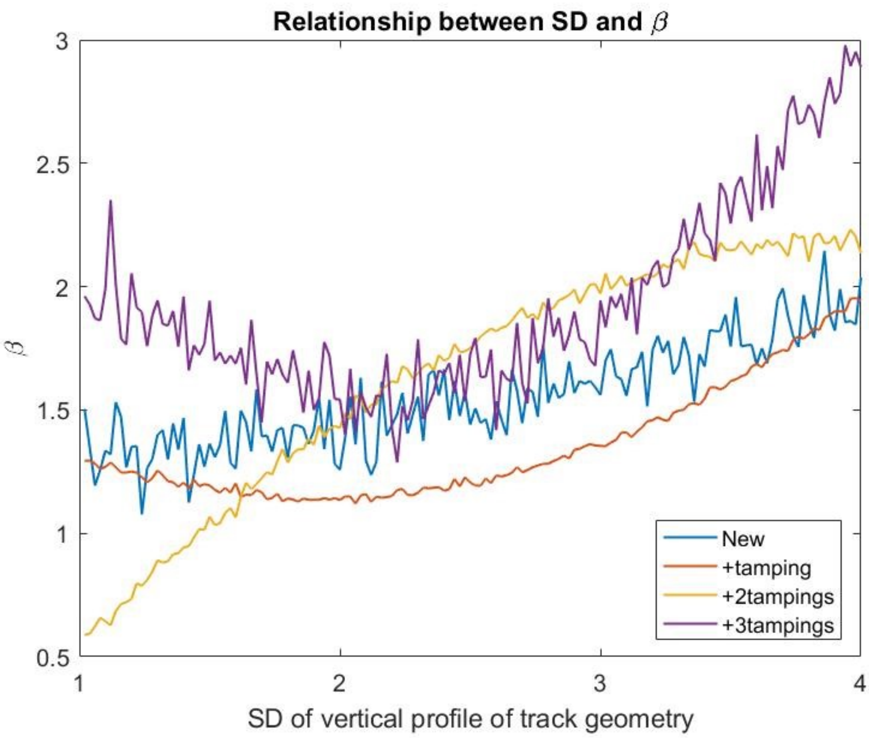

Figure 6-17 Relationship between β and standard deviation of measure of ballast condition for BML1 (ballast est. 2000)

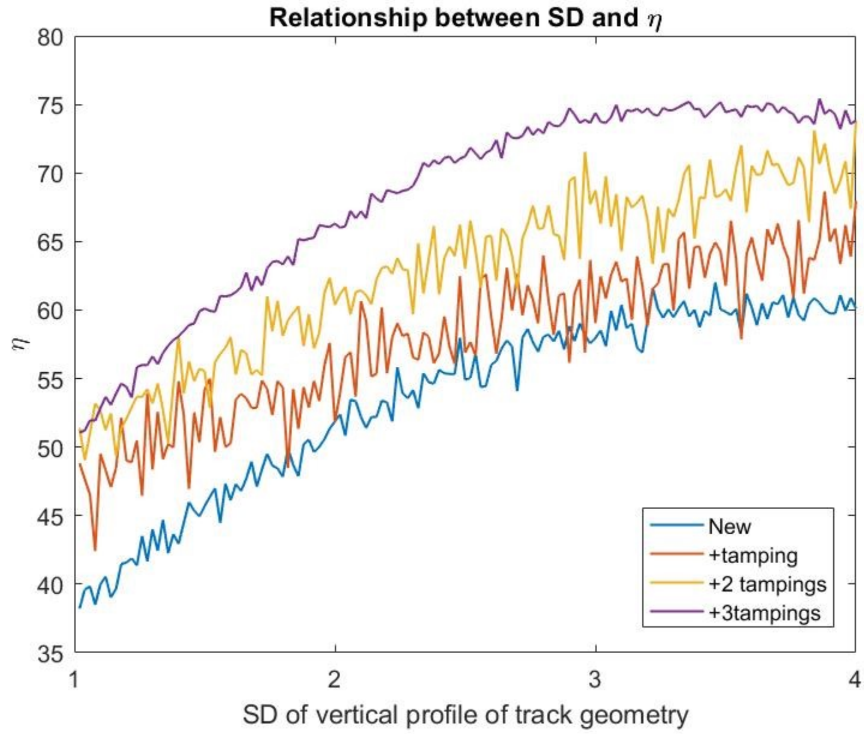

Figure 6-18 Relationship between η and standard deviation of measure of ballast condition for SPC1 (ballast est. 2000)

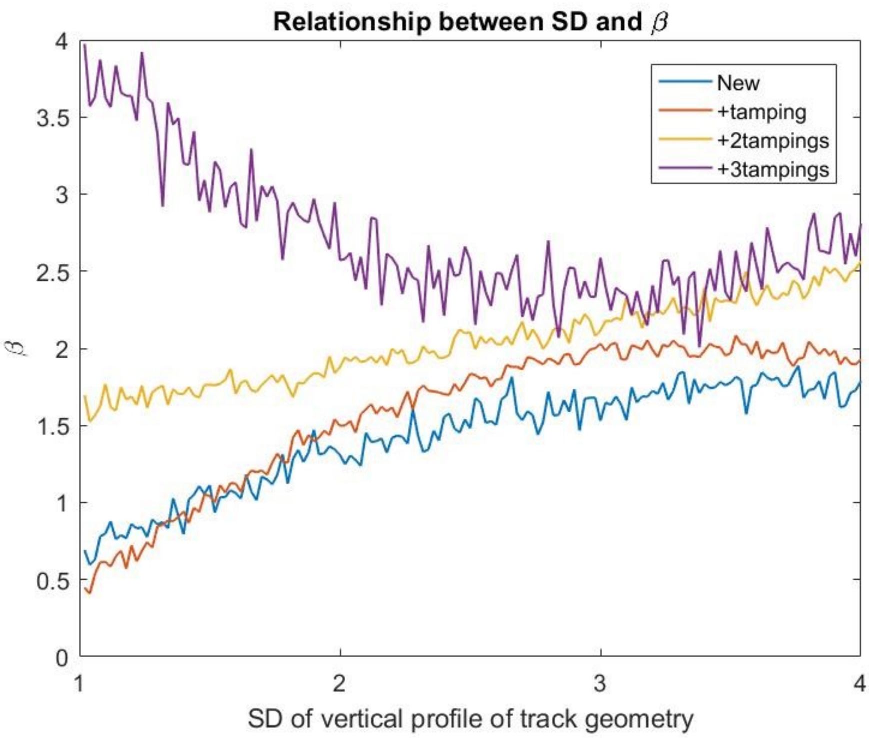

Figure 6-19 Relationship between β and standard deviation of measure of ballast condition for SPC1 (ballast est. 2000)

It can be seen from Figures 6.12, 6.14, 6.16 and 6.18 that the characteristic life, η, increases after each maintenance intervention. This indicates that tamping and stoneblowing improve ballast condition in some cases. Figure 6.12 and 6.14 indicate that for SPC1 track following stoneblowing the life condition (η) improves.

The β parameter indicates the deterioration rate. It can be seen from Figure 6.17 and 6.19 that after the third tamping cycle for track sections with SD between 1 and 2.7 ('very good' and 'good' states respectively) the β parameter decreases which indicates a decreasing deterioration rate (see Section 6.4.2). From Figures 6.13 and 6.15, for ballast which is renewed, the β parameter for track sections with SD values of between 1 to 1.9, is equal to one. This means a constant failure rate, until β reaches a good condition.

6.4.4.1 Deterioration Rate Transition Matrix

Based on the relationship between β and SD in Equation 6.22 the distribution of predicted values of β for critical values of standard deviation were modelled using suitable distribution (c.f. Section 6.4.2). The results of the fitted distributions for the example data set are given in Table 6.8 where the best fit was determined using the Log-likelihood procedure described above. From Table 6.8 it may be seen that the Lognormal distribution provided the best fit.

Distribution	Log likelihood	Mean	Variance	Parameters
Exponential	-60.2976	1.19998	1.43995	$\mu = 1.19998$
Gamma	100.115	1.19998	0.00115528	$a = 1246.41, b = 0.00096275$
Inverse Gaussian	100.158	1.19998	0.0011539	$\mu = 1.19998, \lambda = 1497.46$
Logistic	99.8207	1.19917	0.00122455	$\mu = 1.19917, \sigma = 0.019293$
Log-Logistic	99.9147	1.19946	0.0012229	$\mu = 0.181451, \sigma = 0.0160656$
Lognormal	100.162	1.19999	0.00117699	$\mu = 0.181904, \sigma = 0.0285839$
Normal	99.9931	1.19998	0.00118316	$\mu = 1.19998, \sigma = 0.0343971$
Weibull	94.5566	1.19725	0.00196015	$\eta = 1.21691, \beta = 33.974$

Table 6-8 Estimated probability distribution parametrers and log-likelihood

Tables 6.9 to 6.11 below determine the results of fitted Lognormal distribution to the distribution of β for critical SD values.

State	SD	Intervention history	μ [95% confidence bound]	σ [95% confidence bound]
Very good	1.9	Renewal	0.0940673 [0.0871345, 0.101]	0.0243941 [0.0203772, 0.0303983]
		+ stoneblowing	0.131176 [0.124039, 0.138313]	0.0253746 [0.0212312, 0.0315426]
		+ stoneblowing	0.181904 [0.173864, 0.189943]	0.0285839 [0.0239164, 0.035532]
		+tamping	0.16203 [0.144564, 0.179495]	0.0614547 [0.0513352, 0.0765808]
Good	2.7	Renewal	0.317957 [0.308919, 0.326994]	0.0321325 [0.0268855, 0.0399432]
		+ stoneblowing	0.387424 [0.383085, 0.391762]	0.0154264 [0.0129074, 0.0191762]
		+ stoneblowing	0.252966 [0.242993, 0.262939]	0.0350909 [0.0293126, 0.043728]
		+tamping	0.347036 [0.340079, 0.353994]	0.0247386 [0.020699, 0.030752]
Poor	3.4	Renewal	0.409249 [0.403646, 0.414852]	0.0199206 [0.0166677, 0.0247628]
		+ stoneblowing	0.342638 [0.33322, 0.352056]	0.0331381 [0.0276814, 0.0412945]
		+ stoneblowing	0.408447 [0.397484, 0.41941]	0.0389781 [0.0326134, 0.0484529]
		+tamping	0.497746 [0.487543, 0.507949]	0.0362768 [0.0303532, 0.0450949]
Very poor	>3.5	Renewal	0.0517954 [0.0267111, 0.0768798]	0.088264 [0.0737299, 0.109989]
		+ stoneblowing	0.13349 [0.105837, 0.161144]	0.0983206 [0.0822657, 0.12222]
		+ stoneblowing	0.486918 [0.449651, 0.524185]	0.132501 [0.110865, 0.16471]
		+tamping	0.0202276 [0.00701357, 0.0334416]	0.046496 [0.0388397, 0.0579402]

Table 6-9 Fitted Lognormal distribution parameters for SPC1 track with ballast age 2009

State	SD	Intervention history	μ [95% confidence bound]	σ [95% confidence bound]
Very good	1.9	Renewal	0.164448 [0.153222, 0.175675]	0.0399169 [0.0333988, 0.0496198]
		+ stoneblowing	0.274122 [0.264241, 0.284004]	0.0351333 [0.0293963, 0.0436734]
		+ tamping	0.398871 [0.365522, 0.432221]	0.117347 [0.0980242, 0.14623]
		+tamping	0.276803 [0.253323, 0.300284]	0.0834851 [0.0698527, 0.103779]
Good	2.7	Renewal	0.507596 [0.471996, 0.543196]	0.126575 [0.105907, 0.157343]
		+ stoneblowing	0.185313 [0.1217, 0.248927]	0.223836 [0.186978, 0.278929]
		+ tamping	0.58384 [0.552721, 0.614959]	0.110643 [0.092576, 0.137538]
		+tamping	0.755408 [0.735343, 0.775472]	0.0713386 [0.0596896, 0.0886794]
Poor	3.4	Renewal	0.345555 [0.318847, 0.372263]	0.0939764 [0.0785016, 0.117107]
		+ stoneblowing	0.409765 [0.382191, 0.437339]	0.0980394 [0.0820304, 0.121871]
		+ tamping	0.580588 [0.551613, 0.609564]	0.103021 [0.0861987, 0.128063]
		+tamping	0.20576 [0.184857, 0.226662]	0.0735496 [0.0614385, 0.0916526]
Very poor	>3.5	Renewal	0.187534 [0.168945, 0.206123]	0.0660936 [0.0553011, 0.0821595]
		+ stoneblowing	0.489107 [0.456202, 0.522012]	0.116993 [0.0978895, 0.145432]
		+ tamping	0.03355 [0.0324506, 0.0995506]	0.232235 [0.193994, 0.289396]
		+tamping	0.539409 [0.513407, 0.56541]	0.092448 [0.0773521, 0.11492]

Table 6-10 Fitted Lognormal distribution parameters for SPC1 track with ballast age 2007

State	SD	Intervention history	μ [95% confidence bound]	σ [95% confidence bound]
Very good	1.9	Renewal	0.73845 [0.72819, 0.748711]	0.0364814 [0.0305243, 0.0453492]
		+ tamping	0.538485 [0.509523, 0.567447]	0.101908 [0.0851269, 0.12699]
		+ tamping	0.509419 [0.478742, 0.540096]	0.109073 [0.0912623, 0.135586]
		+tamping	0.874345 [0.83379, 0.914899]	0.144192 [0.120646, 0.179241]
Good	2.7	Renewal	0.0431048 [-0.00941513, 0.0956247]	0.184801 [0.154371, 0.230287]
		+ tamping	0.400244 [0.379753, 0.420736]	0.0728573 [0.0609603, 0.0905673]
		+ tamping	0.553916 [0.542578, 0.565255]	0.040313 [0.0337303, 0.0501122]
		+tamping	0.0309923 [-0.0504463, 0.112431]	0.286557 [0.239371, 0.357088]
Poor	3.4	Renewal	0.559163 [0.535056, 0.583269]	0.0857105 [0.0717147, 0.106545]
		+ tamping	0.673791 [0.663456, 0.684126]	0.0367456 [0.0307454, 0.0456777]
		+ tamping	0.596556 [0.585018, 0.608093]	0.0405956 [0.0339109, 0.0505876]
		+tamping	0.710007 [0.697893, 0.72212]	0.0430686 [0.0360359, 0.0535377]
Very poor	>3.5	Renewal	0.837734 [0.823933, 0.851536]	0.049071 [0.0410582, 0.0609991]
		+ tamping	0.837734 [0.823933, 0.851536]	0.049071 [0.0410582, 0.0609991]
		+ tamping	0.884943 [0.865664, 0.904222]	0.0685474 [0.0573542, 0.0852097]
		+tamping	0.905975 [0.886556, 0.925394]	0.0690448 [0.0577704, 0.085828]

Table 6-11 Fitted Lognormal distribution parameters for SPC1 track with ballast age 2000

Following the procedure provided in Section 6.4.3, the mean value of time to failure (μ) of components was used to calculate the rate of failure (λ) (see Equation 6.11). Thereafter, Equations 6.9 and 6.18 (see Section 6.4.3) were used to calculate the deterioration transition matrices.

6.5 Restoration effects

As described in Section 5.3.6, the system determines, using transition matrices, the improvements in the condition of the components considering treatment types and maintenance history. For all components if the treatment is renewal the component is returned to the 'very good' condition, no matter its current condition (c.f. Section 5.3.2). However, tamping and stoneblowing do not return the treated sections of the track to the perfect condition and depending on the condition of the ballast the degree of improvement differs. Similarly, rail grinding may not always return the condition of the rail to the perfect condition. To model the effects of these types of maintenance a procedure similar to that described above to determine the transition matrices for component deterioration was developed. The procedure is illustrated below using the example ballast condition (35m SD of track geometry) data described in Section 6.2.1.

Based on the equation developed in Section 6.4.1, which defines the underlying deterioration trend (see Table 6.1), the distribution of SD of track geometry for sections in a conceptual network can be calculated at any point in time. To model the effects of maintenance on track geometry, the distribution of the SD values in time after maintenance is of interest. These are the minimum standard deviation values. This determines the probability of a component reaching a specified condition (i.e. level of standard deviation) after treatment. For this reason, the distribution of the minimum standard deviation values of sections of track with the same condition before maintenance are analysed together. An example of the resulting histograms of minimum standard deviation values after maintenance is illustrated in Figures 6.20 to 6.22 for track sections in a good state under different maintenance history.

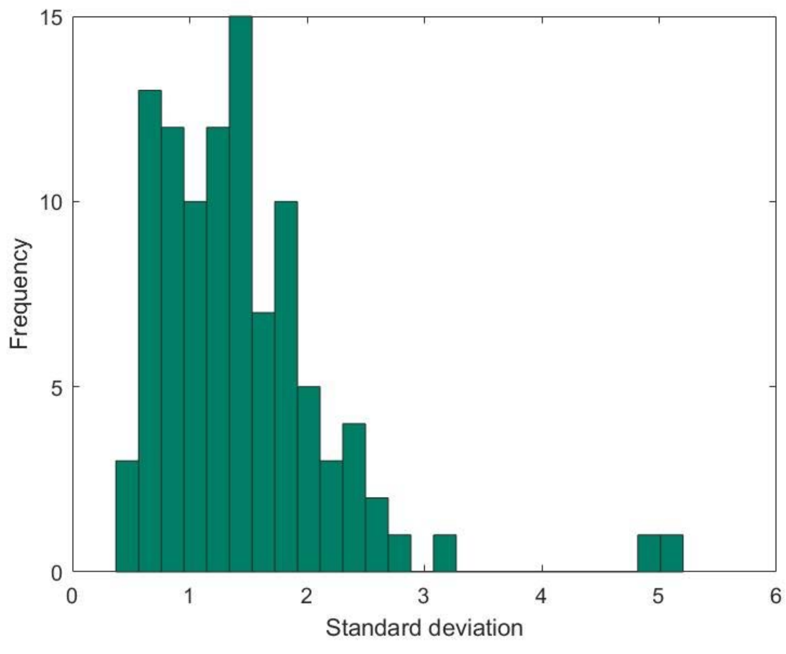

Figure 6-20 Distribution of minimum standard deviation of measure of ballast condition for a SPC1 (ballast est. 2009) track in a good state following one cycle of stoneblowing

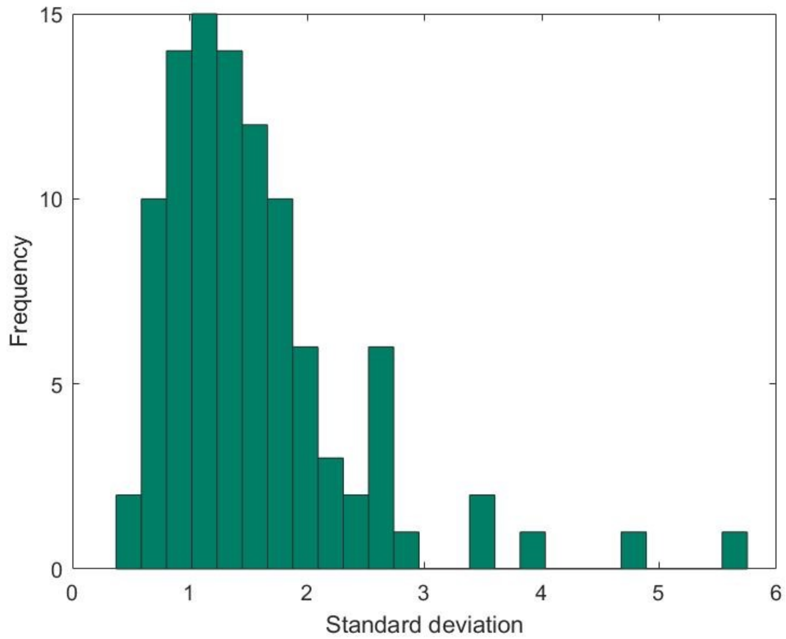

Figure 6-21 Distribution of minimum standard deviation of measure of ballast condition for a SPC1 (ballast est. 2009) track in a good state following two cycles of stoneblowing

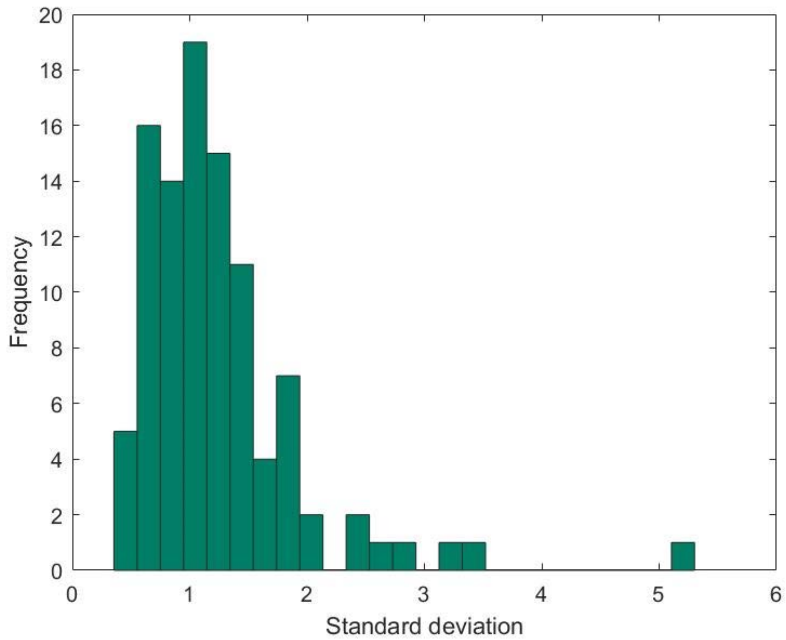

Figure 6-22 Distribution of minimum standard deviation of measure of ballast condition for a SPC1 (ballast est. 2009) track in a good state following two cycles of stoneblowing and a tamp

6.5.1 Probability Distribution Selection

The process described in Section 6.4.2 was used to select the most appropriate statistical distribution for each histogram (see Table 6.12)

Distribution	Log likelihood	Mean	Variance	parameters
Exponential	-192.828	2.53	6.40	$\mu = 2.53$
Gamma	-157.178	2.53	1.62	$a = 3.93$ $b = 0.64$
Inverse Gaussian	-157.806	2.53	2..04	$\mu = 2.53$ $\lambda = 7.92$
Logistic	-166.45	2.38	1.64	$\mu = 2.38$ $\sigma = 0.70$
Log-Logistic	-157.602	2.60	3.03	$\mu = 0.80$ $\sigma = 0.29$
Lognormal	-156.285	2.53	2.09	$\mu = 0.79$ $\sigma = 0.52$
Normal	-170.04	2.53	1.77	$\mu = 2.53$ $\sigma = 1.33$
Weibull	-160.963	2.54	1.71	$\eta = 2.86$ $\beta = 2.03$

Table 6-12 Results of Log-likelihood and parameters of fitted distributions

For the conceptual network example, the Lognormal distribution provided the best fit for tamping and stoneblowing.

6.5.2 Transition Probability Matrix

Using the process described in Sections 6.4 for the development of a Markov chain for component deterioration, transition probability matrices were developed to model the effect of stoneblowing, tamping and rail grinding.

The transition matrix after maintenance, can be written as follows:

(6.23)

$$[P_{bx1}, P_{bx2}, P_{bx3}, \dots, P_{bxn}] \times T = \sum_{k=0}^{m} [\rho_{bx1k}\ \rho_{bx2k}\ \rho_{bx3k}\ \rho_{bx4k} \dots \rho_{bxnk}] \times T_{rk}$$
$$= [P_{ax1}\ P_{ax2}\ P_{ax3}\ P_{ax4} \dots P_{axn}]$$

Where P_{bxn} is the probability of track with condition x at band n before maintenance. Because individual components in each condition state may have different maintenance histories, ρ_{bxnk} is the percentage of track before maintenance with condition x, at severity band n, requiring maintenance treatment of type k. When $k = 0$, indicates no maintenance and the restoration transition matrix, T_{rk} becomes an identity matrix.

(6.24)

$$\sum_{i=1}^{n} \sum_{k=0}^{m} \rho_{bxik} = \sum_{i=1}^{n} P_{axi} = 1$$

For the example dataset, the resulting Lognormal parameters associated with tamping and stoneblowing are given in Tables 6.13 to 6.16.

State	SD	Intervention	μ	95%	SD	95%
Very Good	2	1st stoneblow	0.067	0.040-0.094	0.43	0.42-0.45
		2nd stoneblow	0.094	0.068-0.12	0.419	0.401-0.438
		1st tamp	0.306	0.277-0.335	0.463	0.444-0.484
Good	2.7	1st stoneblow	0.080	0.048-0.113	0.525	0.503-0.549
		2nd stoneblow	0.269	0.239-0.298	0.473	0.453-0.495
		1st tamp	0.156	0.128-0.185	0.460	0.440-0.481
Poor	3.5	1st stoneblow	0.482	0.452-0.512	0.481	0.461-0.503
		2nd stoneblow	0.611	0.580-0.642	0.498	0.477-0.521
		1st tamp	0.596	0.565-0.627	0.498	0.477-0.521
Very Poor	>3.5	1st stoneblow	0.740	0.708-0.772	0.513	0.492-0.537
		2nd stoneblow	0.797	0.766-0.828	0.501	0.480-0.524
		1st tamp	0.844	0.810-0.878	0.547	0.524-0.572

Table 6-13Parameters of fitted Lognormal distribution for SPC1 (ballast est. 2009)

State	SD	Intervention	μ	95%	SD	95%
Very Good	2	1st stoneblow	0.038	0.012- 0.064	0.422	0.404- 0.442
		1st tamp	0.054	0.028- 0.079	0.412	0.394- 0.431
		2nd tamp	0.087	0.060- 0.115	0.449	0.430- 0.469
Good	2.7	1st stoneblow	0.096	0.070- 0.122	0.421	0.403- 0.440
		1st tamp	0.180	0.152- 0.208	0.449	0.431- 0.470
		2nd tamp	0.213	0.183- 0.243	0.484	0.464- 0.506
Poor	3.5	1st stoneblow	0.058	0.024- 0.092	0.551	0.528- 0.576
		1st tamp	0.109	0.074- 0.144	0.567	0.543- 0.593
		2nd tamp	0.221	0.192- 0.249	0.460	0.441- 0.481
Very Poor	>3.5	1st stoneblow	0.281	0.249-0.313	0.513	0.491-0.537
		1st tamp	0.276	0.249-0.302	0.430	0.412-0.450
		2nd tamp	0.387	0.355-0.419	0.511	0.489-0.534

Table 6-14 Parameters of fitted Lognormal distribution for SPC1 (ballast est. 2007)

State	SD	Intervention	μ	95%	SD	95%
Very Good	2	1st tamp	0.467	0.438- 0.495	0.456	0.437-0.477
		2nd tamp	0.494	0.464- 0.523	0.474	0.454-0.496
		3rd tamp	0.553	0.524- 0.581	0.458	0.438- 0.479
Good	2.7	1st tamp	0.512	0.482- 0.541	0.470	0.450- 0.491
		2nd tamp	0.572	0.533- 0.611	0.633	0.606- 0.662
		3rd tamp	0.617	0.586- 0.649	0.511	0.489- 0.534
Poor	3.5	1st tamp	0.612	0.578- 0.646	0.553	0.530- 0.579
		2nd tamp	0.706	0.674- 0.738	0.514	0.493- 0.538
		3rd tamp	0.770	0.735- 0.805	0.560	0.536- 0.586
Very Poor	>3.5	1st tamp	0.744	0.714- 0.773	0.468	0.449- 0.490
		2nd tamp	0.840	0.806- 0.875	0.553	0.530- 0.579
		3rd tamp	0.580	0.551- 0.609	0.467	0.447- 0.488

Table 6-15 Parameters of fitted Lognormal distribution for BML1 (ballast est. 2000)

State	SD	Intervention	μ	95%	SD	95%
Very Good	2	1st tamp	0.0883	0.086-0.090	0.036	0.035- 0.038
		2nd tamp	0.148	0.116-0.179	0.510	0.489- 0.534
		3rd tamp	0.548	0.501-0.594	0.748	0.717- 0.782
Good	2.7	1st tamp	0.0453	0.005-0.085	0.646	0.619- 0.676
		2nd tamp	0.103	0.043-0.163	0.964	0.923- 1.008
		3rd tamp	0.948	0.88-1.00	0.974	0.933- 1.019
Poor	3.5	1st tamp	0.180	0.128-0.233	0.850	0.815- 0.889
		2nd tamp	0.578	0.549-0.606	0.459	0.439- 0.480
		3rd tamp	0.991	0.958-1.025	0.541	0.519- 0.566
Very Poor	>3.5	1st tamp	0.621	0.566-0.676	0.888	0.851- 0.929
		2nd tamp	0.901	0.898-0.903	0.041	0.039- 0.042
		3rd tamp	1.095	1.090-1.099	0.066	0.063- 0.069

Table 6-16 Parameters of fitted Lognormal distribution for SPC1 (ballast est. 2000)

Figures 6.23 and 6.24 respectively illustrate the probability density and cumulative distribution functions of SPC1 line with ballast renewed at 2009 following one stoneblowing. Based on the results of fitted distribution, the probability of sections of track moving to each state can be determined by either calculating the area under the curve of the probability density plot between two condition indices or from the cumulative distribution plot.

For instance, it may be seen from Figure 6.24 that when the ballast of a section of track is in a very good condition (SD=1.9) after the first cycle of stoneblowing it has 91.22% probability of remaining in the same state and 7.7% (98.91%-91.22%) probability of moving to a good state (SD=2.7). On the other hand, when a section of track is in poor condition after first stoneblowing, there is 70.74% probability that the ballast of the section of track will be restored to the very good state. Whereas for a section of track in a good state, there is 87.18% probability of being restored to a very good state. In the same manner, for a section of track with very poor ballast condition, after the first stoneblowing action, there is only a 40.49% chance that condition of the ballast of the section will be restored to a very good condition and a 26.27% (66.76%-40.49%) chance that it will be restored a good condition. Additionally, there is a 14.16% (80.92%-66.76%) probability that a section of track will move to a poor state and a surprisingly large 19.08% (100%-80.92%) probability that the ballast condition of the section will remain in a very poor state (i.e. no improvement will occur).

The transition matrix (based on Figure 6.24) for the new ballast section following one cycle of stoneblowing is given in Table 6.17. More examples of restoration transition matrices for ballast and rail are shown in Section 7.3.

Condition		**Very Good**	**Good**	**Poor**	**Very Poor**
	State	**1**	**2**	**3**	**4**
Very Good	**1**	0.9122	0.077	0.009	0.0018
Good	**2**	0.8718	0.0937	0.0228	0.0117
Poor	**3**	0.7074	0.1927	0.0607	0.0392
Very Poor	**4**	0.4049	0.2627	0.1416	0.1908

Table 6-17 Restoration transition matrix after first cycle of stoneblowing

An example of the restoration process is demonstrated below.

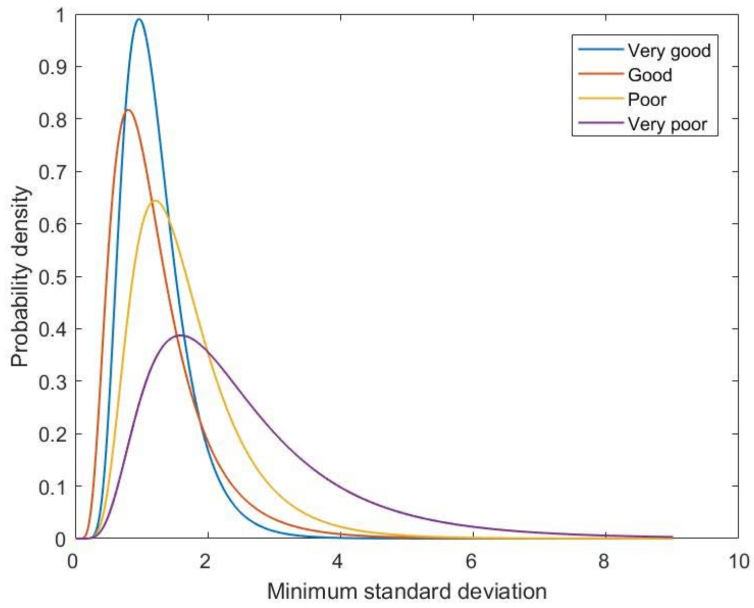

Figure 6-23 Probability density plot for minimum standard deviation values after first stoneblowing for SPC1 (ballast est. 2009)

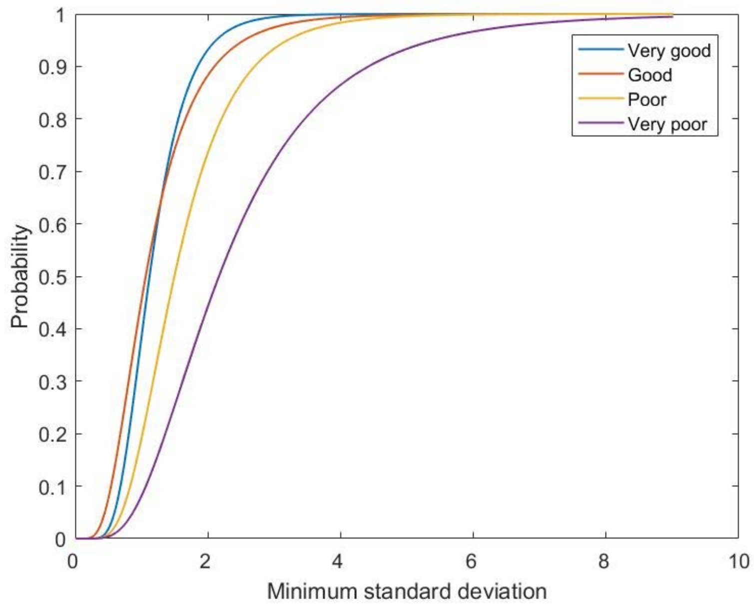

Figure 6-24 Cumulative distribution plot for minimum standard deviation values after first stoneblowing for SPC1 (ballast est. 2009)

Assume that the current condition of the conceptual network, as measured by the SD of 35m vertical profile of track geometry, is as shown in Figure 6.25, from which it may be seen that 30% and 70% of track sections in the very poor state have been respectively tamped once and twice before respectively. Therefore, in the next tamping cycle 30% of the track in the very poor state will be tamped for the second time, whereas 70% of track will be tamped for the third time. As a result, the level of improvements will not be the same for all track sections in a very poor band. Using Equation 6.23 the condition after maintenance was calculated using transition matrix determined for two and three consecutive tamping cycles and is shown in Figure 6.26.

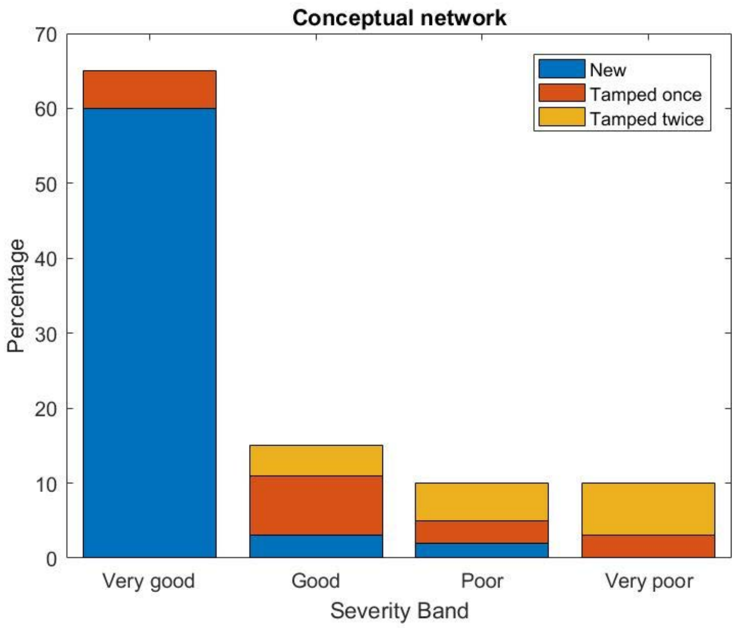

Figure 6-25 Initial ballast condition of the conceptual network measured by the standard deviation of 35m vertical profile of track geometry

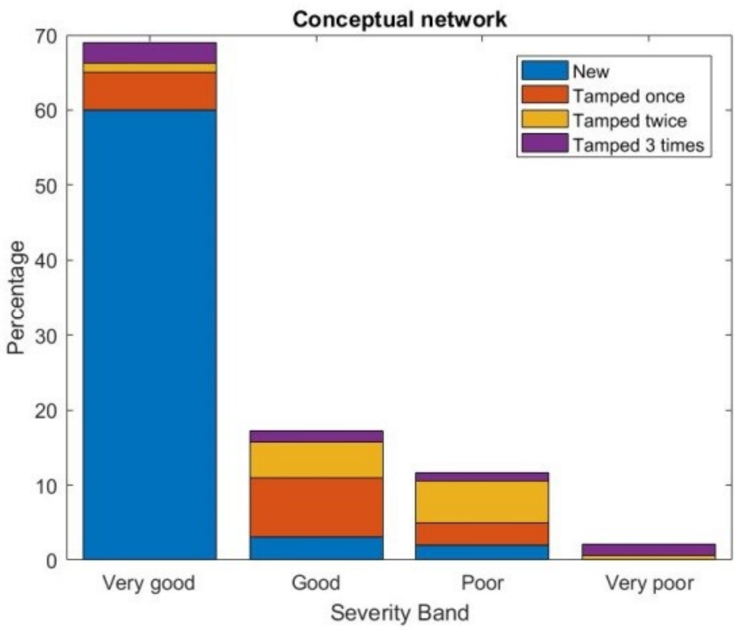

Figure 6-26 Condition of ballast after maintenance (tamping on very poor state) for the conceptual network measured by the standard deviation of 35m vertical profile of track geometry

6.6 Effects of Climate on Deterioration

Given that the UK's climate is changing, in order to predict the condition of the railway track in the future it is necessary to take into account the effects of future climate on deterioration (see Section 5.3.8). For the purposes of the system developed herein, to include the effects of climate, namely temperature and precipitation, on the deterioration of railway track components, an approach was adopted which attempted to determine the current deterioration rates of relevant track components due to climate alone in different regions of the UK (see Figure 6.27). The approach was to determine total deterioration rates for track sections which could be considered homogenous except for their climate and then compare these rates for different climate zones in the UK. Two measures of component condition were considered to be affected by climate, namely rail buckling (extreme temperature) and subgrade stiffness (precipitation) (see Section 5.3.8.3 and 5.3.8.4).

The appropriate temperature and precipitation variables for a section of track were determined by establishing the location of the track section in relation to the 25-km grid squares used to represent the UKCP09 administrative regions (see Figure 2.27).

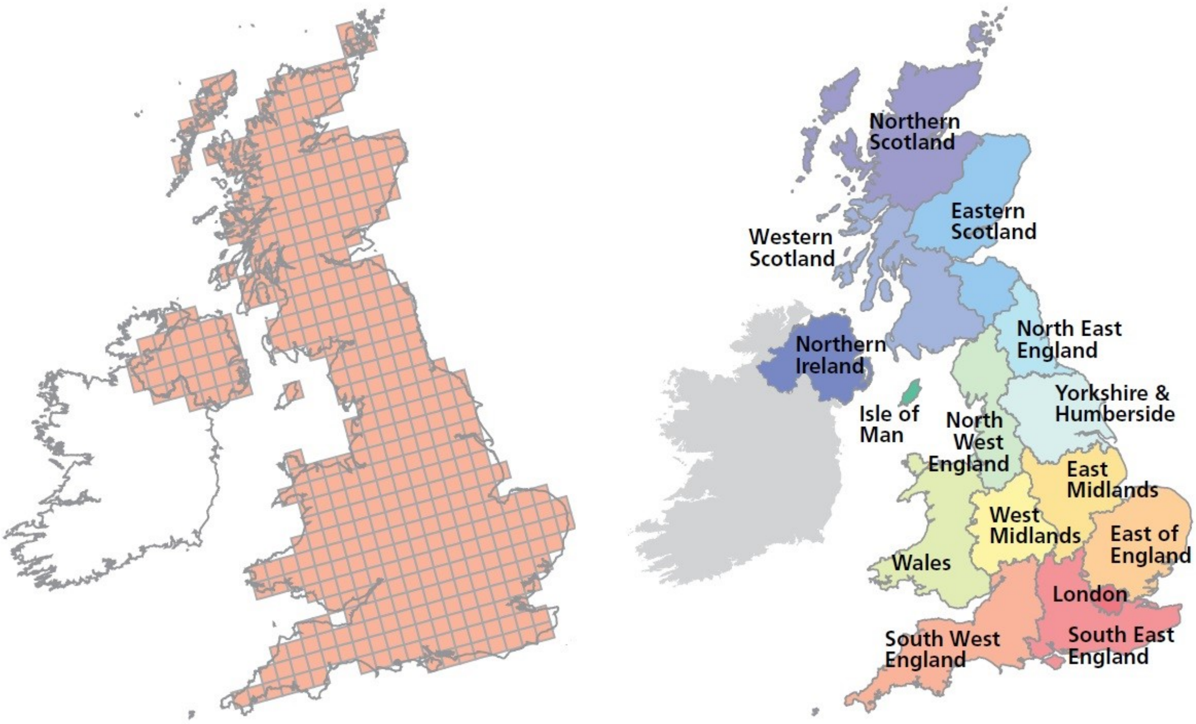

Figure 6-27 UKCP09 25-km grid square (on the left-hand side) and\administrative regions (on the right-hand side) (UK Climate Projections, 2009)

6.6.1 Modelling the Probability of Buckling Occurrence

To determine the probability of buckling occurrence, the system requires a dataset that includes the number of occurrences of buckling together with the corresponding maximum temperature at which buckling has occurred and the track geometry measurements in terms of SD of 35m vertical track geometry (see Section 6.3 and 6.4).

For the example dataset the number of track failures per day with respect to maximum temperature occurred on those days were obtained from Network Rail's Weather Analysis Report (2015). The dataset relates to total number of track failures within the UK between April 2006 to March 2015 with respect to maximum daily temperature. Because the exact cause of failure was not included in the dataset it was assumed that only failures which occurred at temperatures equal to, or greater than, the SFT temperature (assuming that SFT is 27°C) were caused by buckling.

The historical geometry data (35m vertical track geometry) was extracted from available geometry datasets and mapped onto temperature related failure data to approximately determine the condition of ballast on those days where buckling occurred. Because the historical data of the maximum daily temperature was not available for the entire UK, the procedure described in Section 5.3.8.2 was used to determine the maximum daily temperature between the baseline and 2020. A sample of the dataset so developed is shown in Figure 6.28. In Figure 6.28, the recorded temperature data were converted to rail temperature using Equation 2.1 (see Section 2.3.1.4).

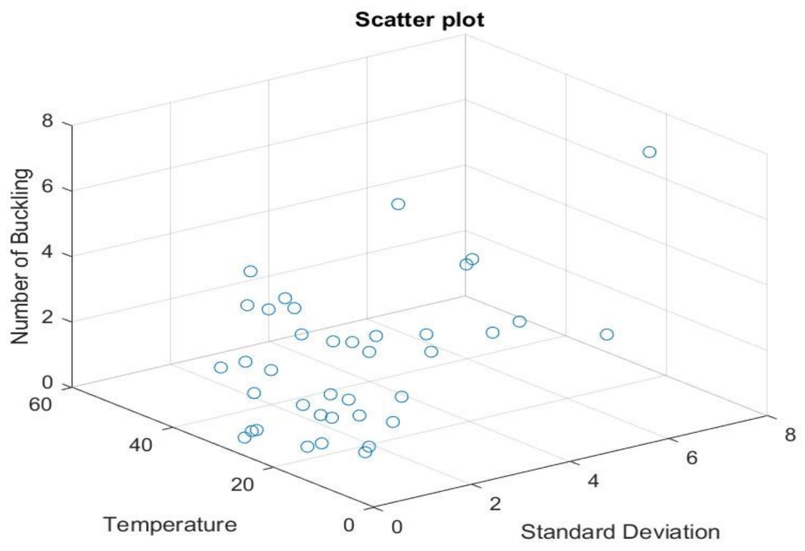

Figure 6-28 Data of number of occurrences o buckling with respect to rail temperature and track geometry

6.6.1.1 Multivariate Regression Analysis

Multivariate regression analysis is performed on the data to find a relationship between the number of buckling events and ballast condition and rail temperature. Based on the coefficient of determination (R^2) the goodness-of-fit is determined (see Section 6.4.1) and accordingly the most suitable equation is selected. The results of this process for the example data set are shown in Table 6.18.

Model	R^2	$Adj\ R^2$
Polynomial (1,1)	0.5796	0.5556
Polynomial (2,1)	0.6374	0.5935
Polynomial (3,1)	0.7176	0.663
Polynomial (1,2)	0.6609	0.6198
Polynomial (2,2)	0.803	0.772
Polynomial (3,2)	0.7199	0.6426
Polynomial (1,3)	0.6704	06189
Polynomial (2,3)	0.7050	0.6236
Polynomial (3,3)	0.7401	0.6302

Table 6-18 Results of fitted models (polynomial (i,j) indicates the degrees of σ and T_r respectively)

As shown in Table 6.18 a polynomial function with two degrees of σ and T_r provided the best fit for the example data set. Equation 6.25 describes the resulting relationship.

$$N = a_0 + a_1\sigma + a_2T_r + a_3\sigma T_r + a_4\sigma^2 + a_5T_r^2 \tag{6.25}$$

Where N is the number of buckling events, and σ and T_r indicate the condition of ballast and temperature of the rail respectively, a_0 is the intercept and a_1 to a_5 are the coefficients determined by regression analysis (see Table 6.19).

Coefficient	a_0	a_1	a_2	a_3	a_4	a_5
Value	1.8526	-0.429	-0.127	0.0147	0.024	0.002

Table 6-19 Coefficient determined from multivariate quadratic function

Figure 6.29 graphically illustrates the developed multivariate regression equation.

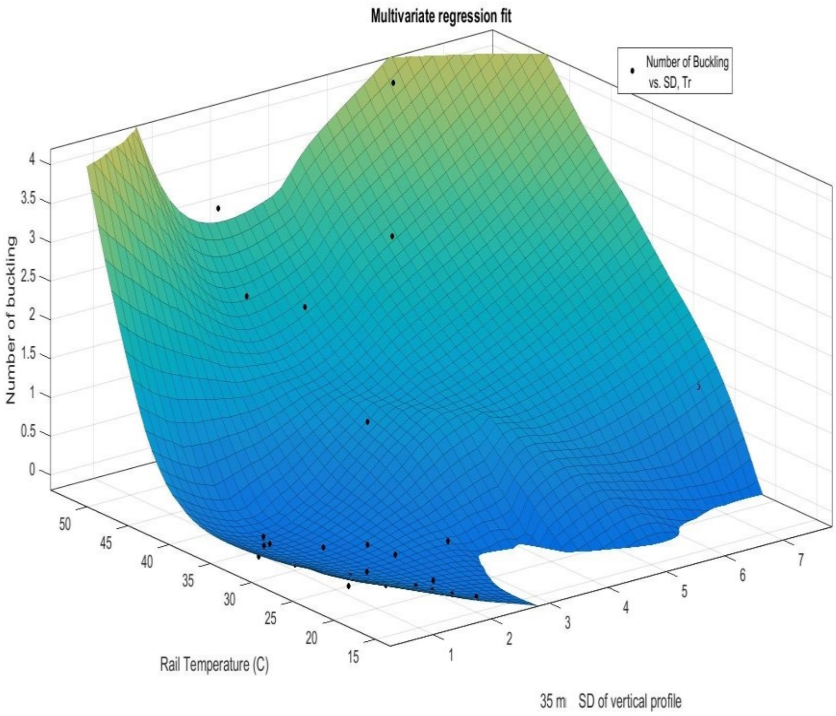

Figure 6-29 Fitted multivariate quadratic function relating buckling occurrence to rail temperature and ballast geometry

6.6.1.2 Calculating the Probability of Buckling

Once a relationship has been founded between the number of buckling events, ballast condition and temperature as mentioned above, Monte Carlo simulation is used to determine the distribution of buckling events (i.e. using Equation 6.25 in the example). For this reason, the distribution of σ and T_r are required. As described in Section 2.3.1 and 3.3.2, maintenance interventions such as tamping and stoneblowing may alter the SFT of rails. Therefore, rails in the same condition state with the same temperature could be prone to buckle differently depending on their differing previous maintenance regimes (see Section 5.3.8). For this reason, the distribution of track geometry variation, σ, is determined based on condition of ballast (using 35m vertical alignment as a measure of condition) at each state with respect to its past maintenance using suitable distributions (see Section 6.4.2). To model the distribution of T_r, for the regions under consideration the distribution of maximum daily temperature is determined using the UKCP09 WG simulation (see Section 5.3.8) and Equation 2.1 is used to convert the ambient temperatures to rail temperature (see Section 2.3.1.4).

Monte Carlo simulation uses repeated random sampling of σ and T_r, based on parameters representing each distribution, to generate the distribution of buckling events. Herein, the sampling of track geometry was carried out using the Markov Chain Monte Carlo (MCMC) method, which uses the transition probability matrix to generate samples of geometry variation based on the proposed density function (Robert, 2017). The Metropolis-Hastings algorithm was used to carry out MCMC sampling. The Metropolis-Hasting method generates samples iteratively, in which the distribution of next iteration of samples depends on the current sample value (Yildirim, 2012). In this manner, samples are accepted if their value is either equal or greater than the previous sample value and rejected if their value is lower than the current sample (this ensures that there are no improvements in the condition of track unless maintenance is carried).

The probability of buckling, P_b, is determined by

$$P_b = \frac{N_{buckle}}{N_{total}} \times 100 \tag{6.26}$$

Where N_{total} is the total number of iterations and N_{buckle}, the number of buckling events.

Finally, it must be mentioned that buckling occurs when temperature reaches its highest every time. For example, Figure 6.30 demonstrates the change in maximum monthly temperature over a period of a year (i.e. T=1) under the medium emission scenario for the years 2020 and 2040 for the South East England administrative region. Considering year 2020, tracks are more likely to buckle during June, July and August since maximum temperature is close to the value of SFT (i.e. $27°C$) and the temperature of each of these months are higher than their previous month. For sections of track that did not buckle and survived during this period, there is a low probability that they will buckle during September since the temperature have already reached its highest in August (with the assumption that SFT is not altered during this period). However, if a rail buckles in August because the temperature exceeded the SFT and is subsequently replaced, the SFT of the renewed rail might exceed again in the next month and it may buckle (depending on its ballast condition). For year 2040, track sections that survived buckling until the end of July, are less likely to buckle in August since temperature have already reached its maximum in July. However, for rails that have been renewed this is not true.

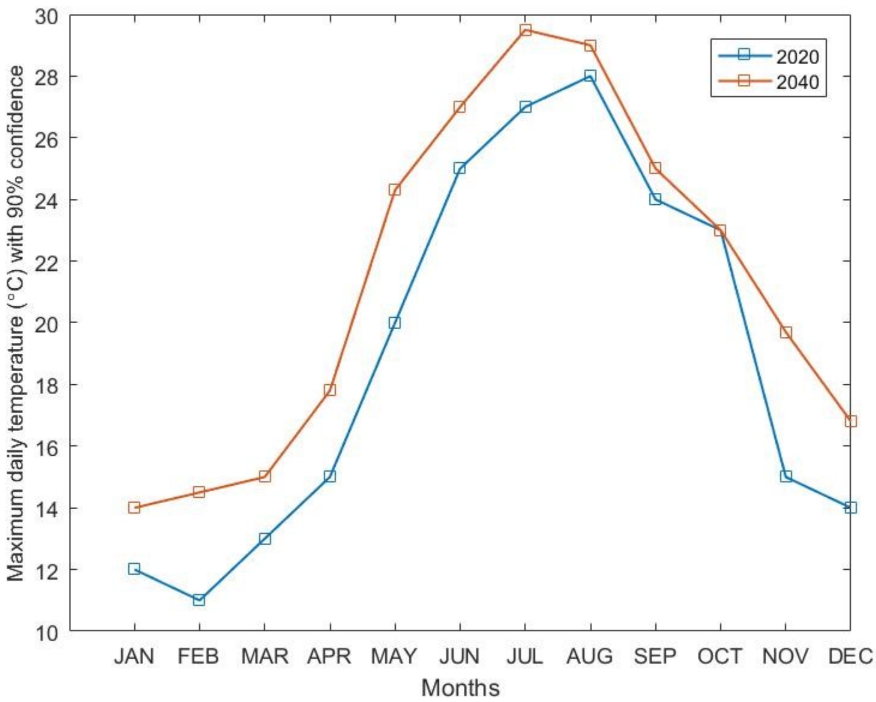

Figure 6-30 Maximum daily temperature of UKCP09 South East England administrative region (East Wessex according to NR classification) for years 2020 and 2040 under medium emission scenario

To generate the probability distribution for track geometry a Weibull distribution was generated using the approach given in Section 6.4.1 to generate transition matrices to be used in MCMC simulation and variations in maximum temperature were determined using a Normal distribution (see Section 5.3.8).

The following presents an example using the example data set, of solving Equation 6.25 using the above described Monte Carlo process. For the purposes of the example, only the statistical variation in maximum daily temperature was considered when determining the probability of the occurrence of buckling. The condition of ballast was as given in Table 6.6. Appropriate values of σ were determined for each condition band with respect to maintenance history using the Weibull parameters.

Figure 6.31 to 6.34 show examples of the resulting probability of the occurrence of buckling as a function of rail temperature for sections of track whose track geometry is in very good, good, poor and very poor states respectively. It can be seen from Figure 6.31 and 6.32, that a section of new track with very good or good track geometry are likely to buckle at higher temperatures compared to a section of track with very good or good track geometry but which has been previously tamped. Furthermore, for sections of track with track geometry in very good or good condition, as the number of tamps increases the probability of buckling increases.

A section of railway track with 'poor' track geometry which has been tamped once before is less likely to buckle compared to a section of untamped track whose track geometry is in a similar condition. Similarly, a section of railway track with 'very poor' track geometry which has been tamped once or twice before is less likely to buckle compared to a section of untamped track whose track geometry is in a similar condition. This is because when track is tamped, ballast particles are squeezed together, and better resistance is provided in the crib area. However, sections of track in very poor, poor and good condition which have been tamped three times are like to buckle higher at lower temperatures compared to other sections of track. This can be due to breakage of ballast particles and increase in fouling.

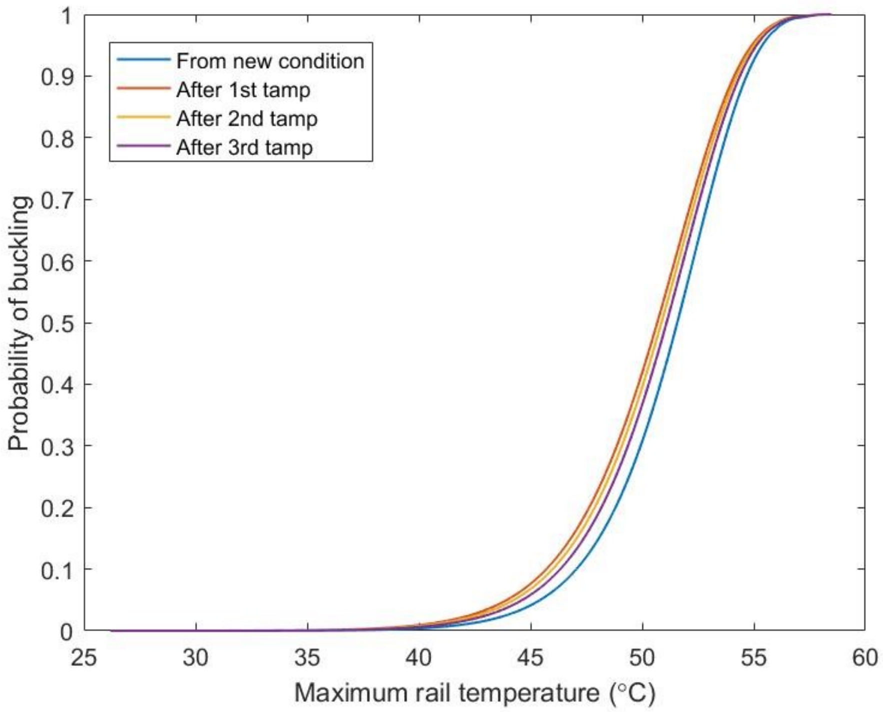

Figure 6-31 Probability of buckling under medium emission scenario for tracks in a very good state

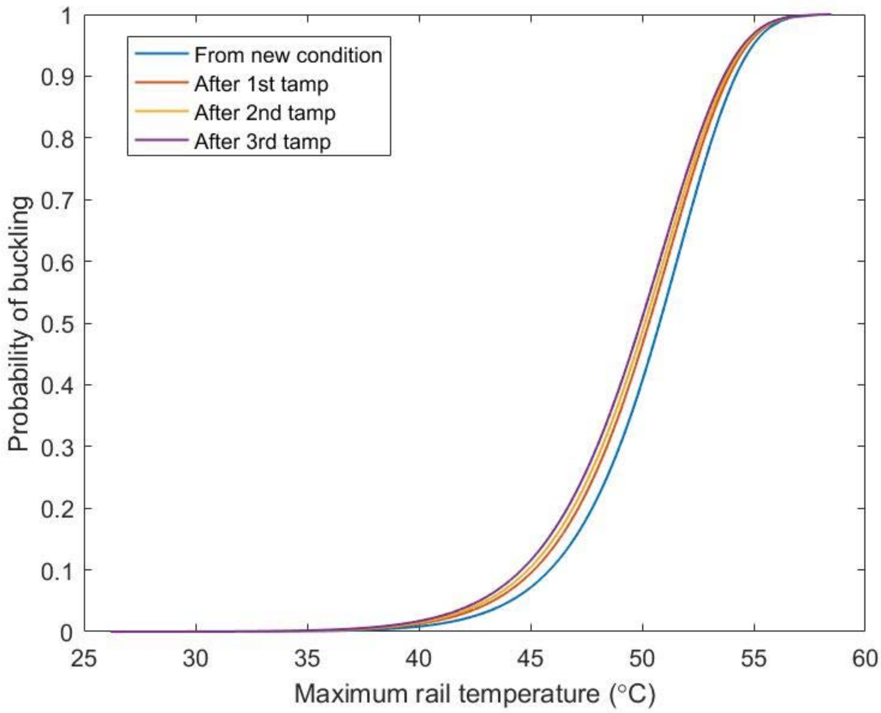

Figure 6-32 Probability of buckling under medium emission scenario for tracks in a good state

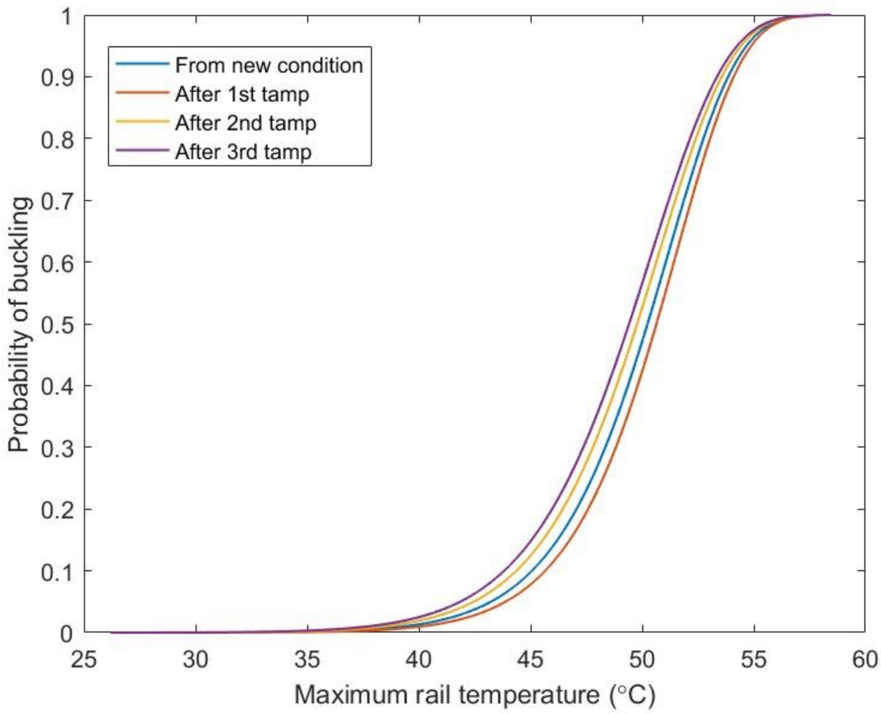

Figure 6-33 Probability of buckling under medium emission scenario for tracks in a poor state

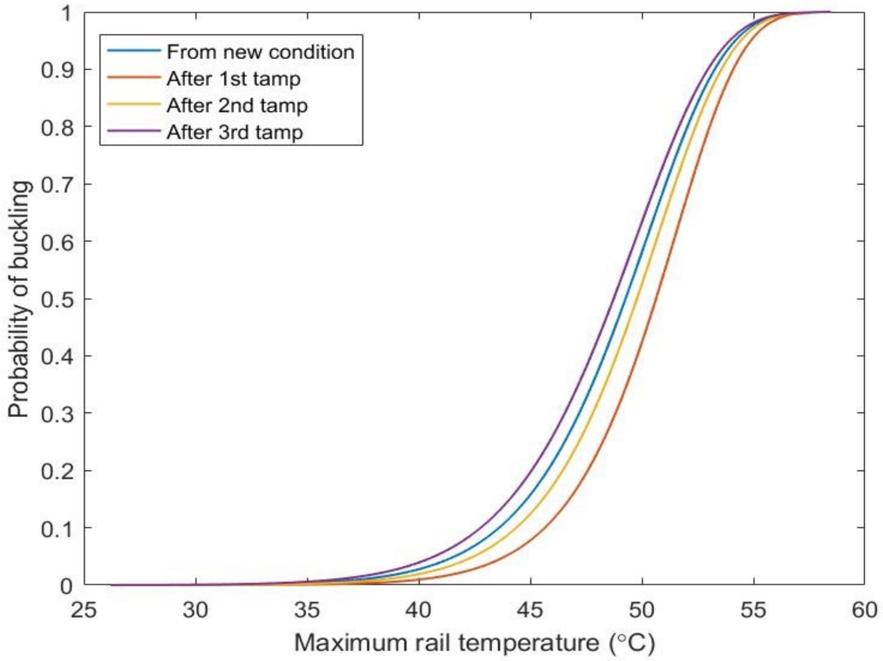

Figure 6-34 Probability of buckling under medium emission scenario for tracks in a very poor state

In reality, both σ and T_r are represented by distributions. Therefore, in order to solve Equation 6.25, Monte Carlo simulation was used and the results of this analysis for the example given above are shown in Figure 6.36. Figure 6.35 determines the current condition of track considering its maintenance history and Figure 6.36 illustrates the probability of buckling determined using Monte Carlo simulation.

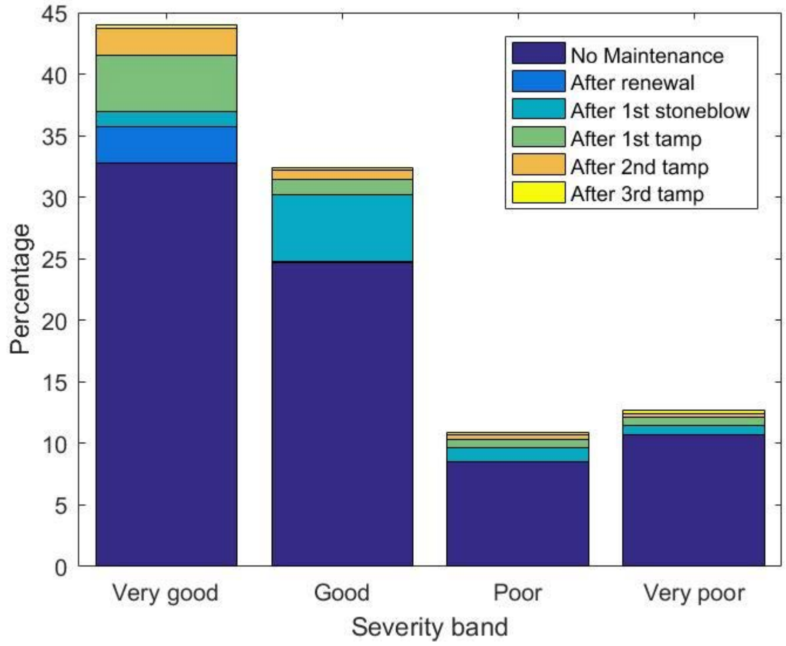

Figure 6-35 Condition of track at each band using 35m standard deviation of track geometry as a measure of condition

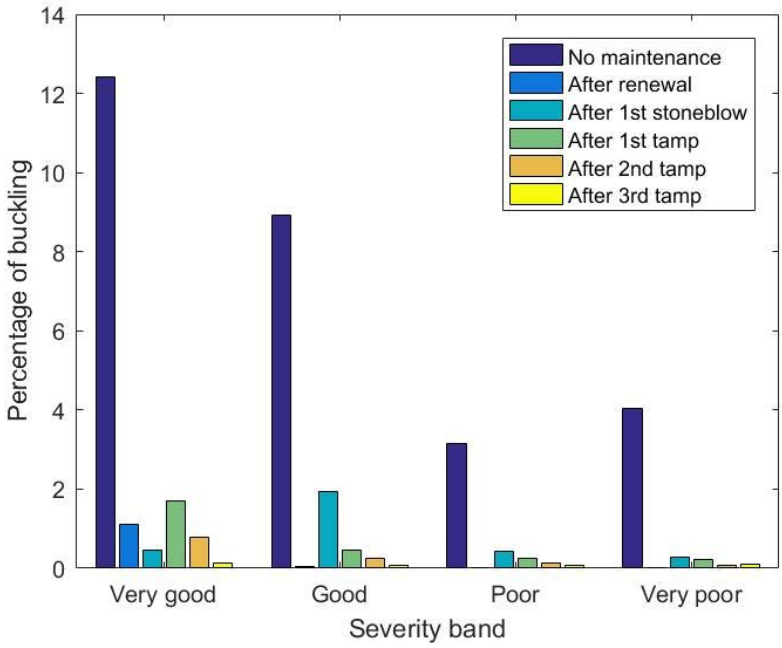

Figure 6-36 Probability of buckling of track at each band based on previous maintenance using Monte Carlo simulation

6.6.2 Precipitation Deterioration Factor

Within the prototype system the future increased deterioration of the subgrade caused by predicted increases in precipitation resulting from climate change are determined from a precipitation degradation factor. The factor is determined by comparing the deterioration of the subgrade for conceptual networks in different regions.

Based on the methodology explained in Section 5.3.8.4, first the monthly precipitation of different regions where the conceptual networks are located are determined (see Figure 6.37). The conceptual network used in this section is described in Section 6.3. Because, subgrade stiffness data were not available, the deterioration of the ballast, as measured by track geometry changes (i.e. SD of vertical ballast geometry) was used as a proxy. This was considered a reasonable assumption since geometry deterioration is related to the condition of the subgrade (see Section 2.3.6). After scrutinising the characteristics of the track sections available, track sections over a straight line whose ballast were renewed at year 2002 and consist of CWR with a line speed of 100 mph were considered for the analysis. According to the information given in the dataset, the last inspection on these track sections were carried during November 2012 and no maintenance had been undertaken on these sections since the date of their ballast renewal. However, there was no information regarding the drainage conditions of these track sections and the materials forming their subgrade.

The amount of average daily precipitation for each month for the regions under consideration were modelled using the central estimate of average daily precipitation (see Section 5.3.8.2 and Figure 6.37).

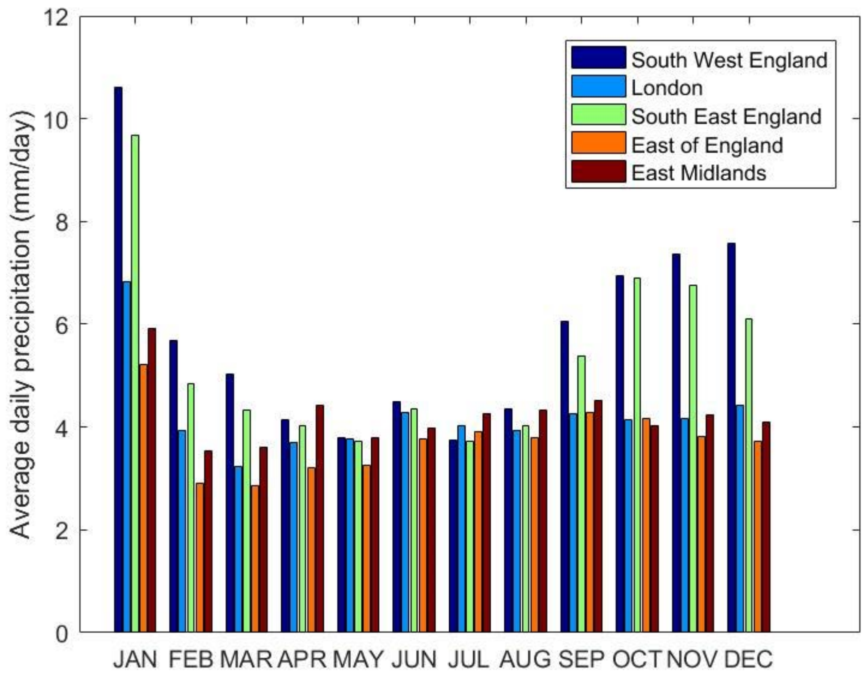

Figure 6-37 Average monthly precipitation for 2012 for different regions

To determine the effects of precipitation induced deterioration, because the deterioration data were recorded on November, the difference of precipitation of this month was calculated between each region. For instance, based on Figure 6.37, the average amount of daily precipitation in November for the East Midlands is 4.2476 mm/day. however, for East of England this value is 3.8275 mm/day. Therefore, the amount of increase in precipitation is 10.97% ($\frac{4.2476-3.8275}{3.8275} \times 100$). Whereas, the percentage of increase in precipitation between the East of England and South East England is 76.87% ($\frac{6.7699-3.8275}{3.8275} \times 100$). The amount of increase in precipitation amongst the given regions is calculated and tabulated in Table 6.20.

The next stage of the analysis is to determine the difference between subgrade deterioration of the conceptual network in each two regions using Equation 5.4 (see Section 5.3.8.4). For the purpose of the example, the ballast data were used as mentioned above. The deterioration of the ballast for these particular networks was modelled according to Section 6.4 and the results are shown in Tables 6.21 to 6.25.

Track ELR	Administrative regions	Increase in precipitation (%)
SPC1 – SPC3	East of England – East Midlands	10.97
SPC1 – BML2	East of England – South East England	76.87
SPC1 – BML1	East of England – London	8.59
SPC1 – BML3	East of England – South West England	92.36
SPC3 – BML2	East Midlands – South East England	59.38
BML1 – SPC3	London – East Midlands	2.14
SPC3 – BML3	East Midlands – South West England	73.34
BML1 – BML2	London – South East England	62.88
BML1 – BML3	London – South West England	77.14
BML2 – BML3	South East England – South West England	8.75

Table 6-20 Percentage of increase in precipitation for different regions for November 2012

State	SD	η	95% confidence bound	β	95% confidence bound	MTTF	λ
Very Good	2	109.6798	[68.5329 - 104.0245]	1.0518	[0.8488 - 1.1493]	107.525	0.0094
Good	2.7	80.8208	[76.6434 -109.1011]	1.2749	[1.0031 - 1.3645]	75.009	0.0133
Poor	3.5	92.5772	[81.4869 - 96.4011]	1.1875	[1.0891 - 1.8706]	87.464	0.0114
Very Poor	>3.5	86.6639	[78.0141 - 89.5273]	1.429	[1.2704 - 2.5075]	78.796	0.0127

Table 6-21 Deterioration parameters of BML1 (ballast est. 2000) located in London region

State	SD	η	95% confidence bound	β	95% confidence bound	MTTF	λ
Very Good	2	55.1195	[48.752 - 66.300]	1.6512	[1.1617 - 1.8550]	49.3516	0.0203
Good	2.7	74.9256	[75.786 -92.511]	1.8678	[1.7965 - 2.4082]	66.53	0.0150
Poor	3.5	62.6573	[54.510 -63.563]	1.5846	[1.3090 - 2.1360]	56.23	0.0178
Very Poor	>3.5	74.6397	[67.097 -75.677]	2.298	[1.732 - 3.0030]	66.115	0.0151

Table 6-22 Deterioration parameters of BML2 (ballast est. 2000) located in South East England

State	SD	η	95% confidence bound	β	95% confidence bound	MTTF	λ
Very Good	2	95.1128	[78.338 - 102.532]	2.1895	[1.3171 - 2.7882]	84.23	0.0119
Good	2.7	68.6873	[63.612 - 74.8681]	2.8212	[2.1929 - 3.0647]	61.1789	0.0163
Poor	3.5	35.3542	[33.2680 -38.7824]	2.9155	[2.3168 - 3.4121]	31.52	0.0317
Very Poor	>3.5	45.5022	[44.0523 -49.2534]	4.8703	[3.1774 - 5.2046]	40.797	0.0245

Table 6-23 Deterioration parameters of BML3 (ballast est. 2002) located in South West region

State	SD	η	95% confidence bound	β	95% confidence bound	MTTF	λ
Very Good	2	88.5918	[72.793 -122.423]	0.1305	[0.068 - 0.925]	1×10^4	5×10^{-6}
Good	2.7	165.7201	[142.233 - 253.739]	0.2066	[0.167 - 0.829]	6×10^2	1.66×10^{-4}
Poor	3.5	75.7512	[80.930 -105.249]	1.0334	[0.94 - 1.43]	74.843	0.0134
Very Poor	>3.5	175.0950	[160.156 - 192.251]	1.042	[1.035 - 1.619]	172.22	0.0058

Table 6-24 Deterioration parameters of SPC1 (ballast est. 2000) located in East of England

State	SD	η	95% confidence bound	β	95% confidence bound	MTTF	λ
Very Good	2	42.095	[41.246 -142.738]	0.2357	[0.1003 - 0.3104]	39.318	0.0254
Good	2.7	9.371	[21.255 -41.618]	1.07288	[0.8510 - 1.2039]	9.113	0.109
Poor	3.5	99.35	[90.226 -100.524]	1.12138	[1.0492 - 1.2670]	95.310	0.0105
Very Poor	>3.5	121.45	[114.39 - 124.733]	1.25	[1.0388 - 1.5843]	113.116	0.0088

Table 6-25 Deterioration parameters of SPC3 (ballast est. 2000) located in East Midlands

To determine the precipitation deterioration factor (see Section 5.3.8.4) the amount of deterioration per millimetre of rainfall was calculated for different regions using Tables 6.21 to 6.25 and Figure 6.37. For example, based on Table 6.21, the deterioration rate of track (β)

for BML1 track sections in a very good state is 1.0518 and the average monthly amount of precipitation in that region during November is 4.156 mm/day (Figure 6.37). To normalise the data, the ratio of deterioration for tracks in very good state per millimetre precipitation would be 0.2531 ($\frac{1.0518}{4.156}$), whereas for the sections of track in a good state the corresponding value is 0.3068 ($\frac{1.2749}{4.156}$). This procedure is carried out for all the states within each region for each subnetwork used in this example and the results are shown in Table 6.26.

Track ELR	**Administrative region**	**Deterioration rate per millimetre rainfall at each condition state**			
		Very Good	Good	Poor	Very Poor
BML1	London	0.2531	0.3067	0.2684	0.3216
BML2	South East England	0.2651	0.2998	0.2544	0.3689
BML3	South West England	0.2981	0.3841	0.3969	0.6630
SPC1	East of England	0.0360	0.0570	0.2850	0.2873
SPC3	East Midlands	0.0572	0.2605	0.2722	0.3035

Table 6-26 Deterioration rate per one-millimetre rainfall for the conceptual network at different regions

The next stage of the process is to calculate the difference in the deterioration rate of a homogenous network in a region with regards to a network with the same characteristics in a different region (see Equation 5.4). For example, the percentage of increase in the deterioration rate for sections of track in very good state between the conceptual network located in East of England and East Midlands is 59.02% ($\frac{0.0572-0.0360}{0.0360} \times 100$).

Based on the assumption that the difference in the deterioration rate of sections of track with homogenous properties, but located in different regions, is due to the difference in climate (i.e. average daily precipitation), it was found that for the example data set, when the amount of average daily precipitation increases by 10.97%, the precipitation deterioration factor for sections of track in a very good state increases by 59.02%. However, for the same network when there is 76.87% increase in average daily precipitation (Table 6.20), there would be 636% increase in precipitation deterioration factor for sections of track in the very good state. For the example data set, this process is repeated for all the severity bands and the results are tabulated in Table 6.27.

Based on Table 6.27, it can be seen that in majority of cases when there is an increase in average daily precipitation, there is an increase in the precipitation deterioration factor. However, in one case, although there is an increase of 2.14% in the amount of average daily precipitation between London and East Midlands, there was a decrease in the precipitation deterioration factor. This means that tracks in East Midlands region are deteriorating at a lower rate, notwithstanding the slightly higher amount of average daily precipitation in this region. This could be due to a number of reasons. Because the subgrade and formation layer materials were not available for the conceptual network considered there could be variations in the materials making up the subgrade of the respective networks. In addition, the networks could have different saturation levels and moisture contents due to differing antecedent rainfall patterns. Furthermore, the fouling index and the drainage conditions of the conceptual network used were not available. It can be seen from Figure 6.37 that during October the average daily precipitation in London was 4.14 mm/day, whereas this figure is 4.035 mm/day for East Midlands. This could affect the saturation level and moisture contents of tracks and based on the drainage conditions and the liquid and plastic limits of the materials forming the substructure, the stiffness could vary. Moreover, the exact time of inspection during November was not known. Therefore, based on the exact inspection time, whether early or late November, the rates could differ slightly.

Track ELR	**Administrative regions**	**Increase in precipitation (%)**	**Precipitation deterioration factor (%)**			
			Very good	Good	Poor	Very poor
SPC1 – SPC3	East of England – East Midlands	10.97	59.02	357.20	-4.47	5.61
SPC1 – BML2	East of England – South East England	76.87	636.59	426.30	-10.7	28.38
SPC1 –BML1	East of England – London	8.59	603.05	438.07	-5.82	11.93
SPC1 – BML3	East of England – South West England	92.36	728.29	574.14	39.26	130.74
SPC3 – BML2	East Midland – South East England	59.38	363.22	15.11	-6.56	21.55
BML1 – SPC3	London – East Midlands	2.14	-77.40	-15.06	1.41	-5.63
SPC3 – BML3	East Midlands – South West England	73.34	420.88	47.44	45.78	118.47
BML1 – BML2	London – South East England	62.88	4.74	-2.24	-5.22	14.70
BML1 – BML3	London – South West England	77.14	17.77	25.23	47.87	106.15
BML2 – BML3	South East England – South West England	8.75	12.44	28.09	56.02	79.72

Table 6-27 Amount of increase (decrease) in deterioration rate of the conceptual network for every two regions

The processes illustrated in Section 5.3.8.2, is used to determine the amount of average daily precipitation for every month over the period of analysis. By using the data, the change in average daily precipitation, from the present to future years, is calculated for each month. In this manner, special analogue scenarios can be used to determine the future climate (i.e. average daily precipitation) of a region based on the climate of another analogous region which experienced a similar precipitation rate. This is explained in a form of an example below based on the results obtained above.

For example, there is 8.5% increase in average daily precipitation between East of England and London (Table 6.27). On the other hand, the calculated percentage of increase in average daily precipitation rate between East of England, on November 2012, and the predicted precipitation rate of East Midlands for November 2019 (see Figure 6.38) is also approximately 8.2%

($\frac{4.141-3.827}{3.827} \times 100$). Following the assumption used in Section 5.3.8.4, it can be stated that the increase in deterioration rate of the ballast sections of the conceptual network located in East Midlands during November 2019 could be similar to those sections located in London during November 2012. Therefore, to model the deterioration rate of the conceptual network located in East Midlands (and to calculate its transition matrices) for 2019, the model determined for the conceptual network located in London for 2012 can be used. Based on Table 6.27 it is seen that the precipitation deterioration factor for track in the very good state is 603%, (increase in deterioration rate) whereas for good, poor and very poor state this value is 438.07%, -5.82% and 11.93% respectively.

Moreover, it was determined that the percentage of increase in precipitation for East of England between 2012 and 2048 is approximately 8.5% ($\frac{4.155-3.827}{3.827} \times 100$) (Figure 6.39). Consequently, to predict the deterioration transition matrices of this region in year 2049, the deterioration transition matrices developed for the homogenous conceptual network for London region during 2012 could be used (assuming the same volume of traffic and maintenance history).

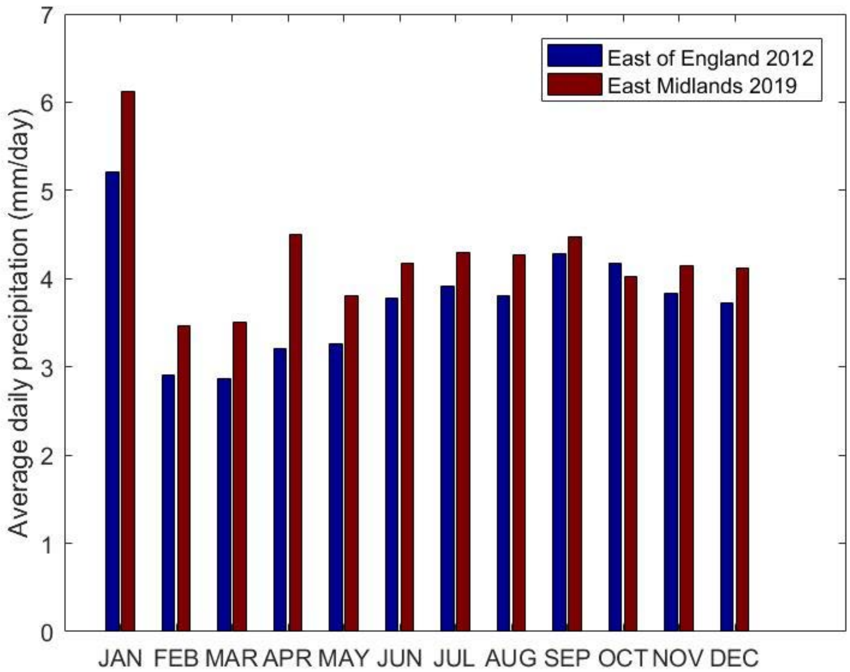

Figure 6-38 Average daily precipitation for administrative regions of East Midlands for 2019 and East of England in 2012

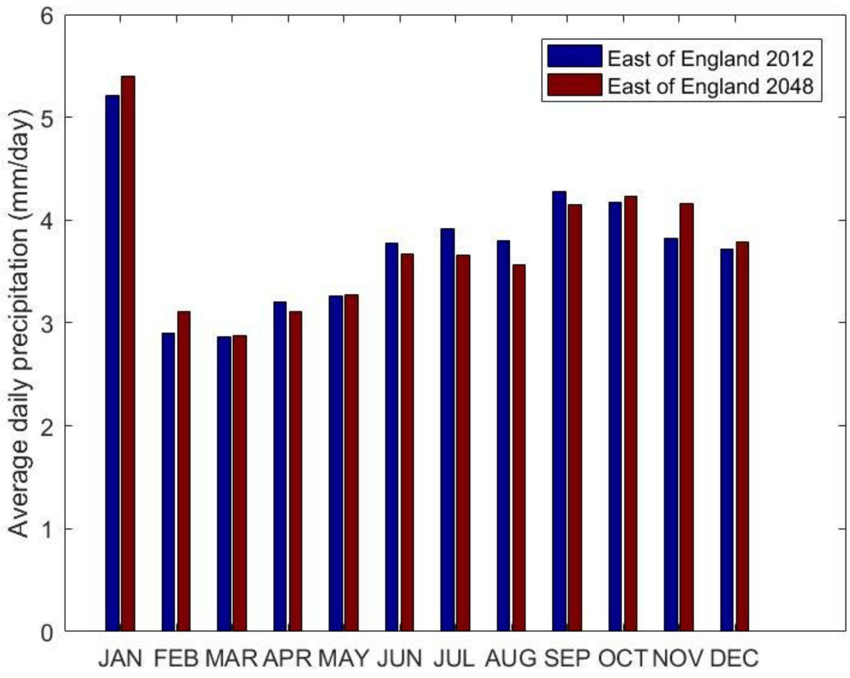

Figure 6-39 Average daily precipitation for East of England administrative region for year 2012 and 2048

6.7 Summary

In this chapter, the required inputs, associated maintenance and deterioration processes and outputs of the system were described in Sections 6.2 and illustrated using real data from the UK's railway network in Sections 6.4 and 6.5. Using condition indices (see Section 5.3.4), the process of developing transition matrices using the Kolmogorov equation was illustrated. The use of the example data set demonstrated, confirming the evidence available in the literature, that tamping and stoneblowing maintenance may affect the subsequent deterioration rate of the ballast and that it is possible for the ballast condition of a section of track to worsen as a result of such maintenance (see Section 6.4.4). To account for this in the tool proposed herein, a number of transition matrices are used. Restoration transition matrices were developed using the distribution of the measure of a particular defect after intervention by considering the previous state of the components (see Section 6.5).

The model determines the probability of buckling occurring by using Monte Carlo simulation to take into account the probability distributions of ballast condition and rail temperature (see Section 6.6.1). To determine the effects of changes in precipitation on the future deterioration of a section of track, an approach was postulated (see Section 5.3.8.4), which tries to infer the amount of deterioration due to precipitation only, by comparing component degradation rates of sections of railway track in different geographical regions of homogenous characteristics, other than precipitation rates. It was evident from applying this approach to a set of case study data that the change in the amount of precipitation affects the rate of deterioration of track geometry.

The subsequent Chapter illustrates the use of the developed system using data obtained from the UK's railway network.

Chapter Seven

7. PROTOTYPE SYSTEM

7.1 Introduction

The logical design behind the proposed prototype system, which uses dataset of track condition and according to condition indices, it develops deterioration and restoration transition matrices, was explained in Chapter Six. Multiple transition matrices are developed based on available data so that Markov chain can be used for predicting the future condition of the (conceptual) network (using Equations 6.19 and 6.23). To determine the effects of extreme temperature on rail buckling occurrence, suitable distribution of rail temperature and track geometry were used, and Monte Carlo simulation was performed to calculate the probability of buckling over the analysis period (see Equations 6.25 and 6.26). The amount of change in deterioration as a result of increase or decrease in precipitation was determined using precipitation deterioration factor (Equation 5.4). Accordingly, different analogue scenarios were used, which based on the rate of precipitation in one region and the future precipitation of another region, which is predicted to experience similar precipitation rates, the change in deterioration was determined (see Section 6.6.2).

In this Chapter, a prototype system is developed and used which according to the inputs and processes of the system (see Section 6.2), it generates outputs to prove the usefulness of the methodology (see Section 7.4). Different case studies are presented to investigate the effects of budget and maintenance policies on the condition of the network by analysing the values of TCIs (see Section 5.3.9).

7.2 Implementation of the Prototype Maintenance Management System

The developed system is in a form of graphical user interface which is designed and programmed in MATLAB (see Figure 7.1). The system consists of number of sections which relates to different inputs and processes. To start, data of recorded measures of condition for conceptual networks are entered to the system by the user. The data must be classified according to the type of component and history of maintenance (see Section 6.3) in Excel (.xls) format. For each defect type (see Section 5.3.3), the system uses the specified condition indices to generate the restoration and deterioration transition matrices (see Sections 5.3.4). For every conceptual network, initial condition and maintenance standards must be entered to the system by the user (see Sections 7.3.3 and 7.3.6). In addition, the user must specify the initial coexistence matrices and the duration of analysis period (see Section 7.3.5).

Extremes in maximum daily temperature for every month of the analysis year are calculated for corresponding regions of conceptual networks and incorporated in the system for the calculation of probability of buckling occurrence (see Section 7.3.8). In the same manner, monthly average daily precipitation rates for conceptual networks are calculated, and the ratio of change in precipitation rate between each two regions is determined. Sensitivity analysis is carried by the prototype system which based on the predicted precipitation rate of a conceptual network it determines the change in its deterioration using precipitation deterioration factor. This is achieved by comparing the future climate of a conceptual network with another homogenous conceptual network which had similar climate (precipitation) in the past (see Section 6.6.2).

Overall annual maintenance budget is specified by the user and the percentage to be used every year must be entered to the system (see Section 7.4). In addition, to determine the present value of the future budget, for the purpose of the analysis, financial discount rate is used, and the rate of discount must be specified by the user (see Section 7.4.1). This way, the prototype system predicts the overall budget of required maintenance as specified by standards and feasible maintenance under budget constraints is calculated for the whole network (or conceptual networks). Based on the condition of track components, the condition of the network (or conceptual networks) is predicted using TCIs in a graphical format over the duration of analysis (see Section 7.4)

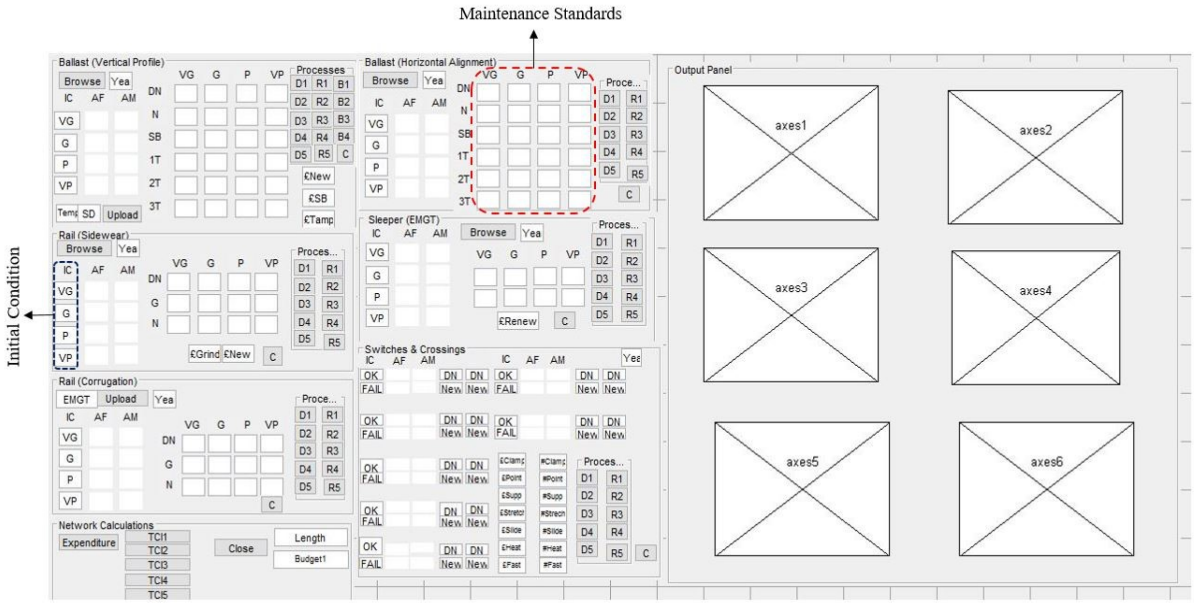

Figure 7-1 Prototype system

7.3 Data Availability

The data used to characterise the conceptual networks in the prototype system are according to the maintenance management information described in Section 4.3.3 and are obtained from various sources (see Section 6.3). In general, the information is classified in two categories.

1. Network information
2. Asset information

7.3.1 Network Information

Based on Section 5.3.2, data of network level track condition must be in a form of percentages of conceptual network per defect type at each condition state. The relevant data in such format were not available, and therefore, to run the prototype system project level data were obtained from NR’s database for BML, SPC and ECM routes (see Section 6.3).

Based on the range of speed limits for each line, three speed categories were defined ranging from 120 – 140 mph, 110 – 120 mph and 90 – 100 mph. Accordingly, three conceptual networks were determined. Based on the classification of track categories by Railway Group Standards (Railway Group Standards, 1999) with respect to their EMGTPA, the average EMGTPA for the conceptual networks were determined using Figure 7.2. For example, for track category 1A (speed range 120 – 140 mph) the average EMGTPA is 25 whereas for categories 1 (speed range of 110 – 120 mph) and 2 (speed range of 90 – 100 mph) this value is 20 and 15 respectively (see Table 7.1).

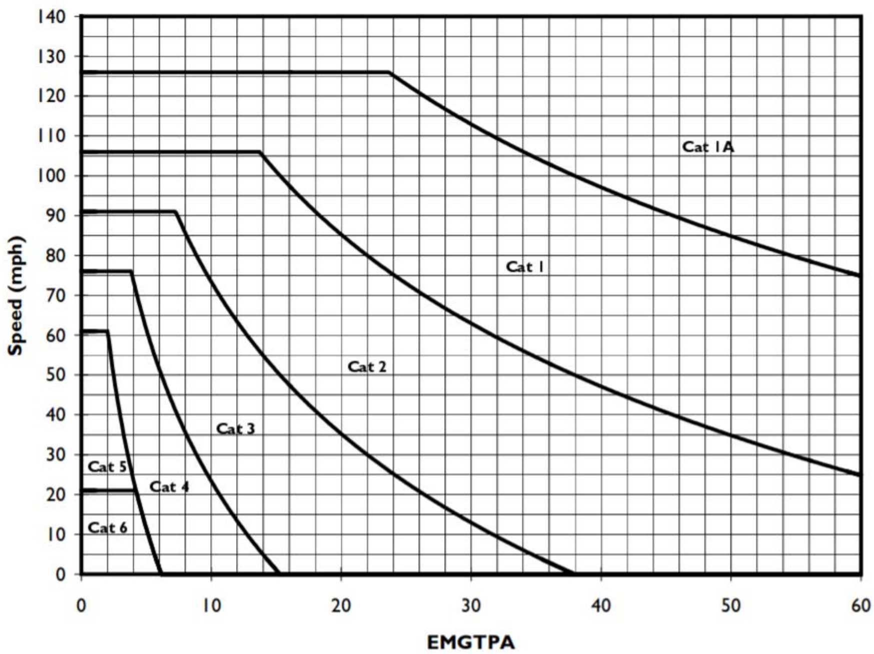

Figure 7-2 Categorisation of track within the UK (Railway Group Standards, 1999)

The length of the network (L) in kilometres is determined based on the total length of tracks in each conceptual network. This information was obtained from the UK Railway Codes (RCs) (Railway Codes, 2017) and L was calculated to be 616.48 km. In this manner, the overall network is determined based on the percentage of conceptual network forming the network (see Table 7.1).

Conceptual Network	**1**	**2**	**3**
Line Speed (mph)	120 – 140	110 – 120	90 – 100
EMGTPA	25	20	15
Length (km)	257.75	30.46	328.27
Percentage of Network	41.81	4.94	53.25

Table 7-1 Network Information

The above conceptual networks are not physically connected and are dispersed over different regions within the UK. Therefore, to evaluate the effects of climate induced deterioration (see Section 6.6) on conceptual networks, the percentage of conceptual networks at each administrative region are determined (see Table 7.2)

Overall Network	Track ELR	Administrative Region	Length (km)	Portions of Network (%)
Conceptual Network 3	BML1	London	125.01	20.27
	BML2	South East England	93.58	15.17
	BML3	South West England	10.44	1.69
	SPC1	East of England	50	8.14
	SPC3	East Midlands	49.24	7.98
Conceptual Network 2	SPC1	East of England	30.46	4.94
Conceptual Network 1	ECM	London	50.93	10.45
		East Midlands	206.81	31.36

Table 7-2 Overall network information considering the location of conceptual networks

7.3.2 Asset Information

Asset information related to rails, sleepers and S&Cs are required to determine the condition of each conceptual network based on the permissible values of measures of condition of the components at each state according to Section 5.3.4. The available asset information for each component are explained below.

7.3.2.1 Rails

Since based on the type of rail, speed and traffic different standards are used for determining the permissible service life of rails, for the prototype system, it is required to determine the percentage of rails within each conceptual network according to its type (JR and CWR). Furthermore, rails on some parts of the network were installed before 1974 (Naito, 2007). These rails have different design standards compared to post 1974 rails, and therefore different standards are used to determine their condition indices (Naito, 2007). Thus, it is important to determine the percentage rails installed prior to 1974 within the conceptual networks. Due to unavailability of such data, it was considered that only CWRs are used within the conceptual networks considered. This was assumed to be a reasonable assumption since the conceptual networks considered as examples belong to tracks with speeds above 90 mph in which CWRs are more suitable and more likely to be used than JRs.

7.3.2.2 Sleepers

As explained in Section 2.2.3, there are three general types of sleepers. Different types of sleepers might be in use in a conceptual network and thereby different standards are used within conceptual networks (see Section 5.3.4). For the prototype system, it is important to determine the percentage of each sleeper type forming the conceptual network. This way the initial condition of sleepers for every conceptual network can be represented based on the percentage of each type of sleeper at each state which is determined by their permissible EMGT. Because this information was not available, it was assumed that only concrete sleepers are used within the conceptual networks considered. This was considered reasonable because, the ballast of conceptual networks used are installed between 2000 to 2009 and due to climate conditions of the UK, timber and steel sleepers are less likely to be used for lower track categories (higher speed) (see Section 2.3.3).

7.3.2.3 Switches and Crossings

As stated in Section 2.2.2, the type of crossing, turn out length and switch radius vary based on speed category and location. Therefore, each conceptual network could contain different types of S&C unit and for each different set of standards are used. Accordingly, portions of different S&C units within each conceptual network must be determined. Although the type and number of units were not available in the data set, the number of the units within the considered conceptual networks were obtained from Open Railway Map (2017), which contains a map of the UK railway network based on maximum line speed. This was achieved using the following steps

1. The mileages of given track sections were obtained from NR database (Network Rail, 2013).
2. Based on the mileage of tracks sections the name of relevant stations within each line was obtained from RCs (Railway Codes, 2017).
3. Based on 2, Open Railway Map (2017) was used to identify BML, SPC and ECM routes and accordingly the number of S&C units within each conceptual network were roughly estimated.

The overall number of S&C units counted based on the above procedure is tabulated in Table 7.3below.

Conceptual Network	**1**		**2**	**3**				
Engineering Line Reference (ELR)	ECM1		SPC1	SPC3	SPC1	BML3	BML2	BML1
Administrative Region	LON	EM	EE	EM	EE	SWE	SEE	LON
Number of Units	4	5	2	0	3	2	1	1

Table 7-3 Number of S&C units for conceptual networks

7.3.3 Network Level Track Condition

As mentioned in Section 5.3.4, based on measures of condition of components different condition indices are specified. The initial condition is determined by comparing the condition of components, using their statistical distribution of measures of condition, with condition indices. For instance, the maximum service life of CWRs located in conceptual network 1 with EMGTPA of 25 EMGT, is determined to be 1000 EMGT. This way, for each component the initial condition is calculated using the percentages of their measures of condition at each condition state.

7.3.3.1 Initial Condition of Rails, Sleepers and Switches and Crossings

The measures of condition of rails, sleepers and S&Cs were described in Section 5.3.3 and their condition indices were discussed in Section 5.3.4. To determine the distribution of measures of condition of these components the following methods have been used.

<u>EMGT</u>

The EMGT of rail, sleepers and S&Cs for the conceptual networks was assumed to increase monotonically with time according to EMGTPA (for example, 25 EMGT) (Zhang, et al., 2000). Within a conceptual network, these track components could be of different age since their installation date varies. The EMGT of these components in the conceptual networks are calculated using their age in years and the EMGTPA of their section (cumulative tonnage=age of component × EMGTPA) (Naito, 2007). Due to limitation of data availability, only CWRs and concrete sleepers were considered. For S&Cs, it was assumed, all the units are same in terms of type and curvature. In this manner, portions of network at each condition state, based on EMGT of rails, sleepers and S&Cs, are calculated by dividing the length of track sections at each state by the total length of tracks in each conceptual network. For the conceptual networks considered, such data were not available. However, the initial condition determined by Naito (2007) for rails based on EMGT was used instead. This was assumed adequate, since the conceptual networks in his work were also classified based on track categories as in Figure 7.2. Because track sections within the conceptual networks considered are located at different administrative regions, the initial condition for every region within each conceptual network is determined based on portions of track sections at each region (Table 7.2). Thereafter data can be normalised for each administrative region so that sum of portions of track in every state adds to unity. The initial condition of rails and sleepers using EMGT as a measure are demonstrated in Tables 7.4 to 7.9.

Condition state	Condition index (EMGT)	Portions (%)	EM	LON
1	0 – 334	24.4	18.3	6.1
2	334 – 668	41.4	31.05	10.35
3	668 – 1000	22.4	16.8	5.6
4	1000<	11.8	8.82	2.98

Table 7-4 Initial condition of rails using EMGT for conceptual network 1(CN1)

Condition state	Condition index (EMGT)	Portions (%)	EE
1	0 – 334	34.3	34.3
2	334 – 668	62.8	62.8
3	668 – 1000	2.9	2.9
4	1000<	0	0

Table 7-5 Initial condition of rails using EMGT for conceptual Network 2 (CN2)

Condition state	Condition index (EMGT)	Portions (%)	LON	SEE	SWE	EE	EM
1	0 – 334	44.8	17.05	12.76	1.42	6.84	6.71
2	334 – 668	54.2	20.63	15.44	1.72	8.28	8.11
3	668 – 1000	0.9	0.34	0.25	0.03	0.13	0.13
4	1000<	0.1	0.03	0.02	0	0.01	0.01

Table 7-6 Initial condition of rails using EMGT for conceptual Network 3 (CN3)

Condition state	Condition index (EMGT)	Portions (%)	EM	LON
1	0 – 350	25.8	19.35	6.45
2	350 – 700	39.4	29.55	9.85
3	700 – 1050	23.6	17.7	5.9
4	1050<	11.2	8.4	2.8

Table 7-7 Initial condition of sleepers using EMGT for CN1

Condition state	Condition index (EMGT)	Portions (%)	EE
1	0 – 309	17.3	17.3
2	309 – 618	30.6	30.6
3	700 – 925	48.6	48.6
4	925<	3.5	3.5

Table 7-8 Initial condition of sleepers using EMGT for CN2

Condition state	Condition index (EMGT)	Portions (%)	LON	SEE	SWE	EE	EM
1	0 – 217	13.5	5.14	3.84	0.43	2.07	2.02
2	217 – 434	55.4	21.1	15.78	1.76	8.47	8.29
3	434 – 650	22.3	8.49	6.35	0.72	3.40	3.34
4	650<	8.8	3.35	2.5	0.28	1.35	1.32

Table 7-9 Initial condition of rails using EMGT for CN3

<u>Wear and Corrugation</u>

Network level data of wear and corrugation was not available in the given datasets. However, to run the prototype system it was necessary to determine the initial condition of rails and rails located on S&Cs at each condition state based on measures of wear and corrugation according to suitable condition indices.

To achieve this, project level data of Portuguese railway network which consists of UIC60 rail was used to determine the condition of rails using their amount of wear as measure of condition (Valente, 2009). This was considered to be a reasonable assumption because, in the data set used the EMGT and speed of the lines were the same as for conceptual networks considered (see Tables 7.10 to 7.12).

To determine the initial condition using corrugation as a measure of integrity, data were obtained from Naito's research (2007), whom used West Japan Railway Company datasets to determine the initial condition. For the purpose of this research only track categories 1A, 1 and 2 (i.e. conceptual networks 1, 2 and 3) were of interest (see Table 7.13 to 7.15).

Condition state	Condition index (Wear mm)	Portions (%)	EM	LON
1	70 – 67	81	60.75	20.25
2	67 – 64	11	8.25	2.75
3	64 – 61	6	4.5	1.5
4	61>	2	1.5	0.5

Table 7-10 Wear Conceptual Network 1

Condition state	Condition index (Wear mm)	Portions (%)	EE
1	70 – 67	81	81
2	67 – 64	11	11
3	64 – 61	6	6
4	61>	2	2

Table 7-11 Conceptual Network 2 Wear

Condition state	Condition index (Wear mm)	Portions (%)	LON	SEE	SWE	EE	EM
1	70 – 67	81	30.83	23.07	2.57	12.37	12.13
2	67 – 64	11	4.19	3.13	0.35	1.68	1.64
3	64 – 61	6	2.28	1.70	0.19	0.92	0.89
4	61>	2	0.76	0.56	0.06	0.3	0.29

Table 7-12 Conceptual Network 3 Wear

Condition state	Condition index (corrugation)	Portions (%)	EM	LON
1	0 – 0.04	85	63.75	21.25
2	0.04 – 0.08	10	7.5	2.5
3	0.08 – 0.1	3	2.25	0.75
4	0.1<	2	1.5	0.5

Table 7-13 Corrugation Conceptual Network 1

Condition state	Condition index (corrugation)	Portions (%)	EE
1	0 – 0.04	85	85
2	0.04 – 0.08	10	10
3	0.08 – 0.1	3	3
4	0.1<	2	2

Table 7-14 Corrugation Conceptual Network 2

Condition state	Condition index (corrugation)	Portions (%)	LON	SEE	SWE	EE	EM
1	0 – 0.04	85	32.35	24.21	2.7	12.98	12.73
2	0.04 – 0.08	10	3.8	2.84	0.32	1.52	1.49
3	0.08 – 0.1	3	1.14	0.85	0.09	0.45	0.44
4	0.1<	2	0.76	0.57	0.06	0.3	0.3

Table 7-15 Corrugation Conceptual Network 3

7.3.3.2 Initial Condition of Ballast

Based on section 5.3.3, 35m SD of vertical profile and horizontal alignment of track geometry (SD) and its rate of change over time (dSD/dt) are used to determine the initial condition of ballast. Detailed data of ballast sections and their maintenance history for the conceptual networks considered were discussed in Section 6.3.1. Based on the SD and the modelled dSD/dt (see Section 6.4.4), the initial condition of ballast for each conceptual network was determined using the latest date of recordings. Examples of initial conditions of the ballast sections using 35m SD and dSD/dt of vertical track geometry as a measure of condition for the conceptual networks are tabulated in Tables 7.16 to 7.23.

			SD			
		State	**1**	**2**	**3**	**4**
	State	**Condition Index**	**0 – 1.9**	**1.9 – 2.7**	**2.7 – 3.4**	**3.4<**
dSD/dt	**1**	**0 – 1.9**	16.9	16	4.4	1.7
	2	**1.9 – 2.7**	12	13.7	6.5	2.6
	3	**2.7 – 3.4**	2.6	4.2	2.6	1.2
	4	**3.4<**	2	6.5	3.8	3.3

Table 7-16 Conceptual Network 1 East Midlands

			SD			
		State	**1**	**2**	**3**	**4**
	State	**Condition Index**	**0 – 1.9**	**1.9 – 2.7**	**2.7 – 3.4**	**3.4<**
dSD/dt	**1**	**0 – 1.9**	14	9.5	0.7	0.3
	2	**1.9 – 2.7**	16.6	14.4	1.3	0.9
	3	**2.7 – 3.4**	11.4	7.2	1	0.5
	4	**3.4<**	7.3	10.9	2.1	1.9

Table 7-17 Conceptual Network 1 London

			SD			
		State	**1**	**2**	**3**	**4**
	State	**Condition Index**	**0 – 1.9**	**1.9 – 2.7**	**2.7 – 3.4**	**3.4<**
dSD/dt	**1**	**0 – 1.9**	23.7	21.2	7.1	2.1
	2	**1.9 – 2.7**	8.8	9.4	4.8	2.5
	3	**2.7 – 3.4**	2.5	3.5	2.4	1.4
	4	**3.4<**	1.5	4.1	2.2	2.8

Table 7-18 Conceptual Network 2 East of England

			SD			
		State	**1**	**2**	**3**	**4**
	State	**Condition Index**	**0 – 1.9**	**1.9 – 2.7**	**2.7 – 3.4**	**3.4<**
dSD/dt	**1**	**0 – 1.9**	23.3	9.9	0.7	0.3
	2	**1.9 – 2.7**	28	15.3	1.3	0.9
	3	**2.7 – 3.4**	1.9	5.5	0.5	0.3
	4	**3.4<**	4.2	5.4	1.2	1.3

Table 7-19 Conceptual 3 London

			SD			
		State	**1**	**2**	**3**	**4**
	State	**Condition Index**	**0 – 1.9**	**1.9 – 2.7**	**2.7 – 3.4**	**3.4<**
dSD/dt	**1**	**0 – 1.9**	32.8	31.4	9.9	2.1
	2	**1.9 – 2.7**	2.7	6.7	4.5	1.4
	3	**2.7 – 3.4**	0.9	1.9	1.5	0.5
	4	**3.4<**	0.5	1.4	1.2	0.6

Table 7-20 Conceptual 3 SWE

			SD			
		State	**1**	**2**	**3**	**4**
	State	**Condition Index**	**0 – 1.9**	**1.9 – 2.7**	**2.7 – 3.4**	**3.4<**
dSD/dt	**1**	**0 – 1.9**	39.8	21.1	2.2	0.8
	2	**1.9 – 2.7**	13.2	13.2	1.9	2.1
	3	**2.7 – 3.4**	2.2	2.2	0.7	0.4
	4	**3.4<**	1.6	3.7	0.6	1.4

Table 7-21 Conceptual 3 SEE

		SD				
		State	**1**	**2**	**3**	**4**
	State	**Condition Index**	**0 – 1.9**	**1.9 – 2.7**	**2.7 – 3.4**	**3.4<**
dSD/dt	**1**	**0 – 1.9**	27.8	35.2	8.6	4.9
	2	**1.9 – 2.7**	0.3	7.3	4.9	4.3
	3	**2.7 – 3.4**	0.3	2.6	0.6	2.3
	4	**3.4<**	0	0.3	0	0.6

Table 7-22 Conceptual 3 EE

		SD				
		State	**1**	**2**	**3**	**4**
	State	**Condition Index**	**0 – 1.9**	**1.9 – 2.7**	**2.7 – 3.4**	**3.4<**
dSD/dt	**1**	**0 – 1.9**	44.1	19.5	1.5	3.4
	2	**1.9 – 2.7**	3.4	6.5	0.4	2.7
	3	**2.7 – 3.4**	0	1.1	0.4	0.1
	4	**3.4<**	0	3.1	3.1	10.7

Table 7-23 Conceptual 3 EM

7.3.4 Transition Matrices

To predict the change in measures of condition of the components over time, transition matrices are developed based on the principles described in Sections 6.4 and 6.5 for ballast deterioration and restoration respectively. For other measures of condition, the transition matrices are developed using the following methods.

7.3.4.1 Deterioration Transition Matrices

EMGT

To model the transition matrices of rails, sleepers and S&Cs it is necessary to analyse the year on year progression of EMGT. The modelling process is explained below.

1. To model the effects of mixed cumulative EMGT within the conceptual networks, it was assumed that the distribution of cumulative EMGT within each state follows a Normal distribution with a mean value equal to the average range of condition indices specified for that state.
2. Deterioration of conceptual networks are determined based on the assumption that the yearly increase of EMGT (EMGTPA) is equal to the EMGTPA of each conceptual network. A schematic of the process is depicted in Figure 7.3.
3. Using the relevant condition indices specified for rails, sleepers and S&Cs, similar process as in Section 6.4 are applied to determine the transition matrices.

Examples of deterioration transition matrix for rails and sleepers are shown in Tables 7.24 and 7.25 respectively.

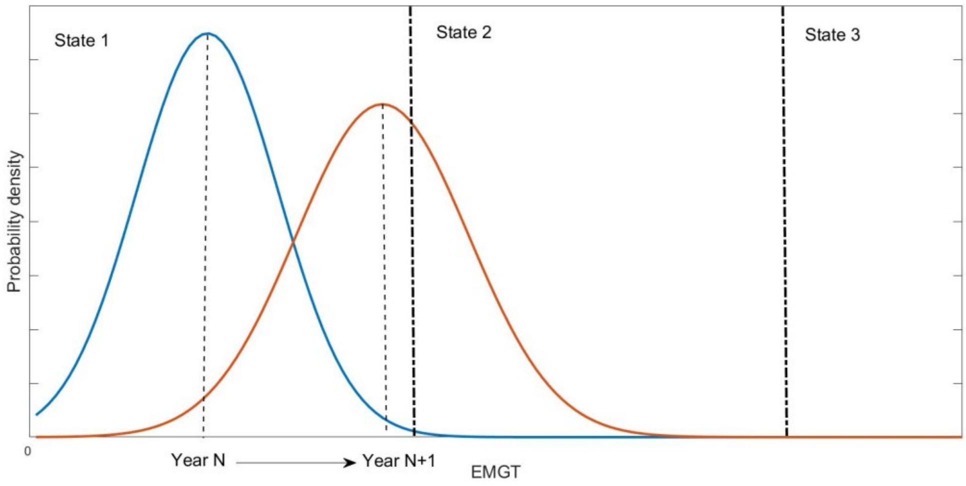

Figure 7-3 Annual progression of cumulative EMGT using Normal distribution (Naito, 2007)

Condition (Year N)	(Year N+1) State	Very Good 1	Good 2	Poor 3	Very Poor 4
Very Good	**1**	0.9831	0.0168	0.0001	0.0000
Good	**2**	0	0.9831	0.0168	0.0001
Poor	**3**	0	0	0.9831	0.0169
Very Poor	**4**	0	0	0	1

Table 7-24 Transition matrix for rails using their cumulative EMGT

Condition (Year N)	(Year N+1) State	Very Good 1	Good 2	Poor 3	Very Poor 4
Very Good	**1**	0.9620	0.0379	0.0001	0
Good	**2**	0	0.9620	0.0379	0.0001
Poor	**3**	0	0	0.9620	0.0380
Very Poor	**4**	0	0	0	1

Table 7-25 Transition matric for sleepers using their cumulative EMGT

Wear

To calculate deterioration transition matrices using wear as a measure of condition, project level data of Portuguese railway network was used (Valente, 2009). The data determined the amount of wear over the period of 2007 to 2009. The process is determined as follows.

1. Based on trend of data, and that the condition cannot not improve itself (see Section 6.3), it was determined that grinding was carried at 2008. Using Section 6.4.1, a linear function was used to define the underlying trend of data from 2007 to 2008 and from 2008 to 2009.
2. According to Section 6.4.2, using condition indices, the sojourn times (time of transiting from one state to another) are modelled using Weibull probability distribution function (see Table 7.26).
3. The transition matrices were calculated using the processes shown in Section 6.4.3 (see Tables 7.27 and 7.28).

State	Headwear	Intervention	η	C.B 95%	β	C.B 95%	MTTF	λ
Very Good	70 – 67	New	47.68	45.01-50.51	1.14	1.08-1.21	45.44	0.022
		After grinding	51.42	49.83-53.02	2.01	1.94-2.13	43.94	0.0203
Good	67 – 64	New	46.42	44.42-48.51	1.23	1.18-1.29	43.32	0.0231
		After grinding	50.40	48.83-52.02	2.03	1.94-2.13	44.65	0.0224
Poor	64 – 61	New	54.78	53.01-56.62	1.61	1.54-1.68	49.08	0.0204
		After grinding	55.91	54.47-57.39	1.82	1.75-1.89	49.69	0.0201
Very Poor	<61	New	61.21	60.17-62.26	2.15	2.09-2.21	54.21	0.0184
		After grinding	55.78	54.59-56.99	1.47	1.43-1.51	50.44	0.0198

Table 7-26 Fitted Weibull parameters to the distribution of wear

Condition	(Year N+1)	Very Good	Good	Poor	Very Poor
(Year N)	State	1	2	3	4
Very Good	**1**	0.9783	0.0215	0.0002	0
Good	**2**	0	0.9771	0.0226	0.0002
Poor	**3**	0	0	0.9798	0.0202
Very Poor	**4**	0	0	0	1

Table 7-27 Transition matrix for wear from new condition

Condition	(Year N+1)	Very Good	Good	Poor	Very Poor
(Year N)	State	1	2	3	4
Very Good	**1**	0.9779	0.0219	0.0002	0
Good	**2**	0	0.9779	0.0219	0.0002
Poor	**3**	0	0	0.9801	0.0199
Very Poor	**4**	0	0	0	1

Table 7-28 Transition matrix for wear after one cycle of grinding

Corrugation

To determine the transition matrices to model the effects of corrugation of track condition, the formula used in (Burrow, et al., 2009) which determined the rate of increase in corrugation of the UK railway network was used which is defined as

$$y = 0.0105e^{0.0204x} \tag{7.1}$$

Where y is the height from peak to trough of corrugation in millimetres and x is the cumulative gross tonnage in MGT. The transition matrices were determined using the following steps:

1. Based on Equation 7.1, the values of MGT which causes corrugation (y) to be equal to the average values of condition indices at each state are determined.
2. The rate of progression of corrugation in millimetres per MGT was converted to millimetres per EMGT using the conversion factor defined by ORR (Office of Rail Regulation, 2008).
3. The amplitude of corrugation was determined using Equation 7.1.
4. To determine the rate of corrugation in millimetres per year considering that rails in conceptual network could be of mixed cumulative EMGT, Normal distribution was used with the mean value calculated as in step 3 above.

5. The mean value of the Normal distribution at each band before deterioration was increased by an amount equal to the rate of deterioration in millimetres per year obtained in step 4 above (same as in Section 7.3.4.1, Figure, 7.3).
6. The method used in Section 6.4, is performed to determine the elements of transition matrices.

Condition	(Year N+1)	Very Good	Good	Poor	Very Poor
(Year N)	State	1	2	3	4
Very Good	1	0.9989	0.0011	0	0
Good	2	0	0.9989	0.0011	0
Poor	3	0	0	0.9989	0.0011
Very Poor	4	0	0	0	1

Table 7-29 Transition matrices for corrugation

<u>Switch Components</u>

Data of switch component were obtained from (Rama & Anderws, 2013). The data were recorded over some parts of the UK network which included the failure of different switch components over time and are used to determine their useful life. Accordingly, suitable probability distribution was applied to the distribution of the measured data to calculate the failure rate of the components. Table 7.30 shows the results of the fitted Weibull distribution to the data.

Components	EMGT	η	C.B 95%	β	C.B 95%	λ
Clamp Lock	62.2<	78.25	31.25-195	0.71	0.43-1.17	0.2577
Point Machine	70.7<	170.25	44.25-653.5	0.48	0.29-0.80	0.0693
Supplementary Drives Sets	162.5<	443.5	90-2-186.25	0.41	0.25-0.65	0.0183
Point Heater	112.5<	1146.5	600.81-1000	1.07	0.67-1.70	0.0224
Multiple Stretcher Bars	100<	669.75	200.24-1075	0.55	0.35-0.88	0.0225
Multiple Fastenings	187.5<	22.51	175.01-1800	0.55	0.33-0.92	0.0267
Multiple Slide Chairs	131.25<	562.75	45.6-253.5	0.75	0.45-1.25	0.1975

Table 7-30 Fitted Weibull parameters to the distribution of failed switch components

An example of the transition matrix for POE using the parameters calculated in Table 7.30 is shown in Table 7.31.

Condition	(Year N+1)	OK	Failed
(Year N)	State	1	2
OK	1	0.9989	0.0011
Failed	2	0	1

Table 7-31 Transition Matrix developed for POE

<u>Track Geometry</u>

Deterioration transition matrices of ballast were determined based on the processes explained in Section 6.4 for SD and dSD/dt. Based on history of maintenance suitable transition matrices were developed and used to model the effects of tamping and stoneblowing on deterioration of track sections. Few examples of calculated transition matrices are shown in Tables 7.32 to 7.34.

Condition (Year N)	(Year N+1) State	Very Good 1	Good 2	Poor 3	Very Poor 4
Very Good	**1**	0.9825	0.0174	0.0001	0.0000
Good	**2**	0	0.9836	0.0163	0.0001
Poor	**3**	0	0	0.9839	0.0161
Very Poor	**4**	0	0	0	1

Table 7-32 Transition matrix after one tamping cycle for SPC3

Condition (Year N)	(Year N+1) State	Very Good 1	Good 2	Poor 3	Very Poor 4
Very Good	**1**	0.9820	0.0178	0.0002	0.0000
Good	**2**	0	0.9816	0.0183	0.0001
Poor	**3**	0	0	0.9841	0.0159
Very Poor	**4**	0	0	0	1

Table 7-33 Transition matrix after two tamping cycles for SPC3

Condition (Year N)	(Year N+1) State	Very Good 1	Good 2	Poor 3	Very Poor 4
Very Good	**1**	0.9808	0.0190	0.0002	0.0000
Good	**2**	0	0.9824	0.0175	0.0002
Poor	**3**	0	0	0.9829	0.0171
Very Poor	**4**	0	0	0	1

Table 7-34 Transition matrix after three tamping cycles for SPC3

7.3.4.2 Restoration Transition Matrices

Component Renewal

When the permissible life of components is reached, renewal is carried, and components are replaced with new ones. However, in reality not always new components are used as replacements. For example, upon sleeper renewal used sleepers but still in good condition might be used. Due to unavailability of such information, it is assumed that renewal of components will revert the condition to the good as new. Renewal restoration transition matrix is tabulated in Table 7.35. For switch components only two condition states are used.

Condition (Year N)	(Year N+1) State	Very Good 1	Good 2	Poor 3	Very Poor 4
Very Good	**1**	1	0	0	0
Good	**2**	1	0	0	0
Poor	**3**	1	0	0	0
Very Poor	**4**	1	0	0	0

Table 7-35 Renewal transition matrix

Grinding

As mentioned in Section 2.5.1, although grinding improves the condition of the rail by removing corrugation, it may not return the condition of track to the good as new state. To model this, the procedure carried in Section 6.5 can be applied to determine the restoration transition matrices as a result of grinding. Based on the date of grinding, the distribution of minimum corrugation in millimetres can be sampled from the data. Using the processes stated in Section 6.5.1, suitable probability distribution can be fitted to distribution of measures of corrugation and using condition indices the restoration transition matrix can be developed to model the level of improvements of grinding on removing corrugation. Due to unavailability of such data it was assumed corrugation is completely removed by grinding. Therefore, Table 7.35 is used to as a restoration transition matrix for grinding.

<u>Stoneblowing and Tamping</u>

As discussed in Section 6.4.5, the level of improvements of tamping and stoneblowing varied based on previous maintenance. Few of the transition matrices developed using the data explained in Section 6.3 are shown in Tables 7.36 to 7.38 below.

Condition	(Year N+1)	Very Good	Good	Poor	Very Poor
(Year N)	State	1	2	3	4
Very Good	1	0.9112	0.0670	0.0171	0.0047
Good	2	0.8386	0.1075	0.0379	0.0160
Poor	3	0.8472	0.1060	0.0343	0.0126
Very Poor	4	0.7252	0.1569	0.0727	0.0452

Table 7-36 Restoration transition matrix after two cycles of stoneblowing

Condition	(Year N+1)	Very Good	Good	Poor	Very Poor
(Year N)	State	1	2	3	4
Very Good	1	0.7979	0.1329	0.0486	0.0206
Good	2	0.8780	0.0874	0.0260	0.0086
Poor	3	0.5768	0.2101	0.1191	0.0940
Very Poor	4	0.3910	0.2161	0.1651	0.2278

Table 7-37 Restoration transition matrix after one cycles of stoneblowing followed by two tamping

Condition	(Year N+1)	Very Good	Good	Poor	Very Poor
(Year N)	State	1	2	3	4
Very Good	1	0.6624	0.1911	0.0916	0.0550
Good	2	0.5755	0.1712	0.1118	0.1415
Poor	3	0.4896	0.2216	0.1445	0.1443
Very Poor	4	0.3950	0.2136	0.1631	0.2284

Table 7-38 Restoration transition matrix after three cycles of tamping

7.3.5 Coexistence Matrices

As stated in Section 5.3.6, some maintenance treatments trigger more than one measure of defect. Coexistence matrixes were considered for ballast and rail maintenance. For ballast the 35m SD of vertical and horizontal alignment of geometry were both available and coexistence matrices were calculated accordingly (see Section 5.3.6). Due to limitation in data, for the prototype system, coexistence matrices used to determine the effects of rail maintenance are same as Table 5.12 to 5.14.

In addition, when S&C or sleeper renewal is carried, a further tamping may be required to correct the track geometry (see Section 5.3.5). Sometime grinding might be used as well. Therefore, to determine the concurrent effects of sleeper and switch component renewal on ballast and rail condition suitable coexistence matrices must be used. Such information was not available and only coexistence matrices for rails and ballast were developed.

7.3.6 Maintenance Standards

Maintenance standards are determined by the user by setting suitable intervention levels for measures of condition (see Section 5.3.5). The user can determine different maintenance standards for the conceptual networks. Overall, two different maintenance standards are used to demonstrate and analyse the output of the prototype system (Tables 7.39 and 7.40). The prototype system allows the user to change the intervention levels and volume of maintenance at each iteration of the model over the duration of analysis. However, in the case studies explained in Section 7.4, the standards are the fixed throughout the whole of analysis period.

Based on the standards (see Tables 7.39 and 7.40) ballast renewal was mainly assigned to track sections in very poor state (severity band 4) in terms of SD and dSD/dt of track geometry. This was assumed logical because for high rates of deterioration of track geometry, tamping and stoneblowing are not effective and renewal must take place (see Section 6.4.4). Because no standards are determined for dSD/dt, same condition indices as used for SD are used to define severity bands of dSD/dt (see Section 5.3.4).

Component	Treatment	Treatment priority	Measure of condition	Defect priority	Severity Band
Rail	Renewal	3	Wear	2	3
				1	4
	Routine grinding	1	Corrugation	1	40% of the network (predefined)
	Grinding	4		2	4
	Renewal	2	EMGT	1	4
Sleepers	Renewal	1	EMGT	1	4
Switch/POE	Renewal	1	EMGT	1	2
Ballast	Routing Tamping	1	SD (vertical/horizontal geometry)	1	20% of the network (predefined)
	Tamping	4	SD (vertical geometry)	1	4
			SD (horizontal geometry)	2	4
			SD (vertical geometry)	3	3
			SD (horizontal geometry)	4	3
	Stoneblowing	3	SD (vertical geometry)	1	4
			SD (horizontal geometry)	2	4
			SD (vertical geometry)	3	3
			SD (horizontal geometry)	4	3
	Renewal	2	SD (vertical geometry)	4	4
			$\frac{dsd}{dt}$ (vertical geometry)	1	4
			$\frac{dSD}{dt}$ (vertical geometry)	2	3
			$\frac{dSD}{dt}$ (vertical geometry)	3	4

Table 7-39 Maintenance standards defined for Case Study in Section 7.4.1

Component	Treatment	Treatment priority	Measure of condition	Defect priority	Severity Band
Rails	Renewal	2	Wear	1	4
	Grinding	3	Corrugation	2	4
	Renewal	1	EMGT	1	4
Sleepers	Renewal	1	EMGT	1	3
Switch (POE)	Renewal	1	EMGT	1	2
Ballast	Tamping	3	SD (vertical geometry)	1	4
			SD (horizontal geometry)	2	4
			SD (vertical geometry)	3	3
			SD (horizontal geometry)	4	3
	Stoneblowing	2	SD (vertical geometry)	1	4
			SD (horizontal geometry)	2	4
			SD (vertical geometry)	3	3
			SD (horizontal geometry)	4	3
	Renewal	1	$\frac{dSD}{dt}$ (horizontal geometry)	2	4
			$\frac{dSD}{dt}$ (vertical geometry)	1	4

Table 7-40 Maintenance standards defined for Case Study in Section 7.4.2

7.3.7 Budget Allocation and Maintenance Costs

To use the prototype system, two budget allocation methods are used. In the first method the budget is allocated first to conceptual networks (CN) according to their track category. Because CN1 has the highest range of speed and traffic, it is given the highest priority. Thereafter, priority is given to components types. Based on Table 7.41, S&C (POE) was given highest priority since its failure might cause derailment. The next priorities are given to ballast, rails and sleepers respectively. However, in the second allocation method, the first priority is given to components, and then to track categories (see Table 7.42). In this manner, first switches are maintained for the whole network (starting from CN1) and based on the available budget ballast, rails and sleepers are maintained respectively.

Conceptual network	Track category	Priority	Component	Priority
1	1A	1	Switches	1
			Ballast	2
			Rails	3
			Sleepers	4
2	1	2	Switches	1
			Ballast	2
			Rails	3
			Sleepers	4
3	2	3	Switches	1
			Ballast	2
			Rails	3
			Sleeper	4

Table 7-41 First budget allocation method

Conceptual network	Component	Priority	Track category	Priority
1	Switches	1	1A	1
	Ballast	2		
	Rails	3		
	Sleepers	4		
2	Switches	1	1	2
	Ballast	2		
	Rails	3		
	Sleepers	4		
3	Switches	1	2	3
	Ballast	2		
	Rails	3		
	Sleeper	4		

Table 7-42 Second budget allocation method

To calculate the required budget for maintenance, unit cost of treatment types per kilometre of track for majority of components were obtained from (Naito, 2007) and (Office of Rail Regulation, 2012) and are tabulated in Table 7.43.

Type of maintenance	Unit cost
Ballast renewal	112.5 (£1000/km)
Tamping	4.5 (£1000/km)
Stoneblowing	4.5 (£1000/km)
Rail renewal	87.5 (£1000/km)
Grinding	2.575 (£1000/km)
Switch (POE) renewal	3.8 ((£1000/unit)
Sleeper renewal	75 (£1000/km)

Table 7-43 Unit costs of treatments

7.3.8 Network Climate Information

For the prototype system to model the effects of temperature on the probability of buckling and precipitation rate on subgrade deterioration, extreme maximum daily temperature and average mean daily precipitation of each month over the analysis period were modelled using Section 5.3.8. It was decided to use high emission scenario to determine the effects of climate induce deterioration. However, the user is free to choose any desired emission scenario. For the purpose of the prototype system which is to demonstrate the feasibility of the proposed methodology this was considered unimportant.

Because the conceptual networks consist of track sections located at different regions, climate variables for the five administrative regions (see Table 7.2) were used for the duration of analysis (see Appendix A and B).

The probability of buckling is calculated based on rail temperature, track geometry and maintenance history of track sections at each state (see Section. 6.6.1). The change in deterioration as a result of change in precipitation is determined based on Section 6.6.2. Accordingly, if the precipitation rate of a regions is similar to the predicted precipitation rate of another region in the future, precipitation deterioration factor is calculated, and new transition matrices are generated. To determine the combined effects of temperature and precipitation on track deterioration, first the prototype system identifies matching analogue scenarios to determine the effects of precipitation rate on transition matrices and based on the new generated matrices, Equation 6.25 is used to determine the probability of buckling. Based on the duration of analysis period used in the sensitivity analysis (from 2014 – 2024) explained below, only one analogue scenario was specified (see Section 6.6.2).

7.4 Sensitivity Analysis

In this section the feasibility of the proposed methodology is demonstrated using the developed prototype system and the data discussed in Section 7.3. It is assumed that the initial condition of track components (see Section 7.3.3) are for year 2014 (last date of inspection). Based on past maintenance carried over the conceptual networks (prior to 2014) suitable transition matrices are used for different portions of track at each state. The analysis is carried from year 2014 to 2024. Different case studies are illustrated using the following scenarios.

- Available funding for maintenance: Three budget scenarios are examined under fixed maintenance standard.
- Maintenance standards: Three budget scenarios are examined for two different maintenance standards.
- Budget allocation method: Two budget allocations are examined for two different maintenance standards.

7.4.1 Available Funding for Maintenance

In this scenario, three funding mechanisms are used, and their corresponding effects on network condition are investigated. In the first scenario, unlimited funding (100%) is provided so that the required maintenance budget over the analysis period can be determined. In the second scenario, only half (50%) of the required maintenance budget is used. In the last scenario no funding (0%) is available and the deterioration of network is analysed.

7.4.1.1 Case Study 1: Unlimited Funding

In this case study, maintenance standards in Table 7.39 are used and unlimited funding is provided. Figure 7.4 and 7.5 are the outputs of the system which determine the overall budget required and maintenance expenditures of each maintenance treatment under unlimited funding for the network. In Figure 7.4, the required budget for each year is expressed in terms of the percentage against the total budget requirement in year 2014. It can be seen that in the first year the entire budget is used and all the maintenance requirements according to Table 7.39 are accomplished. High portion of the overall budget is used for ballast renewal. This determines that based on the standard used (see Table 7.39), high portions of track required ballast renewal. However, in year 2015, less than half of the first year's budget (around 38%) is required to implement the required maintenance. This reduction is due to the high amount of maintenance and renewals carried in 2014. It can be seen that the portion of track requiring rail and sleeper renewal in years 2014 and 2015 are only slightly different. This is because of the fast initial deterioration rate of some portions of track in conceptual networks which were in lower severity bands in the previous year. The significant decrease in the overall required budget from 2015 and the low levels thereafter is due to the renewals carried in 2014 and 2015. Furthermore, it can be seen that the portions of budget allocated for tamping and grinding are almost the same notwithstanding the decrease in the required budget for other treatments. This is because, of the routine tamping and grinding on predefined portions of track (see Table 7.39). Moreover, at year 2019 the required budget for tamping and stoneblowing increases slightly. This is because of the change in transition matrix of CN3 as a result of increase in precipitation (see Section 6.6.2). To this end, the overall budget is determined and based on the percentage of required budget at each year, the budget over future period is determined using the following formula.

$$C_{PV} = \frac{C_{FV}}{(1+d)^N} \tag{7.2}$$

Where, C_{PV} is the present cost value and C_{FV} is the future cost value. r is the discount rate per year, which is set to be 10%, and N is the number of compounding years (see Figure 7.5).

Figure 7.6 indicates the values of TCI1, TCI2 and TCI3 which respectively, are the required costs to maintain 1 kilometre of track and the overall condition of network based on condition of the ballast and its rate of deterioration. It can be seen that the value of TCI decreases due to improvements in condition. The slight increase in TCI1 at year 2019 is due to the climate effect described above. Furthermore, TCI2 is increasing at first and it remains almost constant thereafter. The reason is because of the effects of routine tamping and stoneblowing on the condition of track (see Section 6.4.4). There is a significant change in the value of TCI3 from the first year to the second, which is due to the huge amount of renewals carried during 2014.

The effects of climate on TCI3 is also evident from the at year 2019 (i.e. decrease in value from 2018 to 2019).

The probability of buckling of the network (TCI5) is determined based on the regions which the conceptual networks are located (see Table 7.2). According to Figure 7.7 it can be seen that the probability of buckling varies amongst regions since the maximum daily temperature for each region differs (see Appendix A). Despite the small variation in the probability of buckling for some regions which is due to the effects of tamping and stoneblowing, it can be seen that the probability of buckling is almost constant over the analysis period. The reason is because of the renewals which is carried for the entire network each year.

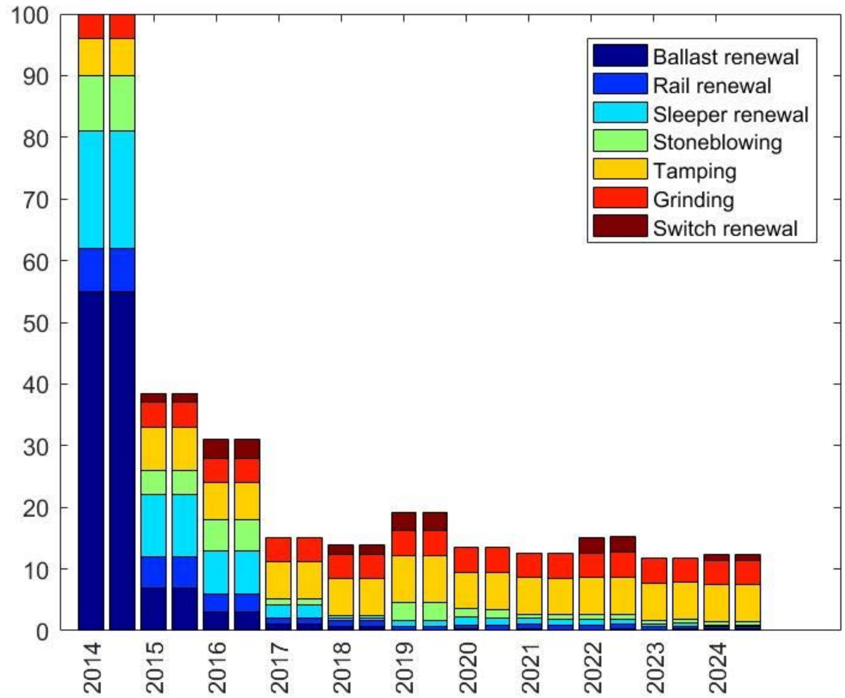

Figure 7-4 Overall required maintenance (first coloumn), maintenance expenditure (second coloumn) for CS1

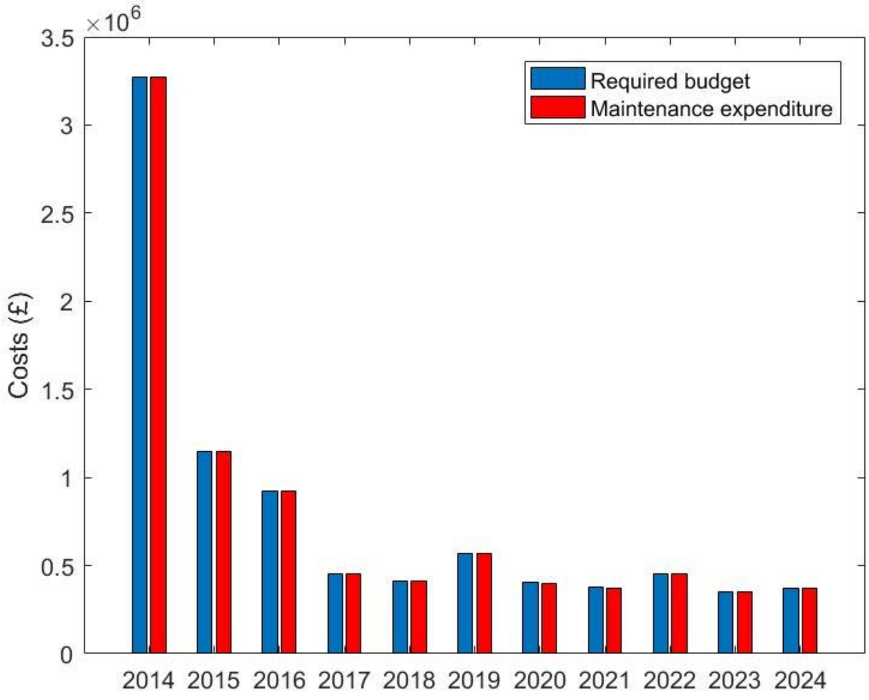

Figure 7-5 Overall maintenance costs for CS1

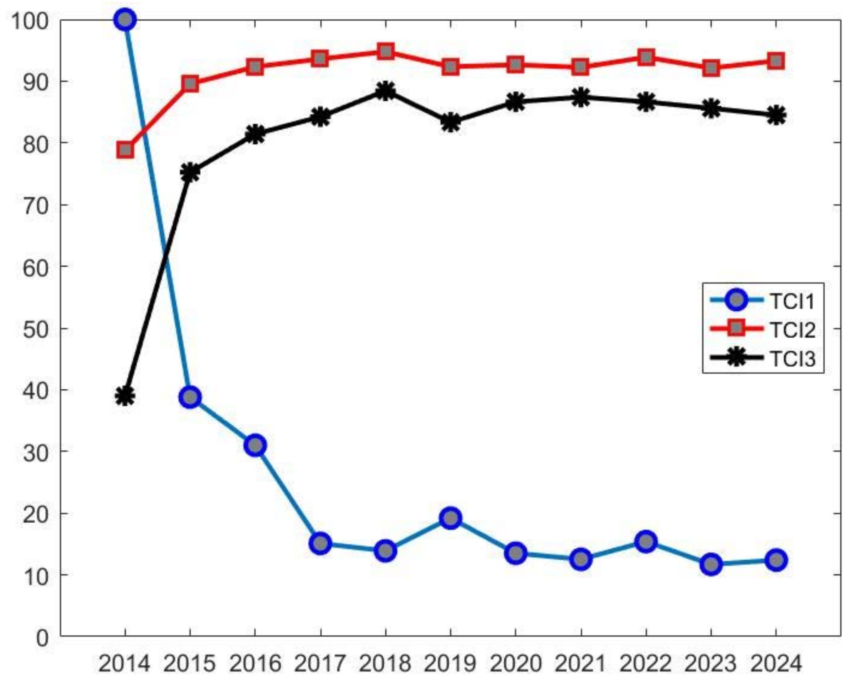

Figure 7-6 Overall condition of the network for CS1

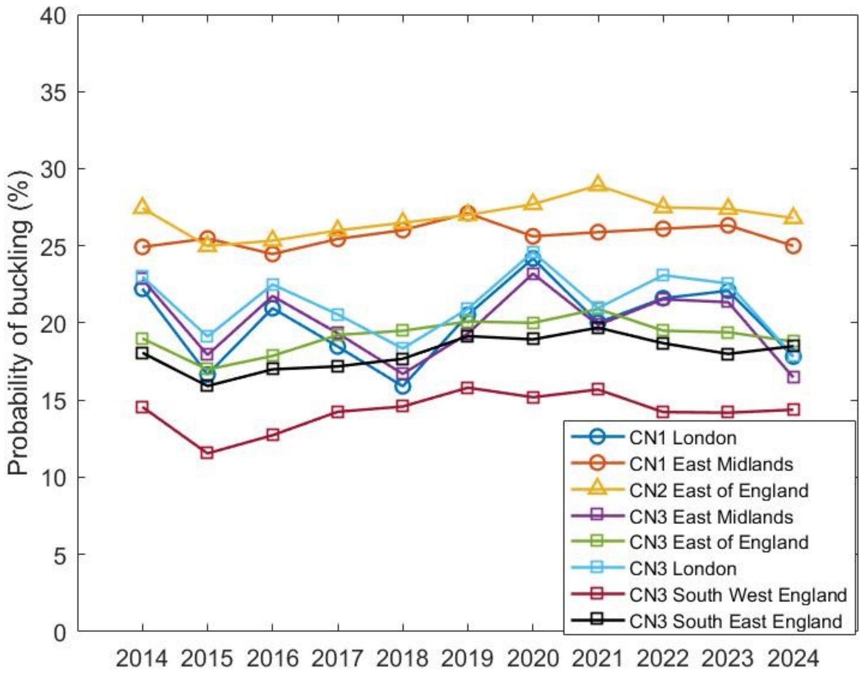

Figure 7-7 Probability of buckliung occurrence over the network for CS1

7.4.1.2 Case Study 2: 50% Funding

In this case study, the same maintenance standard used in Case Study 1 (CS1) is used (see Table 7.39), however, the available funding for maintenance is considered to be half of the total of required budget each year. In Figure 7.8, in the first year the required budget for maintenance is identical to that of in Figure 7.4, since the same maintenance standard is used. The total required budget in the second year is determined based on the feasible maintenance carried in the first year and one-year deterioration. Because the budget is insufficient to undertake all the required maintenance, most of the budget at the first year is allocated to ballast renewal because of its higher priority and less portions are dedicated to rail sleeper renewal. Furthermore, because CN1 has higher priority than other networks, some components in CN3 will not be maintained during the first year. Due to high initial deterioration rate of ballast, also in the second year there is not enough funding to fully carry the required rail and sleeper renewals. It can be seen that between 2020 and 2023 the required budget is almost constant, because the components in higher track categories (CN2 and CN3) still require maintenance. In addition. by comparing Figure 7.8 with 7.4 it is evident that because not all the required maintenance is carried, the required maintenance at each year is higher in this case than that of in CS1. The overall costs using 10% discount rate is shown in Figure 7.9.

In this scenario, the majority of budget was allocated for maintaining the components of the CN1 (lowest track category) which have higher priority. It can be seen from Figure 7.10 that TCI1 significantly decreases due to considerable amount of improvements achieved in 2014. The value of TCI2 initially drops slightly, because of insufficient budget to maintain the entire network (i.e. CN3). However, it gradually increases since over time less maintenance will be required for the CN1 and therefore, more budget will be available to be spent on other conceptual networks. Regarding TCI3, the initial gradual increase is due to renewal of majority of track portions in CN1. From 2018, TCI3 slightly decreases and then increases and thereafter decreases. This is because percentage of components still awaiting maintenance have increased. The subsequent gradual decrease in TCI3 is because of the increased deterioration rate and aging of components due to maintenance being ignored as well as effects of routine tamping on predefined sections.

The probability of buckling in this scenario as shown in Figure 7.11 is completely different compared to Figure 7.7 (CS1). Using Figure 7.11, it can be seen that for the CN1 the probability of buckling is almost constant and similar to Figure 7.7. This is because of the priority of CN1 being higher than CN2 and CN3. For CN3, the value of TCI5 is increasing which is due to insufficient budget to maintain the track sections in CN3 and therefore, due to aging of the ballast sections in this conceptual network the probability of buckling is increasing (c.f. Section 6.6.1).

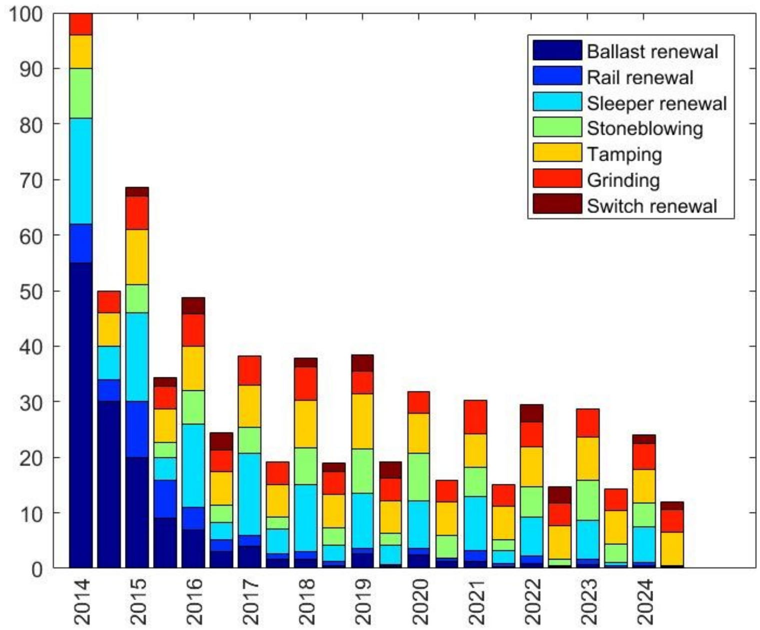

Figure 7-8 Overall required maintenance (first coloumn), maintenance expenditure (second coloumn) for CS2

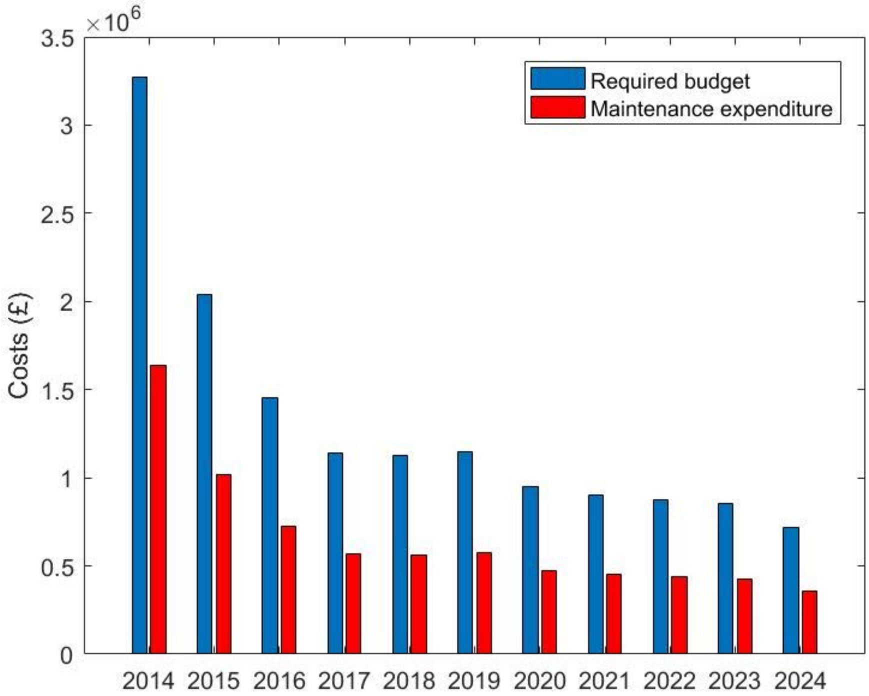

Figure 7-9 Overall maintenance costs for CS2

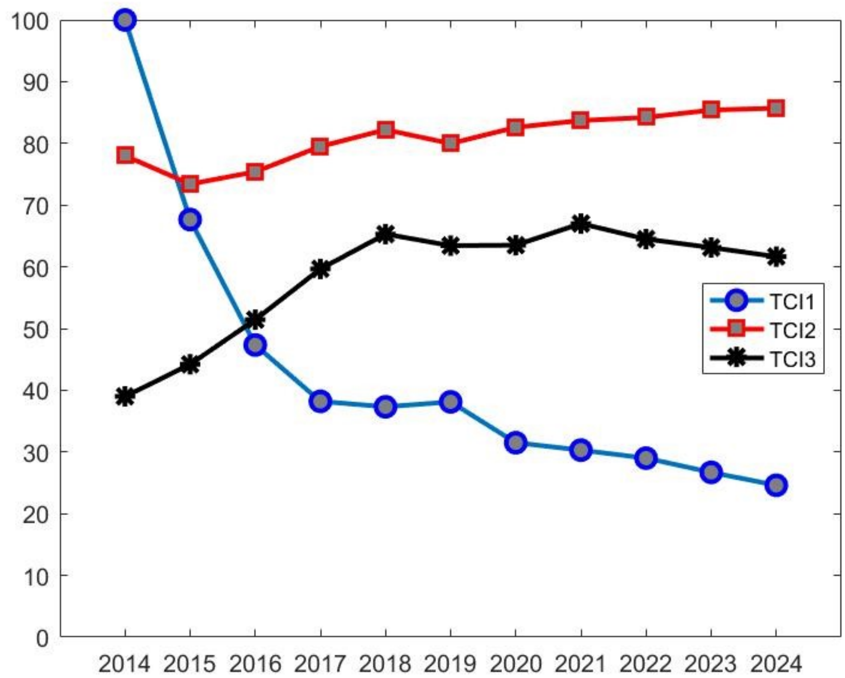

Figure 7-10 Overall condition of the network for CS2

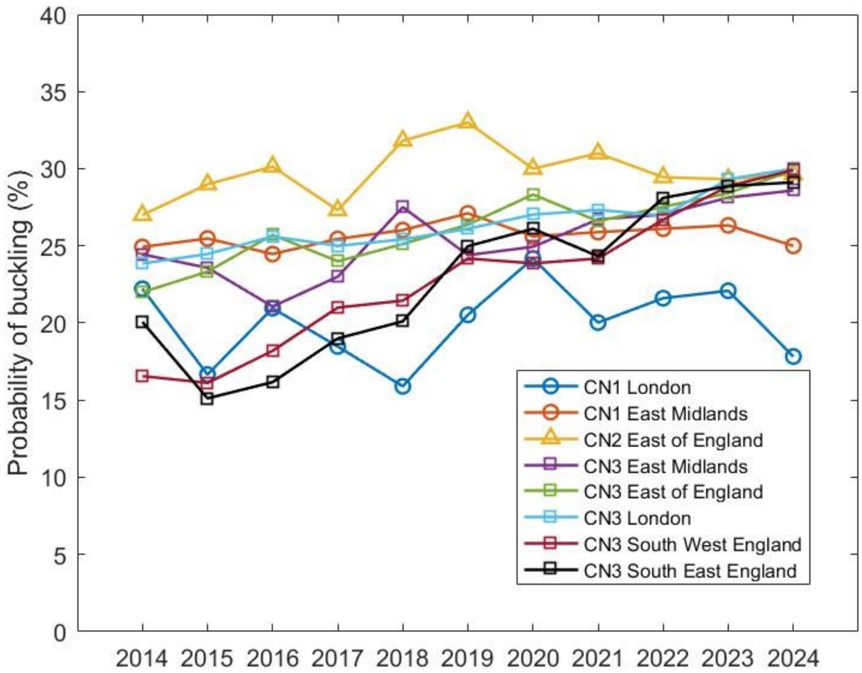

Figure 7-11 Probability of buckliung occurrence over the network for CS2

7.4.1.3 Case Study 3: No Funding

In this scenario no funding is available and the deterioration of the network is demonstrated. Same as CS1 and CS2, the maintenance budget is same for year 2014. Because there is no budget available to for maintenance, the network continues to deteriorate over time. It can be seen from Figure 7.12 that the required budget to perform maintenance according to Table 7.39 is increasing, meaning that more track portions are moving from lower condition states to higher states (i.e. deteriorating to poorer condition). In case of grinding it is seen that there is a small difference in the percentage of required budget for years 2023 and 2024. This is because majority of track portions in very good and good states have already moved to poorer states. Based on Figure 7.12, at year 2019 the rate of increase in budget requirement for ballast renewal is slightly higher than its previous years. This is due to the increase in precipitation at this year over CN3 (see Section 6.6.2). This is also shown in the values of TCI1 and TCI3 in Figure 7.14. The significant increase in TCI1 is due to the high initial deterioration rate at the components which is demonstrated by TCI3.

The deterioration of the network also increases the likelihood of buckling as shown from the values of TCI5 illustrated in Figure 7.15. This is because the deterioration and aging of ballast reduces its strength to provide adequate stability for the track. Therefore, the rails become more prone to buckling at lower temperatures. For CN3 located in South West and South East of

England the probability of buckling is almost the same as in Figure 7.11 (CS2) since due to budget limitation in CS2, some track sections in CN3 were not maintained.

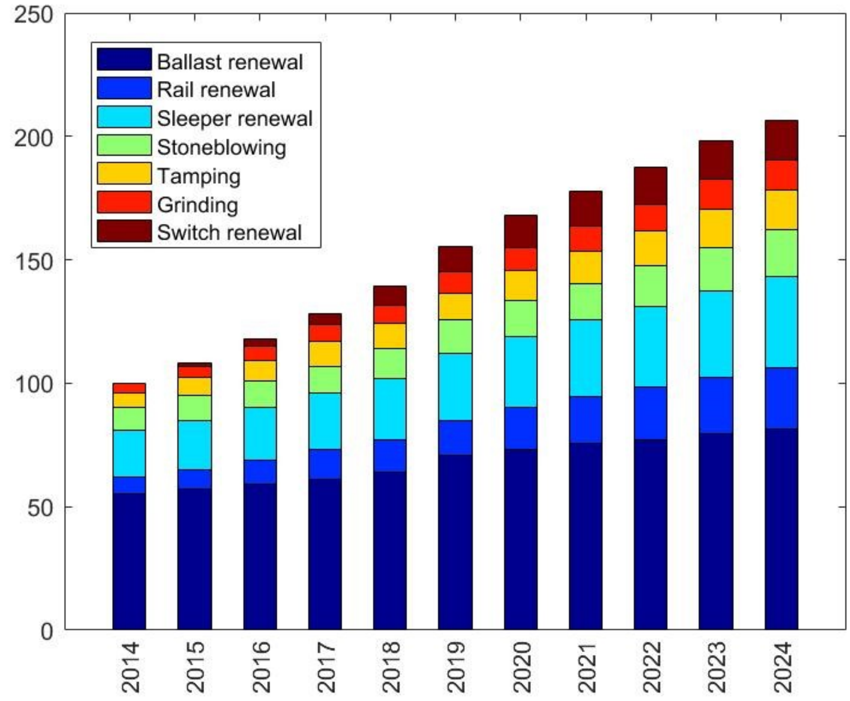

Figure 7-12 Overall required maintenance (first coloumn), maintenance expenditure (second coloumn) for CS3

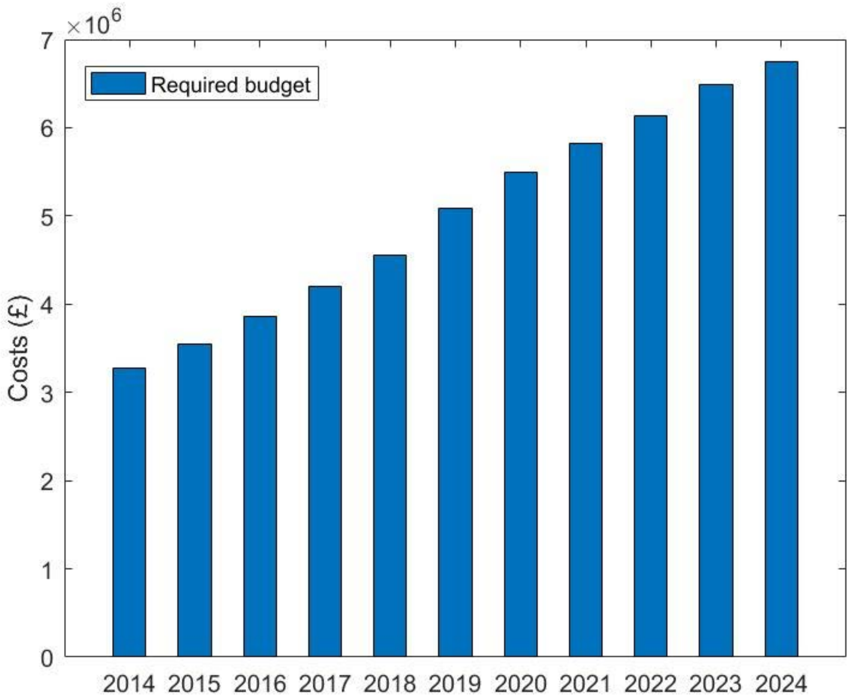

Figure 7-13 Overall maintenance costs for CS3

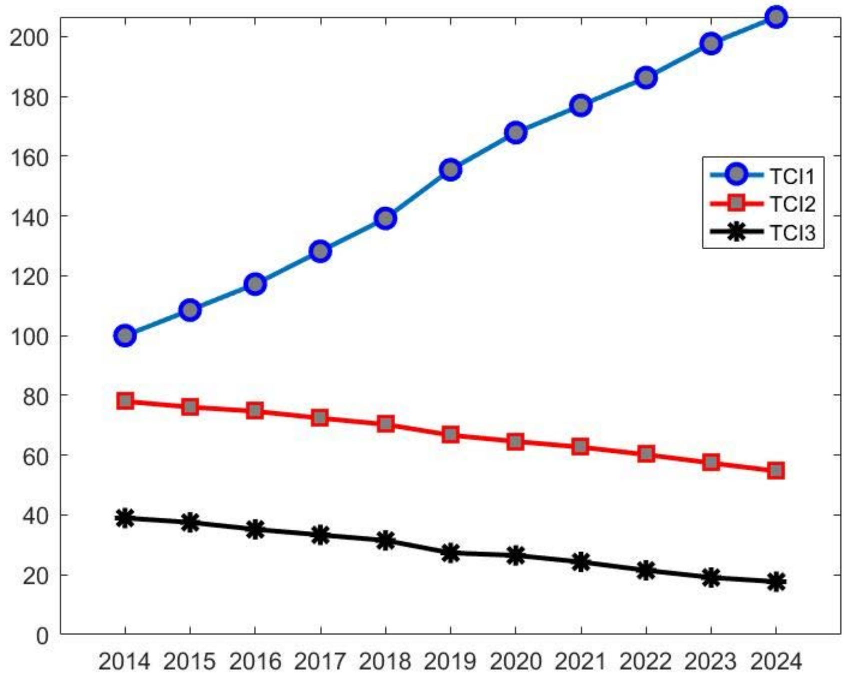

Figure 7-14 Overall condition of the network for CS3

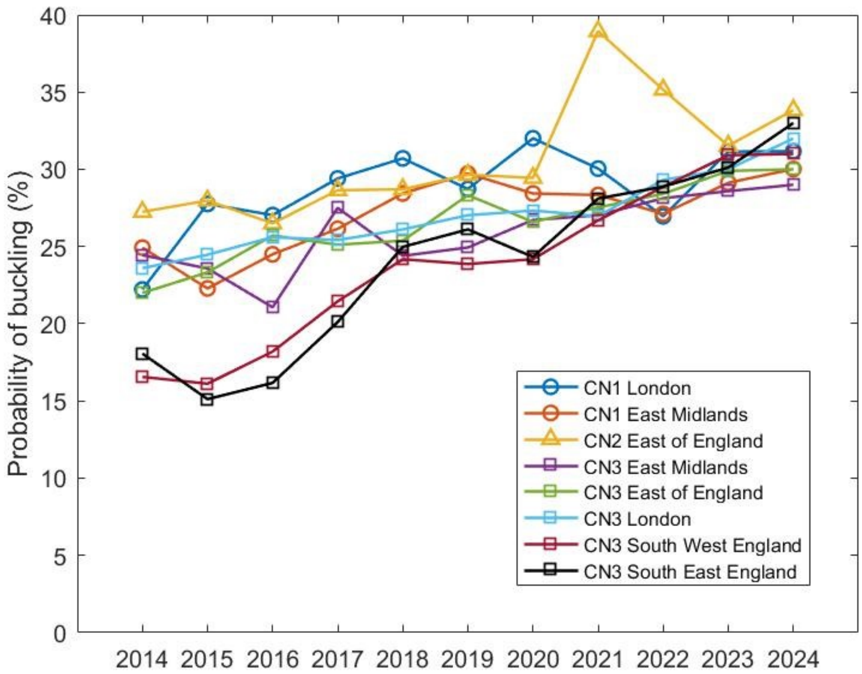

Figure 7-15 Probability of buckliung occurrence over the network for CS3

7.4.2 Maintenance Standards

In the following case studies different maintenance standards (see Table 7.40) are used and the change in the outputs of the prototype system are investigated and compared with the outputs calculated in Section 7.4.1. In this maintenance standards, ballast renewal is only considered for sections with very poor SD and dSD/dt and rail renewal to remove wear is considered only for the very poor state. Furthermore, routine maintenance is also not considered and its effects on condition of the network is assessed.

7.4.2.1 Case Study 4: Unlimited Funding

The total budget requirement for the network under this maintenance standards is illustrated in Figures 7.16 and 7.17. By comparing Figure 7.16 with 7.4, it can be seen that the overall maintenance costs in 2014 approximately declines by 31%. This is because of the change in the intervention level of ballast renewal as explained above and also the cheaper costs of tamping and stoneblowing compared to ballast renewal. In year 2015, the overall required maintenance budget in this case is higher compared to CS1 (Figure 7.4). The reason is due to the high initial deterioration rate of ballast and that tamping and stoneblowing did not return the condition to the good as new at the first year. Hence, it can be seen that almost every year some portions of network, require ballast renewal. For the same reasons, it is also evident that the effects of increase precipitation at year 2019 on track deterioration is more severe in this scenario than that in CS1.

The values of TCI1 in Figure 7.18 also indicates a lower overall maintenance cost per kilometre of track in the first year compared to the calculated TCI1 in Figure 7.6. However, this value increases by approximately 28% in 2019 compared to the same year in CS1. Furthermore, the values of TCI2 in this scenario never get as high the values of TCI2 in CS1 (see Figure 7.6). This is because of the effects of different intervention levels defined in this maintenance standard (see Table 4.40) compared to Table 7.39. TCI3 in Figure 7.18 increases significantly at the beginning due to the renewal of track sections with very poor dSD/dt. However, the rate by which it increases reduces from 2015 to 2017. Whereas from year 2021 to 2014 this value decreases gradually. The reason is due to the high volumes and repetitive cycles of tamping and stoneblowing which causes increase in deterioration rate of the ballast.

By comparing Figure 7.19 with 7.7, it can be seen that in this case the probability of buckling of the network, in general, is higher compared to CS1. During the first three years TCI5 decreases very slightly for majority of conceptual networks. The reason was discussed in

Section 6.6.1, where it was shown that during the first few cycles of tamping the probability of buckling improves for track sections in lower severity bands, whereas as the cycles of tamping increases the probability of buckling increases in all severity bands.

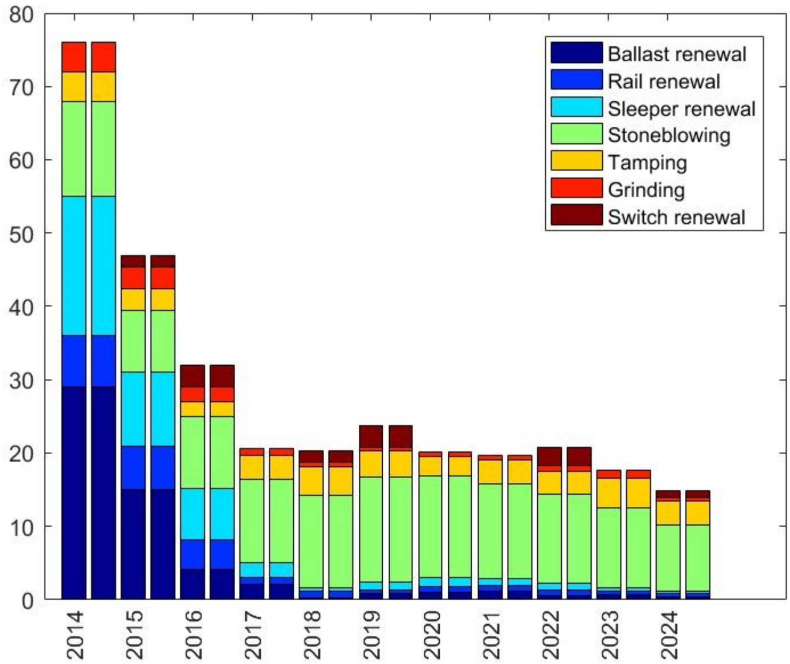

Figure 7-16 Overall required maintenance (first coloumn), maintenance expenditure (second coloumn) for CS4

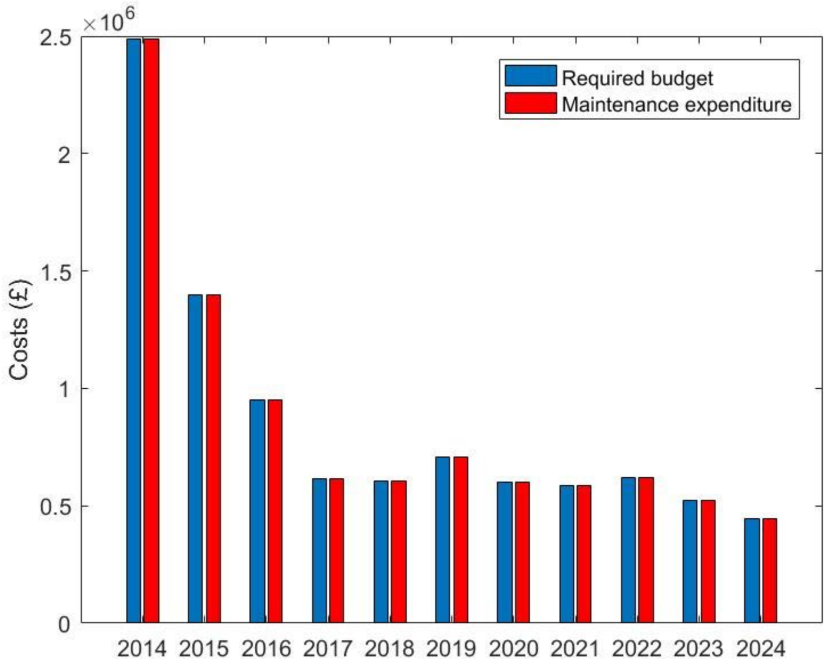

Figure 7-17 Overall maintenance costs for CS4

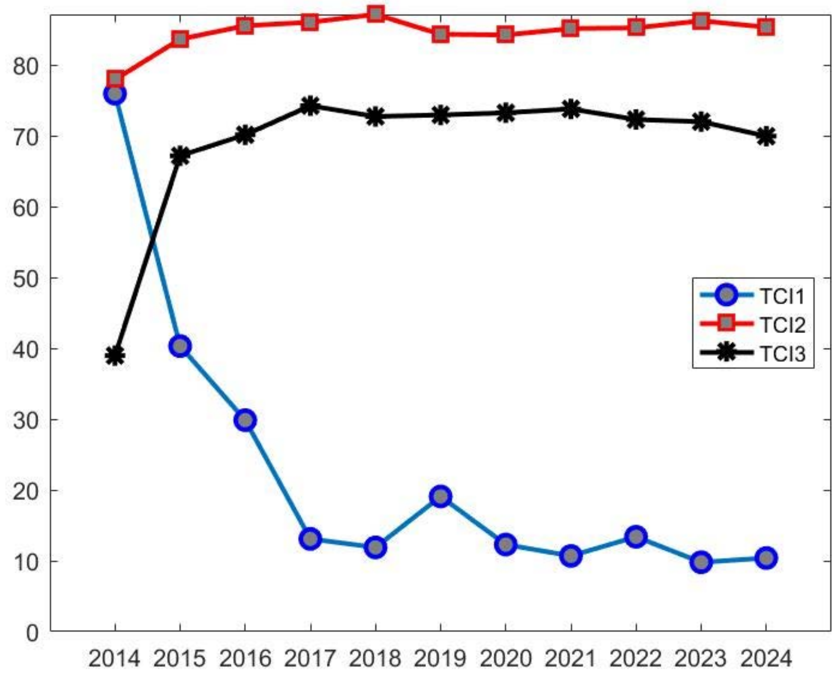

Figure 7-18 Overall condition of the network for CS4

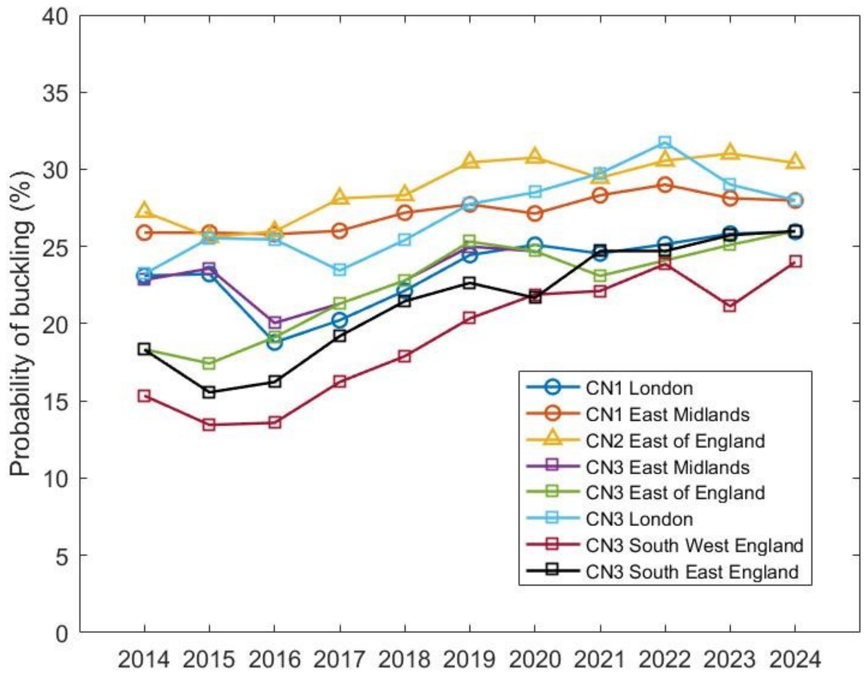

Figure 7-19 Probability of buckliung occurrence over the network for CS4

7.4.2.2 Case Study 5: 50% Funding

Under 50% funding mechanism, the calculated overall budget requirement (see Figure 7.20) is lower compared to Figure 7.8 (CS2). This is due the difference in the unit cost of ballast renewal compared to stoneblowing and tamping. In addition, by comparing Figure 7.22 with 7.10 (CS2), it can be seen that the from year 2014 to 2015 the drop TCI2 is higher in this case. This is because in CS2, the required ballast renewal restored the condition to the good as new, whereas this is not the case for tamping and stoneblowing. Although, the values of TCI2 over the entire analysis period are generally lower than in CS2, over years 2023 and 2024 the values of TCI2 for both cases (CS2 and CS5) are almost equal. This is because of the lower unit costs of tamping and stoneblowing which as a result, more track portions can be maintained over time, and thereby more portions of track in higher severity bands will move to lower bands to some extent (see Section 6.5). Considering the values of TCI3, using Figure 7.22, it can be seen that tamping and stoneblowing slightly improve the deterioration rate at the beginning (2014 – 2017), however at a slower rate than observed in Figure 7.10. More importantly it can be seen that over time the values of TCI3 smoothly decrease which indicate the effects of maintenance history on track deterioration.

The probability of buckling in this scenario is shown in Figure 7.23. It can be seen that in the first four years the probability of buckling of tracks within CN3 is very similar to CS2 (Figure 7.11). This is because of the insufficient level of funding available to maintain the entire network and the lower priority assigned to CN3. However, when majority of tracks within CN1 and CN2 are maintained budget is allocated to CN3. This is the reason that the probability of buckling for CN3 gradually decreases from 2018 to 2019. However, due to incomplete maintenance and aging of track sections in CN3, TCI5 increases during the last four years of the analysis period.

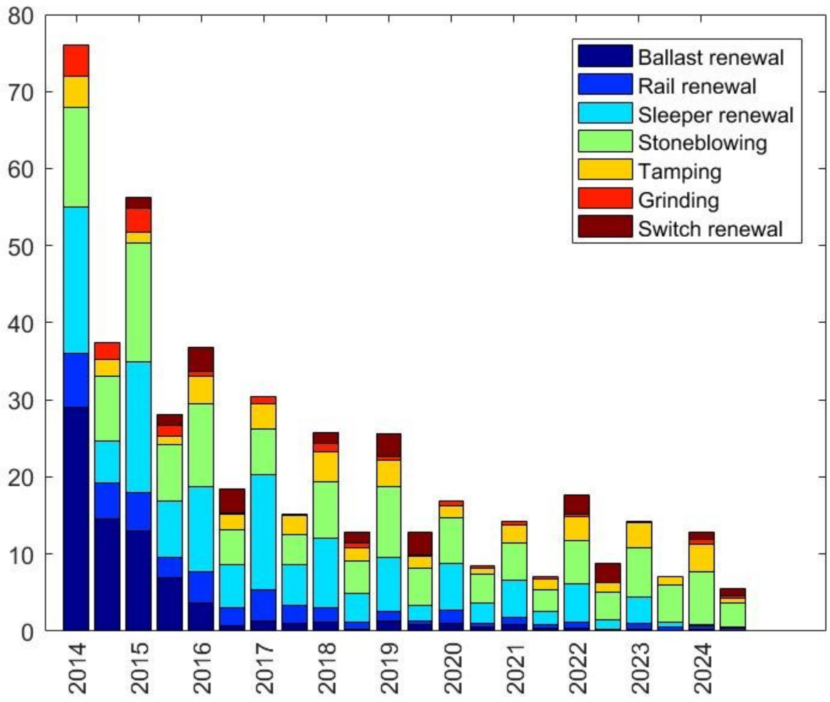

Figure 7-20 Overall required maintenance (first coloumn), maintenance expenditure (second coloumn) for CS5

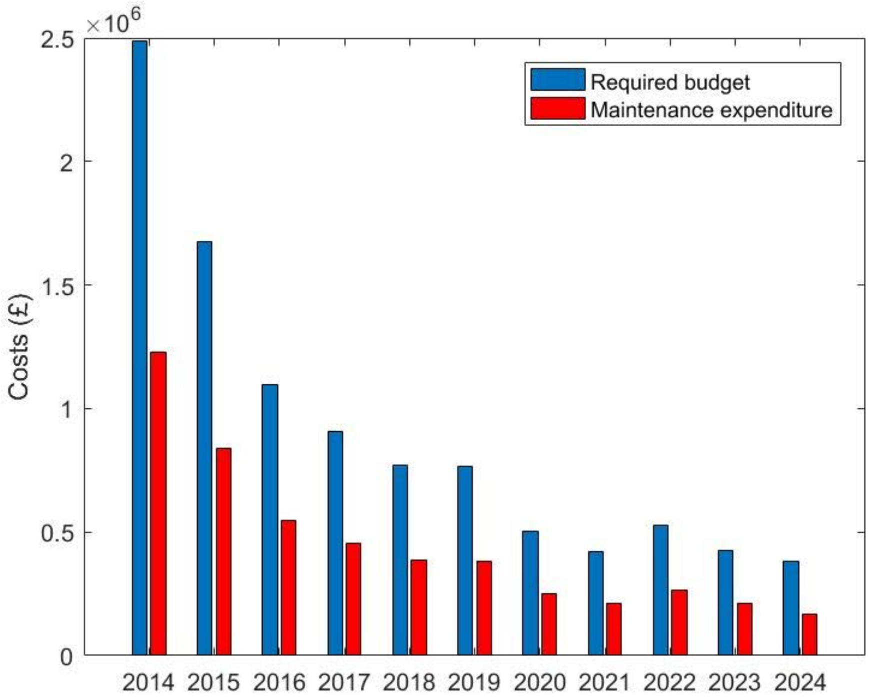

Figure 7-21 Overall maintenance costs for CS5

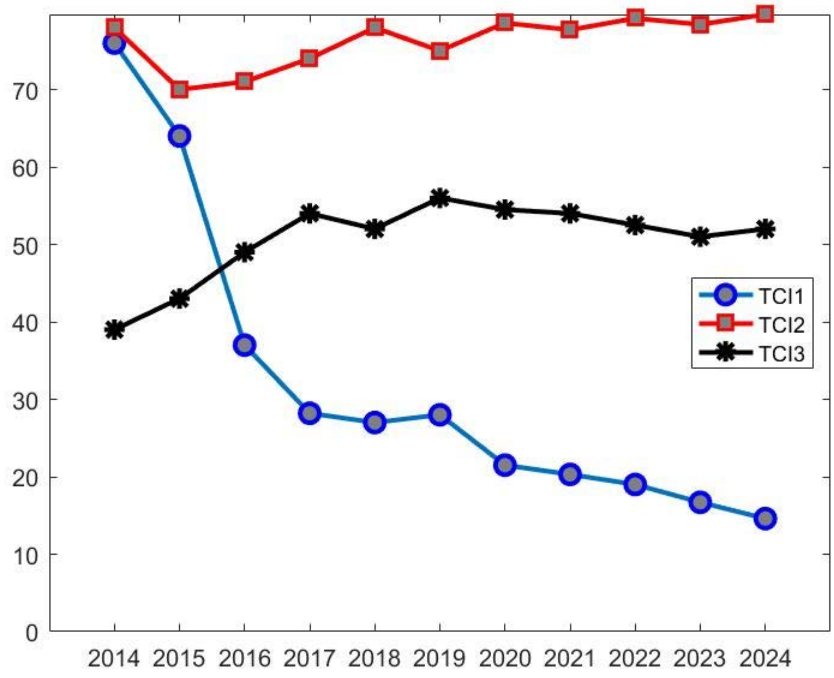

Figure 7-22 Overall condition of the network for CS5

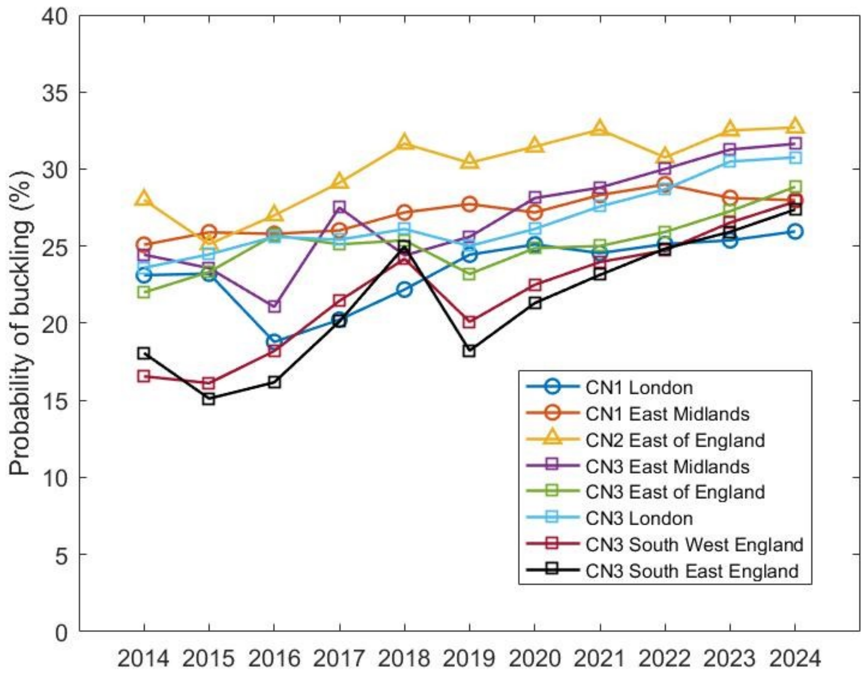

Figure 7-23 Probability of buckliung occurrence over the network for CS5

7.4.2.3 Case Study 6: No Funding

This scenario is similar to CS3, in which no money is invested, and the network deteriorates. Therefore, the values of TCI2 and TCI3 and TCI5 would be same as in CS3 (see Figures 7.14 and 7.26). However, this is not the case for TCI1. Based on Figure 7.26, the values of TCI1 is lower compared to that of in CS3 (Figure 7.14). This is due to extending the intervention levels of stoneblowing and tamping (see Tables 7.39 and 7.40). Therefore, after time more portions of track will require stoneblowing/ tamping compared to ballast renewal and since the unit cost of stoneblowing is cheaper than renewal the rate of increase in TCI1 is smaller.

Based on Sections 7.4.1 and 7.4.2 it can be stated that when the intervention level of ballast renewal is extended to cover more severity bands, the level of funding becomes insufficient to carry the required maintenance. It was seen in Section 7.4.2 that when instead of ballast renewal, the intervention level of stoneblowing and tamping is extended, more portions of the network can be maintained and after eleven years the condition of network under both scenarios using TCI2 were the same. However, this caused faster deterioration rate of the overall network (TCI3), which also resulted in higher probability of buckling occurrence.

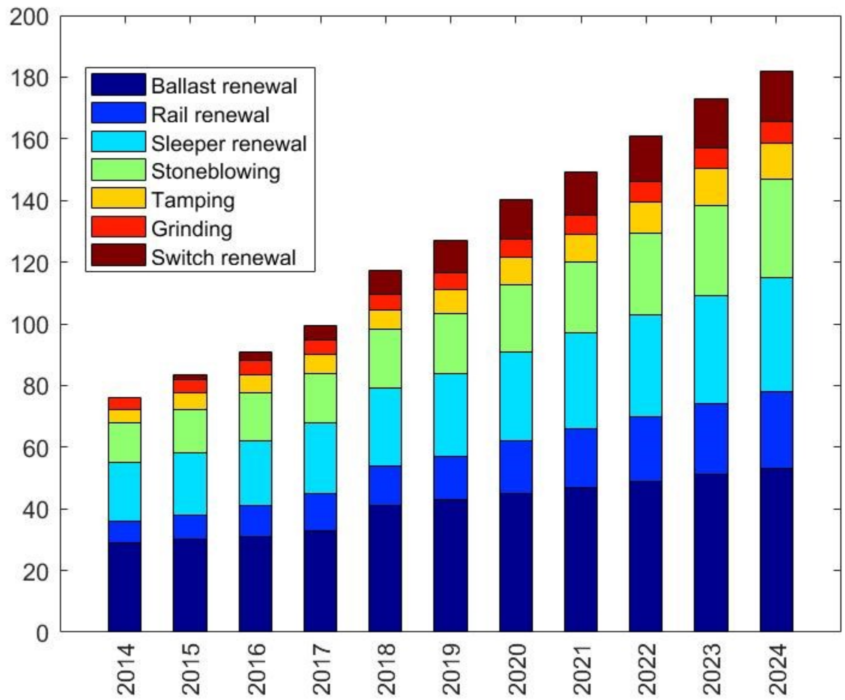

Figure 7-24 Overall required maintenance (first coloumn), maintenance expenditure (second coloumn) for CS6

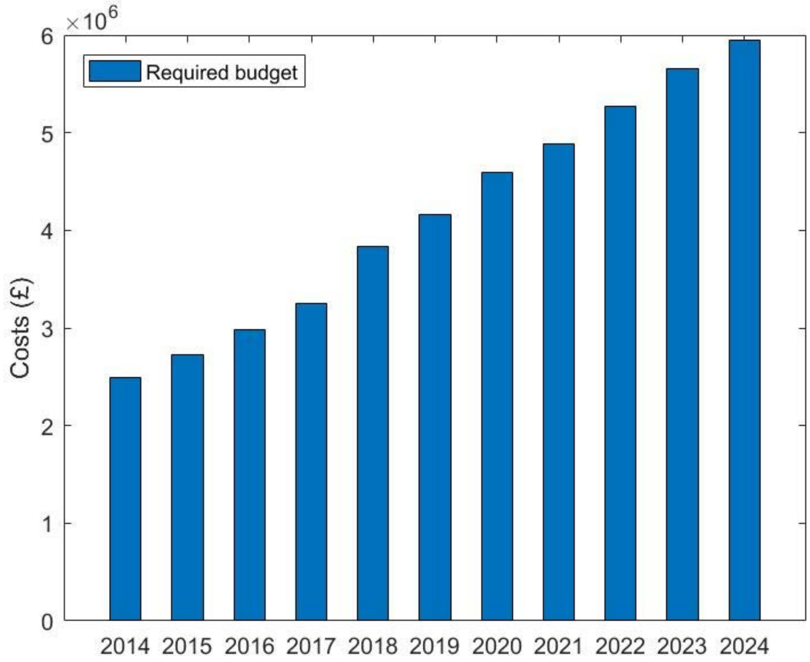

Figure 7-25 Overall maintenance costs for CS6

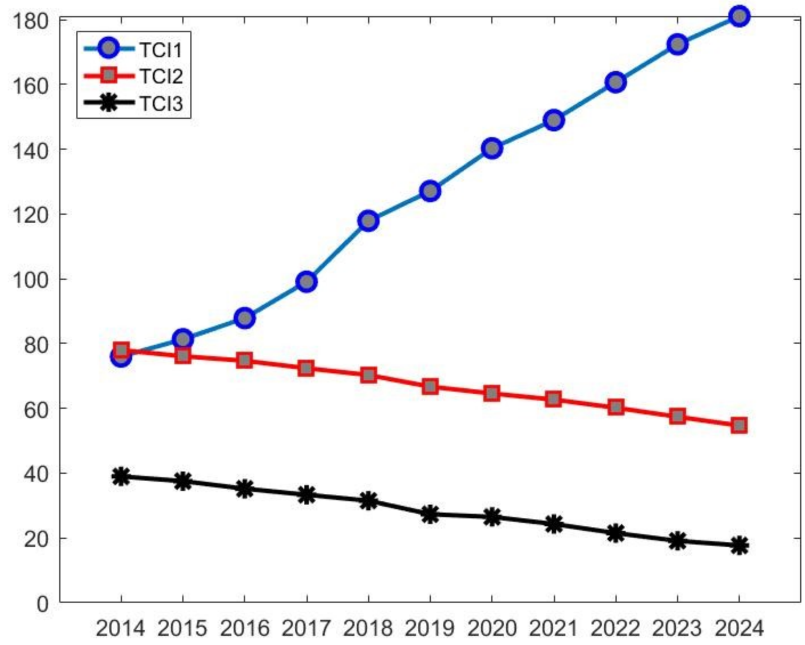

Figure 7-26 Overall condition of the network for CS6

7.4.3 Budget Allocation Method

In this section, budget allocation is altered, and Table 7.42 is used for setting budget allocation priorities. Effects of this budget allocation method under two different maintenance standards are determined (Tables 7.39 and 7.40). Table 7.42 indicates that the first priority is given to components rather than track category. In this manner, first switch components are maintained in order for CN1, CN2 and CN3. Thereafter, budget is allocated to ballast based on its track category priority, and then to rails and sleepers in the same manner. In any case, as long as routine maintenance is included in the standards it has highest priority. The maintenance standard used in Table 7.39 is used for CS7, whereas for CS8 Table 7.40 is used as standards. Because same maintenance standards are used, the outputs of the system are the same for unlimited funding and no funding scenarios. Therefore, only 50% funding is discussed.

7.4.3.1 Case Study 7: 50% Funding

Because components have higher priorities than track category, according to Figure 7.27, in the first year after all the routine maintenance are carried, and that there is no maintenance required for switch components, the entire budget is used for ballast renewal. However, in 2014 the level of funding becomes insufficient to carry rail and sleeper renewal and their maintenance are postponed. In 2015, is can be seen that after higher priority maintenance are carried, small portion of the budget is used for rail renewal. Whereas, more rail renewals are taken place on 2016 since majority of ballast over the network have been renewed in the 2014 and 2015. In case of sleeper renewal, it is seen that over the analysis period, renewals are carried only for small portions of the network notwithstanding the high level of renewal requirements.

Based on Figure 7.29, during the first five years the value of TCI1 is decreasing. However, as sleeper renewals are postponed due to budget constraints, their deterioration causes TCI1 to remain high and almost constant level during the period of analysis. The values of TCI2 and TCI3 are both at high levels which is due to huge amount of ballast renewal carried specially in 2014 and 2015. It can be seen that after the initial increase in TCI2, the value TCI2 remains at a constant level. The increase is because of the budget allocation (see Table 7.42) used which allows more portions of ballast to be maintained over the network. The steady level of TCI2 is due to the levels of improvements achieved after tamping. In addition, the effects of tamping on deterioration can also be seen from the values of TCI3 as it gradually declines from 2021 to 2024, which indicates slight increase in network deterioration rate.

From Figure 7.30 the effects of ballast renewal can be seen on the probability of buckling. Based TCI5, in the first couple of years the probability of buckling occurrence is decreasing as a result of major ballast renewals. However, as the cycles of routing tamping increases it can be seen that the probability of buckling gradually increases. In addition, in regions with higher maximum daily temperature the probability of buckling is determined to be higher (see Appendix A).

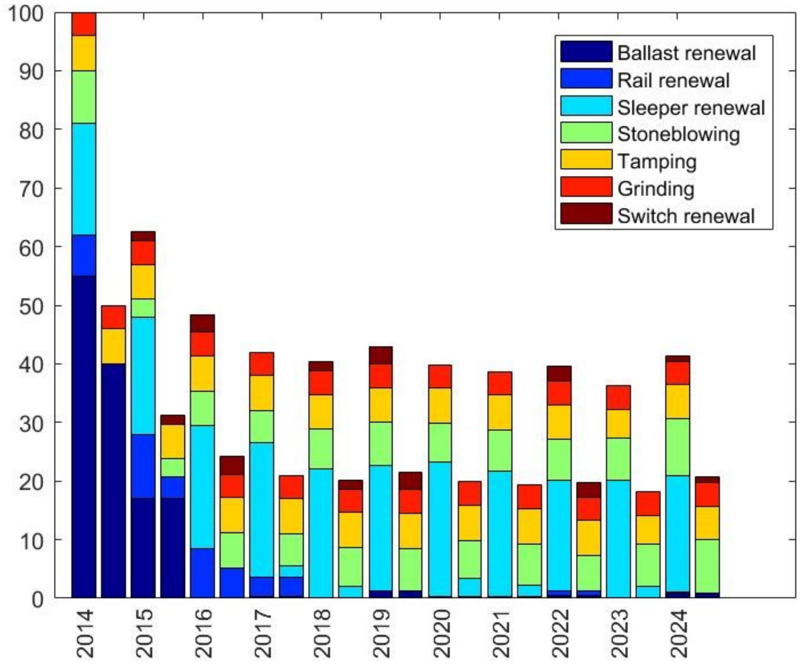

Figure 7-27 Overall required maintenance (first coloumn), maintenance expenditure (second coloumn) for CS7

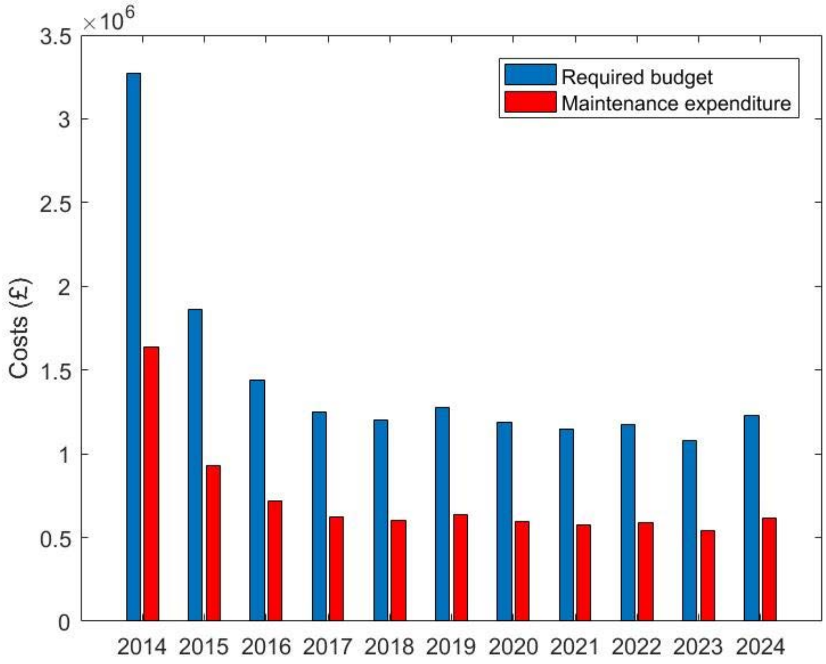

Figure 7-28 Overall maintenance costs for CS7

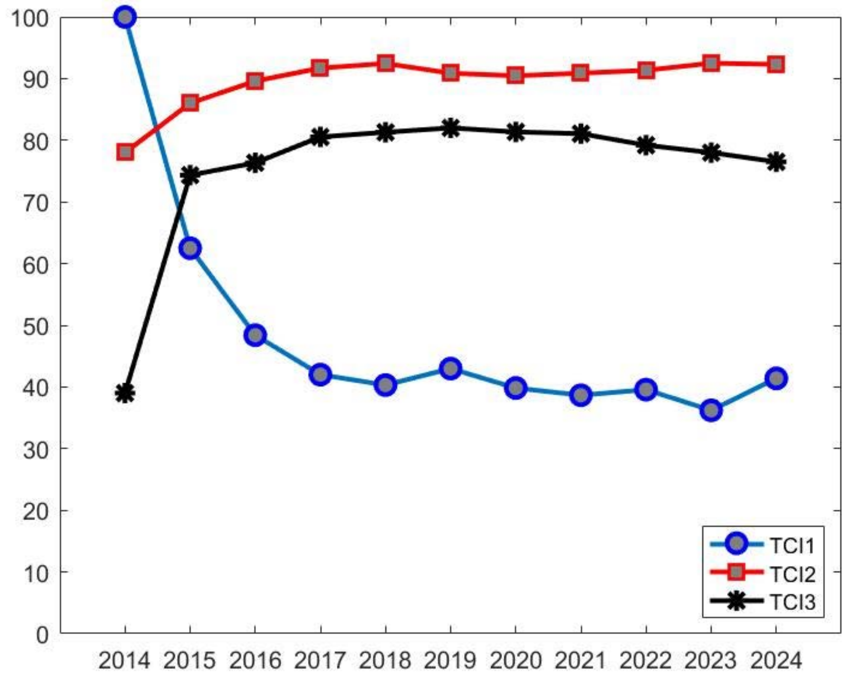

Figure 7-29 Overall condition of the network for CS7

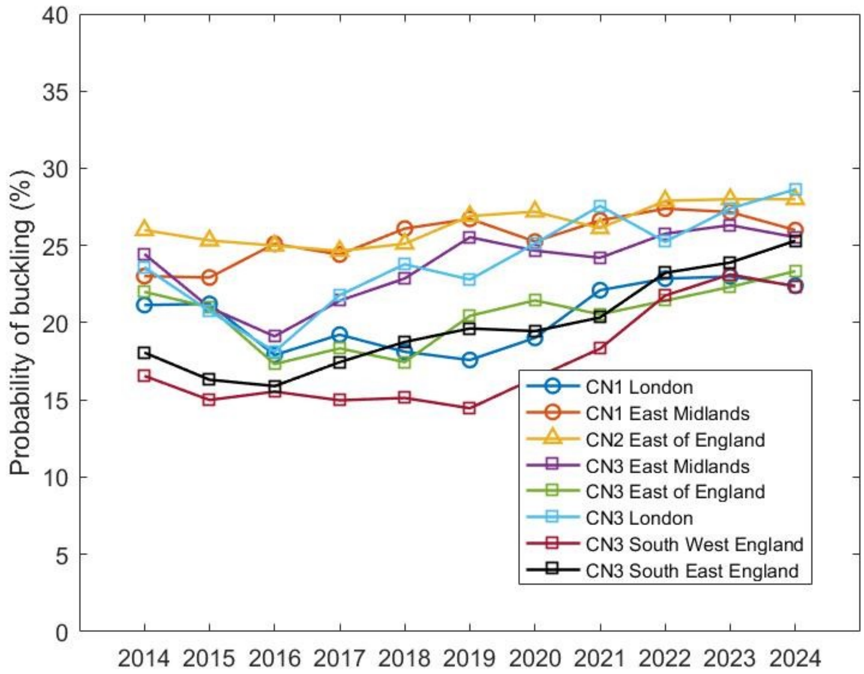

Figure 7-30 Probability of buckliung occurrence over the network for CS7

7.4.3.2 Case Study 8: 50% Funding

In this scenario, the maintenance standard used is according to Table 7.40. It is illustrated in Figure 7.31 that the entire ballast renewal is carried in the first year. The effects of this is also evident from the value of TCI2 and TCI3 (see Figure 7.33). Also because of the complete ballast renewals there is also a decrease in the value of TCI5 during the 2014 and 2015. It is seen from the Figure 7.31 that when majority of components are maintained, budget becomes insufficient to carry sleeper renewals and therefore, over the analysis period only small portions of sleepers are renewed. This was also seen in CS7.

By comparing Figure 7.33 with 7.29 (CS7), it is seen that under this maintenance standard, the values of TCI1 for both cases follow the same trend. However, the values of TCI1 in this scenario is lower because, routing maintenance is not included and due to change in intervention levels, ballast renewal is less required.

By comparing the values of TCI2 and TCI3 in Figures 7.33 and 7.22 (CS5), it can be seen that higher levels of improvement have been achieved under this scenario than in CS5. The reason is due to using different budget allocation method. In CS5, track categories were given higher priority than components. Therefore, majority of the budget was used for CN1 and CN2 and no money was available for ballast renewals in CN3. However, in this case the ballast sections of the entire network are renewed and for this reason, higher TCI2 and TCI3 is observed.

The effects of major ballast renewal on probability of buckling is illustrated in Figure 7.34. By comparing Figure 7.34 with 7.23 (CS5), it can be seen that, in the former from 2014 to 2016 there is a drop in the value of TCI5, however, based on Figure 7.23 (Case 5), the decrease is only observed for track sections located in CN1 because of their higher priority. Notwithstanding the decrease in TCI5 in Figure 7.34, it is seen that there is a gradual increase in this value. This is due to the effects of tamping and stoneblowing s explained in the above scenarios. Because ballast in all conceptual networks are tamped, the increase in TCI5 is evident for all the conceptual networks.

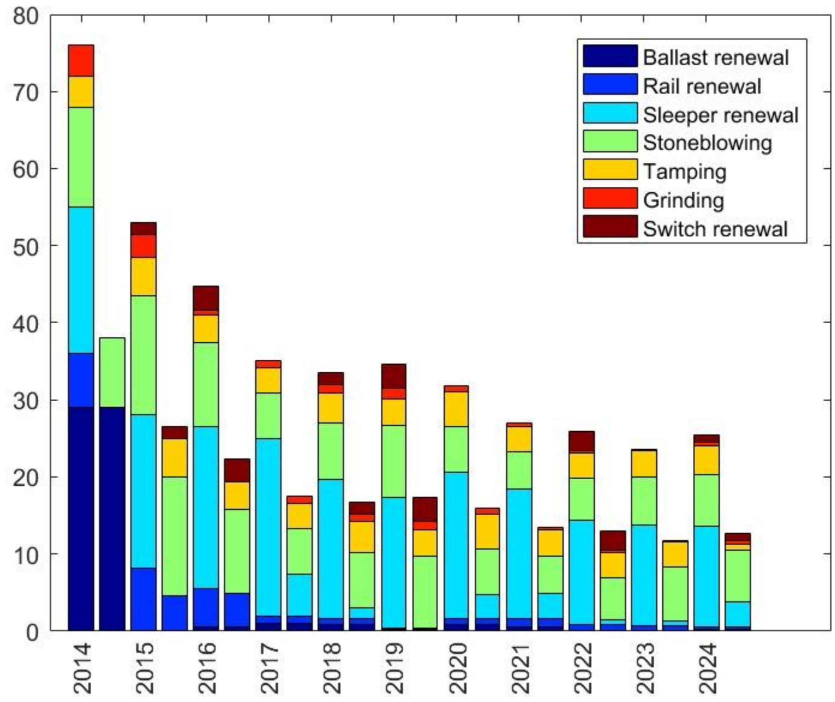

Figure 7-31 Overall required maintenance (first coloumn), maintenance expenditure (second coloumn) for CS8

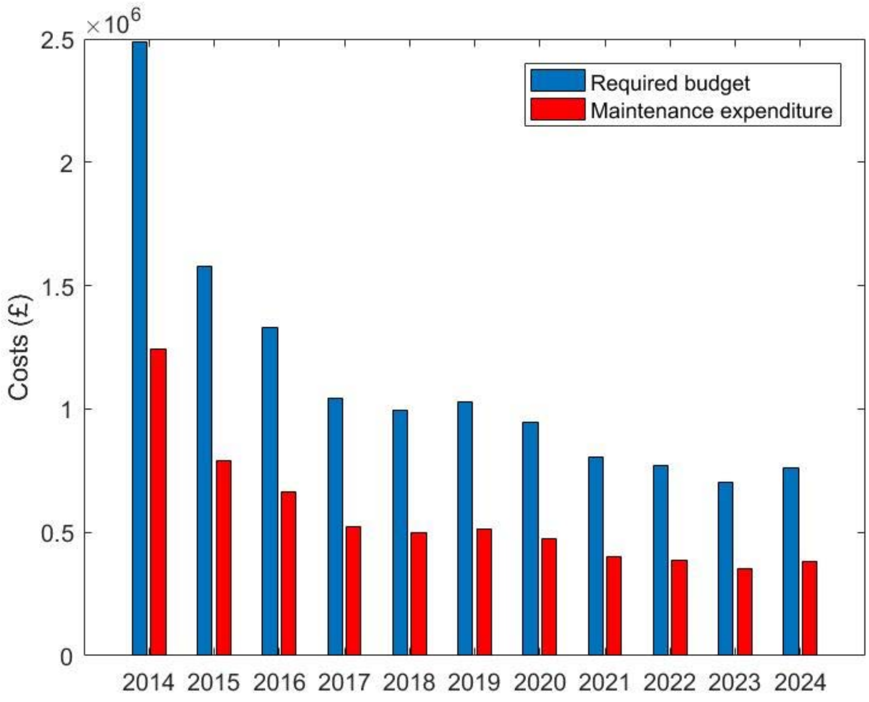

Figure 7-32 Overall maintenance costs for CS8

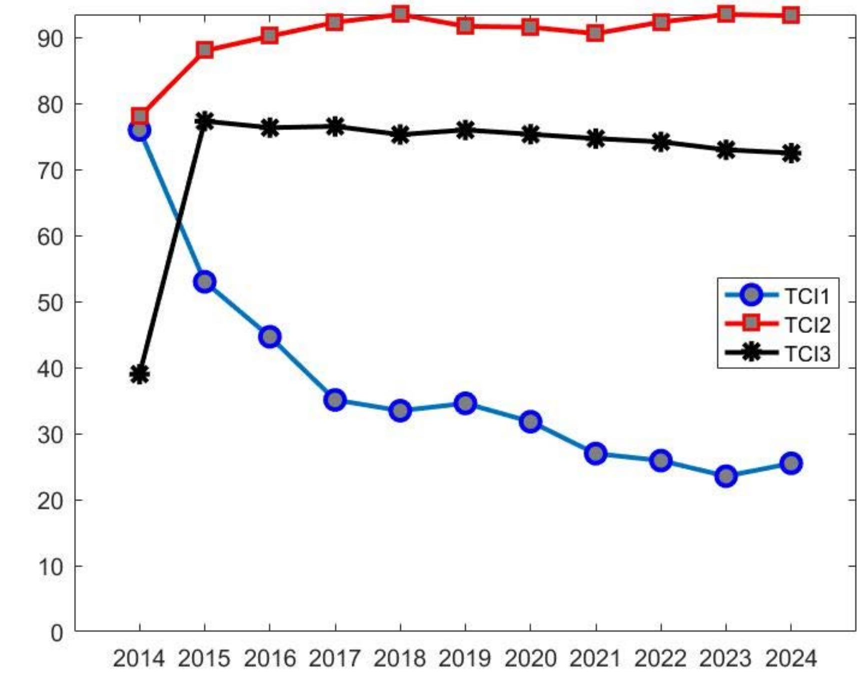

Figure 7-33 Overall condition of the network for CS8

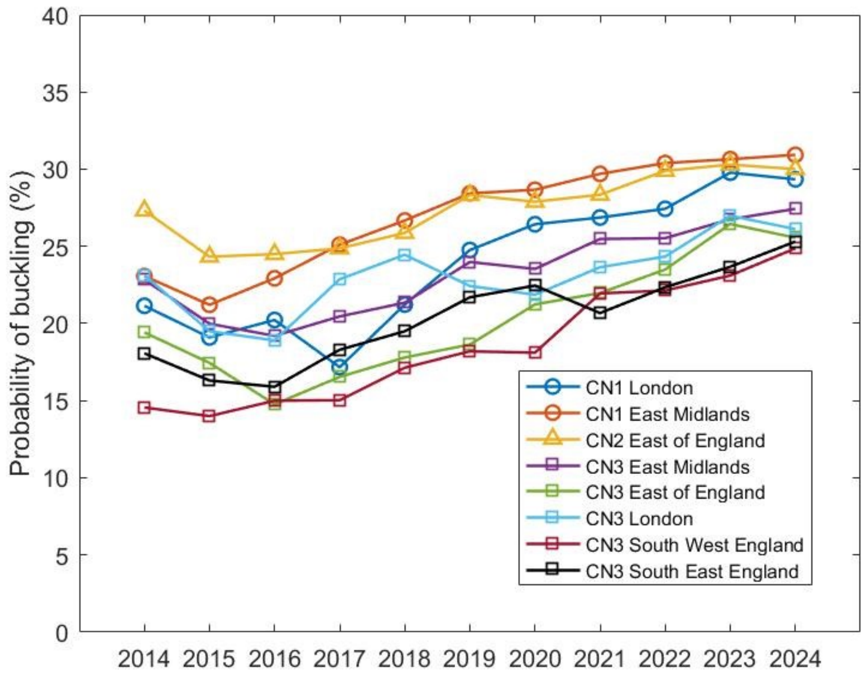

Figure 7-34 Probability of buckliung occurrence over the network for CS8

7.5 Discussion

Based on Section 1.2, the aim of the prototype system is to predict the condition of the network as a function of maintenance expenditure. As demonstrated in the Sensitivity analysis carried in Section 7.4, the developed tool was able to determine the condition of the network under different levels of investment and maintenance policies. The effects of maintenance policy on the condition of the network was described in Sections 7.4.1 and 7.4.2. The effects of change in intervention levels on the overall condition of the network was demonstrated using TCIs. It was shown in CS1 that when substantial portions of the network are renewed the overall maintenance costs over the subsequent years are at low levels. This was determined based on the values of TCI1, TCI2 and TCI3. It was seen that as the intervention levels of stoneblowing and tamping were extended in CS4, the overall condition improved (TCI2), although the rate of deterioration of the network increased (TCI3) as did the probability of buckling (TCI5). It was shown that the prototype system can determine the amount of feasible maintenance under budget constrains using the specified standards. It was demonstrated that under budget constraints, because the overall required maintenance cannot be carried fully, the condition of the network is at lower levels. In addition, the effects of budget allocation on overall network condition was investigated in the sensitivity analysis (Section 7.4). It was seen that, when significant portions of the budget are invested in ballast renewal and maintenance the overall condition of the network improves significantly. This was shown using the values of TCI2 and TCI3. However, if the maintenance of other components are neglected over few years, it was shown that the required budget to rehabilitate their condition increases substantially (CS7 and CS8).

In addition, the effects of maintenance such as tamping and stoneblowing on network condition, deterioration and its probability of buckling was shown in the sensitivity analysis carried in Section 7.4. It was shown that when these maintenance treatments improve the condition of the network TCI2 and TCI3 increase, and the overall costs determined by TCI1 decreases. It was shown that as the cycles of tamping and stoneblowing increases, TCI3 decreases. Furthermore, the effects of these maintenance types on the probability of buckling were shown using TCI5 over the analysis period and the results achieved were reasonable.

Therefore, it can be concluded that the sensitivity analysis carried using the prototype tool in Section 7.4 demonstrated the feasibility of the methodology. However, as it was seen in CS7 and CS8, the overall condition using TCI2 indicated good overall condition despite the fact that sleeper renewals were postponed. Therefore, it is recommended to specify more TCIs which consider safety risk factors. In the developed prototype system, the user can study the outputs generated by the system and use best judgement to specify budget allocation and maintenance standards.

7.6 Summary

In this Chapter, based on the methodology described in Chapter Five and the logical design of the prototype system described in Chapter Six, a prototype system was developed and tested (see Section 7.4) to predict the future condition of the railway network using the inputs, processes and outputs explained in Section 6.2.

Although, data were obtained at a project level, it was still suitable enough to demonstrate the functionality of the system under different conditions. The system was able to use the condition of rails, sleepers, ballast and S&Cs to determine the overall network condition. The prototype system was capable of producing deterioration models by taking into account the effects of traffic, maintenance history and climate on network condition. The effects of different maintenance treatments on the condition of network was modelled using the prototype tool and based on transition matrices it was seen that depending on treatment type and history of maintenance the levels of effectiveness of maintenance differs. To this end, the prototype system uses the above processes and produces a number outputs to determine the overall condition of the network as a function of maintenance expenditure. The sensitivity analysis discussed in Section 7.4, determined that the prototype system is capable of determining the effects of change in maintenance standards on budget requirements and overall condition of the network.

In the next Chapter discusses the achievement of the research along with the further refinements required to improve the prototype tool.

Chapter Eight

8. DISCUSSION

8.1 Introduction

The aim of this project has been to investigate a suitable methodology to develop a system which is capable of carrying network level railway track maintenance analyses, intended to aid maintenance managers to make strategic decisions using different scenarios of maintenance policies and investments. To achieved this, suitable means of determining the condition of railway track was investigated and it was found that the condition of track can be assessed by the condition of its consisting components. For the purpose of this project, five track components as, rail, sleeper, ballast, subgrade and S&C were determined to be the most important. This was reasonable since they contain a considerable portion of the overall maintenance budget and few of them were used in previously developed maintenance management systems. It was found that the condition of these components can be defined by suitable measures (see Section 5.3.3). To this end, measures of condition defined for rail are wear, corrugation, buckling and cumulative tonnage. Cumulative tonnage was also used for sleeper as a measure of condition. For ballast, track geometry was determined as a suitable measure. In particular 35m SD and dSD/dt of vertical and horizontal alignment were considered. Measures of condition of ballast and rail were also used as measures for S&Cs and subgrade stiffness was used as a measure to define subgrade condition. Although, subgrade stiffness measurements are not carried regularly, and their frequency correlates with the condition of ballast, for the purpose of the analysis, it was recognised that measures of ballast condition can be used instead in parts were subgrade data were not available. The majority of the defects (measures of condition) leading to deterioration of the railway track are recorded periodically over sections of track and sufficient data are available to use (see Section 2.4).

To predict the future condition of these components, it was considered necessary to investigate the effects deterioration and restoration processes on each component (measures of condition).

It was found that traffic and speed, climate and maintenance are the major contributors to the deterioration of components. To quantify the effects of these influencing factors on track condition, it has been found that railway network can be defined as assembly of tracks in a country subdivided into conceptual networks, each consisting of tracks with homogenous characteristics in terms of traffic, speed and climate (see Section 5.3.1). Therefore, network level track condition can be determined by the aggregated condition of the conceptual networks forming the network. To this end, the condition of the network can be expressed by statistical distribution of measures of condition using suitable quality indices (see Section 5.3.2). It was found that the required and feasible maintenance can be predicted by comparing network level track condition with maintenance standards under different investment levels. Network level condition after maintenance (restoration process) was predicted using a stochastic Markov process which uses transition matrices to determine the change in the future condition of a component based on the type and history of maintenance (see Section 6.5). The subsequent future deterioration of the network was again modelled using Markov chains by taking into account the effects of maintenance history, traffic and climate on deterioration using suitable transition matrices at each iteration (see Section 6.4).

To demonstrate the overall network condition, five TCIs were found (see Section 5.3.9). TCI1 has been defined to be the maintenance expenditure to repair one kilometre of track to levels stipulated in maintenance standards. The overall condition of the network based on the condition of its ballast (using 35m SD of vertical and horizontal alignment as a measure of condition) was defined by TCI2. Whereas, TCI3 was defined to determine the average sections of track with rate of change of SD of track geometry in very good and good condition. In the same manner, TCI4 was found to define subgrade network condition based on subgrade stiffness and its rate of change. To determine the occurrence of buckling at network level, TCI5 was defined which indicates the percentage of buckling occurrence during the analysis period for the conceptual networks.

Based on the methodology used, a prototype system was programmed and tested using data from the UK's railway network, supplied by Network Rail. In general, for ballast deterioration and restoration modelling (transition matrices) actual data of track geometry were used. Whereas for other measures of condition, where data were unavailable, simulated, yet realistic datasets were developed. Using the available data, for the purpose of testing the prototype system, the UK railway network was subdivided into three conceptual networks, based on their track category and speed (see Section 7.3.1). To show the feasibility of the methodology, sensitivity analysis was undertaken and the effects of change in maintenance standards, budget allocation priority and investments on network condition were analysed (see Section 7.4). The results of the analyses were reasonable which indicate that the methodology is successful in addressing the aim and objectives of the research (see Sections 1.2 and 1.3).

This Chapter discusses the progress made in the development of this prototype system.

8.2 General Requirements for a Network Level Maintenance Decision-making System

In general, based on Section 5.2, the requirements for developing a network level maintenance decision-making system are summarised under the following heading

1. Prediction of future network condition
2. Overall network condition
3. Ease of use

8.2.1 Prediction of Future Network Condition

In general, four main processes are incorporated in the prototype system which together enable the prediction of future network condition and provide information regarding budget requirements and maintenance expenditures. Using the methodology depicted in Figure 5.1, these processes are as follows.

1. Determining the required maintenance
2. Determining feasible maintenance under budget constraints
3. Determining the degree of improvements in the condition of the network after maintenance
4. Determining the deterioration in network condition

Each of the above elements are in turn discussed below.

8.2.1.1 Required Maintenance

To identify the required maintenance, using the prototype system, first the initial network condition and set of maintenance standards need to be incorporated to the system. Accordingly, the system was able to identify portions of network requiring maintenance by each treatment by comparing the condition with standards. As demonstrated in the sensitivity analysis carried in Section 7.4, using history of maintenance carried over the network, the prototype system was capable of calculating the effects of feasible maintenance on the condition of network at each year, whilst considering its deterioration in the previous year. Furthermore, it was shown that the system is able to reflect the effects of change intervention levels set by standards on the network condition and amount of feasible maintenance (see Section 7.4).

Network Level Track Condition

It was found that statistical distribution of measures of condition of track components can be used to identify network level track condition. The method uses condition indices, which are permissible values for measures of condition, to define different severity bands (condition states). The overall condition was therefore, based on portions of network at each severity band. This method is appropriate to be used for network level analysis, since intervention levels for treatment types as set by maintenance standards also use the same condition indices to define the requirements in terms of maintenance treatments. Furthermore, because the prototype system uses Markov chains to process the deterioration and restoration cycles, the future condition can be predicted using the initial condition of the network multiplied by suitable transition matrices (see Section 5.3.2). This way the change in statistical distribution of measures of condition at each year is calculated.

Measures of Condition

The measures of condition considered in this project are related to five major components of track, which are mainly used in the UK railway industries and are measured regularly. Moreover, it is likely that the measurement of the condition of track components over time will increase as technology to do so improves. Therefore, sufficient data can be obtained to use the prototype system. However, currently the rate of change of SD of vertical and horizontal alignment of track geometry are not used within the railway industries. In the prototype system, suitable method was used which based on the measured SD values it calculates dSD/dt. This measure is believed to be useful, since track sections with same SD values (condition), can deteriorate with different rates. The applications of this measure of condition are, to prioritise maintenance based on the values of dSD/dt at each condition state, and secondly, by analysing the dSD/dt values after each maintenance cycle the effects of treatment types on ballast deterioration can be analysed. This can also be considered for ballast at S&C units. Therefore, when S&C components need renewal, it can be decided whether to renew the ballast or use other treatments. Unfortunately, data regarding subgrade stiffness over time for a section of track was not available. It is believed that the same method applied to determine ballast deterioration can also be used to determine subgrade deterioration. A new measure of condition of buckling was defined where it considers the combined effects of treatment types on measures of ballast condition, and extreme ambient temperature on rail temperature to determine the probability of buckling occurrence. This provides the user useful information to determine suitable treatments to be used by investigating their effects on the probability of buckling. Because the condition of ballast correlates with the subgrade, the latter also contributes to the probability of buckling occurrence. Unfortunately, due to unavailability of subgrade data, this parameter was not included within the system to calculate the effects of subgrade stiffness on the probability of buckling. Because precipitation also impacts the measure of condition of subgrade, to more accurately determine the probability of buckling it is believed that including the above parameter in the analysis of calculating the probability of buckling occurrence will improve the results. Notwithstanding, for the purpose of the system, to determine the effects of precipitation on subgrade deterioration, measures of ballast condition were used as a proxy and it was assumed to be reasonable (see Section 6.6.2). Lastly, because most S&C units have a curved structure, variables in cant deviation of track geometry is a very useful measure to be considered to determine the condition of ballast underneath S&Cs. However, because no data were available for such parameter, it was not included in the analysis. By adding this parameters to the porotype system, more accurate results regarding S&C maintenance requirements can be achieved.

Condition Indices

For the purpose of this research, for the majority of measures of condition suitable condition indices were used to define different states of deterioration. For ballast the measures used were according to the standards defined by NR for geometry irregularities. For rails and sleepers condition indices were specified based on track category which were adopted from Naito's research. Although, no standards are available for S&C units, same indices used for ballast and rails were also used to determine the condition of ballast and rails located at S&C sections. Appropriate threshold values to be set as condition indices for cant deviation is also recommended so that suitable condition states can be determined for this measure of condition. In case of switch components such as POE no standards are specified. In this project, only one condition index was defined and used to determine the useful permissible life of the component. This value was based on the assumption that the components are either in a good state or a failed state. The condition indices were determined based on the useful life of the switch components (Rama & Anderws, 2013), and expressed in terms of cumulative EMGT for each switch component. Although this method was convenient for the purpose of the prototype system, it is recommended that by using more condition indices, more condition states can be determined and based the state of deterioration of the components suitable preventive maintenance can be carried.

With regards to subgrade condition indices, no standards are available to be used. Few recommendations were explained in Section 5.3.4.5 for determining such indices. However, further research is required to determine suitable permissible values of both subgrade stiffness and trackbed thickness since the latter is designed based on the former (see Figure 2.3). Moreover, because the rate of SD of vertical and horizontal geometry are not used within rail industries, for the purpose of the prototype tool, same condition indices determined for SD of vertical and horizontal alignments were used for dSD/dt. Although the results shown in Sections 6.4 and 7.4 were convenient for determining dSD/dt, it is recommended to define suitable standards to more accurately determine the permissible values for each condition state. This is important because decision of ballast renewal is determined by the rate at which track geometry is deteriorating.

Initial Network Condition

The level of accuracy of the outputs of the prototype system are clearly dependent on the quality of the input data. Based on the data obtained for ballast and the information in the datasets only three conceptual networks were defined. The classification was done based on the level of traffic and speed of the conceptual networks. Information regarding the date and history of maintenance of sections of ballast were available in most cases. However, drainage conditions were not included. For parts were information of past maintenance were unavailable, some assumptions were used (see Section 6.3). For other components project level data and some theoretical datasets, yet realistic, were used (see Section 7.3).

It is believed that data required for the purpose of network level track maintenance management are collected on regular basis at project level for most of the components (see Section 2.4). Although subgrade stiffness data is not recorded periodically over time for track sections, using current continuous rolling stiffness measurement vehicles sufficient data is believed to be available in near future. It was shown that such project level data can be used for network level analysis (as shown in this project), however, classifying the data in order to be compatible with network level tasks is time consuming and sometimes complex due to missing information. Therefore, further research is required to improve the methods of classifying and collecting data based on network level requirements. It can be stated that, although, network level analysis requires huge amount of data, most data are collected periodically, and the trade-off is obtaining more accurate outputs regarding future maintenance budget requirements.

Maintenance Standards

As discussed in Section 5.3.5, maintenance standards can be defined by setting different intervention levels using the condition indices of measures of condition. It was seen that based on the specified intervention levels, the prototype system is capable of calculating the required maintenance of the network (see Section 7.4). For routine maintenance, portions of track requiring routine maintenance are specified in the maintenance standards and the results of sensitivity analysis showed that the prototype system is capable of calculating the required routine maintenance at every year of the analysis period.

It was shown that the prototype system is capable of predicting the effects of different maintenance standards on the condition of the network. Although, the priorities of treatments were not altered during the analysis period, the user is allowed to change treatment priorities to at any iteration to simulate more scenarios. For the purpose of this research it has been tried to use best engineering judgement to rank the priorities of treatments. Furthermore, as discussed above, by extending the severity bands of S&C units more appropriate intervention levels can be specified for maintaining the components before reaching the failure state. Intervention for ballast renewal was used based on dSD/dt and accordingly renewal was triggered for portions of track with poor and very poor dSD/dt. For reasons mentioned above, in this project, the condition indices used for dSD/dt is same as for SD of track geometry. As shown in the sensitivity analysis, budget requirement is highly influenced by maintenance standards. To improve the intervention levels for ballast renewal it is therefore, highly recommended to more accurately define the condition indices for dSD/dt. Moreover, in the sensitivity analysis the volume of ballast maintenance changed based on the level funding available. For unlimited budget, using maintenance standards, the entire portions of track requiring maintenance at each state received maintenance. However, for cases where budget was insufficient, the volume of maintenance on portions of track requiring maintenance varied based on the budget available. However, the prototype system allows the user to use intervention levels and specify the required volume of maintenance at each band as it was done for routing maintenance.

Based on the outputs of the sensitivity analysis, it has been found that the prototype system is capable of determining the effects of maintenance standard on the condition of the network and the level of investments required. Therefore, the user can investigate the effects of different maintenance policies on network condition and determine the most effective standard.

8.2.1.2 Feasible Maintenance Under Budget Constraints

In practice, the level of funding to implement maintenance is limited and the required maintenance cannot be fully enforced. For this reason, maintenance was prioritised so that defects with highest severity and importance are treated first. For the prototype system, the first budget allocation method (see Table 7.41) was according to track category of the conceptual networks and used in the sensitivity analysis demonstrated in Sections 7.4.1 and 7.4.2. Whereas in the second budget allocation method (see Table 7.42), components were given higher priorities compared to track categories and it was used in the sensitivity analysis carried in Section 7.4.3. The feasible maintenance under both budget allocation methods were successfully calculated by the proposed system and the results were reasonable. The user can use the prototype system and specify any desired maintenance policy and budget allocation, however, it would be expected that they would have safety considerations in mind in so doing. The reason for assigning a higher priority to track category in the Sections 7.41 and 7.4.2, was due to the reason that tracks with higher traffic and speed deteriorate at a faster rate and in practice these are given higher priority (see Section 2.5). Because the track sections with higher speed and traffic were considered more important and treated first, in the sensitivity analysis it was shown that this caused insufficient budget to be used for maintaining tracks in other categories. Decision of maintenance priority amongst track components is more difficult. It could be argued that as the entire support of the track infrastructure is provided by the subgrade, the maintenance of the subgrade should be given the highest priority. In the second budget allocation method used in Section 7.4.3, when budget becomes insufficient, the renewal of sleepers was postponed whereas ballast renewal and rail renewal were given a higher priority and were maintained throughout the analysis period. The values of TCI2 and TCI3 which indicates the overall condition of the network were also reasonable. However, as mentioned in Section 2.3.3, when number of consecutive defected sleeper over a length of track increases more force will be imposed to the layers underneath resulting in accelerated ballast and subgrade deterioration. Therefore, it is anticipated that the user considers such information together with knowledge of how the conceptual network under consideration deteriorates and safety considerations, to set effective budget allocation policies using the developed system. To this end, the prototype system can be used as a form of a calculator which predicts the effectiveness of maintenance policies and budget allocation on condition of the network to assist the user in determining the most effective budget allocation and maintenance policy. However, the indies used as outputs for the prototype system lack considering the safety risk whilst safety risk of operation should be considered paramount. This requires a safety risk factor to be added to the system, to enable the user to identify key areas of risk associated with maintenance to better prioritise investment under risk based approach. Specially in situation where maintenance of conceptual networks or components are postponed. Using the current outputs of the system, TCI5 can be used as a parameter in determining the effects of postponing ballast maintenance on the probability of buckling.

In the sensitivity analysis (see Section 7.4), when budget is insufficient, the system carries maintenance on the required sections of network until the budget is exhausted. However, for each severity band the user can set the required percentage of track portions to be maintained (see Section 5.3.5). Therefore, the prototype system considers any surplus or deficit in the budget at any year of analysis and it includes them the subsequent iteration.

8.2.1.3 Improvements in the Condition of the Network After Maintenance

In the prototype system, a novel method has been used which determines the effects of treatment types on condition of components by using their distribution of measures of condition (see Section 6.5). In case of ballast maintenance, the approach uses the distribution of minimum SD of track geometry values after maintenance interventions considering their condition before the intervention to develop transition matrices. Probability distribution models were fitted to the data and using the condition indices the likelihood of components moving to lower states from their current condition were determined. To this end, a stochastic Markov process was used which uses transition and coexistence matrices to predict future change in condition of components as a result of maintenance (see Section 5.3.6). Based on the analysis carried in Section 6.5, it was shown that the degree of improvements of treatments such as tamping and stoneblowing correlates with the condition of the ballast (defined by condition states) and the previous maintenance work carried. The results also indicated that as cycles of tamping and stoneblowing increases for same sections of track the level of improvement decreases. In the sensitivity analysis (see Section 7.4) it was demonstrated that even in cases where all the potions of track with poor and very poor conditions were treated by either tamping or stoneblowing, the condition after maintenance was not the same as when renewal was selected as a treatment. Furthermore, it was shown than when budget is insufficient, not all the sections can be treated. The condition after feasible maintenance in these cases were at lower levels compared to the unlimited budget scenario. In the prototype system real datasets were used to develop multiple restoration transition matrices using different histories of maintenance (see Section 7.3.4). By using more dataset with greater variety and cycles of maintenance history more restoration transition matrices can be developed for the conceptual networks. It can be stated that the restoration models used in the prototype tool provide more reliable outcomes regarding the condition of network as represented by TCI2 and TCI3 compared to other existing systems discussed in Section 4.7. For other components, although by analogy same approach (see Section 6.5) can be applied the following considerations must be taken into account.

Rail Renewal and Grinding

Restoration transition matrices developed to model the effects of rail renewal and grinding were based on the assumption that renewal and grinding will restore the condition of the components to the very good state. Rail renewal and replacement can take place due to rail break, buckle, excessive wear or when their useful service life is reached. In cases where rails are removed from, for example, higher track categories due to their amount of wear being greater than those specified in standards, they may be used in other sections (lower track categories) where the maximum permissible values of wear are higher. Therefore, in practice a removed section of rail is not always replaced with a new piece. To include the restoration process of reused rails in prototype system, further research is required to investigate a network level analysis which considers the portions and condition of reused rails in the conceptual networks. As mentioned in Section 7.3.4, suitable data is required to determine the effects of grinding on corrugation removal. Based on the current inspection techniques (see Section 2.4), sufficient data can be obtained from HTRC and ultrasonic rail testing trains and suitable transition matrices can be determined to model the effects of grinding on corrugation by considering the previous grinding cycles. It is believed that the approach used in Section 6.5 can be successfully applied to a suitable dataset of rail corrugation to determine grinding restoration transition matrices.

Sleeper Renewal

In the prototype system, sleeper data were not available and realistic theoretical data sets were developed (see Section 7.3.4) and only one type of sleeper (i.e. concrete) was considered. In reality, different types of sleeper are used over the network and in cases where timber sleepers are renewed they are mainly replaced by concrete sleepers to reduce maintenance costs and for some other reasons as explained in Section 2.2.3. However, the decision of type of sleeper to be used is determined at project level. If suitable guidelines are provided suitable decisions regarding sleeper renewal can be made and added to the prototype system. Furthermore, same as rails used sleepers in good condition might also be used as replacements (see Section 5.3.6).

S&C Renewals

In the sensitivity analysis described in Section 7.4, only POE were used to determine the condition of switch components and their replacements were assumed to restore their condition to the good as new. In order to reduce delays and the costs incurred due to S&C renewals, in practice, sometimes partial renewal of switch units are made. Furthermore, full renewal of S&C components may lead to replacement of components that are not life expired. In the prototype tool each of the switch components are modelled separately therefore, it is possible to consider partial renewal of S&C units. In practice the maintenance of S&C units is some cases are due to poor ballast quality and therefore, instead of S&C maintenance, ballast maintenance is recommended to be carried. This is addressed in the prototype system as the condition of ballast under S&C units are considered separately. As mentioned in Section 8.2.1, further investigation to determine suitable condition indices for S&Cs are required. Accordingly, the maximum permissible life of their components can be determined and using the same methodology an improved S&C restoration model can be achieved.

Ballast Maintenance

In the prototype system, the developed restoration transition matrices reflected the effects of tamping and stoneblowing on the condition of ballast in terms of SD and dSD/dt. This was done for different yet limited maintenance history. The result of effectiveness of the proposed methodology in determining restoration transition matrices was clearly shown in the results explained in Sections 6.5 and 7.4. Using current inspection methods (see Section 2.4) such as HTRC, appropriate amount of data of track geometry irregulars are recorded. Although, information of previous maintenance cycles was not included for some sections of track, it is envisaged that over time using the current methods of inspection more consistent asset information regarding maintenance history will available. Notwithstanding the huge amount of data required for network level analysis, most recent measurements are digitized and can be incorporated into the system using few buttons and all the computations of transition matrices are automated thereafter (this is also the case for deterioration modelling). Therefore, it is believed that using the prototype system reasonable results regarding the effects of ballast maintenance can be achieved.

However, in this project, data regarding the cant deviations of track geometry were not available. It is recommended that further research is required to determine a suitable method of developing transition matrices which can reflect the effects of tamping and stoneblowing on improving cant irregularities. This is a very useful measure for sections of ballast located on at curves.

Multiple Occurrence of Defects

As described in Section 5.3.6, coexistence matrices are used to map the effects of treatments on multiple measures of condition. To develop appropriate coexistence matrices comprehensive amount of data is required. In the prototype tool (see Section 7.3.5) network level data were not available and coexistence matrices were developed from project level data of ballast condition. However, for rails, coexistence matrices developed by Naito were used. Although such classification of data is not stored in the datasets, using inspection techniques and asset information, such matrices can be developed.

The coexistence matrices considered in this the prototype system were limited to one component due to inconsistency of data. However, in practice, when S&Cs or sleepers require renewal or replacement, further tamping or grinding might be carried out on those sections to correct geometry irregularities, or if the subgrade is in very poor condition and it needs to be maintained the entire track must be reconstructed (see Sections 2.5.6). Therefore, track reconstruction, sleeper and S&C renewals trigger the condition of more than one component. These and other similar effects can also be modelled using coexistence matrices. Therefore, further research to determine suitable coexistence matrices to detect such effects would be necessary.

8.2.1.4 Deterioration in Network Condition

To predict the future deterioration in network condition, the prototype system uses Markov chains to determine the progression of network at each condition state over time using deterioration transition matrices (see Section 5.3.2). The deterioration of the network was shown in the sensitivity analysis in CS3 and CS6 (no funding), which indicates that values of TCI2 and TCI3 decreases and the required cost to repair one kilometre of track increases. The reason behind selecting Markov model was discussed in Section 3.5. Although Markov model have been previously used for project level analysis, in this project novel methods were developed and incorporated to the system which considers the effects of traffic, maintenance and climate on deterioration of track components (transition matrices). This are explained in detail below.

Traffic and Maintenance Induced Deterioration

To model the effects of traffic and maintenance on condition of the network, it was found that the change over time of measures of condition of components after each maintenance cycle needs to be analysed. Suitable relationships between the measures of condition and time were modelled and transition matrices were calculated. This procedure was fully explained for ballast using real datasets (see section 6.4). Due to unavailability of data for other components different approaches have been used and some assumptions were made. These are discussed below.

Rail

Data regarding the measure of condition of rails in terms of EMGT were not available. For the purpose of the prototype system Naito's approach was used to calculate the transition matrices for rails using EMGT as a measure (see Section 7.3.4). Because the age of rails differs within each conceptual network, it was assumed that the percentage of network within each condition state was Normally distributed. The change in EMGT from one iteration to the next was determined using the mean value of the Normal distribution which was assumed to be increased by the specified EMGTPA of the track category. Accordingly transition matrices were developed using suitable methods as described in see Section 6.4. Due to reasons described in Section 8.2.1.3, rails might be reused over the network. Therefore, the rate by which they deteriorate and their SFT are different compared to a new piece rails. It is recommended that more research needs to be carried to determine a suitable method to include such factors in rail deterioration modelling.

To develop transition matrices to model the progression of wear over time, theoretical datasets based on measurements of wear on Portuguese railway network were used (see Section 7.3.4). Using appropriate regression techniques, as used for ballast (see Section 6.4.1), the deterioration trend of wear over time was modelled and transition matrices were developed using the processes explained in Section 6.4.2. Based on the data it was possible to model the effects of one cycle grinding on the rate of progression of wear. However, due to inconsistencies in data, asset information of rails were not available. Therefore, it was assumed that data were for track sections with new rails.

To model the behaviour of corrugation over time, a method used by Burrow *et al,* (2009) was suggested to be used due to lack of data. It must be mentioned that, deterioration as a result of corrugation is significantly influenced by the amount of traffic and speed and therefore, for network level analysis more suitable datasets need to be used. Moreover, as discussed in

Section 2.3.1, the effects of wear and corrugation are more severe and frequent at curves than tangent tracks. As mentioned in Section 2.4.1 regular inspections are carried and the amount of wear and corrugation are recorded. Using appropriate asset information regarding track structure and data of measures of rail condition, same principals discussed in Section 6.4 can be applied and transition matrices can be developed.

Sleepers

In the prototype system, same processes used to model the deterioration of rail using EMGT were used to model the deterioration of sleepers. As discussed in Section 2.3.3, the rate of deterioration of sleepers varies based on its type and is highly affected by the amount of traffic and speed and the number of unsupported sleepers over a length of track. Track drainage conditions also affect the rate at which sleepers deteriorate. For example, poor drainage and settlement of the subgrade increases the deflection imposed from passing train and results in sleepers being unsupported (see Section 2.2.3). Therefore, further work is recommended for modelling sleeper deterioration considering the effects of above influencing factors on its condition.

S&Cs

As mentioned in Section 7.3.4, the deterioration models for ballast and rails were used to model the deterioration of track located at S&C units. Based on Section 2.2.2, due to the reason that majority of S&Cs have a curved structure defects in cant variables are more prone on S&Cs. Maintaining correct cant is necessary since it results in less corrugation. Thus, same as SD of vertical and horizontal alignment of track geometry, this parameter also needs to be analysed over time so that appropriate transition matrices can be developed using suitable sets of condition indices.

To model the deterioration of other switch components such a POE, clamp-lock and stretcher bars, suitable data were obtained from the work carried by Rama and Andrews (2013). The data related to failure of switch components over time. Therefore, using this data, the time taken for components to reach the failure state were modelled and transition matrices were calculated. The data related to the entire UK and no asset information in terms of track category and line speed were provided. Since traffic and speed highly influence the deterioration rate, it is recommended to classify the data based on track categories to be compatible with network level analysis (such as Table 2.1). This can be achieved by the existing inspection tools such as SIM.

<u>*Ballast*</u>

In case of ballast, huge amount of data relating to 35m SD of vertical and horizontal alignments of track geometry over time were obtained from NR. The data related to track section located on SPC, BML and ECM. To classify the data based on maintenance history, although asset information regarding previous maintenance interventions were only available for few sections of track, for other sections were this information was unavailable, suitable assumption regarding time and type of maintenance were made (see Section 6.3). In this manner, a regression analysis was performed on data and suitable relationship between the change in measure of condition and time was established for the conceptual networks. Using the condition indices adopted from NR standards, processes described in Section 6.4.2 were implemented and deterioration transition matrices were developed. Based on the data in hand, maintenance history was limited only to the maximum of four cycles (e.g. renewal, followed by four cycles of tamping at equal intervals). The results calculated in Section 6.4, clearly shown that the deterioration rate of the track geometry differs based on treatment types and maintenance history. The effect of this was also shown in the values of TCI2 in the sensitivity analysis carried in Section 7.4. Although, only limited information of maintenance history was available, it is envisioned that using inspection methods such HTRC sufficient amount of geometry recording can be obtained since track geometry inspection is carried regardless of ballast condition. Therefore, based on asset information of such data, the prototype tool is capable of developing as many transition matrices as possible to increase the level of accuracy of the outputs. In this project the calculated results were compared by available reports of NR (Network Rail, 2013) and they were considered reasonable.

The change in deterioration rate of the ballast (dSD/dt) is not currently used within the UK railway industries. In this project it was found that, the deterioration of components having the same condition differs and is correlated with the maintenance history. Therefore, a relationship between the deterioration parameter and values of SD of track geometry was determined. Using suitable mathematical functions, the distributions of dSD/dt at each state were calculated and transition matrices were developed (see Section 6.4.3). The effects of this variable on overall condition of the network was determined using TCI3. In the sensitivity analysis it was shown that as the cycles of tamping and stoneblowing increased over the analysis period, the values of TCI3 decreases, which indicates faster deterioration rate of the network. Using the prototype system, the user can implement different maintenance standards and accordingly using the values of TCI3, the most appropriate treatment types to be used at each iteration can be determined. Again, it is anticipated that in near future comprehensive amount of data will be available to improve the accuracy of the outputs generated by the prototype tool. Since no current guidelines exists for renewal of ballast, it is believed that this parameter can be very useful is the decision-making process of ballast maintenance renewals.

Subgrade

Because data over time for measure of subgrade stiffness and its special variation, k and dk/ds respectively, were not available for the conceptual networks, these parameters were not included in the analysis. However, it is anticipated that using advanced technologies more frequent subgrade stiffness measurements are recorded (2.5.6). Based on the literature carried in Chapter Two few recommendations which are required to be considered for modelling network level subgrade stiffness over time are discussed below.

Based on current trackbed design standards it has been understood that stiffness of the subgrade is an important factor in determining the thickness of the trackbed layers (see Section 2.2.5). Based on Section 2.3.6 subgrade soil strength depends on the soil type, drainage condition and the stress history and depending on the soil type, repeated loading may decrease or increase soils resistance to deformation. The strength of subgrade itself may also be affected by the amount of saturation and moisture content and thus can be correlated with the amount of precipitation. Using the above factors homogenous subgrade sections can be specified. Current inspection methods can be used to measure the change in stiffness of the subgrade over time. On the other hand, using GPR suitable measurements of trackbed thickness are recorded periodically over track sections. Using such data, it is possible to determine a relationship between trackbed thickness, subgrade stiffness and time and using suitable condition indices for both variables different condition states and transition matrices can be determined. To achieve this further research is recommended to be carried. Incorporating this parameters in the prototype system is necessary since, TCI4 determines the overall network condition based on subgrade condition which is important to be considered whilst making decisions regarding the level of investments required.

Effects of Climate on Network Deterioration

In this project a novel approach has been developed to model the effects of climate on the deterioration of track components under different CO_2 emission scenarios (i.e. low, medium and high). It was found that temperature and precipitation affect the condition of rails and subgrade respectively. The former has potential to cause buckling of rails whereas the latter causes problems associated with subgrade stiffness which can also manifest themselves in terms of poor track geometry. The following processes are the requirements for modelling the effects of climate induced deterioration.

1. Predicting the future climate
2. Determining the effects of temperature on network condition
3. Determining the effects of precipitation on network condition

Predicting the Future Climate

Due to different ranges of temperature and precipitation over the country, it was considered necessary classify the UK railway network into smaller regions. To this end, it was considered to use UKCP09 classification method in which the UK is divided into different administrative regions. To model the future values of precipitation and temperature parameters, for each administrative region, UKCP09 WG was used to generate 100 different time series of maximum daily temperature and average daily precipitation rate samples over 30 overlapping years for the baseline scenario and again for years 2020 and 2050 (see Section 5.3.8). Using suitable processes, distribution of average daily precipitation and maximum daily temperature for each month were calculated and determined to follow a Normal distribution. To determine the future amount of the above climate variables, it was assumed that the increase in the mean value of Normal distribution from year 2020 to 2050 follows a linear function. Accordingly, for each month data were divided equally between years 2020 and 2050. The results shown in Section 5.3.8 and Appendix A and B, clearly indicated that in the future climate there is an increase in maximum daily temperature and average precipitation rates. For temperature, it was mainly seen that in August and July the rate of increase in higher than other months, whereas in case of precipitation, the increase was higher for January, December and November. Therefore, the results are believed to be reasonable which indicates the usefulness of the methodology. There are some uncertainties is UKCP09 WG models itself such as, natural variability and uncertainties in emission scenarios (see Section 4.4.1). The models are improving constantly and an updated version of UKCP18 is soon to be launched in 2018.

Effects of Temperature on Network Condition

In this project the effects of extremes in temperature on rail buckling was investigated and a novel methodology was used to calculate the probability of buckling for conceptual networks over time (see Section 6.6.1). To this end, the probability of buckling is determined based on the combined effects of rail temperature and ballast condition (as represented by 35m SD of track geometry). Based on the available data and information, theoretical datasets were developed for determining the probability of buckling occurrence (see Section 6.6.1). Data of track failures with respect to maximum temperature, obtained from NR (Network Rail, 2015), were used. Data were related to the entire UK network and no network information was available to specify the location, type of rail and track geometry. Therefore, using suitable methods and reasonable assumptions the ballast condition of buckled rails was determined. Due to lack of network information only one equation was defined and used to determine the probability of buckling (see Equation 6.25). In the sensitivity analysis carried in Section 7.4, based on relative regions of conceptual network, suitable ranges of temperature were incorporated into the system and used in Equation 6.25. TCI5, indicated that the probability of buckling of track sections, within the same conceptual network but located at different regions, is highly affected by the amount of maximum daily temperature. It was seen than for regions with higher levels of maximum daily temperature, the calculated probability of buckling was higher. It was also shown that maintenance of tamping and stoneblowing also affect the occurrence of buckling and this was clearly seen in the values of TCI5. The values of TCI5 and the results shown in Section 6.6.1, were compared with the literature carried in Section 2.3.1, and the results were believed to be reasonable. This indicates the feasibility of the methodology. By adding sufficient network information regarding the location buckled rails and their corresponding track geometry, same methodology can be carried, and suitable equations can be developed for each administrative regions or conceptual networks separately to achieve more accurate predictions.

The other application of the methodology is to use the calculated probability of buckling in predicting the future delay minutes and the corresponding costs. Using Dobney's approach (Dobney, 2010) the total delay costs (C) as a result of buckling is found based on Equation 8.1.

$$C = mdpc \tag{8.1}$$

Where m is the estimated delay minute determined based maximum daily temperature (t) on the day of the buckling event. To calculate this value, the UK was divided into four regions and m was determined based on t using suitable linear equations for each region (e.g. $m = 42t - 923$). d is the total number of days that that particular temperature (t) is going to occur, which is determined based on the number of days in each month and the probability distribution of maximum daily temperature for that month. p is the probability that that temperature causes buckling and c is the average cost of delay minute (estimated to be £73.47). However, in

Dobney's approach the probability of buckling was estimated using the total number of rail related incidents divided by the total number of days when maximum temperature is above 25°C and track geometry was not included in the analysis. It is believed that the methodology used in this research is more accurate in determining the probability of buckling since the effects of ballast condition and maintenance are both considered in the calculations. By adding this feature to prototype system, the calculated probability of buckling can be used in Equation 8.1 to determine the total cost of delays. However, further work is required to model the estimated delay minute (m) for the administrative regions used in this project. It is believed that the regions used in the UK for this project is more suitable to be used compared to the regions classified by Dobney. The reason is because the size of administrative regions aisre smaller and based on UKCP09 WG suitable location (25km grid square) can be used to represent the future climate each region. Furthermore, as explained in Section 8.2.1.1, it is useful to include the effects of subgrade stiffness in calculating the probability of buckling. Therefore, it is believed that taking into account such considerations will improve the predicted values of TCI5.

Effects of Precipitation on Network Condition

It has been found that the effects of climate in terms of precipitation highly affects the deterioration of the subgrade. To determine such effects, for the purpose of this research, the deterioration of subgrade for conceptual networks located at different regions were compared. This was based on the assumption that the change it deterioration rate of homogenous subgarde sections, considering its stiffness as a measure of condition, is caused as a result of change in the amount of precipitation of the corresponding regions. Although measurements of subgrade stiffness over time for the conceptual networks were not available, the change in ballast deterioration was used instead since it is correlated with the condition of the subgrade (see Section 6.6.2). To this end, homogenous ballast sections located at five different administrative regions were used, and their monthly average daily precipitation was determined. Precipitation deterioration factor (see Section 6.6.2) was calculated and the change in deterioration rate of subgrade in conceptual networks as a result of change in the amount of precipitation rate in corresponding regions were determined. To model future precipitation induced deterioration using the predicted future amount of average daily precipitation rates (see Section 5.3.8) different analogue scenarios were assessed, in which a regional precipitation rate is used to describe the future precipitation rate of another region that is predicted to experience similar precipitations. The results were shown in Section 6.6.2, and it is believed to provide a useful starting point to investigate the impact of precipitation induced deterioration on the railway network. Based on the calculated results (see Section 6.6.2), in majority of cases it was found that, increase in precipitation increases the precipitation deterioration factor. However, in few cases, the precipitation deterioration factor for track with poor ballast geometry decreased despite the increase in precipitation rate. The reasons causing this were discussed in Section 6.6.2. In general, this could be due to unavailability of drainage conditions and physical condition of the subgrade (saturation level and moisture content and stress history). Therefore, climate change model needs further refinements as it does not currently consider existing ground condition nor antecedent rainfall.

The predicted future average daily precipitation rates can also have other applications. Currently within NR the number earthworks failures with respect to precipitation are recorded for the UK network. Therefore, based on the strength of subgrade and the level of saturation suitable relationships can be determining between stiffness variable and precipitation to define the occurrence of earthworks failures. Therefore, similar processes carried in Section 6.6.1 may also be useful to determine the probability of earthworks failures. However, this requires considerable amount of further research.

8.2.2 Overall Network Condition

The prototype system uses five TCIs to determine the overall condition of the network. To this end, TCI1 determines the cost of required maintenance for one kilometre on track, whereas TCI2 and TCI3 indicate the overall condition of network using condition of its ballast and its rate of change in deterioration which respectively are calculated by the average portions of network with very good and good ballast condition. TCI4 is an indicator of structural condition of the track which uses the condition of subgrade to determine the overall structural condition of the network. This variable is very useful in analysis the future effects of precipitation on the railway network under different maintenance budget and policy. TCI5 is an indicator of overall percentage of buckling occurrence on the network. Based on the results of the sensitivity analysis realistic outputs were developed by the prototype system under different budget allocation methods and maintenance standards. It can be concluded the TCIs used in the prototype system provide the user with sufficient information regarding the effects of climate and maintenance budget and standards on network condition. However, as discussed above. safety risk factor needs to be included in the prototype system and therefore, further research is required to add this feature to the prototype system.

8.2.3 Ease of Use

The prototype system was developed and programmed in MATLAB and is in a form of graphical user interface. For each track component suitable sections are defined (see Figure 7.1), which allows the user to enter the required inputs. For the prototype system data needs to be in a form of .xls and there are no limitations on the amount of input data. The user can browse relevant data using suitable buttons, and the rest of the complex calculations are done by the system. Furthermore, to enter the climate data to the system, the system requires the raw data obtained from the UKCP09 WG which are generated in .xls format and no processes are required to be carried by the user. Using the desired emission scenario, the user can browse the relevant dataset for the system to carry suitable processes. In addition, suitable sections are provided by the prototype system for setting the total available budget and suitable maintenance standards. The outputs as demonstrated in the sensitivity analysis are in a graphical format and straightforward to be understood.

8.3 Summary

In this project and prototype system which is capable of carrying network level maintenance analysis was developed. The general concept of the system was based on NETCOM (see Section 4.7.1) and the proposed system developed by Naito. Significant refinements were carried for the development of deterioration and restoration models and new components such as subgrade and S&Cs were also added to the system. Furthermore, novel methods to determine the effects of climate induced deterioration on network condition were featured in the system.

For the purpose of network level analysis, the condition of the network was described in a form of statistical distributions of measures of integrity which represents different defect types. It was illustrated that this method is convenient to be used for network level analyses. The prototype tool was capable of determining the overall required and feasible maintenance of the network by using maintenance standards and budget and treatment priorities. It was shown that transition matrices are suitable to be used to determine the change in condition of the components over time. In addition, transition matrices were derived from real datasets and they change as a result of maintenance and climate-induced effects. This ensures that the future prediction of deterioration is accurately being calculated considering the influencing factors. The system demonstrates the overall condition of the network in a straightforward manner and is conceptually simple for the user to understand using TCIs. Consequently, the requirements of the system as discussed in objectives in Section 1.3 are satisfied.

It is believed that the developed prototype system can be useful to be used by asset managers and senior decision-makers within the railway industry. However, few other recommendations and future work which are necessary to be considered are discussed in the next Chapter.

Chapter Nine

9. CONCLUSIONS AND FURTHER RESEARCH

9.1 Accomplished Work

The accomplished work in this project illustrates the development of a theoretical framework for railway asset managers to assess the future performance of the railway network as a function of maintenance expenditure. The developed system allows senior decision-makers to investigate the effects of level of investment, maintenance policies and budget requirements on the condition of network. To this end, the system determines the effects of traffic, maintenance and climate on network condition using suitable stochastic processes. The accomplished work in this project are summarised below:

1. The requirements in terms of the necessary railway track components to be considered in determining network level track condition was identified based on the literature review carried in Chapter Two.
2. The current models which identify the effects of traffic and maintenance induced deterioration on each component were investigated and suitable stochastic methods used to model the deterioration processes were explained (see Chapter Three).
    a. It was found that the models lack considering the effects of climate on deterioration of track components.
    b. There are no adequate models to determine the level of improvements on components after maintenance.
3. Based on the literature carried in Chapter Four, it was found that currently there appears to be no appropriate system for network level railway track maintenance management.
4. Suitable methodology to develop a framework of network level railway track maintenance management system was demonstrated in Chapter Five.

5. The logical design of a network level management system for railway track maintenance which is capable of predicting future network condition by taking into account the maintenance and deterioration was described in Chapter Six. The logical design of he system consists of number of processes as described below.
   - 5.1. A process to identify the requirements in maintenance at a network level for the railway track to achieve desired level of condition using maintenance standards.
   - 5.2. A method to calculate the feasible maintenance under budget limitations
   - 5.3. A process to determine the effects of feasible maintenance on the condition of the railway network by taking into account the effects of treatment type and history of maintenance on the level of improvements.
   - 5.4. Probabilistic processes to predict the overtime deterioration of the network by considering the effects of traffic, maintenance on the deterioration rate
   - 5.5. Probabilistic processes to predict the future climate over the UK and to determine the effects of temperature and precipitation on railway track network condition.
   - 5.6. Set of five TCIs to show the progression of railway network track condition over time as a function of investment.
6. A prototype system developed based on 5 above, which uses track condition data and generates graphical outputs to demonstrates the overall network condition in future based on maintenance expenditures (see Chapter Seven).

9.1.1 Conclusions

Based on the developed prototype system the key conclusions are as follows:

1. The prototype system has been able to predict the future condition of the network as a function of maintenance expenditure using TCIs.
2. It has been found that the prototype system is capable of determining the effects of change in interventions levels and budget allocation on the overall condition of the network.
   - a. The restoration module is capable of considering the effects of treatment types and history of maintenance on the condition of components.
   - b. The deterioration module is capable of predicting the change in deterioration of track components by considering the effects of tamping, stoneblowing and grinding induced deterioration.

c. The deterioration module predicts the future maximum temperature over the network to determine probability of buckling based on rail temperature, track geometry and the effects of maintenance history.

d. The deterioration module can predict the future change in the condition of track geometry and subgrade stiffness as a result of change in precipitate rate using special analogous scenarios.

9.1.2 Findings

It was found that the various processes performed by the prototype system are implemented successfully using the following techniques:

9.1.2.1 Data Analysis

To be able to determine the behaviour of components over time the following processes need to be applied to the data:

1. Classification of data of track components (measures of condition) based on the homogenous characteristics (see Section 5.3.1) to define conceptual networks.
2. Determining the locations of conceptual networks for determining their regional climates using UKCP09 WG.

9.1.2.2 Deterioration Analysis

It was found that to model the deterioration using Markov chains the following processes are required:

1. Determination of deterioration trend of components between each maintenance intervention using regression analysis.
2. Prediction of change in condition of components over time, by specifying suitable means, via condition indices.
   - 2.1. Specifying probabilistic condition states using condition indices.
   - 2.2. Determining the distribution of time to reach critical condition indices to calculate the transition rate matrices.

The change in deterioration of ballast was analysed using its measures of condition and the following have been found:

1. In the majority of cases tamping causes the deterioration rate to increase. This is also true for stoneblowing however the deterioration is affected less so.

2. Increase in cycles of tamping causes a rapid increase in the deterioration rate of the ballast.

9.1.2.3 Restoration Analysis

Restoration processes were also modelled using Markov chains using the following steps:

1. Fitting a probability distribution to the distribution of minimum values measures of condition after maintenance interventions.
2. Specifying the change in portions of track at each state using condition indices.

Based on the developed models it has been found that treatments such as tamping and stoneblowing improve the condition of the ballast but only to some extent. The degree of improvements is highly correlated with the present condition of ballast and the maintenance carried in the past.

9.1.2.4 Effects of Climate

To model the effects of climate (temperature and precipitation) the following processes are required:

1. Determining the future climate over the network:
    - 1.1. Use the UKCP09 WG to generate random samples of daily climate variables for administrative regions under desired emission scenario for the baseline period, 2020s and 2050s.
    - 1.2. Determining daily values of climate variables for each month using suitable probability distribution.
    - 1.3. Predicting the future climate variables by assuming a linear increase in the mean value of distributions of monthly temperature and precipitation between 2020 and 2050.
2. Determining the probability of buckling as a result of extremes in temperature:
    - 2.1. Defining a relationship between track geometry and rail temperature to determine the occurrence of buckling.
    - 2.2. Use the distributions of maximum daily temperature and track geometry to carry Monte Carlo simulation to determine the probability of buckling occurrence.
3. Determining the effects of precipitation on track geometry and subgrade stiffness:

   3.1. Determining the percentage of change in monthly precipitation rate of conceptual networks located in administrative regions.
   3.2. Defining a precipitation deterioration factor to determine the ratio of change in the deterioration of subgrade stiffness.
   3.3. Using analogous scenarios to predict the change in transition matrices as a result of increase in precipitation.

Based on the results the followings are achieved:

1. Maximum daily temperature over the UK is increasing, especially in summer months, and the rate precipitation is increasing, where its rate of increase is higher in winter months
2. The probability of buckling increases as a result of deterioration of track geometry and increase in maximum daily temperature.
3. Frequent intervention of tamping and stoneblowing adversely affect the probability of buckling.
4. The increase in the rate of precipitation in most cases increases the deterioration of subgrade which can also result in poor track geometry which increases the probability of buckling.

9.1.3 Remaining Problems

Although the prototype tool was able to address the requirements identified in the objectives, there are limitations which are listed below:

1. Lack of sufficient network information to determine suitable initial network condition and coexistence matrices
2. The majority of data were in a graphical format and manual sampling have been carried for most of track condition data. This might cause inaccuracies in predictions since the quality of the outputs are dependent of the quality of inputs.
3. Continuous stiffness measurement:
   3.1. FWD is usually performed for small track sections and is not taken periodically over time. This problem can be solved using RSMV (see Section 2.4.7) which measures continuous dynamic stiffness of track over a length. By using RSMV routinely on track sections suitable database of subgrade and trackbed stiffness can be obtained. Using such data would allow the same approach, as developed

for all of the other components, to be used to predict the condition of subgrade over time.

3.2. Using periodic stiffness measurement more accurate precipitation deterioration factors can be determined and better analogous scenarios can be considered to determine the change in subgrade deterioration as a result of increase in precipitation.

3.3. Using such data TCI4 can be calculated and used to demonstrate the overall network condition based on subgrade condition and aid in analysing the effects of precipitation on its deterioration.

4. Unavailability of track geometry and subgrade stiffness data for track failures such as buckling:

   4.1. Track geometry and subgrade stiffness data for failures caused by rail buckling are not included in the datasets currently available. Although suitable methods can be used to determine such values, to achieve more accurate results it is beneficial to include such parameters in the recorded track failure datasets.

9.2 Future Work

To improve the network level decision-support tool to assess railway track maintenance needs, the following future work are recommended:

1. Further research is required for specifying suitable condition indices to determine condition states for measures of condition of S&Cs, rate of deterioration of track geometry (dSD/dt), and subgrade stiffness (k) and its spatial variation (dk/ds).
2. Suitable method to store network level track condition data to improve the quality of initial network condition and coexistence matrices.
3. Suitable method to include the effects of unsupported sleepers on sleeper deterioration and its effects on network level track condition.
4. Including the effects of subgrade stiffness in the probability of buckling occurrence
5. Further work to improve precipitation deterioration factor by including subgrade stiffness, ground conditions and antecedent rainfall.
6. Suitable method to model the effects of cold temperature related failures on S&Cs which needs investigating the effects of minimum daily temperature on its condition
7. Identifying a safety risk factor for setting maintenance priorities.
8. Further work to establish guideline for reusing rails and sleepers and partial S&C renewals

9. Determining the effects of precipitation on earthworks failure such as Embankments and analysing the effects of low temperature on saturated earthworks.
10. Optimising the prototype system so that the user can specify the desired level of network condition at any future year, for the prototype system to determine the most suitable maintenance standard to achieve that level.

10. APPENDIX A

10.1 Future Monthly Maximum Temperature

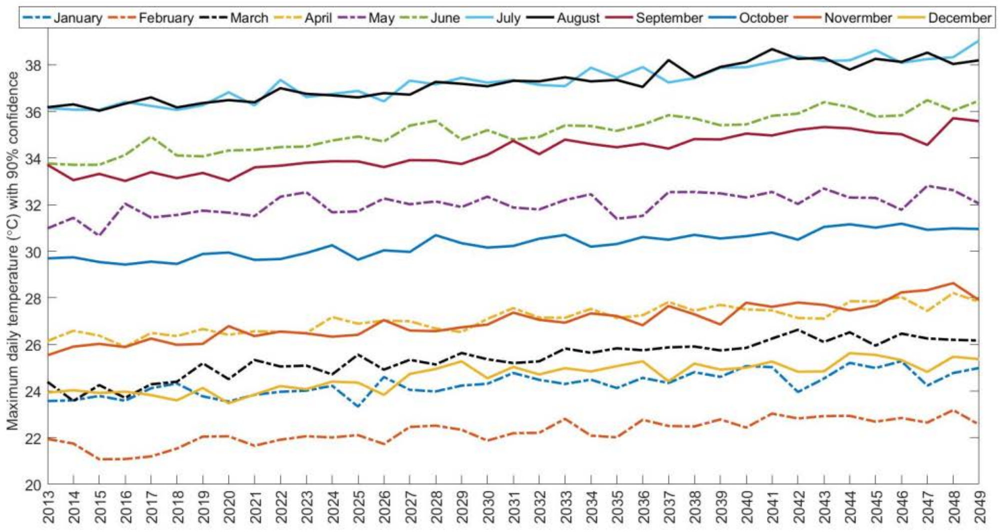

Figure 10-1 Monthly maximum daily temperature for East of England

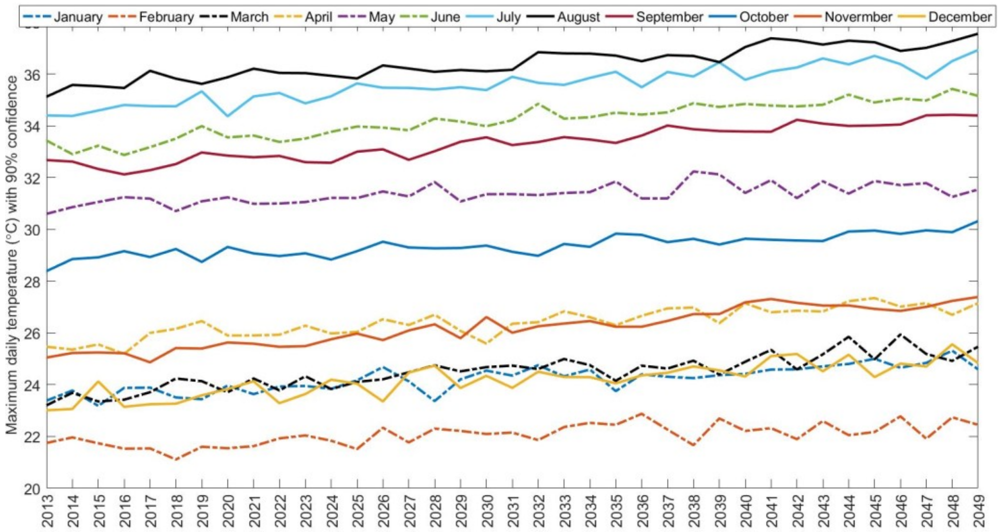

Figure 10-2 Monthly maximum daily temperature for East Midlands

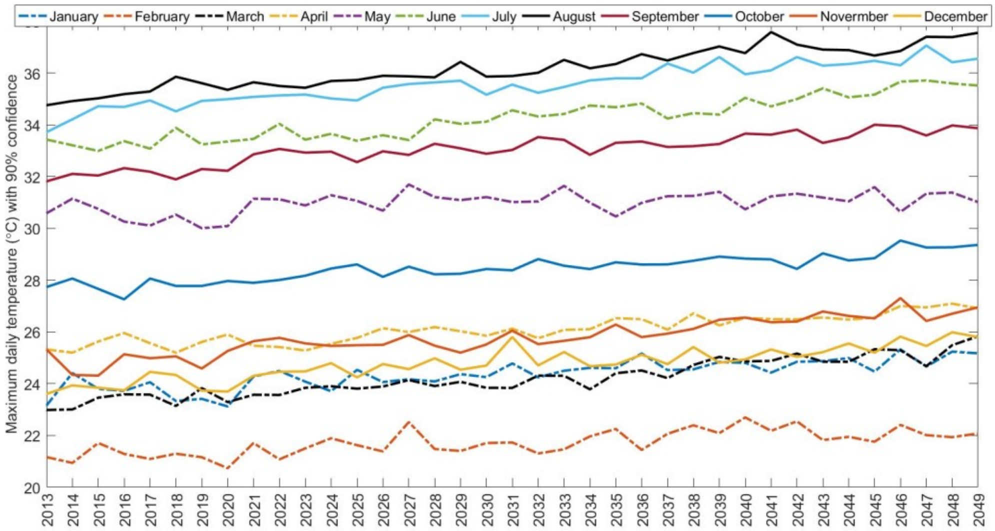

Figure 10-3 Monthly maximum daily temperature for London

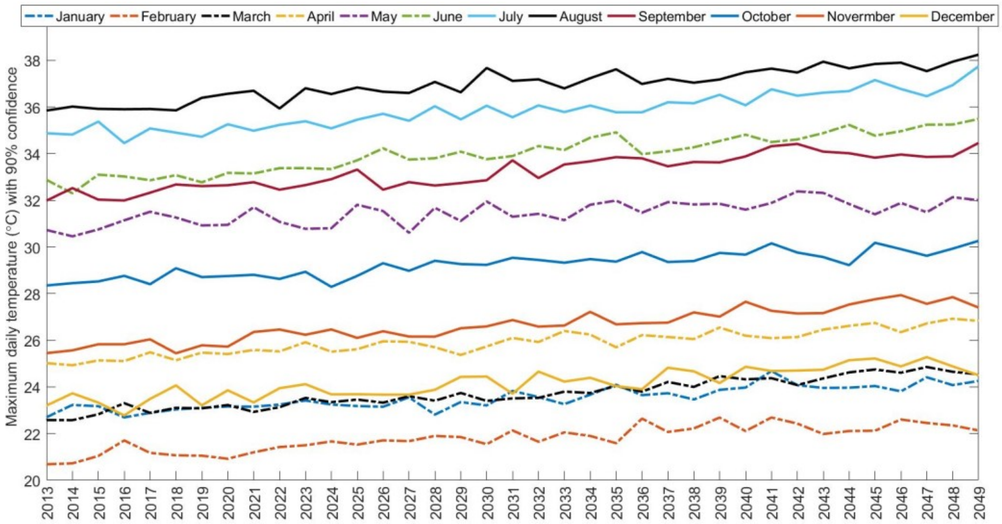

Figure 10-4 Monthly maximum daily temperature for South East England

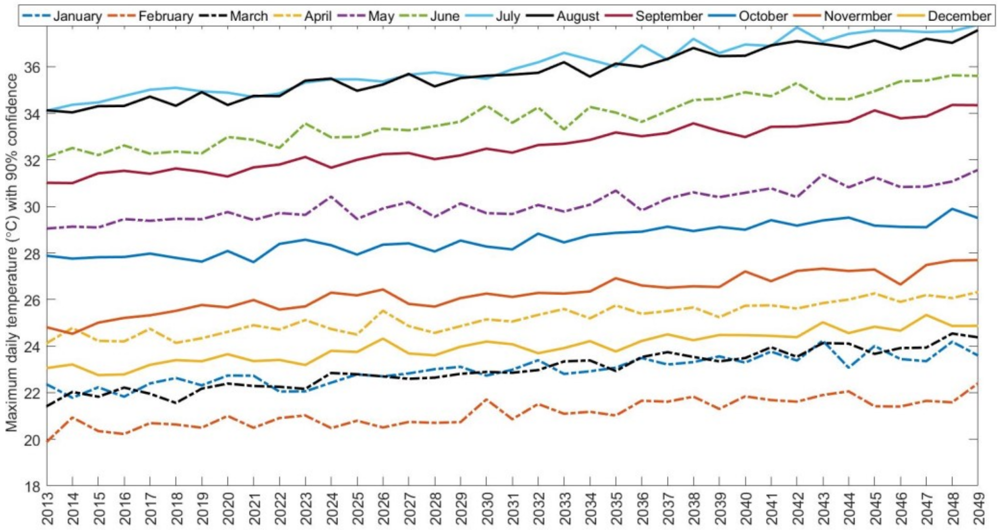

Figure 10-5 Monthly maximum daily temperature for South West England

11. APPENDIX B

11.1 Future Monthly Average Precipitation

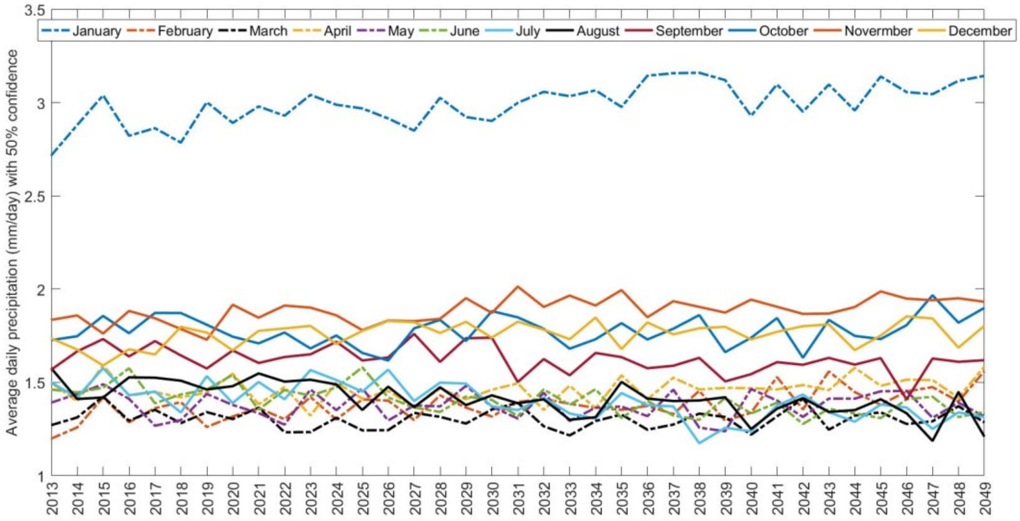

Figure 11-1 Monthly average daily precipitation rate for East of England

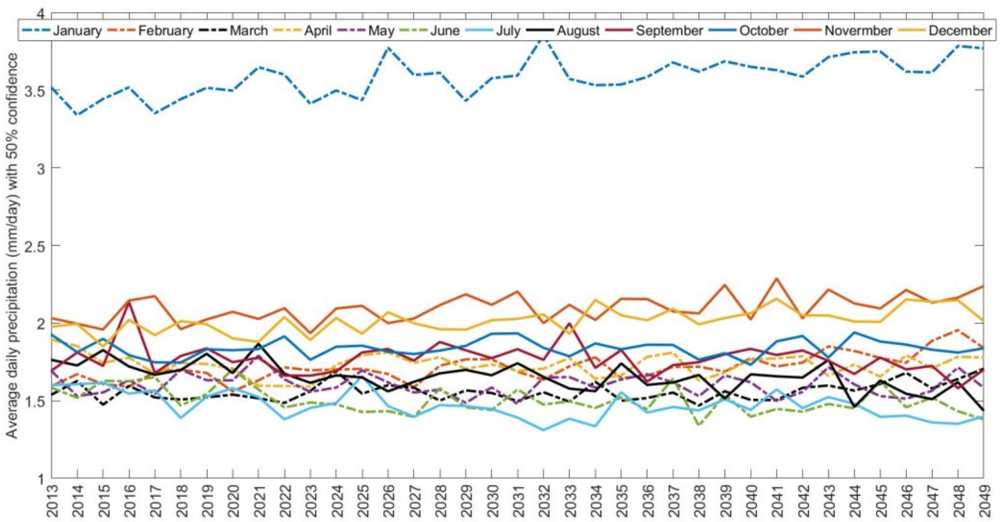

Figure 11-2 Monthly average daily precipitation rate for East Midlands

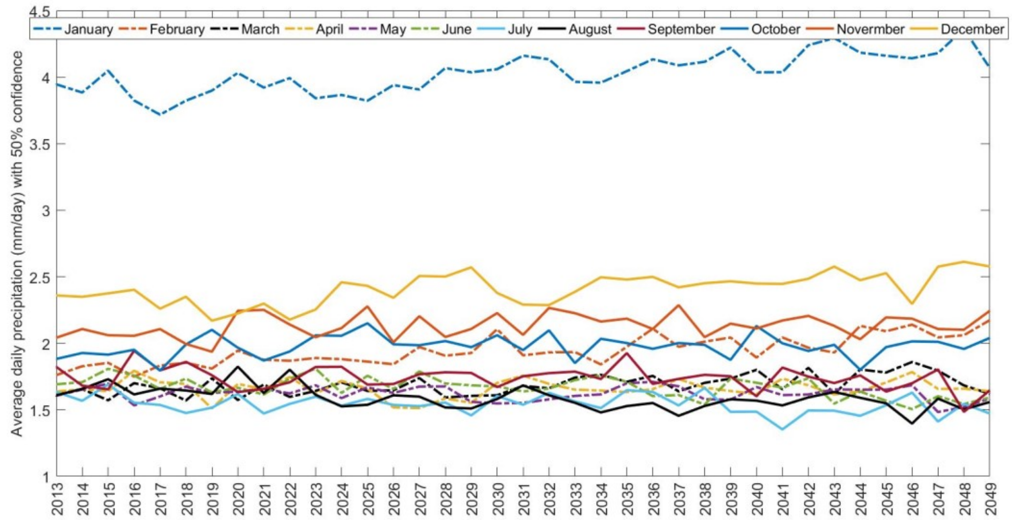

Figure 11-3 Monthly average daily precipitation rate for London

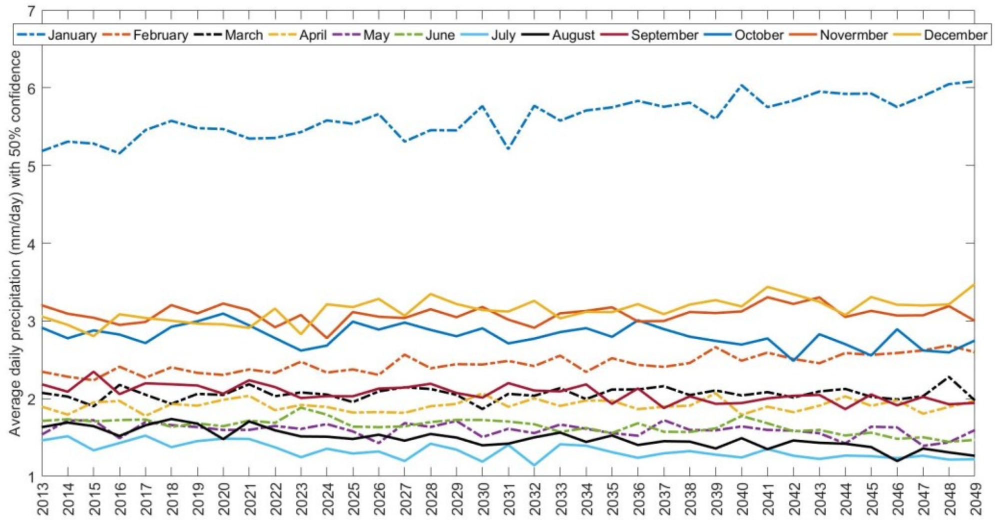

Figure 11-4 Monthly average daily precipitation rate for South East of England

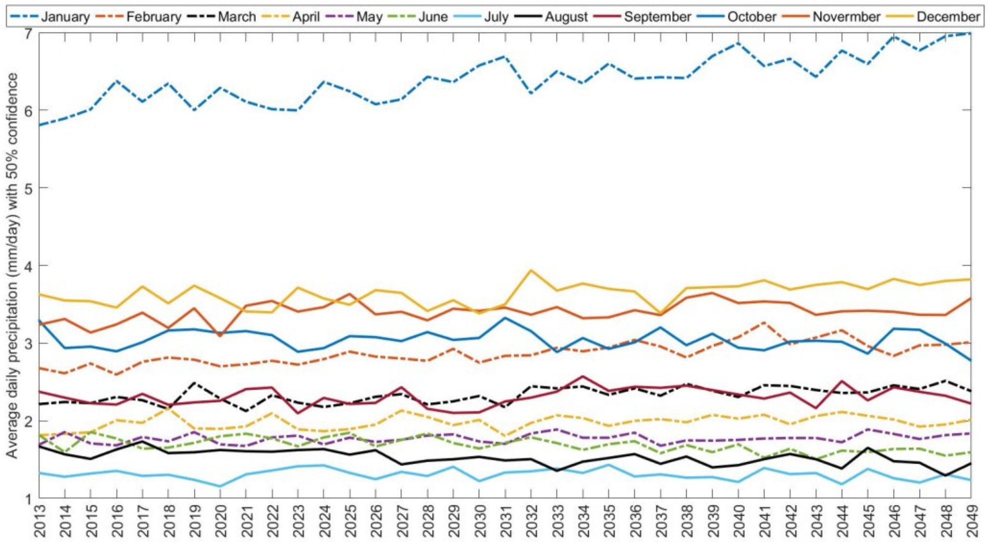

Figure 11-5 Monthly average daily precipitation rate for South West of England

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