QUANTIFYING THE EFFECTS OF AN INCREASINGLY WARMER CLIMATE WITH A VIEW TO IMPROVING THE RESILIENCE OF THE GB RAILWAY NETWORK: IS A NEW STRESSING REGIME THE ANSWER?

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ABSTRACT

This thesis is a study on how climate change is projected to affect future temperature profiles and what impacts these changes could have on GB railway network track and operations. The existing temperature profile in GB determines the stress free temperature of continuous welded rail which ensures that cold-related tension cracks and heat-related rail buckles are kept at an appropriate level. It is predicted that winters will become warmer and summers hotter than the baseline climate. The aim of this thesis is to determine if a new stressing regime for continuous welded rail would be an appropriate adaptive response to predicted future temperature profiles in GB. This will be achieved by assessing the impacts of climate change relating to damage and delays caused by hot and cold weather, quantifying the change in delays and making recommendations to alleviate the adverse impacts of climate change.

It is believed that GB can continue to operate with a stress free (rail) temperature of 27°C under future climate scenarios, provided the tolerable range is narrowed upwards towards 27°C and that the quality of track, track-bed and subgrade are improved. These actions should limit the potential damage caused by more challenging temperature extremes. If changes are not made to make the track more resilient to hotter summers the cost of buckles and heat related delays are projected to increase from £3.3m under baseline climate conditions to £24.7m in the 2080s under the high emissions scenario. In winter the temperature range that causes the majority and most severe ice and snow delays is not expected to undergo much change for most of GB until the 2080's under the high emissions scenario, when there will be nominal reductions, mostly in the south region.

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NOTATION

% → percentage

£ or GBP → Pounds Sterling or Great British Pounds

°C → Degrees Centigrade

2020s → time series ranging from the year 2011 to 2040

2050s → time series ranging from the year 2041 to 2070

2080s → time series ranging from the year 2071 to 2100

ADB → Network Rail's alterations database

cm → centimetres

CRT → critical rail temperature

CWR → continuous welded rail

DfT → Department for Transport

EARWIG → Environment Agency Rainfall and Weather Impacts Generator

ESR → emergency speed restriction

FOC → freight operating company

GB → Great Britain

GCM → global climate models

GIS → geographical information system

H → high emissions scenario

HS1 and HS2 → high speed 1 and 2

IPCC → Intergovernmental Panel on Climate Change

km^2 → kilometres squared

kph → kilometres *per* hour

L → low emissions scenario

M → midlands region

m → million

MH → medium high emissions scenario

ML → medium low emissions scenario

mm / yr → millimetres *per* year

mph → miles *per* hour

N → north region

OLE → overhead equipment

ORR → Office of Rail Regulation

RAIB → Rail Accident Investigation Branch

RSSB → Rail Safety and Standards Board

S → south region

SD → standard deviation

SFT →stress free temperature

Tair → air temperature

TOC → train operating company

Trail → rail temperature

UKCIP02 → UK Climate Impacts Programme 02

UKCP → UK Climate Projections 09

USA → United States of America

VERSE → Equipment for non-destructive measurement of SFT

W → west region

WG[1/2/3] → Working Group [1/2/3] (IPCC)

CONTENTS

CHAPTER 1

INTRODUCTION AND BACKGROUND

1.1 Weather and the Railway Network

Railways are a robust mode of transport (Eddowes *et al.,* 2003). Weather in GB is rarely as extreme as in other countries (Chapman *et al.,* 2008), however, damage and delays can be caused by even minor weather events. Network Rail owns and operates GB rail infrastructure which is comprised of 10,000 route kilometres of infrastructure, 40% of which is electrified (DfT, 2007b). 43,348 million passenger kilometres and 20,933 million tonne kilometres were travelled in 2004 (Noreland, 2008). The capacity for the expansion of services and passenger numbers is reaching critical levels in some areas and in these areas many commuters and business travellers rely on a consistent and trustworthy service. Weather-related delays can cause significant disruption on these lines, where there is little flexibility to adjust to unplanned delays. At no time has the need for slick functionality been more critical than on the present (Figure 1.1) and future railway network.

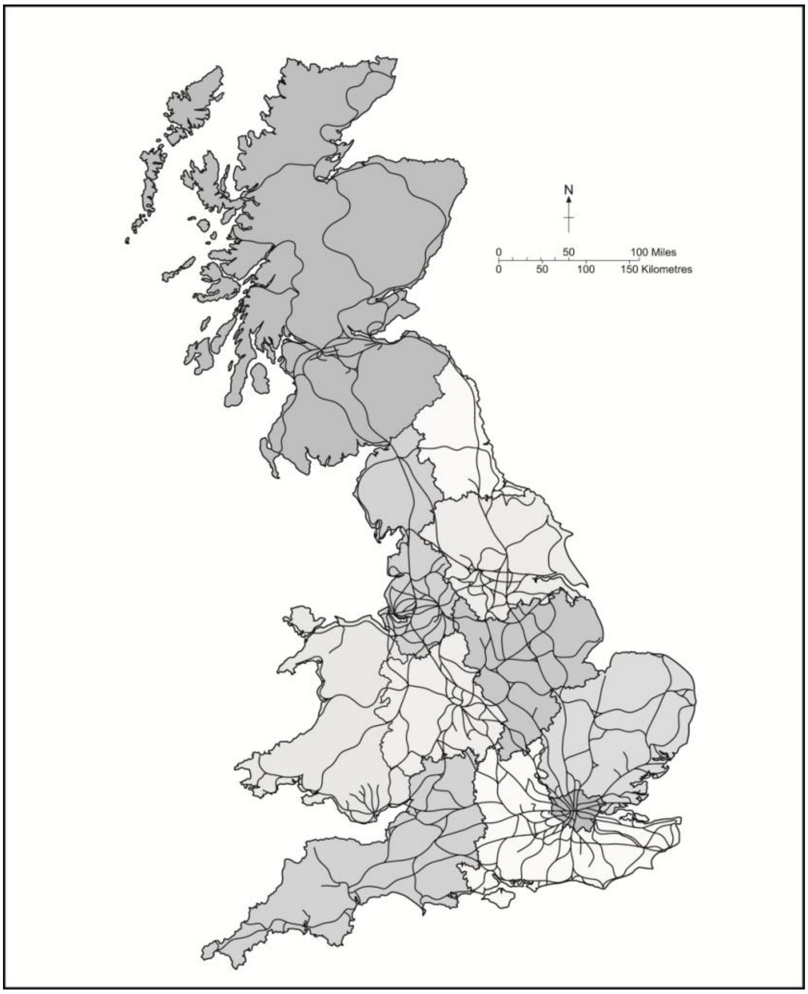

Figure 1.1: Map of GB railway network (and EU regions)

The Intergovernmental Panel on Climate Change (IPCC) are 90% certain that anthropogenic activity is causing atmospheric changes that are triggering fundamental global cycles to alter (IPCC, 2007). These global cycles influence the features of global climate and weather that govern many aspects of the human and natural world. GB needs to adapt to the future climate predictions made for our global region. Forecasting the potential impacts of climate change on the railway network could prove vital for successful adaptation to future climatic conditions. This will allow for the future network to continue offering a robust, competitive and environmentally sensitive service.

1.2 Climate Change – Overview and Background

Environmental awareness has progressed significantly in the last 60 years. In the 1950s and 1960s the impact of localised pollution was the focus of government legislation following the smog of 1952 in London. Other socio-environmental issues came to the forefront of people's awareness through literature such as Carson's "Silent Spring" (Carson, 1962) and the high-profile nuclear debate. A series of legislative changes have produced dramatic results in the improvement of city air quality, localised particulate contamination and levels of river pollution. In the last two decades a global approach has been adopted to improve environmental well-being. Sustainable development has been at the core of this, with the aim of improving environmental, social and economic well-being without hindering the success of future generations. Sustainable development is being driven by the need to alleviate climate change through reducing greenhouse gas emissions and reducing the use of non-renewable energy sources to improve energy security. Changing to renewable energy resources, reducing and reusing materials and products, and changing to "greener" modes of transport will reduce the quantities of carbon dioxide and other greenhouse gases believed to be responsible for climate change.

The predictions for future global climates are made using global climate models (GCM) which make use of fundamental equations that describe coupled oceanographic and atmospheric dynamics as well as sea-ice and land surface component influences. Large-scale computer models make global climate predictions based on these fundamental equations, to which future greenhouse gas emissions scenarios are applied. The climatic models produced are validated against the changes in global climate that have already been experienced in recent decades. The trends are extrapolated relative to the influence of future emission scenarios to produce future climate predictions, like those created as part of GB Climate Impacts Programme (UKCIP) 2002 (UKCIP02). UKCIP02 predictions cover four emissions scenarios: Low (L); Medium Low (ML); Medium High (MH) and High (H).For the range of predicted climatic variables, predictions are made across three time series called the 2020s (2011 – 2040); 2050s (2041 – 2070) and 2080s (2071 – 2100). Some of the predictions made in UKCIP02 can be broadly summarised as follows:

- Warmer, wetter winters
    - Precipitation may increase in winter by up to 30%, under the high emissions scenario in the 2080s, precipitation can, under the right conditions, become snow or other frozen forms of precipitation, therefore, winter snowfall has the potential to increase in future winters, based on current projections.
    - A rise of around 1.5°C in average winter temperatures

- Hotter, drier summers
    - The annual average temperature may rise by between 2°C and 3.5°C
    - The extremely hot summer of 1995 may become a one-in-five-year summer by 2050 and a three-in-five year summer by 2080 according to the high emissions scenario

- Summer precipitation may reduce by up to 50%, under the high emissions scenario in the 2080s

- Sea-level rise
    - A range of 9cm to 69cm rise from baseline sea levels by 2080 across all the emissions scenarios

- More extreme storms
    - Under the medium high emissions scenario a one-in-fifty-year storm is predicted to become a one-in-ten-year storm for the low emissions scenario by the 2080s and a more than annual event for the high emissions scenario for the 2080s

The South East of GB is predicted to experience the most extreme changes in climate, whereas the North West is expected to experience the least changes. Predictions of future temperatures have the highest levels of certainty assigned; whereas, wind and rain predictions show significant variability across adjacent regions. In addition, wind has the lowest reliability assigned to UKCIP02 predictions and therefore should be applied with caution.

Uncertainty in climate projections come from three main sources:

1. Natural climate variability
2. Uncertainty from the process of modelling climatic cycles and understanding the Earth's system processes
3. Uncertainty in future emissions scenarios

The recommendations made in Jenkins and Lowe (2003) for handling uncertainty when using UKCIP02 projections are: the need to consider more than one UKCIP02 scenario for most studies and include consideration of predictions from other climate models. HadCM3 is the model used to produce UKCIP02 projections, comparing HadCM3 with other global climate models (GCM) simulating future temperature trends, the magnitude of HadCM3 falls roughly in the middle. HadCM3 also performed very well when compared with current climate, an exercise performed to establish how well the modelled projections represent existing climate cycles. UKCIP02 is also internally consistent, meaning that direct comparisons across time series and emissions scenarios can be justifiably performed. Considering that other GCM produce temperature projections that are roughly evenly higher and lower than HadCM3, considering other GCM would produce a ± variability around the results produced from HadCM3, a ± variability will be included through considering trend variability from weather related railway delay data. Significantly, " While there is uncertainty about climate change, RSSB considers that the United Kingdom Climate Impacts Programme (UKCIP) provides an acceptable set of assumptions for present purposes" (Eddowes et al., 2003, p1).

Using a climate change model that produces results in the mid-ground compared with other climatic models is advantageous in this study because ± variability will be included in the analysis of trends. Furthermore, the scale of variability from trend analysis and the scale of the geographical regions is likely to outweigh subtle differences between the range of GCM available.

UK Climate Projections (UKCP09, formerly UKCP08) is the 5th generation of predictions. One of the main differences, from a user's perspective, between UKCIP02 and UKCP09 is that the three sources of uncertainty have been quantified to produce probabilistic projections. Decadal steps in the new time series were used to give a more detailed idea of how climate change is projected to develop over time, rather than the end to end time series in UKCIP02. The advice from UKCP09 literature is to use GBCP09 datasets over UKCIP02 in new projects, however, these sets of data were not published until June 2009, which was considered too late to be used in this project, which began in October 2006. By June 2009 the majority of analysis had been performed, some of it published and the methods established and based on the information available from UKCIP02.

1.3 Railways - Part of a Sustainable Future?

1.3.1 Greenhouse Gas Emissions from Transport

According to EDGAR (2008) 14% of global emissions are directly caused by transport. Emissions from power stations are also used for electrically-powered transportation, fuel production and fuel transportation. In 1990 transport contributed around 30% of greenhouse gas emissions in GB and the proportion of emissions caused by transport continues to rise. Any initiatives to reduce the impact of human activity on global climate change must target transport.

A large proportion of passenger and freight transport in GB is carried by road. In 2004 5.4% of passenger kilometres and 10.5% of freight tonne kilometres were travelled by rail (EDGAR, 2008), which contributed 2% of UK transport emissions in 2007, compared with 92% from all types of road transport (including, cars, vans, lorries and buses) (CFIT 2007). Over the past four decades energy consumed by rail transport has remained comparatively constant, however, road and air travel have increased dramatically, essentially doubling from 1970 to 2001. The growth trend is continuing; there has been an 8% mean increase in the number of passenger kilometres travelled between 2000 and 2006 across all modes. The majority of these, around 65%, are travelled by road (DfT, 2007a). The evidence suggests that a modal shift to travelling by railway would indeed lower transport-related greenhouse gas emissions that contribute to global climate change. For this to be feasible the railway network has to be considered a viable alternative transport option, both now and in the future.

The railway network is considered to offer a more environmentally-friendly future for transport, providing a reduction in greenhouse gases and thus being part of the solution to climate change. However, the reality of "environmentally-friendly levels" of greenhouse gas emissions is more complex:

> "*To be comprehensive, carbon accounting must include not just the emissions during operation, but also the emissions associated with the energy use in construction of the plant and the materials used in its construction. Full life-cycle energy analysis of this sort is becoming*

increasingly important for all products and systems as part of their environmental assessment." (Elliot, 1997, p.63).

For the sustainable future potential of the railway network this raises a number of issues:

- How the full life-cycle emissions caused by rail compare with other modes of transport
- The extent of electrification and the sources of energy that produce the electricity used, and the pollution associated with non electrified operations
- How the existing network could cope with an increase in traffic, and whether this represents a modal shift or an overall increase in transport use
- Finally, high speed lines offer an alternative to highly polluting short-haul air travel, but where the energy consumption is (broadly) proportional to the square of the velocity

1.3.2 Future Growth and Capacity Issues

One aspect of operations key to future growth is the capacity potential of the railway. At present, GB's road network carries some 170,000 million tonne km of freight and 730,000 million passenger km of passenger transport; compared with 20,000 million tonne km and 43,000 million passenger km for rail (respectively). For a significant modal shift to occur, the service provided by the railway network will have to increase significantly, which raises the issue of capacity. At present an increase in traffic of this magnitude is not possible. Key lines and routes such as intercity routes and commuter lines that feed London and other major cities are close to capacity at the present levels of operation (Cox *et al*., 2006). The

Department for Transport (DfT) outlines an aim to double freight and passenger movements on GB's railway (DfT. 2007a). However, the report does not address the capacity issues in any way, other than a passing mention of the potential problems. There is no quantitative analysis of future network growth and capacity for the time scales considered in future climate analysis. The predictions for the cost of future delays documented in this thesis are based on the existing network; the documentation that exists on future operations is not quantifiable at this stage.

1.3.3 Electrification

Around 40% of GB's rail network is electrified (DfT, 2007b). The rolling stock on non-electrified network relies on diesel-powered locomotives, which produce greenhouse gases and localised particulate pollution. The future of the railway network as a "green" mode of transport is reliant on the extent to which the network is electrified and the proportion of low-carbon energy sources contributing to the national electricity supply.

In the DfT's White Paper (DfT 2007a), GB Government made no commitment to further electrification of the network and "self-powered" trains seemed to be the preferred option. Alternative power supplies for self-propelled locomotives, such as hydrogen fuel cells may be a low carbon option in the future. However, hydrogen has to be actively extracted from stable molecules, this requires energy that is most likely sourced from non-renewable energy. Hydrogen is also commonly extracted from natural gas and other hydrocarbons in an energy intensive process, which is far from carbon neutral. More recently the environmental and other merits of electrification seem to be persuading the government towards a less anti-electrification stance.

GB Government recently announced a £1.1 billion plan to electrify the Great Western route from London to Swansea – one of the last major lines using diesel-powered trains – over the next 8 years, also a second line between Liverpool and Manchester over a four-year scheme (DfT, 2009). The railway network has a long "memory" for decisions on the type of infrastructure and rolling stock. Vehicles last around 30 years so changing rolling stock groups is a long-term infrastructure investment. The long-term future of fuel security and availability is uncertain. Current trends would suggest that the cost of fuel is likely to increase due to reduced availability, security, global market influences and national taxes. Emissions legislation is most likely to tighten, which will also influence taxation - a key, cross-sector incentive to reduce emissions-heavy activities. Such a combination of factors is likely to make a move towards "self-powered" diesel-reliant vehicles a naïve decision when considering future power supply reliability. In addition, the same factors would encourage a modal shift from road travel to rail travel for commuter lines and from short-haul flights to high-speed train travel.

1.3.4 High Speed Rail

High speed rail currently links London (St. Pancras) with Europe and is known as High Speed 1 (HS1). There are plans afoot to link HS1 with Heathrow, the Midlands and Scotland. Trains that travel at speeds greater than 200kph require significantly more power to overcome the drag coefficient, which broadly increases the energy consumption proportionally to the square of the train speed. This also equates to an equivalent increase in greenhouse gas emissions associated with the increased energy consumption. An increase in train speed from 200kph to 300kph, results in an increase in energy use by a factor of 2.25. Despite the energy requirements for high speed it is considered that train travel taking between 3 to 4 hours is a viable alternative for domestic and short-haul flights of the same journey. Another significant benefit is that having a dedicated line for high speed intercity travel would alleviate some of the traffic on existing lines. In addition this would create a more uniform operating speed on both types of line, leading to improved efficiency.

HS2 is the company set up by GB government to analyse options for a new high speed rail service in GB. Although HS2 are yet to publish their report on the optimal route plans and the related business cases, Network Rail have published a report in which the options for the new high speed routes are outlined. The optimal destinations of a new high speed route, according to Network Rail are shown in Figure 1.2. The proposed route will travel to Edinburgh or Glasgow from Central London, with spurs off to Preston, Liverpool, Warrington, Manchester and Birmingham. It was also proposed that a line from London to Manchester with a diverging line to Birmingham would be advantageous. However, the business case for this option proved that it did not capture enough market share and that extending the route further north and having more spurs to financial centres would ultimately have an estimated return of 1.8 times the investment over 60 years. The investment for the initial construction and operational costs, including maintenance and rolling stock over the 60-year period was calculated to be £41.3bn, £34.012bn of which is initial construction. There is also the question of how to connect to

Heathrow airport, the study concluded that having a spur connecting to Heathrow independently of the London connection would not waste the time (an extra 15 minutes) of customers not travelling to Heathrow and would not cause significant delay for those wishing to travel into London. Further recommendations include considering the business case for connecting to Leeds and financial centres in the East Midlands and North East of GB. HS2 and Network Rail are aiming to finalise a business case for more high speed rail travel in GB in 2010.

Figure 1.2: Route proposed by New Lines Study (Network Rail, 2009)

If GB railway network is able to adapt to future demands on capacity and the possible impacts of future climate then it can offer a practical and low carbon mode of transport to help alleviate climate change in the future.

1.4 Changing Climate: New Challenges

1.4.1 Hot, Dry Summers

Under future climate change hotter, drier summers can be expected to have the following impacts on future railway operations:

- Increased incidence and severity of track buckles
- Desiccation of earthworks
- Need for more air conditioning
- More vegetation due to longer growing season (subsidiary implications for autumn leaf fall contamination)
- Thermal comfort issues on trains and in underground networks (Eddowes *et al.,*2003)

In general, the issues caused by hot, dry weather are well understood. Speed restrictions are enforced when temperatures are high and rails are at risk of buckling (see Table 2.1). The influences of temperature on network operations will be discussed in more detail in Chapter 2 of this thesis, including discussion of the stress free temperature of continuous welded rail. The stability of embankments, earthworks and slopes is reliant on the presence of water and the evaporation of water. According to Rouainia *et al*., (2009), precipitation may be of higher intensity but less persistent and average temperatures are predicted to be higher, resulting in negative pore water pressures continuing through winter and thus improving stability. Unexpected earthworks failure can be very damaging to infrastructure and costly in delays and repairs. Effective medium-term warning methods are described by Sakai (2008) in the visual identification of cracks and also in the quality of water seepage from monitoring the site. Controlled use of plants on earthworks greatly improves slope stability, while controlling plants through pruning will also reduce the foliage that can cause lowered rail head adhesion in autumn. However, a combination of climate change and new engineering practices like compacting earthworks is likely to have an effect on vegetation and therefore slope stability (Glendinning *et al.*, 2009). Hot days will require the implementation of more air-conditioned rolling stock or the introduction of passive cooling techniques. On many of the underground routes air-conditioning is not possible, the depth of the tunnels means that the heat discharge from air-conditioning units cannot be moved away from the tunnels, resulting in no overall cooling effect. More innovative methods of cooling the environment must be found. This problem is already becoming critical on the London Underground. Passive cooling techniques are being explored, for example, methods of dissipating heat energy into the ground water and moving it away from the underground network.

1.4.2 Warmer, Wetter Winters

In GB winters are rarely as extremely cold as in other European countries, which can infamously lead to poor preparedness when snow falls and ice forms on infrastructure. The prediction of warmer winters promises a reduction in cold-related delays, which include cold-related tension cracks. However the predictions also suggest an increase in winter rain and the excess water could lead to the following problems on the network:

- Increased flooding due to inadequate drainage
- Damage to earthworks saturated by water or washed away by flash floods
- Track circuit problems
- Scour at the base of bridges

Warmer winter temperatures are likely to have a positive effect on the instances of delays caused by extremely cold weather, ice and snow. Temperature, ice and snow will be discussed in more detail in Chapter 2. River flood risk and severity is well documented through extensive studies and is available as a routine design tool (IOH, 1999). There are also widely used methods for assessing the capacity of drainage systems. However, upgrading drainage systems can be very costly, particularly for railways where a great deal of complex infrastructure can cover much of the network land. Having to shut down major lines for such invasive upgrades can be very costly in delays as well as time, man-power and equipment required for extensive and complex procedures. It may be that the cost-benefit ratio does not support pre-emptive route flood improvement work over the delay incurred by allowing a flooding event to occur. Nevertheless, the time frame for climate change is still long, even compared with the life of most aspects of infrastructure; therefore it may be that drainage equipment is upgraded in due course.

1.4.3 More Extreme Storms

According to UKCIP02 the incidence of extreme storms are likely to increase along with the associated heavy downpours and high winds. The effects of heavy rain are documented in section 1.4.2. This section will focus on the effects of high winds on railway operations and infrastructure. With an increase in storms the associated high winds are predicted to cause the following damage:

- Greater likelihood of de-wiring (the pantograph losing contact with the overhead line equipment (OLE))
- Increased possibility of train derailment
- Debris from trees and buildings being deposited on the track, which can cause disruption and accidents

Existing work in these areas is based on developing industry standards in order to ensure equipment operates safely in extreme conditions. Work has been conducted in order to understand and minimise the risks posed by wind on infrastructure and vehicles (Baker 2007, Baker *et al.,* 2004, Bouferrouk *et al.,* 2008). At present, making predictions specifically for future wind scenarios is difficult as the UKCIP02 predictions have a very low confidence level assigned (<10%, where: virtually certain > 99% probability of occurrence; extremely likely >95%, very likely > 90%; likely > 66%; more likely than not > 50%; unlikely < 33%; very unlikely < 10%; extremely unlikely < 5%). However, high, gusty winds associated with storms are certainly a possible threat in the future. Depending on the time of year that storms are likely to occur, an additional impact that is likely to worsen is an increase in damage and delay caused by autumn leaf fall contamination. If high winds and damp conditions occur at the right time, many of the autumn leaves can fall within a few days or even hours, which can cause wrong side track circuit failures as well as problems associated with adhesion, such as station over-runs and signals passed at danger (SPAD).

Network Rail has developed an online geographical information system (GIS) based weather warning tool. It uses Meteogroup weather forecasts to predict the areas of the network that may be exposed to high winds and heavy rain. A colour coded warning system is provided, which is based on the forecast weather and the capacity of the affected network to cope with potential delays. Both short and long-term forecasts are available and the information is archived in order to assess the success of action taken based on the information provided. The system is being developed to provide similar warnings for other damaging weather extremes such as extreme heat. A map of the density and species of leaf cover is also being compiled and it is hoped that this will serve to predict autumn leaf contamination hotspots, in conjunction with typical weather triggers, such as high winds.

1.4.4 Sea Level Rise

According to UKCIP02 predictions the sea level may rise by up to 36cm by the 2050s and up to 69cm by the 2080s. A sea level rise equal to the worst case scenario in the 2050s would have significant consequences for coastal, low land and estuarial railway lines. Arkell and Darch (2006) discuss the impact of future scenarios and tidal flows in the River Thames on the London Underground. The same mechanisms would also affect some overland lines in London. In addition, the protection offered by the Thames Barrier is already considered to reduce over the next few decades. The need to ensure an adequate protection strategy for London is very apparent.

A stretch of coastline considered to be at great risk is the Great Western Mainline between Dawlish and Teignmouth on the south Devon coast (Figure 1.3). Here the line runs parallel to the coast right along the shoreline. When the tide is high and/or there are storms causing high waves the sea defences can be topped preventing normal network operations (Figure 1.3). In addition the salt water damages the infrastructure and trains. The Rail Safety and Standards Board (RSSB) used a range of UKCIP02 predictions to calculate future instances of the sea wall being topped. The results suggest that such disruptions will increase by 50% in 2020, 100% in 2050 and 200% in 2080. The increase in track closure caused by dangerous sea levels is even more extreme; 100% in the 2020s, 200% in the 2050s and 550% in the 2080s. The effect of rising sea level was more significant than increased wave heights (RSSB, 2008).

Coastal (isostatic) subsidence is also a major contributing factor to local sea levels in the South West of GB. A project is currently underway to improve the accuracy of the existing knowledge of coastal wear, based on newly-collated historical trends and future climate predictions (Dawson, 2007). According to Dawson (2007), the figure used in UKCIP02 predictions of a subsidence rate of 1mm/yr, is based on insufficient and low quality data. Dawson (2007) aims to improve the accuracy of this figure and include a variability range, which will be based on higher quality sea-index points enabling a relative sea-level history to be constructed for the past 4,000 years. The impacts predicted at Dawlish are likely to be repeated along many lines and routes on GB network; sections along the east coast are at risk of the same storm surges that threaten London. However, a key issue is how financially sustainable fortifying and maintaining defences may be. Relocating routes further inland may be a more cost effective solution overall.

Figure 1.3: Effects of stormy seas along the coastal line between Dawlish and Teignmouth (Photo: David Dawson, 2007)

1.5 The Context of this PhD Project

A reliable and safe railway is a necessity for GB and research into identifying and improving weather-related adversities has increased in accordance recently. Since the mid 1980s research on weather effects on the railways has increased; much of this research has been compiled and updated in Thornes and Davis (2002). The key turning point for applying future climate change scenarios to the railway network was a report produced for the RSSB (Eddowes *et al.,* 2003). It focuses on subjective safety implications of existing weather and climate and the possible future climate impacts according to climate change predictions. The RSSB make recommendations based on the information presented. Significantly: "*It is considered that the most valuable way forward is to begin quantifying the changes to safety risk and traffic delay that are likely to result from extreme weather events*" (Eddowes *et al*., 2003, p. 3). In particular, the report highlighted high air temperature as an area requiring quantification. Summers are predicted to be hotter and drier so it would follow that heat-related incidents would increase. Conversely, winters are predicted to become warmer and wetter, meaning the incidence of icing and snowfall-related delays would be expected to decrease. However, from the subjective analyses in reports like Eddowes *et al.,* (2003) the extent to which this may happen is uncertain. Therefore, it is also important to quantify potentially "positive" future effects in order to make cost effective decisions about future mitigation and maintenance strategies.

To alleviate some of the possible effects of future temperature profiles, recommendations for changes to maintenance regimes will be made. This will also include considering changes to the stress free temperature (SFT) of continuous welded rail (CWR) adopted in GB in order to redress the balance between the risk of cracked and broken rails at low temperatures and buckled rails at high temperatures.

In addition to this is the need to increase awareness of the dangers of complacency. The nature of the railway network's reputation is such that the public expect a good service all year round, regardless of weather conditions and particularly when other transport modes are incapacitated by extreme weather. Ice and snow-related delays could reduce in frequency and severity but having the means to cope when they do occur will be vital to the success of the future network.

1.6 Aims and Objectives

The overall aim of this thesis is to determine if a new stressing regime for continuous welded rail would be an appropriate adaptive response to predicted future temperature profiles in GB. This aim will be realised by the following objectives:

1. Quantifying the effects of hot weather on infrastructure and operations on GB railway network
2. Quantifying the effects of cold weather, ice and snow contamination on infrastructure and operations
3. Fiscally quantify the impacts that future summer and winter temperature profiles may have on infrastructure and operations
4. Make recommendations for changes in future network infrastructure and operations in a warmer climate based on evidence from spatial analogies and quantified changes in temperature related delays.

This thesis will first present a thorough review of the literature, which follows the development of the area of study by exploring and critiquing the literature available on temperature, climate change and UK railway network operations. Secondly, a methodology detailing the data available and approach adopted to analyse the preliminary study on the south east region of GB and then both hot and cold temperature-related delays across the whole of GB. This is followed by results and discussion for UK-wide future heat and cold-related delays. Finally, conclusions and recommendations will be made from the results.

1.7 Conference Papers, Journal Papers and Articles

- Baker, C.J., Chapman, L. Quinn, A.D. & Dobney, K. (In Press) Climate change and the rail industry. *Journal of Mechanical Engineering Science*
- Chapman, L. and Dobney, K. *"Railways, weather, climate and climate change"* Railway Strategies, Infrastructure, October – November (2009)
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- Dobney, K., Baker, C.J., Quinn, A.D. & Chapman, L**.** (2009) Quantifying the Effects of increased summer temperatures due to climate change on buckling and rail related delays in south-east UK. *Meteorological Applications* 16:245-251
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CHAPTER 2

LITERATURE REVIEW

2.1 The Railway Network in GB

GB railway network is operated through collaboration between two industry groups; Network Rail and Train/Freight operating companies (TOC/FOC). TOCs and FOCs are franchises that operate the rolling stock on specific lines and routes across GB. They pay for the use of the infrastructure, which is owned, run and maintained by Network Rail, including overhead line equipment (OLE), track, signals, switches and some stations. Established in 2002 following the collapse of Railtrack, Network Rail is a private sector company without shareholders or dividends; this role is fulfilled by its members who have no equity interest (Network Rail 2010).

Organisations that ensure the successful collaboration of Network Rail and T/FOCs are the Department for Transport (DfT), RSSB and the Office of Rail Regulation (ORR). The ORR is an independent body that ensures that the rail industry and all the component companies are aligned in order for a safe, efficient and cost effective service. The ORR works in collaboration with both the RSSB and the DfT, and they also collaborate with other safety organisations such as the Health and Safety Executive and other government-based transport organisations. The RSSB manage the Railway Group Standards and researches safety-related concerns in order to develop strategies for improvement and regulation. The DfT oversees GB's transport industry, ensuring thorough regulation and collaboration within industries and across modes of transport.

An important aspect of the cooperation between Network Rail and the T/FOCs is if smooth operations are compromised by any infrastructure or rolling stock operator compensation is paid by the party responsible which is owed to the organisation affected by the delay. Consequently there are delay compensations that relate to TOC on TOC, FOC on FOC, TOC on FOC and vice versa and Network Rail to TOC or FOC. The type of delays analysed in this thesis are those caused by the lattermost of these, meaning that the delays relate only to delay minutes caused by infrastructure failures. The cost of compensation is based on the number of delay minutes attributable to an incident causing delay, when and where it happened and whether it was a schedule 4 (planned line closure) or schedule 8 (unplanned delay). For the purpose of this thesis delay minutes are defined as the length of delays suffered by passenger and freight services that are attributed to Network Rail, which are measured for each passenger or freight train against its timetabled journey time between two points (Burr, 2008). An estimated 3 million delay minutes *per* annum are directly caused by weather (Network Rail, 2008), a further 2 million are believed to be caused by indirect damage caused by weather (Thornes and Davis, 2002). Planned mitigation and maintenance for weather-related damage will also cause delays and cost. The estimated number of delay minutes caused by weather are high rounded numbers, suggesting that firstly, it is difficult to know exactly how many delays are caused (directly or indirectly) by weather and secondly that the number of weather related delay minutes can vary greatly year on year. Thus highlighting the importance of establishing trends in real recorded delay data in order to better understand the "reality" of weather related influence on infrastructure and operations.

2.2 Global and UK Climate Change Predictions

Climate change became part of the formal international agenda in 1988 when the World Meteorological Organisation (WMO) established the Intergovernmental Panel on Climate Change, with support from the United Nations Environmental Programme (IPCC, 2004). The first IPCC assessment report was published in 1990 with areas of work covered by three working groups (WG):

- WG1 considered the broad cause and effect of human activity, which identified some rudimentary future scenarios based on "business as usual" (Houton *et al.,* 1990)
- WG2 established possible effects of climate change on global cycles, such as agriculture, ocean and tidal flows, human settlements, hydrology, snow cover, ice and permafrost (Tegart *et al.,* 1990)
- WG3 was based on adaptation and mitigation and combined the work of sub-groups who considered how climate could affect key ecological cycles that in turn influence human activity, such as agriculture, industry and coastal zone management (IPCC, 1990)

The IPCC has produced three more assessment reports, the latest published in 2007, there are still 3 working groups that explore the same themes. The development of the work from the IPCC has shaped global understanding of climate change and allowed individual countries to develop their own climate prediction models and adaptation and mitigation strategies.

UKCIP provide future climate scenarios for GB. Accompanying the scenarios is advice for end users on the best ways of applying the information. A full description of UKCIP is provided in section 3.

Since the conception of the IPCC and the development of UKCIP, one of the primary objectives of the future projections has been to allow sectors of society, industry and the natural world to make predictions for future vulnerabilities (IPCC, 2004). The IPCC stated a 90% certainty that human activity is causing climatic changes (Solomon *et al.,* 2007). It is also believed that even if the production of greenhouse gasses were to stop tomorrow, the climate would continue to change; the climate is determined for the next 30-40 years (Hulme *et al.,* 2002). It is for this reason that identifying vulnerability and planning to adapt to future scenarios should be carried out.

The railway industry is robust (Eddowes *et al.,* 2003); however, by the definition of vulnerability given in Parry *et al.,* (2007, p. 720) - "*the propensity of human and ecological systems to suffer harm and their ability to respond to stresses imposed as a result of climate change*" the railway network can certainly be considered a vulnerable human system through its susceptibility to the effects of weather. In identifying vulnerabilities to a changing climate, adaptation to future climate is essential. Parry *et al*., (2007, p. 869) defines adaptation as "*adjustments in natural or human systems in response to actual or expected climatic stimuli or their effects which moderate harm or exploit beneficial opportunities*".

Adaptation literature from UKCIP02 predictions highlights sectors of businesses or services for which adaptation is likely to be important. The railway industry can certainly be considered a vulnerable business under several of the UKCIP02 vulnerability categories (as well as the definition from Parry *et al*., (2007)), including: businesses currently affected by weather and climate; businesses that make long-term decisions on land use, built assets and infrastructure that are sensitive to changes in climate. In summary, the railway network is exposed to the full range of UK weather and climate and there are aspects of infrastructure and operations that are likely to be further adversely affected by future predicted climate.

2.3 The Nature of Heat-Related Delays in GB

Heat-related delays in GB can be caused by a number of infrastructure failures. Diesel engines can overheat, as can line-side equipment like electrical controls for points and signals. Line-side fires can be a hazard during prolonged periods of drought and on extremely hot days the thermal comfort of passengers can be an issue. However, one of the most significant consequences of hot days is a buckled rail (known as a sun kink in parts of Europe and the USA). A rail buckle is defined in Ellis (2006, p. 50) for the Rail Accident Investigation Branch (RAIB) as "*a sudden, short and un-designed bend in the track caused by a lack of lateral resistance, poor track maintenance and (generally) high rail temperatures. They have the potential to derail a train*" (see Figure 2.1). A buckled rail will rarely happen spontaneously; an additional energy input is required, usually from a passing train. It is for this reason that emergency speed restrictions (ESR) are enforced on days where there is a risk of rails buckling, Table 2.1 shows the temperature thresholds at which ESR are enforced. These themselves cause delays, but this delay is considered to be more favourable than a buckled rail, certainly from a safety perspective.

Figure 2.1: Train derailed by a buckled rail in Sweden (Photo: Frida Hedberg, Aftonbladet Bild)

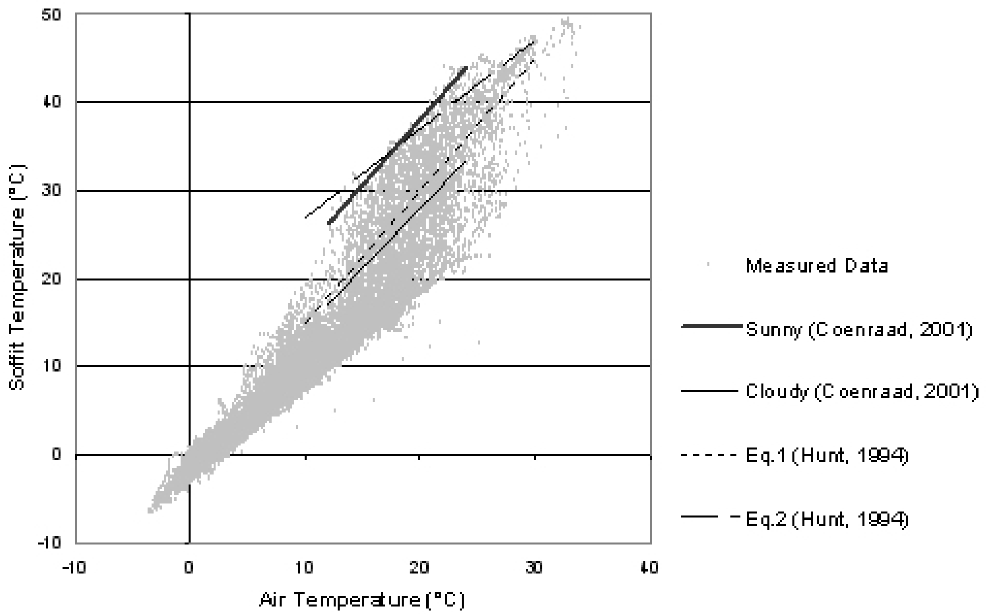
2.3.1 Extremely Hot Weather and Rail Buckles

Extremely hot temperatures cause the metal of the rail to expand resulting in a deformation of the track due to the high compressive forces. Without the expansion gaps in jointed track this new track structure can leave the long lengths of rail very prone to buckling. In order to allow for expansion on hot days, the track is pre-stressed to a *stress free* (rail) *temperature (SFT)* of 27˚C. Continuous welded rail was introduced in the early 1960s. The first SFT adopted was 21˚C, which was chosen based on experiments performed by British Rail Research. After a hot summer in the 1970s the SFT was raised to 27˚C, in addition to heavier sleepers, smaller sleeper spacing, increased depth of ballast and ballast shoulder was also introduced (Cope and Elis, 2001). Figure 2.2 shows four trend line equations used to convert air temperature to rail temperature and how these equations compare to real recorded air temperatures and the corresponding real recorded rail temperature at two sites – Winterbourne (Figure 2.2, graph a) and Leominster (Figure 2.2, graph b). There are many factors that determine the rail temperature at a site including, track orientation, exposure to wind and sun, precipitation, air moisture content and cloud cover. The trend lines from Elsved (2001) show how rail temperature trends vary for hot days with cloud cover and direct sunlight. Although rail buckles occur on hot days, the trend lines from Elsved (2001) are not representative of the majority of data points on the two graphs. More commonly used is an empirical approach for determining rail temperature from air temperature. Eq 1 (Hunt, 1994) in Figure 2.2 has more representative correlation for the range of data points in both graphs a and b in Figure 2.2. The trend line is relevant for converting air and rail temperatures in the mid-range and also, importantly continues to have representative correlation with data points in the higher temperature ranges, those temperatures more likely to cause dangerous rail buckles. Eq 1 (Hunt, 1994) from Figure 2.2 is shown in equation 2.1:

$$Trail \approx 3/2Tair \tag{2.1}$$

where: *Tair* is the air temperature and *Trail* is the rail temperature (both in °C).

a)



b)

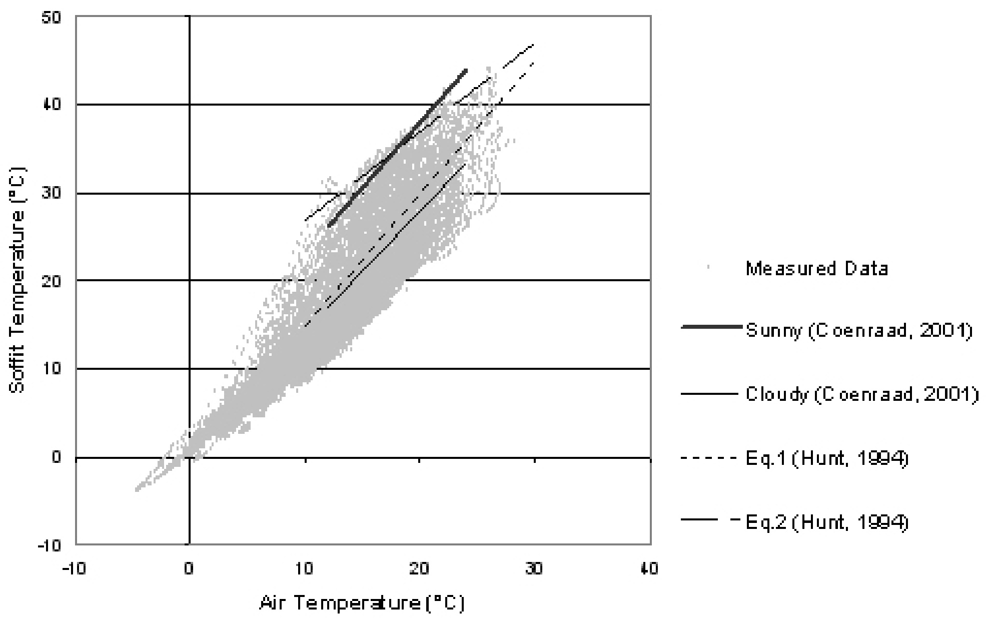


Figure 2.2: Air versus soffit temperature graphs for a) Winterbourne and b) Leominster test sites used in Chapman *et al.,* (2008, p.125)

The condition of the track and track bed influences the vulnerability of the track in high temperatures. If the track is well supported with stable ballast shoulder either side of the sleepers, in an adequate depth of ballast on stable substructure and correctly stressed, then there is not considered to be a danger of buckling or need for ESR until the rail temperature reaches 59˚C, equivalent to approximately 39˚C ambient air temperature based on equation (2.1)(see Table 2.1, based on a 2002 Railway Group Standard, RT/CE/S/011). From Table 2.1, the lowest temperature at which a rail is considered vulnerable to buckling and ESR are enforced is around 25˚C, ambient air temperature (converted from Table 2.1 using equation (2.1))). Understanding and predicting where buckles may occur is not an exact science, there are unknowns and site-specific issues like variable SFT and micrometeorological variability. Recently work has been conducted to map the variability of rail temperature along sections of track (Chapman *et al.* 2008). This work is still in its infancy and will not be used in detail in this thesis.

Table 2.1: UK Critical Rail Temperature (CRT) values for standard track in good and poor states of repair (Chapman *et al.*, 2008, p.123; adapted from Ventry, 2002 - a Railway Group Standard). Two extreme cases are provided, but a continuum exists between the illustrated examples.

Track condition	**On standby**	**Impose 30/60mph speed restriction**	**Impose 20mph speed restriction**
Good condition	SFT + 32	SFT + 37	SFT + 42
Inadequate ballast	SFT + 10	SFT + 13	SFT + 15

[SFT = stress free (rail) temperature is the temperature at which track is laid and is normally 27°C in UK]

2.3.2 Track, Ballast and Substructure

The track, ballast and substructure provide a means for safe and stable transit for rolling stock. The quality of the ride and the propensity for the track to buckle is dependent on the support offered by the ballast to the track and in turn to the ballast itself. Generally the system offers stiff and stable support, however, the cyclic nature of use and wear leaves track vulnerable to several forms of instability. The track foundation is made from compacted earth, the ballast is laid on the compacted earth.. The sleepers are bedded (but not submerged) into the top of the ballast and the running rail is attached to the sleepers by a fastening system. The ballast supports the sleepers longitudinally to maintain the pre-stressed rail and laterally to support against the heat-related expansion that causes buckles. Inadequate fastenings between the running rail and sleepers can cause the rail to buckle off the sleepers in hot weather. Vertical support is offered by the continuity of subgrade and the stiffness of the ballast.

Ballast in GB is typically made from pieces of granite that range from 2.5cm to 5cm, the rough and angular sides of the ballast lumps lock together to form a stable and supportive mass. Ballast degrades as the rough, angular contact surfaces become worn through the constant loading and unloading from passing trains. As contact points become less stable the ballast settles from the vibrations caused by passing rolling stock, which reduces the stability and support offered by the ballast. Ballast setting or migration can be a particular problem on canted track at bends; the ballast settles leaving the outer edge of the sleepers exposed and poorly supported. Curved track can be at higher risk of rail buckles compared with straight sections, if under-maintained and inadequately supported (Figure 2.3).

Figure 2.3: Example of a buckle on curved track (TSB, 2002)

Maintenance of existing ballast comes in two forms: tamping and stone blowing. Tamping is a process where the track is lifted up, the ballast stones are shuffled around and the track re-laid. This reforms the stable bonds between rough edges of the ballast stones. However, tamping should not be performed when the track may be exposed to heat in the near future. It takes time for the ballast to form a cohesive mass again; if the ballast is not stable enough buckles can occur. Stone blowing adds fresh ballast in order to renew and strengthen the contact between the ballast pieces. Fresh ballast is also added to the top and sides of the sleepers to add support when the ballast settles below an appropriate level on the sleepers.

The track foundation is made from compacted earth and between it and the ballast there is a permeable layer, which allows drainage but reduces contamination of the ballast from subgrade. When the track foundation degrades there are two main impacts: ballast contaminating the earth foundation, and soil from the foundation contaminating the ballast (known as pumping) (see Figure 2.4). The former causes the level of the ballast to drop, thus reducing the support on the sleepers and track, which can lead to buckles, changes in SFT and “rough ride” which leads to excessive wear to the rail and wheel. The latter causes reduced ballast stability, in extreme cases the contaminating soil can be seen at the surface of the ballast. However, even low levels of ballast contamination can cause significant reductions in ballast cohesion and track stability. Until the contamination is very severe (Figure 2.4) there is rarely a visual indication of either of these problems, making them difficult to identify.

Figure 2.4: Example of subgrade contamination of ballast and the resulting reduced support offered by the ballast to the sleeper (TSB, 2003)

Track structure and sub-structure play an essential role in limiting damage caused by high temperatures. Table 2.1 shows the importance of subjectively “good quality” track support for the safe passage of trains at normal operating speeds during hot weather. In its most direct form this relates to the support provided by the ballast around the sleeper. Kabo *et al.,* (2005) have demonstrated the importance of a substantial ballast shoulder. However, the width of the shoulder can be moderated depending on the density, weight and speed of traffic. This moderation is a vital consideration for cost effectiveness and efficient use of materials. Raising the ballast level above the sleeper provides negligible additional sleeper support; however, as the ballast settles the raised shoulder replaces the settled ballast and ensures continued sleeper support.

2.4 The Nature of Cold-Related Delays in GB

Winter weather can damage infrastructure and delay operations in a number of ways. Winter storms, cold days, high winds and heavy rain cause:

- Damage overhead line equipment (OLE)
- Objects blown onto the track
- Flooded track
- Subsidence of earthworks
- Ice and snow to form on infrastructure

Figure 2.5: A rail broken along the web of the rail due to high residual stress (Igwemezie 2007, p. 2)

The majority of track in GB is CWR and when it is exceptionally cold CWR can be susceptible to stress cracks (Figure 2.5), particularly if the rail is over-stressed and at weaker parts of the rail, like points or welds. Weaknesses can propagate over time due to the cyclic loading from trains and expansion/contraction caused by fluctuations in temperature; a cold snap can be the final cause or a contributing factor. Wear over time and a range of contributing factors can make it difficult to attribute cracked and broken rails directly to cold weather. Even though a crack can appear as spontaneously as a buckled rail, it is not as easy to detect unless the rail fully breaks (causing a wrong side track circuit failure[1]) and so may not be detected on the day of occurrence.

The effects of ice and snow contamination can be very damaging and dangerous. According to Smith (1990) major disruptions tend to occur on only a few days in the winter months, although overall, punctuality during mid-winter is 6-7% less

[1] The location of trains on the network is monitored by the electrical connection made across the rails by the wheels and bogey. If the connection is broken a train can be present on a line but not show on the monitoring system due to the broken circuit leading to wrong signalling and the potential for SPADs.

than the rest of the year. Smith (1990) also concluded that the presence of settled snow is the most influential weather feature in causing winter delays. During winter approximately 50% of all delays are attributable to the weather (Smith 1990), considerably higher than the annual total of 20% (Thornes and Davis 2002). Consequently, an effective industry-wide strategy for coping with the effects of winter is vital.

2.4.1 Ice and Snow

Electric trains receive their power from two main sources: overhead line equipment (OLE) and conductor rails. OLE supplies electricity from cables suspended over the track from gantries and the train connects to the cable by the pantograph, which extends from the top of the train to meet the overhead line. Conductor rails (also known as con rail, or third rail) are large metal rails that run alongside the running rails. The train conducts from the rail via shoe gear equipment, which is a large, flat-bottomed piece of metal that is suspended under the train. Conductor rail trains operate in London and the South East (generally south of the River Thames) and in Merseyrail's operating territory. Problems with these systems arise when the conduction connection is interrupted. Ice on the OLE is linked to electricity arcing which causes equipment wear and can slow the trains, while ice on the conductor rail can also slow trains but in severe cases can leave them stranded, which blocks the line and can cause severe subsidiary delays. To prevent the formation of ice on the conductor rail anti-icing solution is sprayed on when cold weather is predicted. De-icing spray is also used to prevent and reduce the build-up of ice.

Thompson and Perry (1997) reported the de-icing of the conductor rail in the South East of England was carried out by around 20 specialist de-icing trains which spread de-icing fluid on designated lines and routes overnight when cold weather is forecast. At the time there was little information available about the quantities of de-icing fluid used *per* winter, South Central (one of the nine divisions carrying out maintenance activities, including de-icing) estimated that around 10,000 litres are sprayed in an average winter between South Central's four de-icing trains costing approximately £1 *per* litre. The trains used to distribute de-icing spray cost around £150,000 each *per* annum to operate and maintain (including labour costs). Applying the costs *per* train that south Central operate to the South East fleet of twenty de-icing trains produces a total winter cost of around £50,000 for de-icing fluid and £3million to operate and maintain the fleet.

Ice formation on the rail head can cause low adhesion, which can prevent trains from stopping when required. This is most significant at signals showing danger, directed to a working zone. Poor rail head adhesion can also cause trains to overrun stations which can cause severe delays, particularly at busy times when the network is at or near capacity.

Correctly-functioning points, crossings and switches are essential to direct trains along the correct line, as misdirected trains could cause a collision or enter a protected working zone. Snow can gather in an open joint and ice can freeze a closed joint. To alleviate these effects points heaters are installed extensively across the network, which can be gas or electric powered. This is an expensive procedure to have in extensive use across the network, nevertheless it is highly effective and the consequences of not having points heaters could be severe.

Snow frozen on surfaces has the same effect as heavy ice formation. Snow can also drift and block lines. Airborne snow can reduce visibility of signs and signals, while heavy snow can weigh down line-side trees and cause them to interfere with the OLE, pantograph, windscreen, visibility and fall on the track blocking the line. Deep snow that reaches to the level of the rail can overwhelm switch heaters and snow over 12 inches deep will stop trains running unless fitted with a snowplough.

Network Rail have a range of snowploughs for clearing deep snow from the lines and infrastructure, although deep snow is not a regular occurrence in GB, when it does happen other transport infrastructures, like the road network, can become gridlocked. The railways, on the other hand, are hardier against this form of extreme weather, providing the necessary mitigation and maintenance actions are taken. Furthermore, there is a public expectation that when personal cars and other transport modes fail that train travel will still be operational. This is the nature of public expectations of railway operability and such high public and media scrutiny leads to a fragile reputation, making the need for highly operational services essential, now and in the future.

2.5 UK Railway Industry Response to the Threat of Climate Change

The seminal text in developing industry understanding and awareness of climate change and the railway network in GB is Eddowes *et al.,* (2003). It is a report that highlights how network operations can be disrupted by weather in the existing climate and then uses UK climate change predictions to establish possible future vulnerabilities. Eddowes *et al.,* (2003) then make recommendations for industry responses to the possible problems caused by climate change. In the context of this project the recommendations include analysing extreme events, heat delays, particularly relating to track has been highlighted as one of the main types of infrastructure vulnerable to climate change. When analysing the effects of temperature on railway track it is also essential to consider the effects of cold weather, CWR which forms the majority of track in GB is affected by cold weather as well as hot. The stability of track in extreme temperatures is determined by both the quality of the infrastructure and the SFT of the track. One can be affected by the other, consequently, ensuring both are correctly maintained will keep cold related tension cracks and buckled rails at an appropriate level. This project aims to continue from the work in Eddowes *et al.,* (2003) by assessing the impacts of climate change relating to damage and delays caused by hot and cold weather, quantifying the change in delays and making recommendations to alleviate the adverse impacts of climate change.

CHAPTER 3

METHODOLOGY

This project has developed from an industry desire to understand in real, financial terms what climate change may mean for the future of the railway industry in GB (Eddowes *et al.,* 2003). The impact of climate change on the railway network is an extensive subject and in order to produce a comprehensive quantification, two aspects of railway-related climatic impacts were chosen for assessment. These were the impacts of extremely hot weather and the impacts of ice, snow and cold weather. In general, temperature-related issues manifest delays on the network with almost immediate effect. For a primary quantitative study it was considered that dealing with damage and delays caused directly by a particular weather feature would produce more meaningful and accurate results. In addition, documentation on the effects of temperature is relatively thorough, offering a good qualitative and quantitative basis to analyse the effects of baseline climate, future climate and then validate results.

3.1 A Framework for Quantification

The methodological steps recommended in Metroeconomica (2004, p. viii) for fiscally quantifying the future effects of climate change on businesses are as follows:

- *"Identifying and measuring (quantifying) climate impacts in physical units*
- *Converting these physical impacts into monetary values*
- *Calculating the resource costs of adaptation options*

- *Weighing up the costs and benefits of the adaptation options, and choosing the preferred option, taking account of risks and uncertainties"*

These guidelines have been used and applied to varying degrees in this project, with the extent of use determined by the availability of data and resources. The approaches adopted to quantify the effects of future hot and cold days are detailed in this Chapter. Metroeconomica (2004) identifies a framework methodology for business adaptation; the key to making an assessment of future impacts quantifiable is to have a "*physical unit*" representing climatic impacts, which can then be converted to a monetary value. This is an aim for further work identified by the RSSB in the report on the safety impacts of weather, climate and climate change (Eddowes *et al.,* 2003).

In order to quantify temperature-related delays in accordance with the methodology outlined in Metroeconomica (2004), an extensive range of detailed data is required, some of which is unavailable. For example, in order to quantify the cost of future maintenance requirements, the existing costs and maintenance regimes need to be available - but they are not and so could not be analysed. The results presented in Chapters 4 and 5 show the cost of damage to the future network assuming it remains the same as the existing network in fundamental aspects of infrastructure and operations. Furthermore, making predictions based on projected changes to the network structure and infrastructure was not feasible, particularly in light of the large timescales being considered for future climate scenarios. The methodologies detailed in this Chapter which were used to produce the results discussed in this thesis were determined by the data available but follow as far as possible the methodology outlined in Metroeconomica (2004). Hence the process of data acquisition will be discussed first, then the methodologies adopted for heat and cold-related delays.

A preliminary study was performed for heat-related delays in the south east region of GB. This developed an understanding of the nature of the data available and a UK-wide study on heat-related delays followed. The future impacts of cold winter weather on ice and snow-related delays were also quantified. Finally, climatic evidence for changes in maintenance regimes, including the SFT of CWR is considered, to redress the balance between extreme temperatures and the effects on track stability. Before the approaches adopted for each section of work are described, the data sources used to produce the results are discussed as follows:

3.2 Data Acquisition

3.2.1 Baseline Climate Impacts

The first stage of the recommended methodology in Metroeconomica (2004, p. viii) is: "*identifying and measuring (quantifying) climate impacts in physical units*". This relates to the effects caused by "baseline" climate and weather. Baseline climate is the long-term trends (usually over a time period of 30 years) in weather that are used as a comparison for future climate predictions. To establish a baseline for the impacts of weather and climate on GB railway network two data sources were used: Network Rail's alterations database (ADB) and real recorded weather data from Met Office weather stations.

3.2.2 Network Rail's Alterations Database

The alterations database (ADB) is a record of all incidents that have caused delay minutes on the railway in GB. Network Rail runs and maintains the railway infrastructure in GB and delay minutes incurred due to problems with this infrastructure are their responsibility. A delay minute is defined by Ellis (2006, p. 93) as: "*a) The difference in journey time between that shown in the timetable and the actual time taken between two points in the journey; b) The total delay to trains caused by Network Rail's failures, in a given period*". Network Rail is fined for the delays that are caused by infrastructure failures and maintenance, the ADB records the details of each incident, it includes:

- The date the delay event was discovered
- A start and end location along the line or route
- The number of delay minutes associated with the event
- And a brief description of the incident

Table 3.1: Example of a section of Network Rail's alterations database

Date of Incident	Incident Description	Start Location	End Location
17/09/2002	RAIL FLAW DSL THIRSK	THIRSK	
23/09/2002	annbank railfault	MAUCHLINE	FALKLAND S.S.
24/09/2002	GEILSTON:BUCKLED RAIL REPORTED	HELENSBURGH CENTRAL	CRAIGENDORAN JN
27/09/2002	20ESR@MORECAMBEJN,WITHDRAWN	CARNFORTH D&U.G.L.	LANCASTER
28/09/2002	BROKEN RAIL PLEAN	STIRLING	GREENHILL LOWER JN
30/09/2002	GREENFOOT: BROKEN RAILS	GARTCOSH JUNCTION	CUMBERNAULD
02/10/2002	DBL: BROKEN RAIL DWN LINE	DUNBLANE	

The ADB is used by Network Rail as a record of alterations to operations. Incidents cause delays, these delays are measured in delay minutes, infrastructure failures and the associated delay minutes are used to pay compensation to the parties affected by the delay. Delays can be caused on the railway network by any and all parties operating, like TOCs and FOCs. The incidents causing delays that are used in this thesis relate only to Network Rail infrastructure failures affecting operating companies. How the information contained in the ADB is handled and analysed is described in the methodologies in Chapter 3 and the results Chapters 4 and 5.

The ADB is ultimately a field record of incidents. Often, the incident descriptions are subjective in nature but can also be inconsistent due to an individual's interpretation of a problem. Network Rail introduced a new industry standard which went into practice from 30 April 2006 and has led to the modification of training and documentation associated with recording events causing delay minutes (formerly Rail Track standard RT/E/C/18 302).

Network Rail was established in 2002 and most ADB data prior to this date is unavailable. The data made available for this study ranges from January 2001 to December 2006 (the data sets also include data recorded by Railtrack, the system for monitoring and recording the ADB was changed in 2006), for heat-related delays and for cold-related delays the data ranges from January 2001 to December 2006 and from mid-2007 to February 2009 (inclusive). For the cold-related delays new data became available from the updated ADB system. It was decided to use this data in conjunction with the old data since there was not a significant change in the essential information provided. Also the new data documented the extremely cold winter 2008-09, an equivalent in the cold data to the extremely hot summer 2003, which is included in the heat-related delays analysis. The hot summer 2003 and cold winter 2008/9 show how extreme the effects of heat and cold can be for the railway network.

The delay minutes in Network Rail's ADB offer a "physical unit" of measurement for the impact of weather-related delays on the railway. There is an associated national average cost of a delay minute which has been calculated at £73.47 (Burr *et al.,* 2008), this cost relates to the economic impact to the passengers of an average train on GB railway network being delayed for one delay minute, not the compensation paid by Network Rail to any affected organisations. The precision of the value for the cost of a delay minute is from the precise mean size of a train and the passenger type used in Burr *et al.,* (2008), this value was used in calculating the costs of delay incidents in this study, thus the exact cost will be quoted throughout this thesis and not rounded. This cost does not include financial aspects of the cost of fixing damage (labour, materials, etc). The costs involved in mitigating and maintaining the network against temperature-related delays were not available. This has further implications for the Metroeconomica (2004) methodology, where a benefit cost analysis is to be made based on the cost of adaptation options. This aspect of the recommended methodology is not viably quantifiable for this project due to the poor availability of data. However, a full discussion of mitigation and maintenance techniques, regimes and requirements are included in Chapter 6.

3.2.3 Regionalising GB

The effects of climate vary greatly across GB, which means different regions' railway infrastructure is exposed to different extremes. For a more detailed and comprehensive study it was vital to consider the effects of climate and climate change from a regionalised perspective. However, there were many factors that needed to be considered. TOC territories create railway route corridors that are areas of land that tend to spoke out from main hubs like London and Manchester (etc), linking regions of GB, main centres and suburb commuter lines. The TOC territory regions can cover a long area of land that would include some contrasting climate in GB. The East-Coast Main-Line, for example, will be exposed to climate in central London, up to Newcastle and beyond. Using this approach to define regions would make it very difficult to assign a weather station that would be adequately regionally representative for the whole area. Network Rail defines the network regions differently, which reflects the regionalisation defined by the EU, which in turn follows the boundaries of UK counties. This was the method of regionalisation chosen for the purpose of this study, which divided GB into eleven regions (Figure 1.1). It was clear from inspecting the ADB that the available data could not support eleven regions. Areas with low-density rail like the North East and Humber did not have enough raw data to statistically support trends. Consequently, the eleven EU regions were merged to appropriately support regions with insufficient data (Figure 3.1).

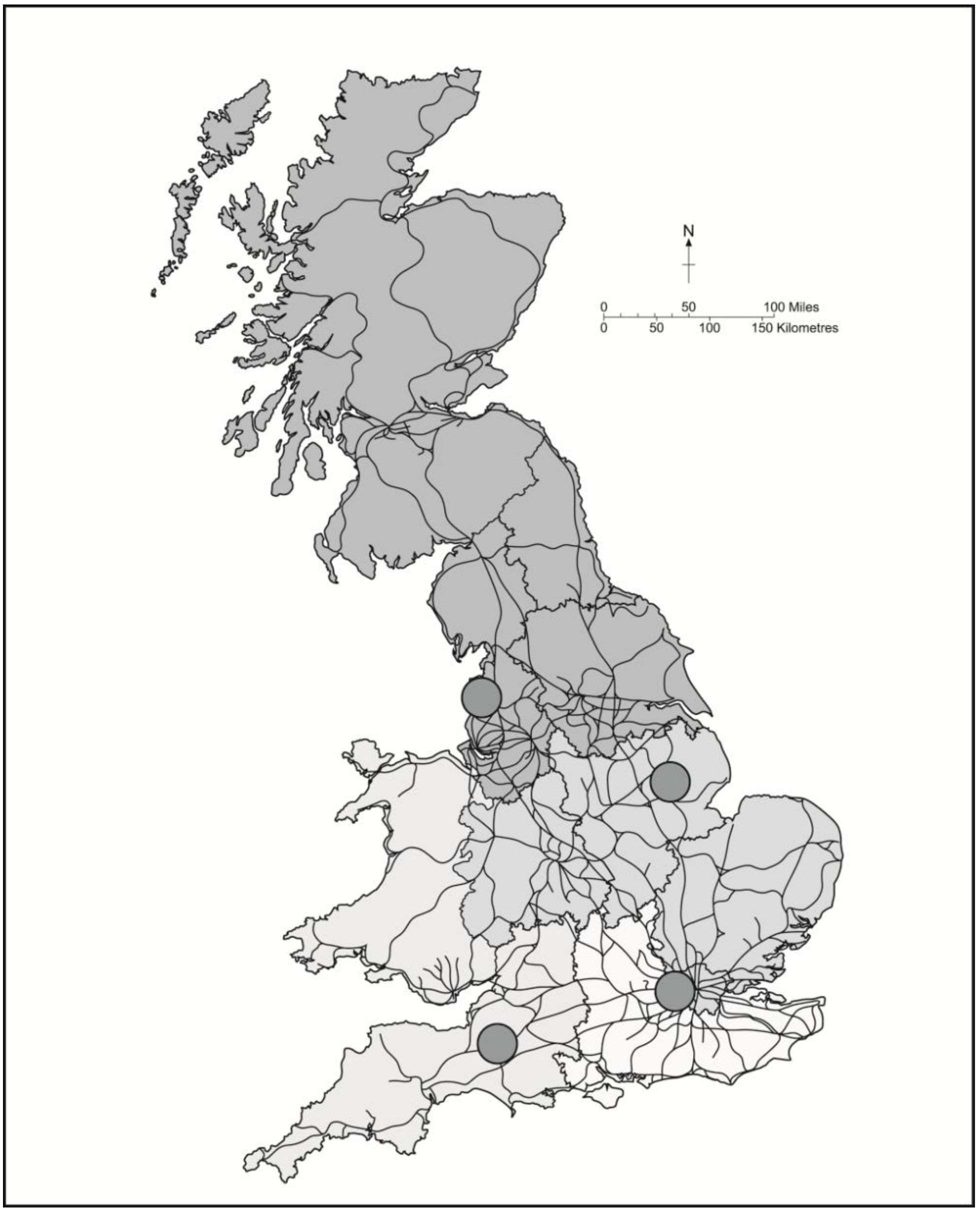


Figure 3.1: Merged regions to produce four regions: north (N); midlands (M); west (W) and south (S) (with the location of the representative Met Office weather station, Table A1.1)

3.2.4 Meteorological Office Weather Data

The Met Office run weather stations across GB and the meteorological data produced is collected every two months and made available via the British Atmospheric Data (BADC) website. The weather data used to compare with the

ADB data was sourced from a list of regionally representative weather stations comprising the regional basic synoptic network from World Meteorological Organisation (WMO). The BADC website was not able to supply adequate datasets for some of these weather stations. The south and west regions are both represented by WMO weather stations, however the north and midlands regions are represented by non-WMO weather stations. The stations were chosen primarily based on the quality and reliability of data from the weather station, however, other factors included the location of the weather station in the region, the time period represented by the station data, the quality of the data supplied for time period that related to the ADB data, 2001 to 2007 (and 2008 and 2009 for the cold related delays) and with good historical records. There had to be no significant gaps in the data relevant to the study, i.e. the maximum and minimum daily temperature, which sometimes occurs if the station stops working or recording the data. Any problems which led to weather data being lost from the weather station files supplied by BADC are noted down in the station profile information (Appendix 1). The two non-WMO stations had exceptionally clean records with regards to failure to record or missing data (see Appendix 1 for copies of weather station records). It is believed that all stations offered acceptable and accurate regional coverage.

The regionally representative weather station for the northern region is not located in the geographical centre of the region (Figure 3.1). The quality of the data, the time period represented and the very low amount of weather station errors for the chosen weather station were all reasons for selection over other, more geographically central stations. Appendix 1 shows how exceptionally few errors there were, even compared with the weather station located at Heathrow, which is a WMO weather station. It was considered that the temperature data for the time period required for analysis was as suitable as other potential weather stations, with the added benefit of being highly consistent and reliable. Furthermore, the weather station is reasonably central compared with the location of the majority and densest areas of rail in the region. The majority of the delay incidents in the north region were occurring in and around Liverpool, Manchester and Leeds and the satellite towns and cities. It was decided that representing the distribution of rail and the delay incidents occurring rather than a centred geographical location was important, as was having reliable and high quality weather data.

3.2.5 UK Climate Impacts Programme

GB Climate Impacts Programme (UKCIP) is the main body in GB that produces future climate predictions for use in adaptation and mitigation strategies (amongst other things). UKCIP has developed from the Climate Change Impacts Review Group which produced basic predictions and strategies from the first IPCC Assessment Report. At the start of this project UKCIP02, the fourth generation of predictions, was the most current and therefore these predictions form the basis of the results in this project.

UKCIP02 bases future climate predictions on four emissions scenarios, which are derived from global future predictions made by the IPCC in the Special Report on Emissions Scenarios, (Nakicenovic *et al.,* 2000). The scenarios are based on four possible levels of greenhouse gas emissions released in the future: Low; Medium Low; Medium High and High emissions. Each of these emissions scenarios occur through three time series: 2011 to 2040 (called the 2020s); 2041 to 2070 (called the 2050s) and 2071 to 2100 (called the 2080s). The process of producing the UKCIP02 predictions has three stages at which uncertainties can be sourced: future emissions; imperfect understanding of climate science and modelling (including downscaling models); and natural variability.

3.2.6 The Environment Agency Rainfall and Weather Impacts Generator

The nature of data provided by UKCIP02 offers a thorough spread of information on future climate predictions. However, in the context of this project more detailed data was required. Weather generators produce an unlimited time series of stochastic, spatially-referenced baseline weather data (Hutchinson, 1986). Weather generators have since been developed to produce data for climate change scenarios (e.g. Semenov and Barrow, 1997). Generally, similar approaches are adopted to simulate weather; based on the presence of precipitation on any given day (Wilks and Wilby, 1999). The success of predictions is reliant on the accuracy of the process used to produce daily precipitation figures (Hutchinson, 1986). The Environment Agency Rainfall and Weather Impact Generator (EARWIG) uses regression relationships with precipitation and the values of other weather variables on the previous day; the daily extremes of temperature, cloud cover, vapour pressure and wind speed can all be calculated. Using EARWIG these weather features can be produced to represent a control period or baseline weather (1969 – 1990, for EARWIG), which is based on UK Met Office observed data (Kilsby *et al.,* 2006).

The future emissions scenarios and time series produced by EARWIG are based on UKCIP02 data, although the approach adopted to produce UK EARWIG predictions can be applied to any location globally. The method uses a variety of statistics for factors of change of relevant weather conditions from the control period (baseline) to the future scenarios, which are then applied to observed statistics for the region (rather than point location observed statistics). For this project GB baseline, future trend statistics and factors of change come from UKCIP02 (Kilsby *et al.,* 2006).

The user interface of EARWIG shows GB divided into a 5km by 5km grid, with options to select river catchment areas or self select grid squares based on longitude and latitude coordinates or by hand from a map. The area selected to represent the weather for each region was based on the coordinates of the regionally representative weather station. One grid square was selected to represent each region, the advice given as part of the users interface in the EARWIG weather generator is that to select multiple grid squares spaced apart produces spurious results. It was also decided that since the representative weather station offers a single point reference for regional weather representation that the future climate projection weather generated should also be a single point reference at the location of the representative weather station. The strength of this approach is justified by the quality of comparison between maximum daily temperature comparison between Heathrow weather station and the EARWIG simulation for the location of Heathrow. Furthermore, Heathrow weather station is used in Kilsby *et al.,* (2007) to justify the projection output from EARWIG for a number of weather features.

That grid square would be representative of a larger (up to $1000km^2$) area but not technically representative of the whole regions as defined in Figure 3.1. However, the limitations imposed by the amount of ADB data dictates that this approach is the only option. Furthermore, it is vital that the future predictions are as closely linked as possible to the Met Office weather station used to establish trends with the ADB, in order to keep all weather and climate data inputs as consistent as possible.

EARWIG was developed for agricultural and water systems management, but it should have the potential to be used for other climate change impact assessments (Kilsby *et al.*, 2007). As this had not been tested, a comparison study was conducted to compare the real recorded baseline maximum daily air temperature data of Heathrow from the BADC database (1961-1990) with an EARWIG ensemble run for the same location for the baseline time period (Figure 3.2). Kilsby *et al.,* (2007) also use real recorded weather data from Heathrow weather station to verify the numerical output for several weather features. The correlation between the two data sets is acceptable with an R^2 value of 0.96. The temperature distributions are particularly similar for the higher extremes of temperature with an R^2 value of 0.997 for temperatures greater than 21°C.

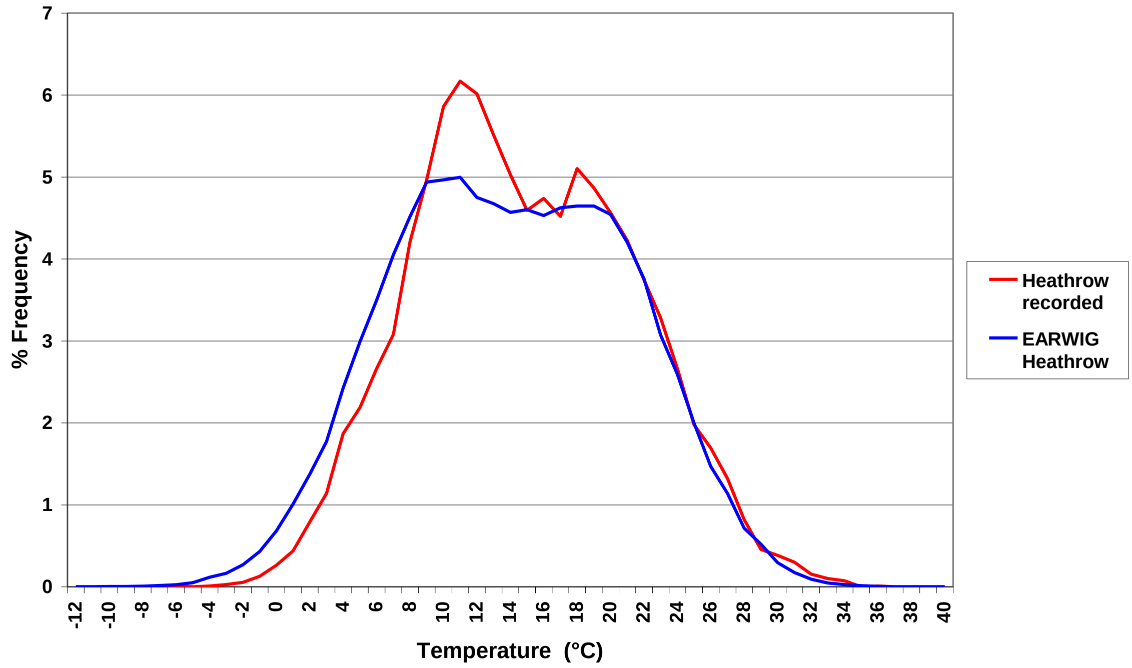


Figure 3.2: Percentage frequency that maximum daily ambient air temperatures (in 1°C increments) occur for EARWIG simulated and actual recorded data at Heathrow, for baseline weather

3.3 Weather Analogues

The use of analogues (e.g. Feenstra *et al.*, 1998) can provide a useful starting point to study the impact of climate change on the railway network. The aim of this section of the methodology is to find an occasion in the past which could be considered representative of the 'normal' situation to be faced in the future. This type of analogue is known as a temporal analogue. Feenstra *et al.,* (1998) discuss analogues in the context of verifying or making future climate predictions. In this thesis the 2003 heatwave will be used as a temporal analogue. August 2003 was an exceptionally hot month in Europe and caused a great deal of damage in many sectors of industry and society (Burt, 2004). Hunt *et al.,* (2006) provide an estimate for the additional costs incurred due to the exceptional weather experienced that summer. Overall, the 2003 analogue provides a useful case study into how climate change may affect the railway network.

The effects of the hot summer 2003 on GB railway network could have been worsened by a low level of understanding of the true condition of track across much of the network. The result of this was that ESR were enforced as a preventative measure on routes where the quality of the track was possibly adequate and did not require ESR, thus creating unnecessary delays. Resulting in the delays in summer 2003 being more extreme than they perhaps would have been had there been a better understanding of the quality of the infrastructure. Network Rail took over the operation and maintenance of the network infrastructure in 2002, hence the low level understanding of the infrastructure at that time. From the data available in Hunt *et al.,* (2006) the number of buckled rails in 2003 (137 buckled rails) is closely similar to the numbers experienced in the hot summers of 1995 (133 buckled rails) and 1976 (132 buckled rails), although this does not account for delays caused by ESR, in terms of heat induced rail buckles three similarly hot summers experienced a similar number of buckles, suggesting that a similar "story" is being told in each case. With regards to analysing the ESR data from the ADB there is no method by which ESR enforced due to known track condition and those enforced due to unknown track condition can be distinguished, therefore, no distinction is made in the analysis.

Another form of analogue is spatial analogue scenarios, whereby a regional climate profile is used to describe the future climate of another region that is predicted to experience similar temperatures (for example) to the analogous region. Parry *et al.,* (1988) used the Scottish climate as an analogy to describe the future of the Icelandic climate. A similar approach can be adopted for the regions defined in this thesis and to compare future, unfamiliar UK temperatures with countries that operate railway networks in similar conditions at present. An advantage of spatial analogues is that mechanisms used to cope with the climate in the analogous region can be identified and recommended to help cope with future predicted climate impacts. This method is described and applied in Parry *et al.,* (1988) and Mendelsohn *et al.,* (1994) for social and natural systems, however, engineering infrastructure and operations are just as applicable.

The key disadvantage identified by Carter *et al.*, (1994) for spatial analogues is that the climate can differ due to geographical variability, even if the average annual temperature is similar. This may be more significant for GB than when comparing other European countries; GB is an island and is warmed by the Gulf Stream, which makes GB's climate relatively temperate all year round. The method is still appropriate for use in this study for the reasons that follow. Firstly, the focus of this study is how temperature affects infrastructure and operations; albeit extreme temperatures which can be influenced by the presence of cloud cover or rain (i.e. other climatic features). To overcome this, a country used for comparison should be considered on the basis of the strength of similar temperature profiles, rather than merely the mean temperature. Secondly, the impacts of temperature that are considered in this thesis cause damage and delays that can be easily categorised as being caused by temperature, with few other climatic influences, whereas in a study of the impacts of climate on socio-environmental issues the presence and influence of other climatic variables can be more significant. A contrasting example for the railway network could be considering the effects of climate change on autumn leaf fall contamination on the rail head. The severity of leaf fall-related delays can be influenced by many aspects of weather and climate as well as the abundant presence of trees across GB. Weather influences include the growing season, precipitation, wind and storms. This would make finding an analogous country for this aspect of future operations difficult, whereas for temperature-related damage and delays a spatial analogue would be appropriate and useful.

A spatial analogy has been made using a range of countries from Europe, particularly Spain, which is presented in full in Chapter 6. The spatial analogy is then used to make recommendations for the future SFT of UK CWR. This is achieved by comparing the regional temperature profiles for the maximum, mean and minimum daily temperatures between GB, France, Germany and Spain, and using these to select a SFT to balance the risk of rail buckling at high temperatures and rail cracking at low temperatures. This is the only analogy made to describe and monitor the effects of future cold weather. It is considered that cold tension cracks are a likely problem for the future network when considering a new SFT to combat hotter summers. It is not considered that future cold delays (including ice and snow) require an analogy. It is predicted that cold days will not increase and since GB rail network is prepared and accustomed to operating under moderately challenging winter conditions on a regular basis, it is believed that future warmer winters should not be a challenge. However, the potential problem of complacency will be discussed in Chapter 7.

3.4 Baseline Methodology

Before the predicted impacts of climate change on weather patterns in GB can be applied to railway operations, the impact of existing weather on network performance must be reviewed and analysed. This section describes the methodology used to establish the impact of baseline weather through comparing incidents in the ADB with the corresponding temperature from the regionally representative weather station. This aspect of the methodology produces a financially quantifiable unit (delay minutes), that relates to the effects of weather and climate on the railway network.

3.4.1 A Preliminary Study – The South East Region of GB

Initially only the “rail-related” delays section of the ADB was made available. In order to understand the nature of the data contained in the ADB a preliminary study was conducted using data for the delays occurring in the south east region of GB. To ascertain that heat was influencing the severity of “rail-related” delays (including buckles) each incident was matched with the maximum daily temperature that corresponded to the date of the incident. The incidents were grouped in 1°C increments based on the assigned maximum daily ambient air temperature and the mean severity (in delay minutes) was taken of each 1°C increment. The purpose of the preliminary study was to discover whether hot days were causing more severe delays on the railway and if this effect was reflected in the data from the ADB. Plotting the mean severity of delay events of each 1°C increment showed an increase in the severity of incidents occurring at higher temperatures. From both the evidence in the data and the evidence from Table

2.1, the network starts to be at risk from rail buckles and other heat-related delays at around 25°C, ambient air temperature (see Chapter 4 for relevant calculations and figures). A linear trend line was plotted through the incidents causing delays on days with maximum daily temperatures greater than 25°C. This trend was used to describe how high maximum daily temperatures affect operations on the railway network and applied to the medium high future climate scenario in Chapter 4.

3.4.2 Refining the Baseline Methodology – a GB-Wide Study

More sections of the ADB were made available later in the study. The delay data now included delays relating to extremes of weather, as well as the "rail-related" delay data used in the preliminary study. The new data contained more delays that were recorded as being directly caused by heat, like "heat ESR"; a filter was applied to the data to extract delays only caused by heat: "heat"; "hot"; "temperature"; "buckle". In addition, the delays extracted were limited to summer months only (May to September, inclusive). The time range for summer months was selected to be longer than the conventional seasons to ensure early and late extreme temperature events would be included in analysis and to account for future changes in seasonality.

As in the preliminary study on the south east the severity of the heat-related delay events (in delay minutes) were compared with the maximum daily temperature on the day of the delay event, from the regionally representative weather station. The trends in the heat-related delays could be uniformly described as delays being more severe the higher the temperature. Although it is believed that the severity of damage caused by heat-related buckles worsens roughly exponentially (as opposed to linearly) as the temperature increases (Hunt, 1994), the trends applied were linear, in the interest of conservative estimates where future predictions made were to be based on unfamiliar future temperature ranges. Furthermore, the severity of a delay does not necessarily reflect the severity of the damage to the infrastructure. Although the two are inherently linked, there are other factors that determine the severity of a delay, such as the location or timing of an incident. A combination of worst case scenarios for all contributing factors is likely to cause the most severe delays, which relies on hot days causing the worst buckles (Hunt, 1994) and ESR (see Table 2.1). Again, with so many factors contributing to a severe delay (heat being significant) there is no evidence to suggest that anything but a linear trend should be applied. Maximum, minimum, mean and standard deviation (*SD*) trends were calculated for the delay data in each 1°C ambient air temperature increment.

The regional maximum, mean, *SD* and minimum were plotted to demonstrate the range of delay data being caused by hot days. The mean trend line was chosen to represent the delays caused by heat-related incidents, which would then be applied to future climate profiles. The mean was considered an appropriate trend because it describes all the ADB data available for analysis. However, the mean trend line was being skewed by the very high number of very minor delays across the full temperature range for all regions. This resulted in the mean trend line not describing the impact of the relatively few major delay events that became worse at the highest temperatures. Relating back to the ADB it was found that there were a high number of incidents causing delays of zero[2] delay minutes and very minor delays. Furthermore, there were many delay incidents that had the same description, occurred on the same day and that caused a range of delay minutes. The result for these delays was that instead of there being one recorded incident causing a number of delay minutes, there were two or more delays recorded which averaged out to cause a more minor delay than the sum of all parts of the incident. In order for the mean trend line to best describe the data as a whole, any incidents from the raw data that were less than the y-axis intercept of the minimum trend line were removed from the analysis. The maximum, minimum and *SD* trend lines were re-drawn from the dataset without the minimum values.

3.4.3 Baseline Methodology – Cold-Related Delays

For the analysis of the cold-related delays a section of the updated ADB was made available. This section contained only delays described as being caused by ice, snow and cold weather, so no filter was applied to this. For the older sections of the ADB (the same data set used for GB-wide heat delays analysis) a filter, similar to that used to extract the heat-related delays, was applied. This extracted delays that were described as: “ice”; “snow”; “freeze”; “frozen” and “cold”. The delays were limited to winter months (November to March, inclusive). Again the months selected represented a longer period of time than the conventional winter season to ensure early and late extreme temperature events would be included in the analysis and to include future changes in seasonal duration. The delay minutes associated with each delay event were then compared with the minimum daily temperature corresponding with the date of the delay event.

[2] It is believed that an incident in the ADB causing zero delay minutes is the result of an event with the potential to cause delay but where the problem was solved before any services were affected.

The raw data from comparing cold-related delays to the associated minimum daily temperature showed a more complex situation than the trends in the heat-related delays. The trends for all regions showed that the highest frequency and most severe delays were occurring around +1°C to around -2°C. Outside this temperature boundary the severity and frequency of delays was less and tended to drop off the further from the temperature range approximating zero, the temperature at which ice is most slippery. For each region the raw data was split into three groups; the range causing the majority of delays, the most severe delays, and the delays associated with temperatures outside these boundaries. The exact method by which the regional data sets were split is described with reference to the figures in the cold-related delays results section in Chapter 5. The boundaries were fixed for each region individually, based on the distribution of the most extreme incidents and the highest frequency of incidents. The graphs used to define the critical temperature range boundaries are shown and discussed in detail in Chapter 5.

The delay data from each critical boundary was grouped and considered representative of that temperature range. For each temperature block the severity of the associated incidents were grouped into 50 delay minute increments and the frequency of delays in each delay minute increment was calculated. The percentage frequency and severity were plotted against each other and a trend established, which describes the frequency distribution of delay minutes *per* incident for that temperature group. This approach allows a precise and thorough understanding of how cold weather, ice and snow affects infrastructure and therefore operations and delays. By excluding “outliers” from the main data set the aim was to reduce the influence of wrongly-recorded ADB data, seen to reduce the statistical significance in the heat-related delays results. By comparing the data from the critical temperature range and the upper and lower outliers it was clear that the main body of incidents in the temperature range causing the most and the worst delays showed a consistent pattern. Since GB railway network is constructed in the same way across the country it would be expected that ice and snow would have similar impacts across all regions of the network. Furthermore, the statistical significance of trends in the critical temperature range was very high, greater than 99%. Both strengths in the data trends suggested that the method adopted for the cold weather delays was appropriate. The validation of the methodology described in this Chapter is justified with evidence in Chapter 5, which contains the results of the study on ice and snow-related cold delays.

3.5 Trend Strength: R^2 and P-value

In order to assess the strength of the trends from the ADB data two statistical tools have been used: the R^2 and the P-value of the trends. The P-value is a measure of the confidence that the trends from the ADB data and daily temperature data reflect how temperature affects the railway network in GB. If the P-value is lower than a certain specified value (usually 5% - 0.1%, although sometimes up to 10%) then the null hypothesis is rejected and the relationship between the temperature and delay events can be considered to have statistical significance. In this case the purpose of calculating the P-values was to compare the strength of the trends across regions in order to subjectively defend the results, rather than to reject or not reject the null hypothesis. For the trends where the null hypothesis would not be rejected (i.e. for a P-value higher than a conventionally justified level (~5% - 10%)), it was not the case that more experiments could be performed or that more data could be obtained. The trends were produced from the only data available, which is of a limited quantity and is real recorded field data with the associated inaccuracies. The R^2 value is important when using the trend line to make predictions. In order to consider the predictions to be accurate an R^2 value of as close to 1 is preferable. The value of R^2 demonstrates how well a trend line represents the data points. When analysing the P-value in conjunction with the coefficient of determination, R^2, in many cases the trends were considered reasonably reliable. Those that were not were discussed subjectively; the quantification of delay events associated with future temperatures was still performed for all regions.

3.6 Applying Baseline Trends to Future Climate Scenarios

Having established trends to quantifiably represent how the railway network is affected by heat, ice and snow the next stage is to apply climate change scenarios to assess how future climate may affect temperature related delays in operations. The approach used to estimate the impact that future climate change may have on temperature-related delay events differs between the heat and cold-related delays due to different trends produced from the baseline data. In both cases the trend lines were applied to future temperature profiles to assess the possible changes in frequency and severity of maximum or minimum temperature days that cause delays. The methodology for this step differed for each section of work; the approaches are described in the following.

3.6.1 Preliminary Study of Heat-Related Delays in the South East

For the preliminary study the trend line taken from comparing all "rail-related" delays with the corresponding maximum daily temperature was used to represent the average severity of a delay event occurring on a hot day. This is represented using a standard straight-line formula as follows:

$$m = 42t - 923 \tag{3.1}$$

where *m* is the estimated delay minutes and *t* is the maximum daily temperature. The cost of delay minutes caused by high temperatures is calculated using equation (3.2).

$$C = m\,d\;p\,c \tag{3.2}$$

where *C* is the total cost for that time series, *m* is the average delay minutes associated with a day of maximum temperature *t* (from equation (3.1)), *d* is the number of days that each maximum temperature is expected to occur in each 30-year time series under the medium high emissions scenario, *p* is the probability that an incident causing delay minutes could happen on that day (based on the number of delay incidents and the number of days) and *c* is the average cost of a delay minute. The data and trend used to define equation (3.1) and the results formed from equation (3.2) are discussed in Chapter 4. At the time that this section of the project was completed and the paper in Appendix 4 was published the average cost of a delay minute was considered to be £50 (Eddowes *et al.*, 2003). More recent literature has updated this to £73.47 (Burr *et al.,* 2008).

However, it is noteworthy that the average cost of a delay minute (£73.47) is described in Burr *et al.,* (2008) to be an underestimate for many delay events. Indeed, the first cost used in the south east study (£50) was also described by Eddowes *et al.,* (2003) as being an underestimate. However, there is at present no method or literature that produces a “true” cost for a delay minute, which is likely to differ substantially according to the time of day and the area that the delay incident occurred.

3.6.2 Future Heat Delays Across GB

The approach used to predict the impact of future heat-related delays for GB-wide study is similar to that used for the south east study. The regionally representative trend lines used for future predictions were the mean severity of delay events. As with the south east costing, the trend line formulae was given a linear format:

$$m = nt + k \tag{3.3}$$

where n and k are constants, t is the maximum daily temperature and m is the associated delay minutes. Constants n and k are defined for each region in Chapter 4.

A linear relationship was chosen for the trend lines from the heat-related delays because there was nothing in the data to suggest any other appropriate trends. Furthermore, in using future temperature projections that include unfamiliar, extremely high temperature data. Trend variations were used in the trend line formula (relating to n in equation (3.3)) to give an upper and lower threshold for the delay minutes incurred due to heat and then for the associated cost. These measures provide a more conservative estimate when dealing with high unfamiliar temperatures and heat-related delays like emergency speed restrictions.

In order to assess the impact that future maximum temperature profiles could have on railway operations in GB, EARWIG simulations of future climate were performed. It is recommended by Hulme *et al.,* (2002) in the UKCIP02 Scientific Report, that a minimum of two contrasting emissions scenarios should be used to assess the scale of a problem. EARWIG was used to produce maximum daily temperature profiles for the low and high emissions scenarios for all time series in each region. The lowest maximum daily temperature that a heat-related delay can occur in each region was taken as the lowest temperature at which a heat-related delay occurred (demonstrated in Chapter 5). This minimum "threshold" for heat-related delays was also used for the future predictions. Under the future predictions, temperatures that are higher than those currently experienced are accounted for by extrapolating the trend line to include the higher temperature ranges, from EARWIG predictions.

For the future cost of heat-related delays equation (3.2) is used, where *C* is the total cost of the delay minutes caused by each temperature increment under future temperature profiles produced by EARWIG. The total annual cost is the sum for all temperature increments. The EARWIG predictions relate to *d*, the frequency of days with a maximum daily ambient air temperature that falls within each 1°C temperature increment within the temperature range that causes heat-related delays. The severity of heat-related delays on days with a maximum daily temperature within each increment (*t*) is defined by equation (3.3) as *m,* in delay minutes. The probability (*p*) of a delay event happening on a hot day in each region is determined from the original ADB data, where the number of delay events was divided by the number of maximum daily temperature days with the potential to cause damage. Finally, the cost (*c*) is the average cost of a delay minute (£73.47 (Burr *et al*., 2008)).

Burr *et al*., (2008) have based the cost *per* delay minute on the monetary value of a minute saved or lost on a journey *per* traveller. The reason for a person travelling defines the cost incurred for each minute of delay to their travel: business travellers cost £41.33; commuters cost £5.64 and other travellers cost £4.99 *per* hour (based on 2007 prices). The respective delay costs were multiplied by a factor of three to account for unexpected delays being more costly to rail passengers. The cost *per* train varies depending on the day and time of day; weekday trains running at rush-hour will have a higher proportion of business and commuter travellers compared with weekend trains. The national average for train passenger journeys throughout the week are 7.6% business travellers, 52.2% commuters and 40.3 % others, which on an average train accounts for 14 business travellers, 95 commuters and 73 other passengers. Multiplying the passenger numbers by the respective values of time produces an average of £73.47 *per* minute of delay for each train. In Burr *et al.,* (2008) the passenger proportions of a national weekly average train are used; this is adequate for this study as the time of day that the delay incident occurred is not included in the ADB data. Furthermore, it is not know how the density of traffic differs by region, however the delay minutes recorded in the ADB already account for the number of trains affected by an incident. Thus the severity of delays in regions that have high traffic density will automatically contain delay incidents that cause more delay minutes than those occurring in low traffic density areas. Discrepancy arises due to the unknown time of delay and the passenger content of the trains affected. Burr *et al.,* (2008) state that for many journeys the cost of £73.47 is likely to be an underestimate. Indeed, for anyone who has experienced the bustle of suits on any suburb/city centre line at peak time, it is clearly understandable that £73.47 is an underestimate for many journeys.

In order to asses the relative severity of the impact of climate change on heat-related delays in each region, the cumulative costs have been normalised as a ratio to the length of rail (km) and the area of the region (km^2), from a GIS of GB railway network sourced from Ordnance Survey maps (Figure 3.1). The GIS of GB and the railway network includes statistics relating to the geographical feature. For the railway network this includes the length of track included within a specified region, in this case the regional boundaries are defined in Figure 3.1. For the area of each region the area of land within the region boarder is recorded within the GIS. These parameters are recorded in Table 4.5. It would also be useful to normalise the results using the number of trains travelling and the total time travelled within each region. Network Rail publishes information on the number of trains operating on lines and routes as part of their annual business plan. However, the lines and routes defined by Network Rail do not correspond with the regions defined in Figure 3.1 and this procedure was not followed. The results of the total costs as a ratio of the area of each region and length of rail in each region are shown in Chapter 4.

3.6.3 Future Costs of Cold-Related Delays

The methods used to predict the cost of future winter ice and snow-related delays were different from the heat-related delays. The trend line taken from the delay incidents in the temperature range causing the majority and most severe delay events was a negative power curve which describes the frequency of delays causing an amount of delay minutes, see equation (3.4):

$$S = nf_1^{\,k} \tag{3.4}$$

where, n and k are regionally defined constants, S is the severity of a delay event (in delay minutes) and f_1 is the frequency of delay events relating to S. n and k are numerically defined for each region in Chapter 5. The trend curve was used to represent the severity of future delay events occurring on days with a minimum daily temperature within the critical temperature range using equation (3.5) to calculate quantifiable values for the x-axis based on future temperature profiles:

$$N = f_2pd \tag{3.5}$$

where N is the number of delay events *per* time series, f_2 is the probability of a delay event causing each increment of delay minutes (f_1 in equation (3.4) divided by the total number of delay incidents to give a probability, rather than a numerical frequency), p is the probability of a delay event happening on a day within the critical temperature (from the number of delay events divided by the number of days), d is the number of days with the minimum daily temperature being within the critical temperature range, according to future climate predictions. Applying N to equation (3.4) in place of f_1 means that the area under each curve describes the total number of delay minutes due to delay incidents that occur within the regionally defined critical temperature range. Multiplying the total number of delay minutes by the mean cost of a delay minute (£73.47 (Burr *et al.,* 2008)) gives the total cost of delay incidents occurring in that region when the minimum daily temperature is within the temperature range causing the majority and most severe delays.

The costs calculated for ice and snow-related delays have also been normalised by regional rail content and land area. The results are discussed in Chapter 5.

3.7 Variations in Trend Formulae

In order to account for the variability in the trend lines, a plus and minus range in trend variability was calculated for each trend line around the X variable. For the heat and cold-related delays the X variable relates to n from equations (3.3) and (3.4), respectively. The value of the ± variability was applied to the respective n values for each regional mean trend line, which was then carried over to the predictions for delays caused by future temperatures. The final cost calculations from the mean trend lines include the cost calculation from the main trend equation and an upper and lower limit of cost based on the variability of n from the original trends.

CHAPTER 4

RESULTS: HEAT-RELATED DELAYS

The methodology in Chapter 3 demonstrates the approach used to quantify baseline and future heat-related delays. This Chapter details the results from the methodology for both the preliminary study on heat-related delays in the south east region of GB and for GB-wide study. The methodology is used as a framework to explain the results, which are justified through statistical significance tests and by using analogues. Discussion and analysis of the results is also included in this Chapter. The results in this Chapter have also been published in the papers contained in appendices 1 and 2. Chapter 6 contains recommendations for future maintenance and SFT practices based on the results of the effects of future summer heat profiles.

4.1 Results of the Preliminary Study on the South East of GB

To recap from the methodology: to establish the impact hot weather has had on the railway network in the south east of GB, a trend was determined using the mean severity of delay incidents occurring on days with a maximum daily temperature greater than 25˚C, based on the data in Figure 4.3 and Figure 4.5. The severity (in delay minutes) of buckle incidents is shown in Figure 4.1. The mean trend line from this data set was analysed to determine the effect temperature has on the severity of rail buckles.

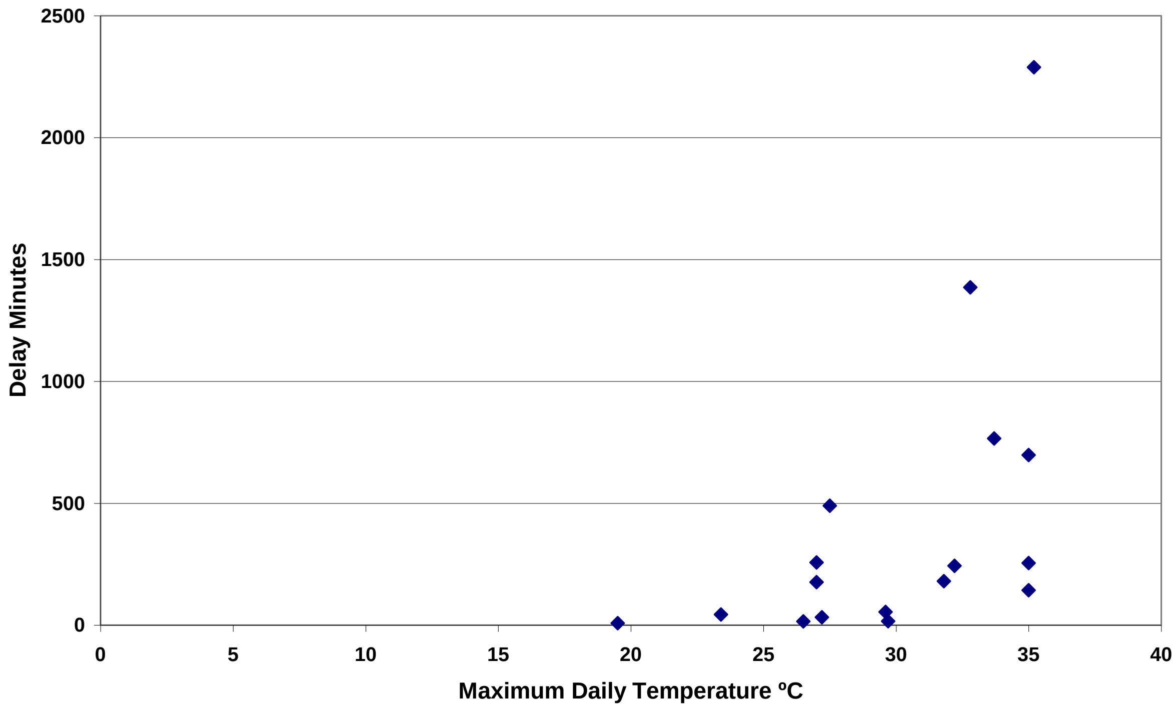


Figure 4.1: Number of delay minutes attributable to “buckle” events recorded in the ADB for London and the South East and the maximum ambient air temperature reached on the day of occurrence (graph includes all recorded buckling incidents, the 25°C “cut-off” is only necessary for the data in Figure 4.3)

EARWIG-simulated weather scenarios demonstrate that climate change is anticipated to cause an increase in the number of days with maximum daily temperature values that can potentially cause serious damage and delays to the railway (Figure 4.2). The following details the data and the approach used to consider the potential future cost of the delays occurring at high temperatures. Figure 4.4 shows the same ADB data as Figure 4.3 compared with minimum daily temperature data.

1 An average cost of £50[3] *per* delay minute (Eddowes, 2003)

2 The average number of rail-related/buckling events expected *per* day in the south east is 0.77. This number is derived from the total number of rail-related incidents from the ADB, divided by the number of days when the maximum daily ambient air temperature is >25°C in the period of time (in days) from May – October for 2001 – 2006 (see equation (4.2))

3 The number of days expected to reach each maximum daily temperature (Figure 4.2)

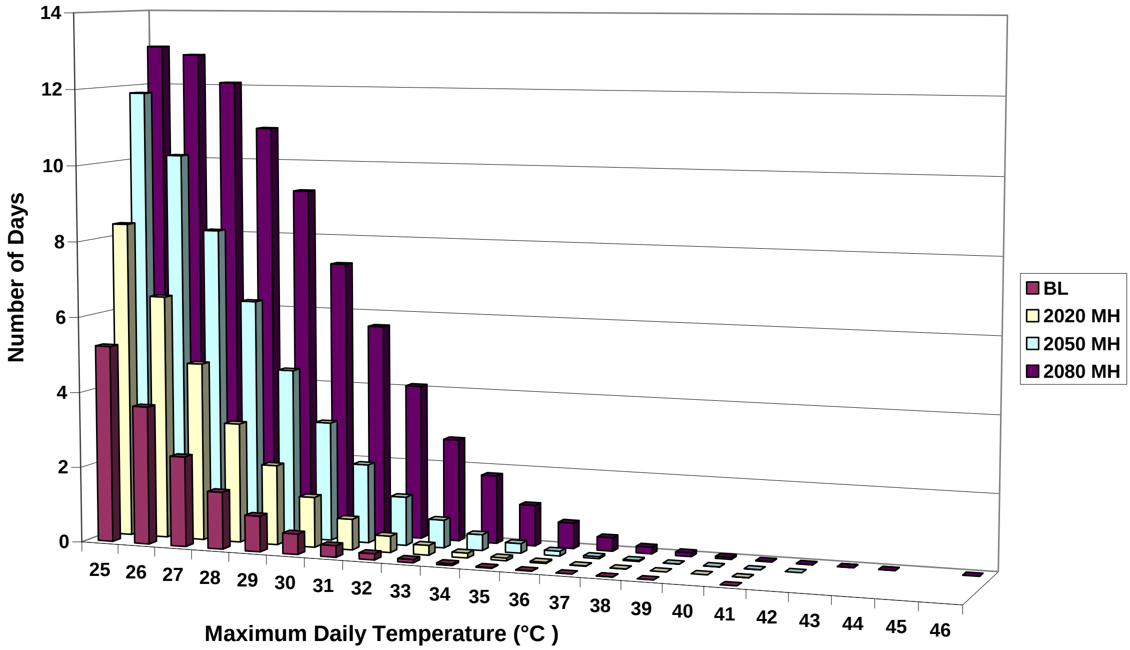


Figure 4.2: Number of days *per* year that the maximum daily temperature is predicted to reach each 1°C ambient air increment in the South East of GB.

[3] £50 was the cost *per* delay minute used in the preliminary study because the report recommending £73.47 as the average cost *per* delay minute was not published at the time.

Data from simulated EARWIG temperature profiles using the medium high emission scenario and all time series

In addition a number of assumptions have been made:

1 The average duration of an event (in delay minutes) on a day when the maximum daily ambient air temperature reaches 25°C or above was ascertained from a line of best fit (equation 4.1) shown in Figure 4.5 derived from the data in Figure 4.3

$$m = 42t - 923 \qquad (4.1)$$

where m is the estimated delay minutes and t is the maximum daily temperature.

2 The future temperature data is simulated through EARWIG for the entire 30-year medium high time series, which will include extremely hot and cooler summers. The cost of the entire 30-year time series will be presented, but also, to make the results comprehensive, they have also been presented as annual averages, which are representative of a mean year in the time series. The medium high emissions scenario was chosen because it represents a compromise between the high emissions scenario and the low emissions scenario so would give an idea of the magnitude of change that could be expected. It is also noteworthy that this part of the study was to establish how appropriate the data and methods were in order to extend the study to heat related delays for the whole of GB.

3 Only temperature days above 25°C ambient air temperature occurring between May and October, for the medium high emissions scenario for all time series, have been included in the future predictions. Although climate change literature recommends a minimum of two contrasting scenarios (Hulme *et al.,* 2002), the aim of this preliminary study was to assess the suitability and compatibility of the data sources. Two contrasting emissions scenarios have been used in assessing future heat and cold-related delays in GB-wide studies

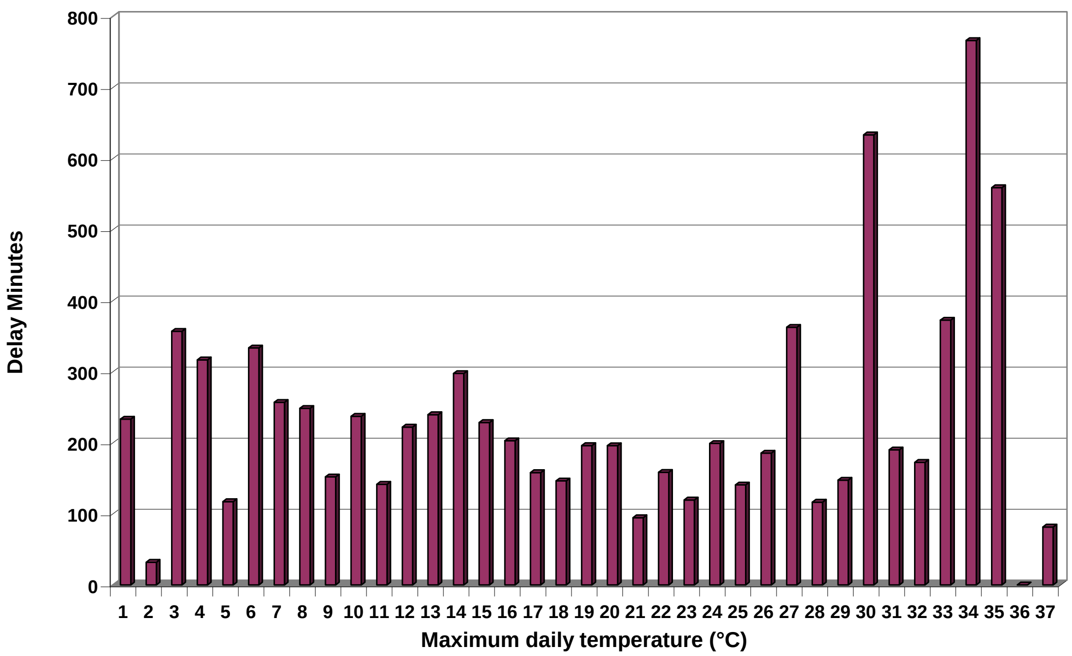


Figure 4.3: Average delay minutes *per* day for maximum daily ambient air temperatures in the range 1°C to 38°C

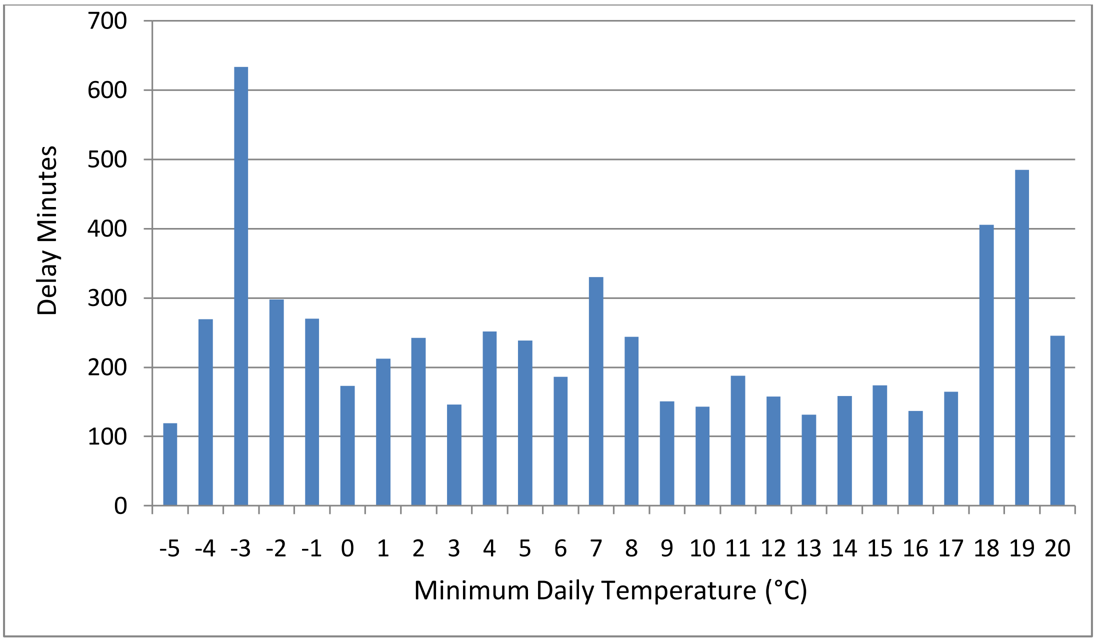


Figure 4.4: Average delay minutes *per* day for the equivalent minimum daily ambient air temperatures relating to Figure 4.3

Figure 4.4 shows the same mean daily ADB data from the "rail related" delays section as Figure 4.3. The data set has been compared with minimum daily temperature data recorded on the day of each incident to show how cold weather affects rail related delays. Rail related delays will include rail breaks and rail buckles, the former are usually associated with cold weather just as buckles are associated with hot weather. The graph shows a considerable peak in mean daily delay minutes at daily temperatures around -3°C and a general rise in delay minutes around this temperature. Although there is also a slight rise in delay minutes around 7°C which is also visible at around 14°C, the sharp rise at -3°C is attributable in the majority to two broken rails, one causing 1099 and the other 1794 delay minutes, occurring on a day when the minimum temperature was recorded to be -2.7.

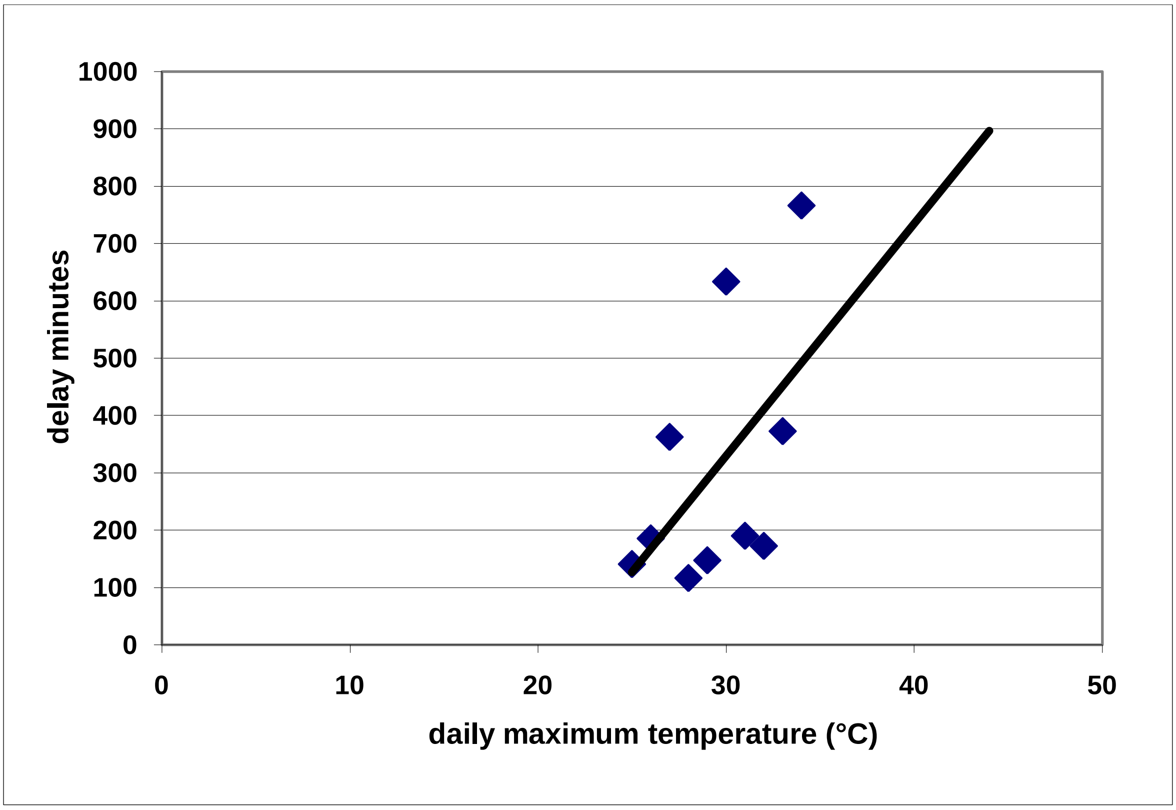


Figure 4.5: Trend line from the most severe incidents causing delays from Figure 4.3, trend line equation in equation 4.1

Based upon these assumptions, the cost of delay minutes caused by high temperatures is calculated using equation (4.2). The results are plotted in Figure 4.6 and the cumulative cost of rail-related delays and rail buckles in each time series is shown in Table 4.1.

$$C = m\,d\,p\,c \tag{4.2}$$

where, C is the total cost for that time series, m is the average delay minutes associated with a day of maximum temperature t (from equation 4.1), d is the number of days that each maximum temperature is expected to occur in each 30-year time series, p is the probability that a delay minute event will happen on that day (0.77) and c is the average cost of a delay minute (£50) (Eddowes *et al.,* 2003).

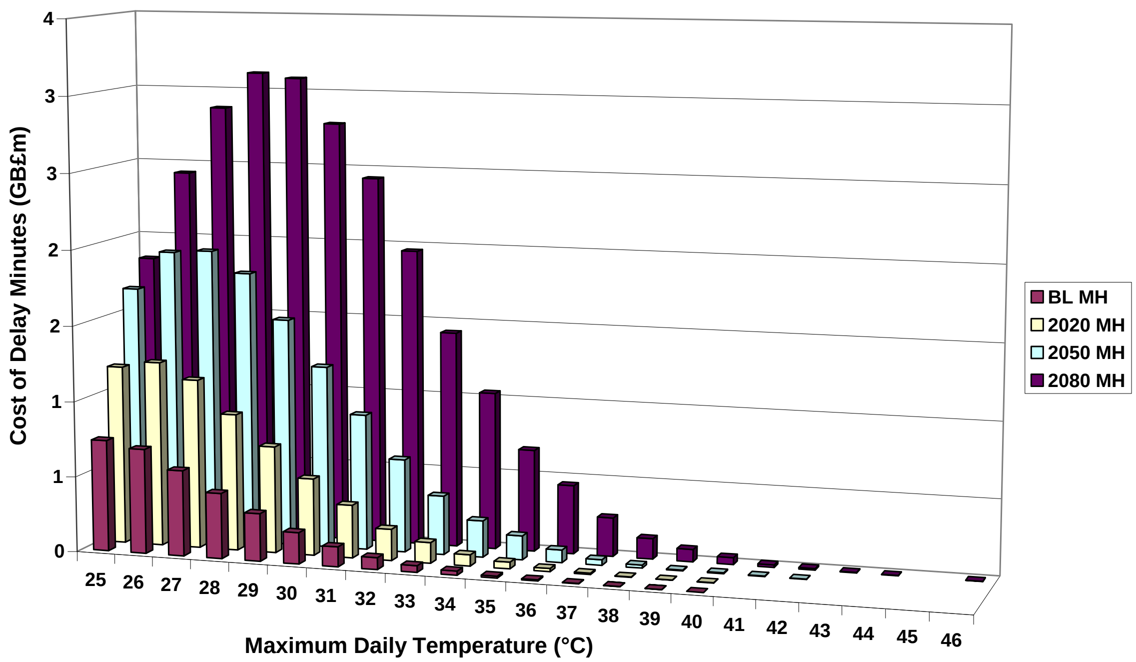


Figure 4.6: The cost (£m) of delay minutes caused on days when the maximum daily ambient air temperature is predicted to reach each 1°C increment associated with the medium high emission scenario in each time series

Table 4.1: The cumulative cost of rail-related delays and buckles occurring on days that have a daily maximum temperature greater than 25°C, each cost is calculated for all 30 years in each time series in the south east region of GB

Time Series	Cause of Delay	Cost (£m)
eBaseline	Buckles	3.3
	Heat Related Delays	3.3
2020 (medium high)	Buckles	6.7
	Heat Related Delays	6.5
2050 (medium high)	Buckles	13.6
	Heat Related Delays	12.5
2080 (medium high)	Buckles	29.0
	Heat Related Delays	24.7

4.1.1 Verifying Results - the 'Normal' Summer 2004

In order to validate the costs calculated and shown in Table 4.1, cost data from the analysis by Hunt *et al.,* (2006) of the hot summer 2003 has been used. In Hunt *et al.,* (2006) comparison was made between the 'normal' summers occurring around the same time and the hot summer 2003, 2004 is specifically analysed as a basis of comparison. This section uses the cost of heat-related delays in 2004 from Hunt *et al.,* (2006) to validate the costs calculated and shown in Table 4.1 for baseline heat-related delays. The hot summer 2003, was an extremely hot summer that caused an exceptional amount of delays, damage and cost. The costs calculated in Hunt *et al.,* (2006) for the extremely hot summer 2003 have been used to compare the costs of future average summers according to climate change predictions. This process provides tangible comparisons to validate baseline calculations and provide context through analogy for costs caused by future temperature predictions. 2003 and 2004 provide satisfactory comparisons because they represent a range of possible summer temperatures in GB, from an "average" summer in 2004 to an "extremely hot summer" in 2003. It has been suggested that the enforcement of excess ESR due to unknown track quality was a problem in 2003, in comparing 2003 with 2004 it is more likely that there was not significant improvement in understanding of the network or the track quality in contrast with a comparison of a more recent year, say 2007.

In 2004, 30,000 delay minutes were attributed to hot weather (Hunt *et al.,*2006) which translates to a total cost of £1.5 million (based on £50 *per* delay minute (Eddowes *et al.,* 2003)). Multiplying this by the 30 years of baseline data gives £45m as the total cost of heat-related delays nationwide. The exact percentage of UK railway contained in the south east was not known at this stage in the study; consequently the national cost is simply split to represent each of the regions, of which there were eleven. The result is a cost of £4.1m for temperature-related delay minutes in the south east based on the above assumptions; this compared with £3.3m calculated using the ADB and EARWIG simulated data. The difference may be attributable to missing heat-related delays that are stored in other sections of the ADB; line-side fires are one example. Also, since buckles cause the most severe delays of all heat-related delays, any non heat-related delays included could have lowered the average delay minutes, therefore, reducing the overall calculated cost. Furthermore, it is likely that the south east of GB will, in general, experience more hot days and more extreme hot days than other regions, it is the region that experiences the hottest driest weather in GB. Thus the south east will have an above average cost associated with heat related delays.

The preliminary study showed that the data contained in the ADB was chronologically accurate enough to be matched with a representative temperature and demonstrate how temperatures were influencing delays. The costs calculated for the south east region showed a favourable comparison with the costs calculated by Hunt *et al*. (2006), which compared costs of the “normal” summer 2004 and the extremely hot summer 2003. Having proved the data to be suitably reliable the next stage was to extend this work to include the rest of GB.

4.2 Results: GB-Wide Heat-Related Delays and Buckled Rails

To recap, more sections of the ADB were made available. These sections related to “all weather related delays”, which included: wind, ice, snow and lightning strikes as well as heat-related delays. The new sections meant that there was more heat-specific data available to form trends. As a result incidents specifically caused by heat could be extracted and analysed. Heat-related delays were extracted from incidents occurring within the months May to September (inclusive); these were grouped by region (north, west, midlands or south (including London). In order to analyse all heat-related delays (including buckles) a filter was applied to the ADB to extract delays described under the terms “buckle”, “heat” and “temperature”. The key words used to extract the heat-specific data from the ADB were established by reading through and searching the ADB for relevant incident descriptions. “Hot”, for example, was not used to describe incidents; “heat” was most common, relating to incidents like “heat ESR”. Once the relevant heat-related information was extracted the data was manually searched to ensure no unrelated data was included. This occurred if a word that contained one of the key words but was unrelated to heat related delays was included in the extracted data – “Lightning strike at Heath Hill” for example would be extracted because it contained the word heat but later would be sorted and removed.

The initial comparison of the ADB data with the corresponding weather data led to the removal of minimum values. The maximum, mean and *SD* were then re-calculated for the delay data in each 1°C increment based on the date of the incident and the corresponding maximum daily ambient air temperature from the representative weather station. Figure 4.7 shows the trend lines for the maximum, mean and *SD* for all regions after removing the minimum values. The maximum, mean and *SD* were used to quantifiably summarise the range of delays caused by heat-related delay events. Figure 4.8 shows the incidents described as “buckled rails” plotted against the corresponding maximum daily temperature. Although no quantification was produced from the data in Figure 4.8, it is important to note how significant buckled rails are in shaping the data, particularly the maximum trend line in Figure 4.7. Figure 4.9 shows the frequency of days with a maximum daily temperature greater than 24°C occurring over the time period that the ADB data contributing to Figures 4.7 and 4.8 was recorded. 25°C is the ambient air temperature that ESR begin to be enforced on low quality track, it is also the temperature that the severity of heat delays and buckles increases based on the evidence in Figures 4.7 and 4.8.

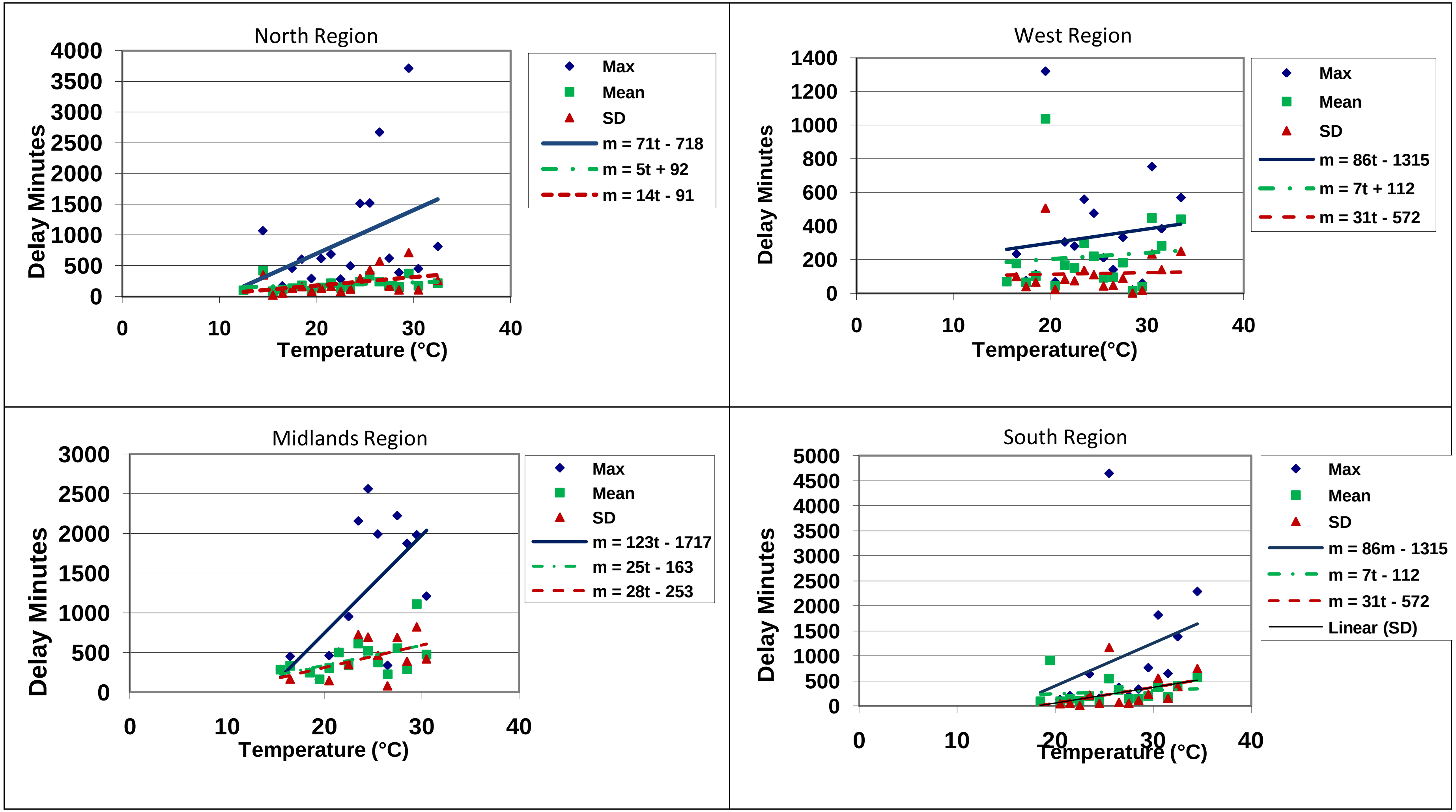


Figure 4.7: Maximum, mean and standard deviation trends in delay minutes of all heat-related incidents from the ADB against the maximum daily temperature on the date of discovery for all regions

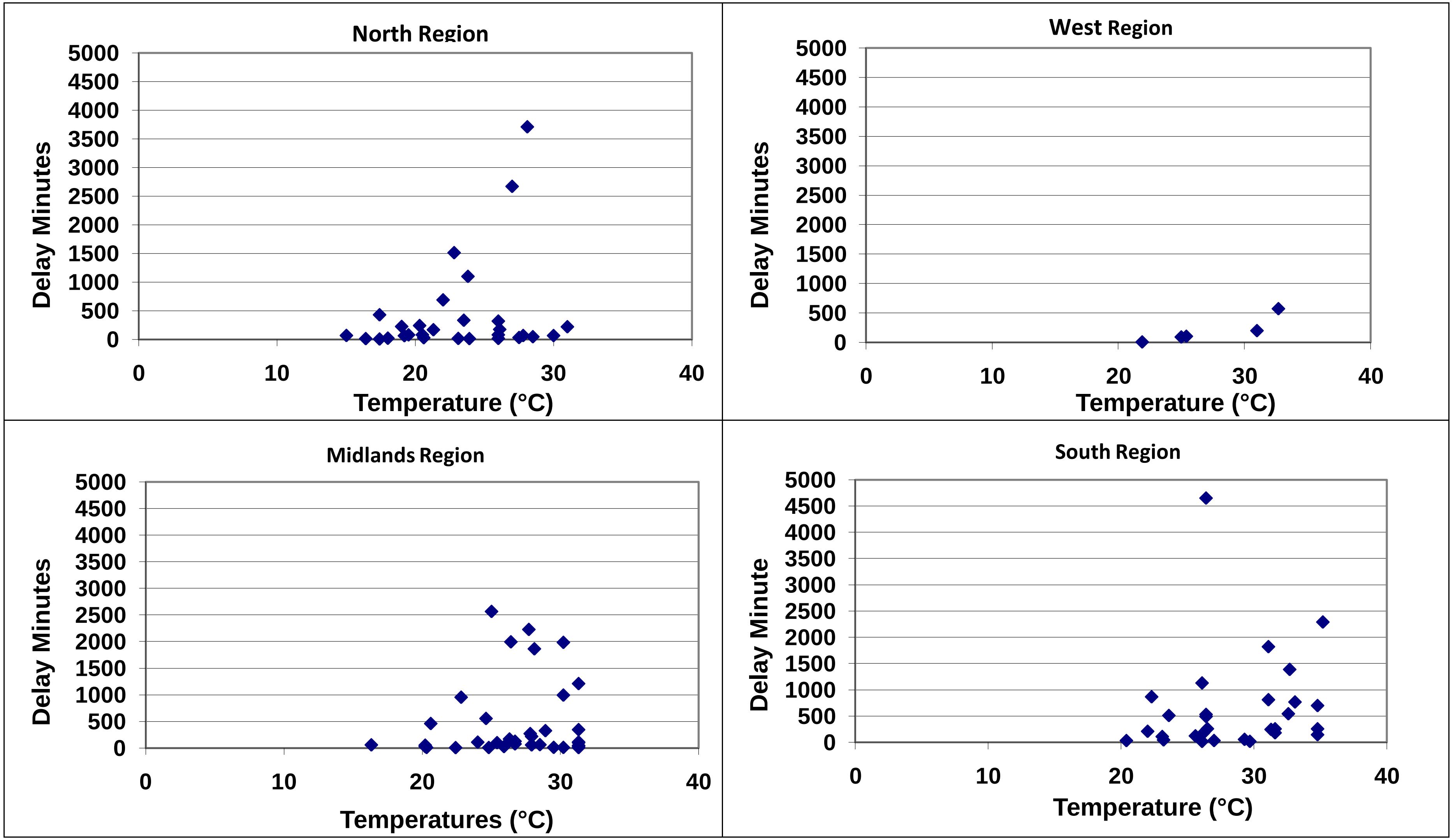


Figure 4.8: Number of delay minutes attributable to “buckle” events recorded in the ADB against the maximum daily temperature

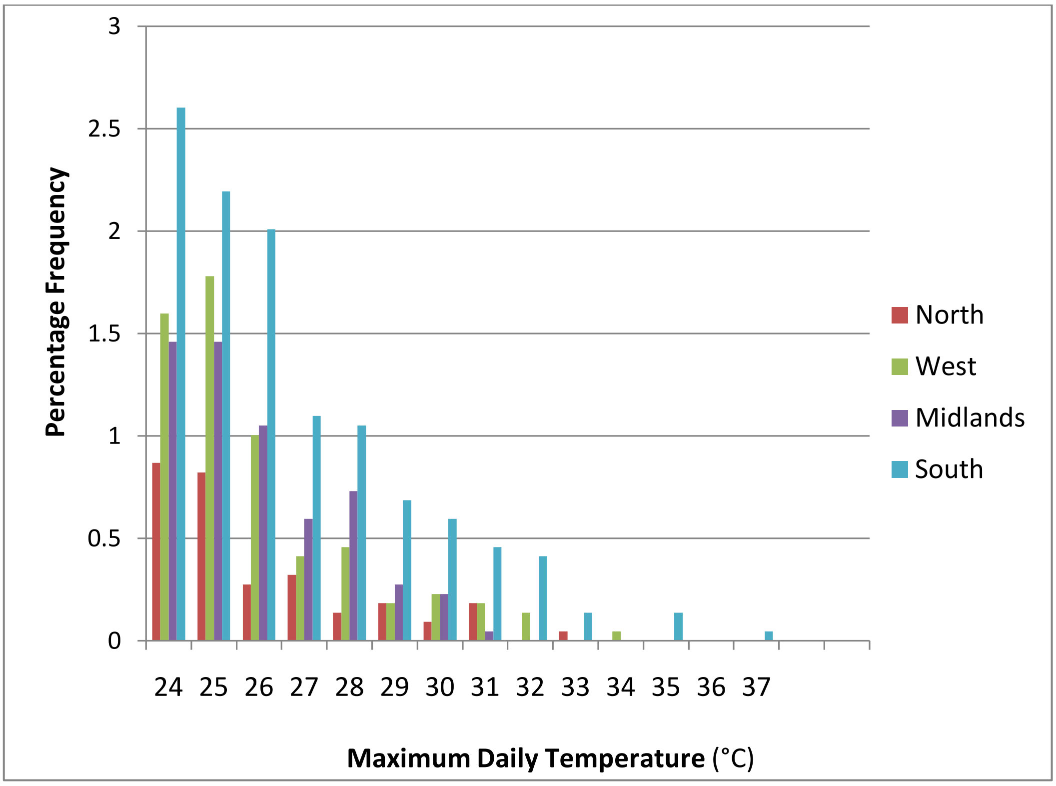


Figure 4.9: Percentage frequency of maximum daily temperatures >24°C from real recorded weather data from each of the regionally representative weather stations

4.2.1 Reliability of Trends

Table 4.2 shows the R^2 and P-value data for the gradient of all trend lines for each region. The initial analysis shows that the relationship is only statistically significant in the midlands region at the 95% accurate level. However, in all regions the removal of one or two data points that were clear outliers immediately improved the significance of the trends, leaving the majority of relationships significant at the 95% level and all within 80%. The outliers were selected from the raw data used to produce the trends in Figure 4.7 and delay events were removed where there were uncommonly high delay minutes attributed to delays on days with lower temperatures than the general trend of the data. However, it was decided to leave all the data in the analysis as there is no justification for the removal of any data points based on the available data in the ADB.

These apparent outliers can be explained through considering both the nature of the railway network and the limitations of the available data for this study. For example, one important factor pertaining to the severity of an incident (in delay minutes) is the location on the network. For example, a buckle in the south region that caused over 4000 delay minutes at ~26°C ambient air temperature happened between Waterloo and Clapham Junction in Central London. This demonstrates that a severe rail buckle that occurs on one of the busiest lines in the country on a weekday will have an enormous impact when compared with a similar buckle on an infrequently used line. This is a critical example demonstrating the difference between the severity of an incident in terms of the damage caused and the severity of an incident as measured by the delay caused to the network. Furthermore, if there were more data available from the ADB then outliers may not be outliers but part of the legitimate data that happen rarely.

Table 4.2: R^2 and P-Values for all trend lines in Figure 4.7

	R^2 (%)			**P-Value (%) (α ≤ 5%)**		
Region	Max	Mean	*SD*	Max	Mean	*SD*
North	20	8	15	5.7	24.3	11.3
West	2	0.7	0.1	57.3	74.0	88.4
Midlands	43	26	21	0.7	5.4	15.8
South	12	2	16	18.2	60.5	15.6

There are clearly results that do not follow the trends shown by most of the data; in the northern region there are a series of heat-related ESR occurring at ~15°C. These all have moderately high delay minutes associated with them (~500 – ~1000). It is possible that the damage may be heat-related but was discovered and/or recorded days after the event occurred. Or that the micrometeorological features of the area meant that there was an area of hotter weather than the regionally representative weather station recorded. These delays significantly alter all the trend lines in the north region and are thought to be the main cause of poor trend significance for this set of data.

Overall, if more ADB data were available the resolution of regions could be reduced and apparent outliers would not be such a frequent occurrence. However, the results from removing outliers showed that the main body of data is reliable, and that in the context of the research and network operations there is no justification for removing these outliers, which are a significant contribution to overall delays and costs.

4.2.2 Future Costs of Heat-Related Delays across GB

Future weather trend predictions show that across GB high temperatures that cause damage and delays are projected to increase (Figure 4.10), a lower temperature threshold of 18.5°C was chosen based on the temperature range that buckles occurred in the preliminary review of the South East (also see Appendices 3 and 4) . The magnitude of delays can be estimated based on the mean trend lines from the ADB analysis of heat related delays for each region (Figure 4.7). Comparing the values contributing to the maximum trend line in Figure 4.7 and the buckles in Figure 4.8 demonstrates that the most severe consequence of high temperatures is buckled rails. The most severe buckles start to occur at ambient air temperatures >25°C, although there are still some severe buckles occurring at >20°C and in the north region some minor buckles occurring as low as 15°C. This is perhaps a consequence of the representative weather station offering an *overview* of regional temperature. In a study of this geographical scale, it is impossible to account for the local microclimate which will have a major effect on local disruption. Other possible causes are wrongly recorded descriptions or dates of events in the ADB or simply very poorly maintained track. In order to account for the variability in the ADB data, variation bars are included in all costing calculations; this will also ensure that the impact of severe buckles is not diminished.

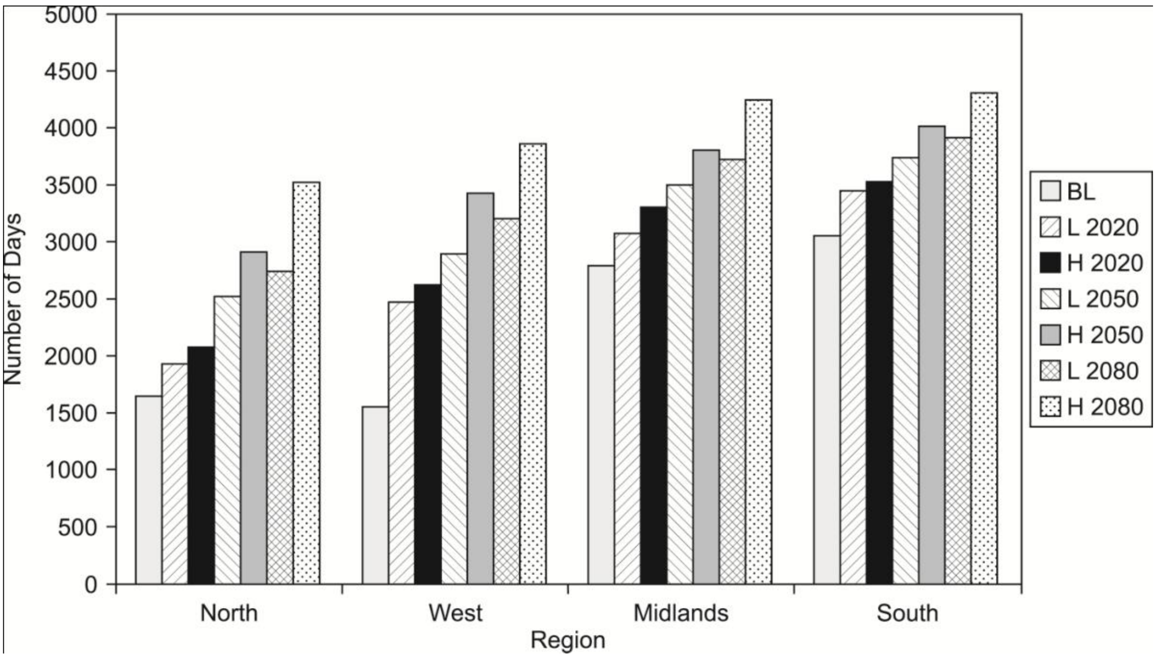


Figure 4.10: Number of days in 30-year time period having a maximum daily temperature ≥18.5°C, simulated by EARWIG

Table 4.3 summarises the data inputs for Figure 4.7 and Chapter 3 defines the assumptions made for establishing costs from the trends in Figure 4.7. Applying these assumptions to the mean linear trends produces the estimated number of delay minutes for a year in each climate change scenario for each region. Equation 4.2 converts these into cumulative costs, which are summarised in Figure 4.11:

$$C = m\,d\,p\,c \tag{4.2}$$

where: *C* is the total cost for the time series and emissions scenario, *m* is the delay minutes associated with a day of maximum daily temperature *t* (from the mean trends in Figure 4.7), *d* is the number of days each maximum daily temperature is expected to occur on an average year, *p* is the probability that a delay minute event could happen on an average day and *c* is the average cost of a delay minute £73.47 (Burr *et al.,* 2008). The variation bars in Figure 4.11 are from the ± x-axis variation from the trend line equations for each region, summarised in Table 4.3.

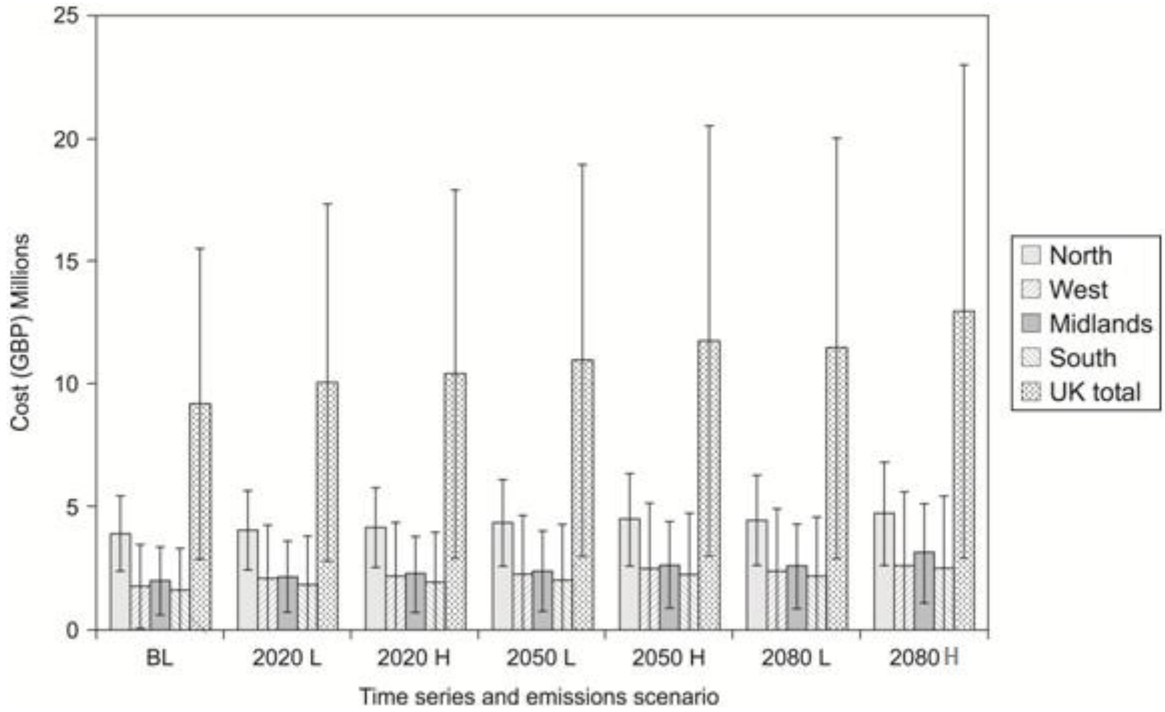


Figure 4.11: The annual cost (GBP (£) m) of delay minutes caused by heat-related delays, based on trends from real recorded ADB data and maximum daily temperature data

Table 4.3: Summary of regional trend data, including ± variability around *n* from the equations in Figure 4.7, trend lines from heat-related delays

Region	Max *n*± trend values	Mean *n*± trend values	*SD n*± trend values	Incident count	Average incidents per day	Temperature range of incidents
North	35	4	8	337	2.2	13.1 – 33
West	15	11	6	165	1.1	15.8 – 34.4
Midlands	39	12	18	93	0.6	16.4 – 31.3
South	61	13	21	120	0.8	18.7 – 35.2

4.2.3 Verifying the Results – the Extremely Hot Summer 2003 and the 'Normal' Summer 2004

To provide baseline costs for heat-related delays, the delays experienced in the extremely hot year 2003 and the "normal" summer of 2004 (Hunt *et al.,* 2006) were contrasted. 2004 was considered to be a "normal" year for heat-related delays, however there are a number of factors which should be remembered in making this assumption. Firstly, 2004 was a normal summer following 2003 - an exceptionally hot summer. Due to the phenomenon of buckle harvesting (Chapman *et al.,* 2008) any weakened rails are likely to have buckled in the August 2003 heatwave, so less than a "normal" year of buckles might be expected in 2004. In addition, buckled rails are responsible for the most severe heat-related delays, which would result in an overall reduction of annual heat-related delay minutes in 2004. This effect is evident in the raw data from the ADB. For example, only one heat-related delay (including buckles) was recorded in Wales in 2004. Secondly, the annual average trend lines calculated for each region in this study are based on an average of 30 years of baseline weather data. During this time there will have been extremely hot, cooler and normal summers, resulting in an average of all summers in a 30 year period. From this evidence it is suggested that 2004 should be considered to be at the lower end in severity for heat-related delays where as 2003 can be considered to be at the upper end. According to Hunt *et al.* (2006), the hot summer 2003 caused 165,000 delay minutes, with the average cost of a delay minute in this study considered to be £73.47 (Burr *et al.,* 2008). The cost of heat-related delays in summer 2003 and 2004 are estimated to be £12.1m and £2.2m, respectively. The total cost of baseline heat-related delay minutes based on the average trend line from this study was £9.2m with a minimum cost of £3m and a maximum cost of £15.5m, based on the ± variation in the trends.

According to the future predictions for the cost of heat-related delays in Table 4.4, the cost of the hot summer 2003 will become an average summer in the 2050s under the high emissions scenario. For the low emissions scenario, summer 2003 will become average by the 2080s. If there is to be an extremely hot summer the future equivalent of the extremely hot summer 2003, the cost will be nearly double that at £23m, under the high emissions scenario in the 2080s. Future climate impacts will be further contextualised using spatial analogies from across Europe, the USA and Australia. These spatial analogies will also serve to make recommendations for future network structuring, SFT and maintenance regimes to mitigate against buckles and reduce the need for often costly ESR.

Table 4.4: UK-wide annual costs for heat-related delays, based on the mean trend line from Figure 4.7

	mean minus trend variation (GBPm)	Mean (GBPm)	mean plus trend variation (GBPm)
BL	3	9.2	15.5
2020 L	3.1	10.1	17.3
2020 H	3.2	10.4	17.9
2050 L	3.3	10.9	18.9
2050 H	3.5	11.7	20.5
2080 L	3.4	11.5	20.0
2080 H	3.8	13.0	23.0

4.2.4 Normalising the Results

Each of the four regions used in this analysis vary in size and by the amount of rail contained with their boundaries. A large region like the north region could be expected to have more delays because there are more route kilometres contained in the region. Normalising the total delays experienced in a region by the density of rail in the region gives an idea of the relative cost of heat related delays in the region and thus an idea of relative investment requirements for improvements. In order to assess the relative severity of the impact of climate change on heat-related delays in each region, the cumulative costs have been normalised as a ratio to the length of rail (km) and the area of the region (km^2) (Table 4.5).

The results of the costs as a ratio of the area of each region and length of rail in each region are shown in Figure 4.12, which clearly demonstrates that heat-related delays have most impact *per* km of rail *per* km^2 in the south region. Up to 0.16GBP *per* year could be spent *per* km of rail in each km^2 of land in high emissions scenario in the 2080s, compared with up to 0.012GBP for the same in the north region. The disparity in relative cost should be expected to be larger when the true cost of a delay minute in each region is used in calculations. The costs of delays in rural areas are less than city commuter lines; the time of day also has significant bearing on the true cost of a delay minute. Burr *et al.,* (2008) acknowledge that £73.47 is likely to underestimate many delay events; nevertheless, in the context of a nationwide study like this using the mean national cost is adequate. This cost of a delay minute does not include the expense of maintenance, materials or labour that are incurred due to an incident. As a result there is no viable method at present of producing a full cost-benefit analysis of changing future mitigation and maintenance regimes.

Table 4.5: Length of railway routes and area of each region

Region	length of rail (km)	area km^2
North	6,800	109,000
West	3,100	46,000
Midlands	4,300	48,000
South	3,300	21,000

It would also be useful to normalise the results using the number of trains travelling and the total time travelled within each region. Network Rail publishes information on the number of trains operating on lines and routes as part of their annual business plan, however the lines and routes defined by Network Rail do not correspond with the regions defined in Figure 3.1.

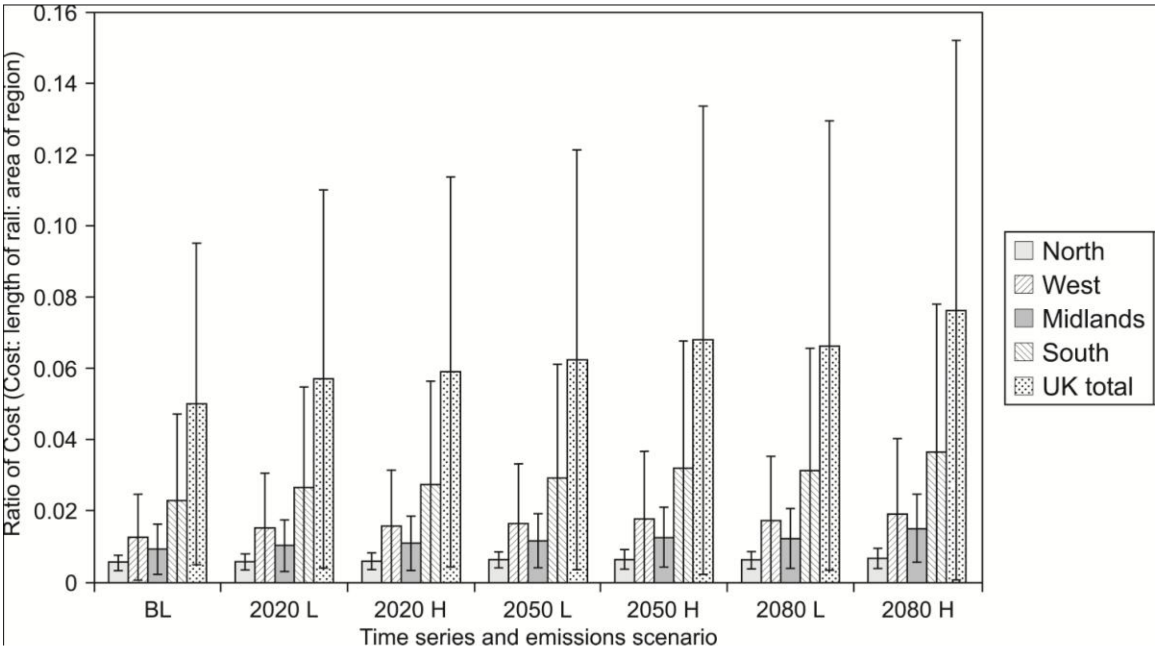


Figure 4.12: The annual cost (GBP) (from Figure 4.11) of delay minutes caused by future heat profiles, as a ratio to the length of rail (km) and area of the region (km^2) (Table 4.5)

4.2.5 Discussion

This analysis has estimated that the cost of the predicted impact of baseline weather on an average year in GB is £9.2m with cooler summers costing a minimum of £3m and extremely hot summers costing up to £15.5m (Table 4.4). Using analogues, this is comparable to the impact of the extremely hot summer of

2003 and the temperate summer of 2004, which produced a range of costs between £2.2m and £12.1m respectively. Due to predicted climate change scenarios this cost is set to increase to up to £23m (at current prices) by the 2080s under the worst case scenario of high emissions, based on the average trend line of real recorded ADB data.

The costs in this study are entirely based on the assumption that £73.47 is the average cost of a delay minute in GB. However, the cost of delays in the south east, London and other major cities are likely to be considerably more and it is in these key commuter and business travel areas that more delay minutes are caused by incidents. For this reason, it is highly likely that that the costs incurred for heat-related delays could be far higher than estimated in this thesis. Only when a more complete method of costing delay minutes has been devised can a more accurate figure for the cost of climate related damage, delays and mitigation be possible.

Although costs have been produced, due to the nature of the data inputs these costs should be considered illustrative, rather than definitive of situations that could arise due to future projections of anthropogenic climate change.

CHAPTER 5

RESULTS OF THE STUDY ON ICE AND SNOW-RELATED DELAYS

The methodology used to quantify the effects of cold winter weather, ice and snow on the railway network in GB is described in Chapter 3. This Chapter details the results from this methodology, which is used as a framework for the Chapter to explain the results in full. Further to this, the results are justified through statistical significance tests and finally, summarised in an analysis and discussion. The focus of this Chapter is delays caused by cold weather, ice and snow; cold-related tension cracks in CWR are not covered in detail in this Chapter. Chapter 6 covers the effects of milder winters and hotter summers and the impact of seasonal temperature change on the SFT, rail buckles and cold-related tension cracks.

To recap:

- Ice, snow and cold weather related delay events were extracted from the ADB and compared with minimum daily temperature data from the regionally representative weather stations;
- The maximum, mean and standard deviation of delay event severity was taken for 1°C temperature intervals. The frequency of delay events *per* 1°C temperature interval was also taken. These plots showed that the severity and frequency of delay events across the regions were highest in temperature ranges around 0°C;
- The temperature range causing the majority and most severe delays was extracted and delay severity was split into 50 delay minute intervals. The

frequency of delay events within each delay severity was calculated and plotted, forming negative power curves;

- the frequency steps of delay events causing each 50 delay minute interval of delay was changed to a probability using the quantity of ADB data points contributing to the trend line. This probability was multiplied by the quantity of days in each regionally defined temperature range (causing the majority and most severe delays) according to future climate projections, finally this was multiplied by the number of delay incidents occurring *per* day based on ADB delay frequency and the number of cold days occurring within each regionally defined temperature range (causing the majority and most severe delays) from each regionally representative weather station;
- This frequency string is the projected number of delay days occurring in future climate scenarios and through the negative power curve trends for each region, the graph can be translated into the projected severity of future cold related delays delay events. The area under each trend (from integrating the trend curve formulae) is the total delays experienced in a future climate time series or an "average" winter within a future climate time series. Translated into a cost through the average cost of a delay minute.

5.1 Trends in Ice and Snow-Related Delays

To establish the impact that ice and snow has on the railways, trends were formed from delay data in the ADB and the corresponding minimum daily temperature from the regionally representative Met Office weather stations. This section documents how this was achieved and the trends that were formed from the data.

The raw data from the ADB was filtered to extract delay incidents that related to “ice”, “cold” and “snow”. There was also a section of the updated ADB made available (mid 2007 – February 2009). There was no need for this to be filtered as the nature of the new ADB meant that this section only contained incidents that related to ice, snow and cold delays. Each delay event was assigned a region based on the start and end location of the route the delay event occurred on. All delay events were assigned a minimum daily temperature based on the date the delay event was recorded. The delay minutes associated with each cold day were divided into 1°C ambient air temperature increments and the maximum, minimum, mean and *SD* of the severity in delay minutes were calculated for each increment. Figure 5.1 shows the plots for each region. The frequency of delay events for each 1°C increment was also plotted (Figure 5.2). In all regions the most severe and the highest frequency of delays were occurring in a temperature range around 0°C. Outside the temperature range causing the most severe and frequent delays, the frequency and severity of delays was less and tended to drop off the further from the temperature range that caused the majority and most severe ice and snow-related delays.

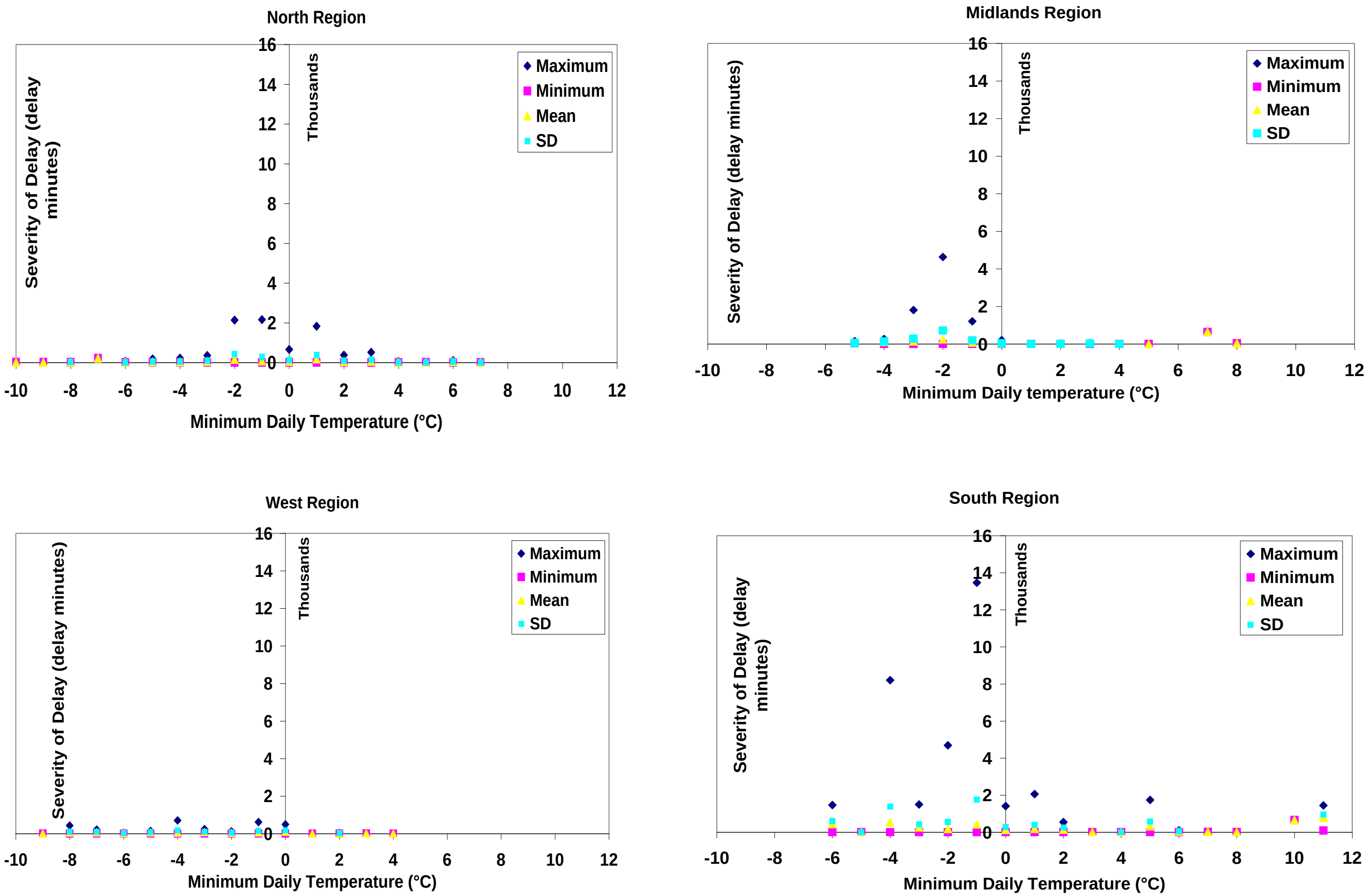


Figure 5.1: Maximum, minimum, mean and standard deviation of ADB delay data summarised in 1°C ambient air temperature increments for each region

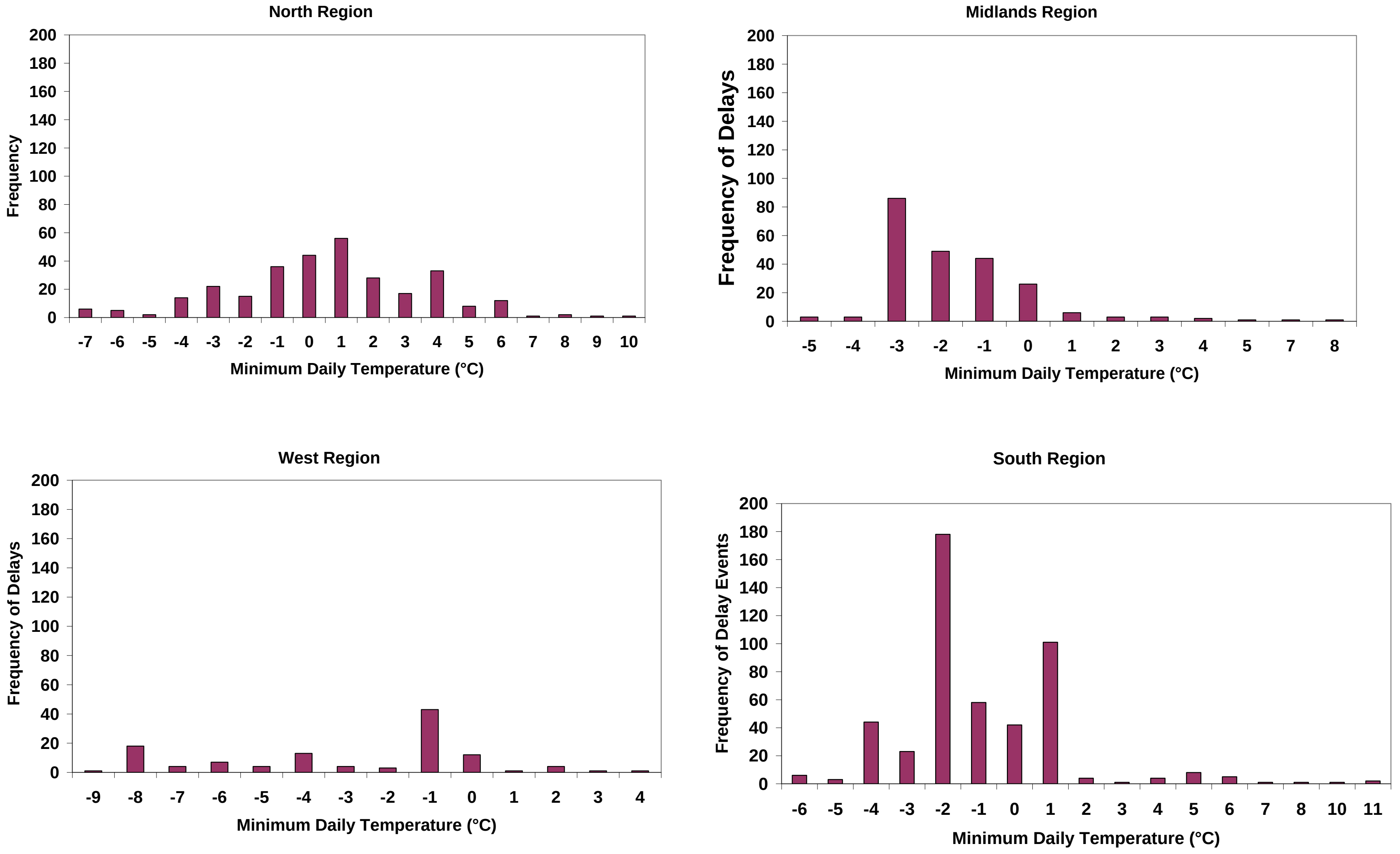


Figure 5.2: Frequency of delay events from ADB data occurring within 1°C ambient air temperature increments for each region

The most severe and frequent delays occurred around 0°C. Figure 5.3 demonstrates that ice is most slippery at 0°C. furthermore, it has been observed that ice can form on a rail at temperature slightly higher than 0°C. Ice formation causing low adhesion and poor conduction connection both result in delays on the railway network. The percentage frequency of days with a minimum daily temperature <0°C is shown in Figure 5.4.

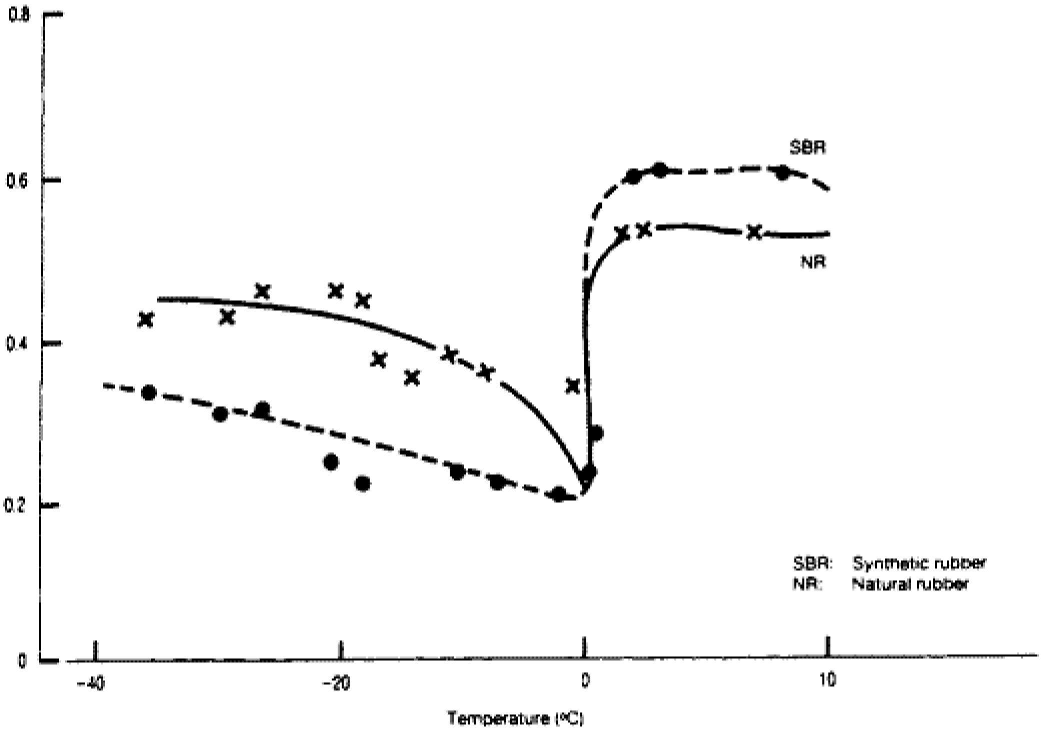


Figure 5.3: The frictional resistance of pneumatic tyres on tarmac at varying temperatures (Moore, D. F., 1975)

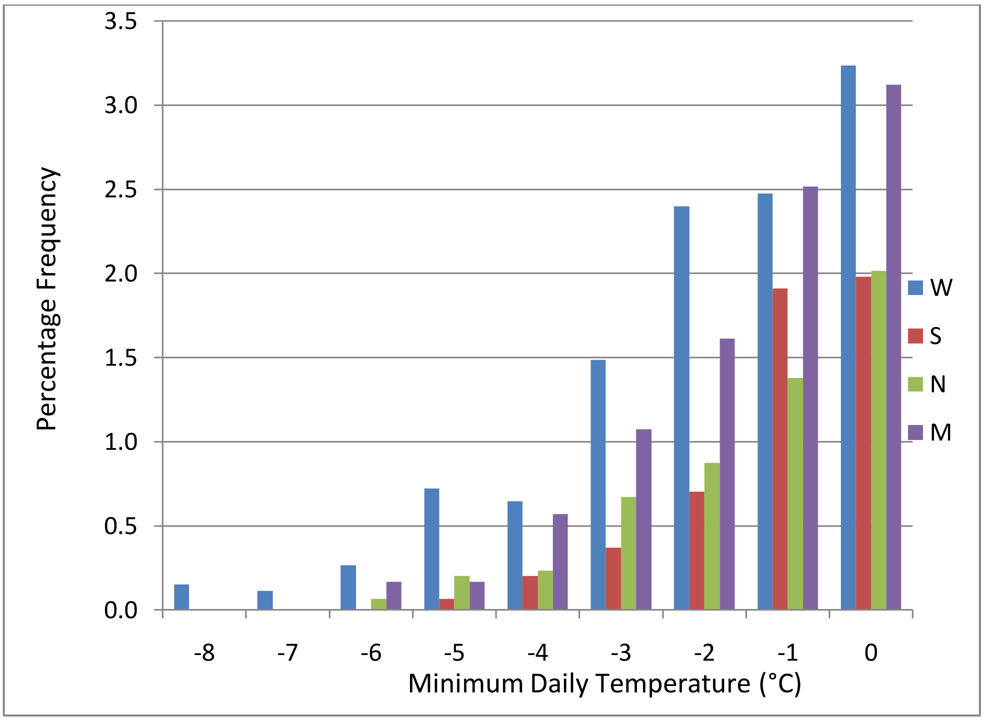


Figure 5.4: Frequency of days with minimum daily temperatures less than 0°C from the regionally representative weather stations over a period of ten years

In order to establish useful trends ADB data occurring on days with a minimum daily temperature within the temperature range causing the majority and most severe delays (Table 5.1) was split into 50-delay minute increments based on the frequency and severity of the delay events (Figures 5.1 and 5.2). The frequency of delay events in each increment of delay severity was calculated and plotted. This was performed for the temperature ranges defined in Table 5.1 and the temperature ranges greater and smaller than these temperature ranges (shown in Figure 5.5, 5.6a and 5.6b) for all regions. In comparing Figures 5.5 and 5.6a/b, the trend lines in 5.6a/b are not showing the same arrangement across the four regions as the trends in Figure 5.5.

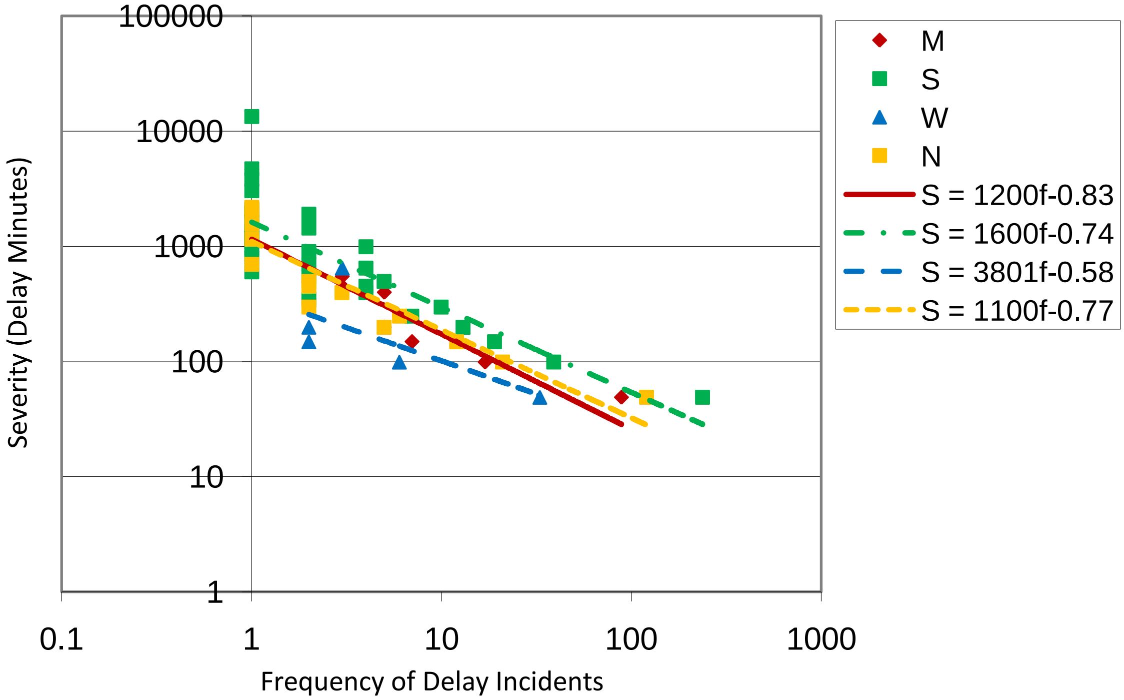
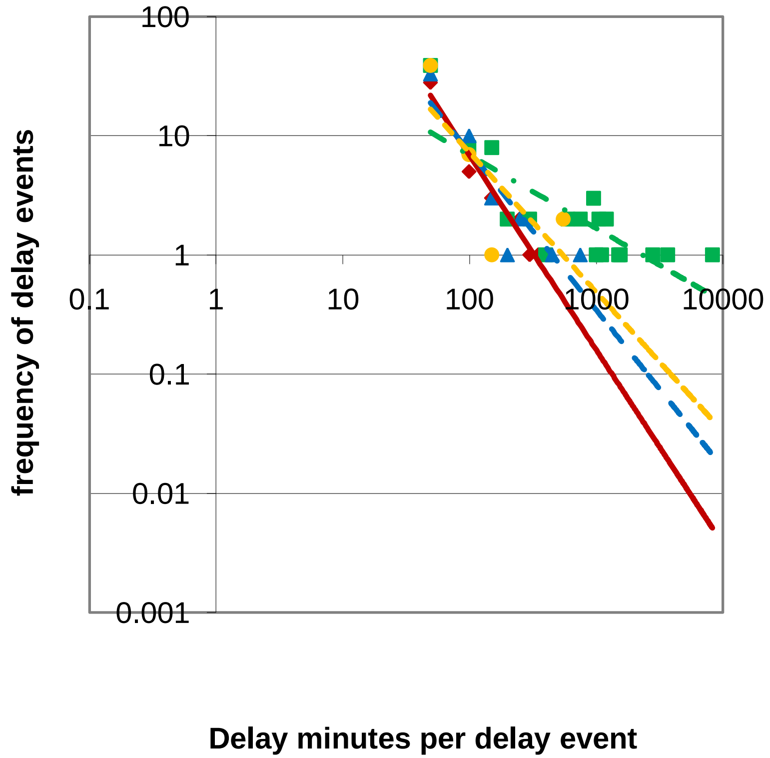


Figure 5.5: Frequency curves for the severity of delays occurring at temperatures within the regionally defined temperature range that caused the majority and most severe ice and snow-related delays



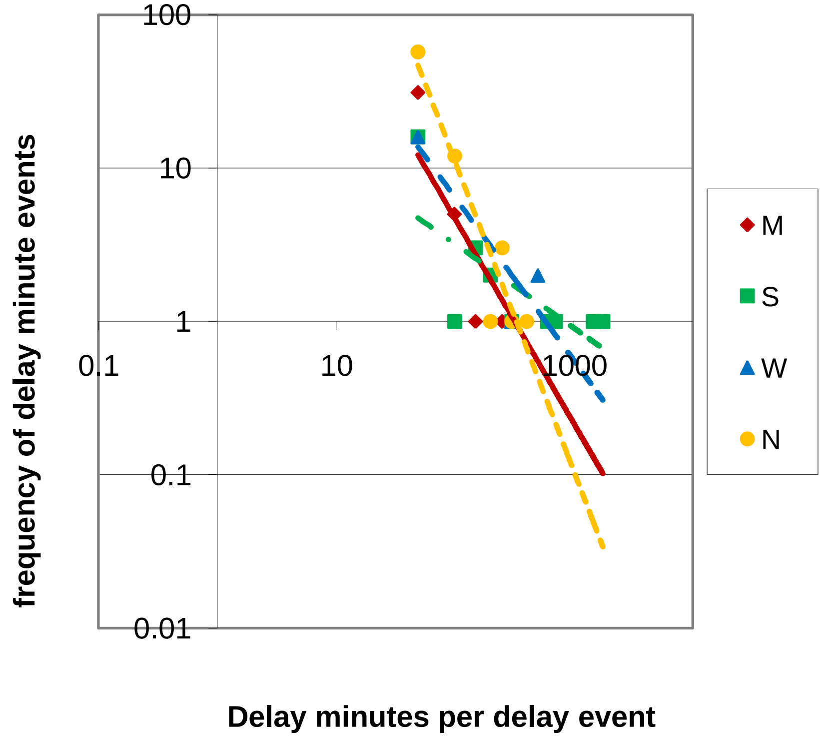


Figure 5.6a: Frequency curves for the severity of delays occurring at temperatures less than the regionally defined temperature range (Table 5.1)

Figure 5.6 b: Frequency curves for the severity of delays occurring at temperatures greater than the regionally defined temperature range (Table 5.1)

The similarity in gradient of the curves in Figure 5.5, when plotted on a logarithmic scale, suggests that when the temperature ranges causing the majority and most severe ice and snow-related delays occur, GB railway network is demonstrating similar and consistent reactions to the weather. This is to be expected, as the railway network is not actively constructed differently by region. Also, the weather conditions that cause a high quantity of - and very severe - delays, occur in a narrow temperature range that is consistent across the regions and consistent with evidence from Smith (1990) and the coefficient of friction of ice at varying temperatures (Figure 5.3). For the temperature ranges shown in Figures 5.6a and 5.6b the disorderly trend plots suggest that the data is not consistent enough to form reasonable and reliable trends. This may be from wrongly recorded delay data in the ADB or micrometeorological effects on sections of the railway that create weather conditions that do not match those recorded by the representative weather station.

The effects of using real recorded field data from the ADB and having a weather station that is representative of a large area is apparent in the slight variation in the temperature range chosen to be the central temperature range for each region. It has been well documented thus far in this thesis of the potential variability from the data sets used, however the consistency of the trend arrangement of the four regions in Figure 5.5 is testament to the overall accuracy of the ADB data and the regionally representative weather stations.

The trend lines in Figure 5.5 are considered representative of the effects of ice and snow on the railway infrastructure in each region. Thus these trends have been used to predict the impact of future cold weather, ice and snow on the railways. Equation (5.1) shows the negative power curve formation of the trend lines in Figure 5.5:

$$S = nf_1{}^{k} \tag{5.1}$$

where, n and k are constants (Table 5.1), S is the severity of a delay event (in delay minutes) and f_1 is the frequency of delay events. n and k are numerically defined for each region in Figure 5.5 and Table 5.1. Table 5.1 also contains the trend line formulae, temperature range containing the highest frequency and most severe delays by region and the number of raw data ADB data points contributing to the trend lines in Figure 5.5.

Table 5.1: Data relating to formation of ice and snow-related costs in equation (5.1), including the regionally defined temperature range causing the majority and most severe cold-related delays (4)

	Temperature range (°C)	n	k	Number of raw ADB data points
S	-2 → 1	1600	-0.74	482
M	-3→ -1	1200	-0.83	228
W	-1 → 0	380	-0.58	117
N	-2 → 2	1100	-0.77	303

5.2 Reliability of Trends

The R^2 and P-values were calculated by taking the natural log of the frequency and severity data inputs for the delay events in Figure 5.5, shown in Table 5.2. The R^2 values suggest reasonably strong trends for all regions, except the west region. Generally, the strength of the trend follows the quantity of raw data input. The west region has a very low quantity of raw data compared with the other regions. Also relating back to Figures 5.1 and 5.2, the spread of data from the delay incidents in the west regions is very wide and as a result it was harder to establish a temperature range that was clearly causing the majority and the most severe delay incidents than it was with the other regions. The south region also has a slightly lower trend significance than the north and west regions. This can be explained by the long tail on the trend distribution, where the south region has experienced several one-off delay incidents that have very high delay minutes associated. There is no justification for removing any data outliers as one-off extreme events are a feature of delays on the railway network. A feature that is illustrated by the negative power curve trend lines, whereby there is a high number of minor delays and a low number of high delay minute delays. Delays in the south region are likely to be more severe because of capacity issues, a heavily used network and very full trains, which describes the long tail of a small number of delays causing high delay minutes. Furthermore, much of the south region is powered by conductor rail which is particularly susceptible to delays caused by the presence of ice and snow.

Table 5.2: R^2 and P-values relating to the baseline trend lines in Figure 5.5

Region	**R^2**	**P-value**
South	0.75	2.1×10^{-11}
Midlands	0.83	5.2×10^{-8}
West	0.60	0.13
North	0.89	1×10^{-7}

5.3 Costing Future Cold Delays

EARWIG was used to simulate minimum daily temperature profiles for the Low and High emissions scenarios across the three time series. The daily minimum temperature data series were cropped to represent the frequency of days with a minimum daily temperature within the regionally defined temperature range (Table 5.1) causing the highest frequency and most severe ice and snow related delays. Figure 5.7 shows how the number of days causing the majority and most severe ice and snow-related delays is projected to change.

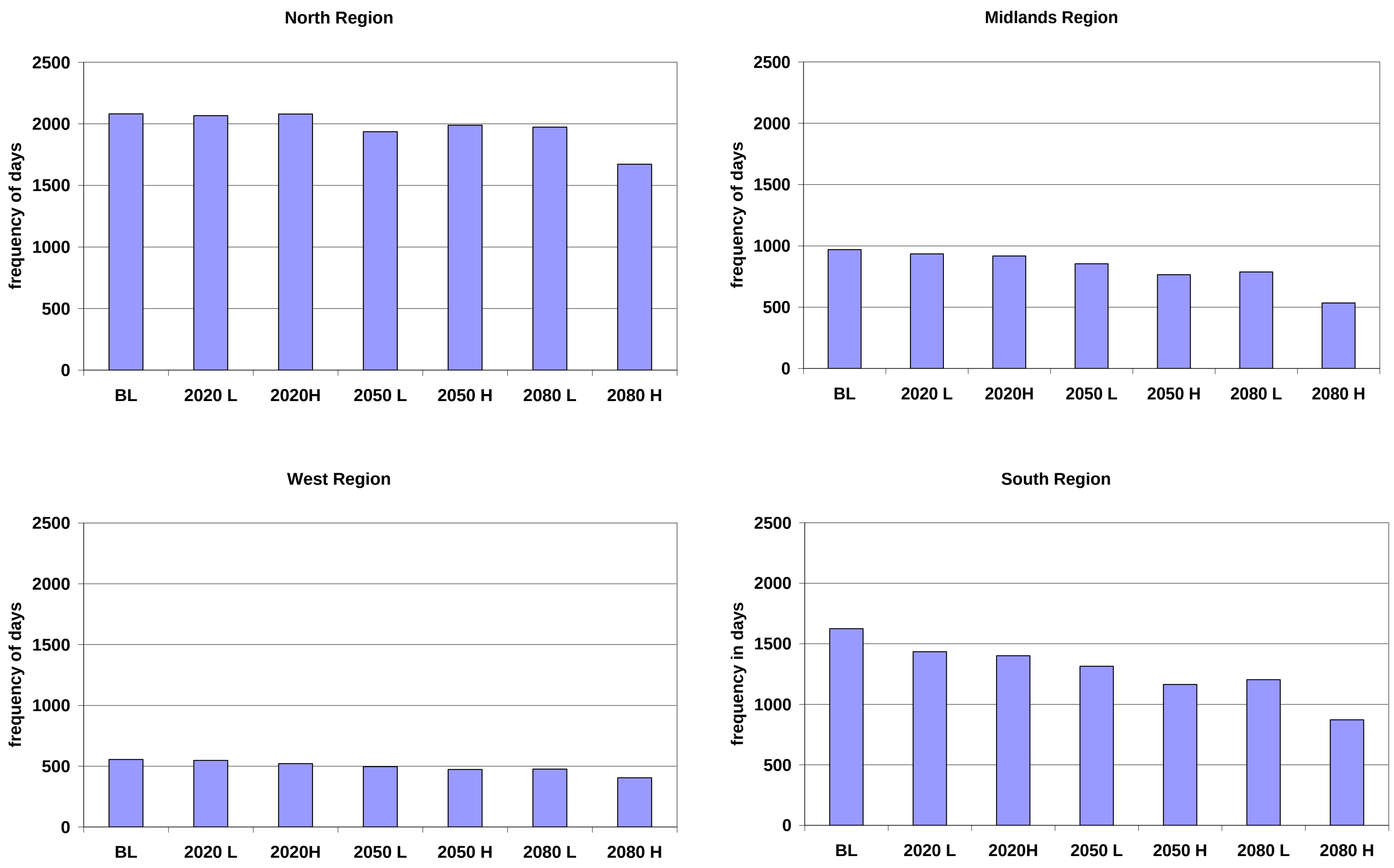


Figure 5.7: EARWIG simulated data for future frequencies of the temperature ranges (Table 5.1) for each region

For each regionally defined temperature range there is little change under the low emissions scenario. For the more northerly regions there is also little change under the high emissions scenario, until the 2080s. The south region is predicted to experience a steady decline in the number of cold days causing the majority and most severe ice and snow delays. However, as with the other regions the reduction starts slowly in the 2020s under both the low and high emissions scenario and 2050s under the low emissions scenario but by the 2080s under the high emissions scenario the south region (the region that experiences the most severe ice and snow delays) is predicted to experience approximately 50% reduction in cold days.

The trend curves in Figure 5.5 represent the infrastructural and operational response of the railway network to the presence of cold weather, ice and snow. In Figure 5.5 the x-axis shows the frequency of delay incidents (f_1 in equation (5.1)), for f_1 to be a unitless likelihood of the severity of future delay events, the probability of a delay event causing the represented severity of delays was calculated using the total number of raw ADB data points in Table 5.1. The probability based frequency (formerly f_1 in Figure 5.5) is represented by f_2 in equation (5.2).

$$N = f_2 pd \tag{5.2}$$

In order to evaluate a projected response of the railway network to future climate projections, the x-axis of the trends in Figure 5.5 must be changed to represent the frequency of future delay events based on the minimum daily temperature profile of future projections. The information sources required for this are:

- f_2, the variable that links the frequency of minimum temperature delay days with the delay severity (from the trends in Figure 5.5)
- d, the potential number of delay days for future climate projections have been extracted from future daily minimum temperature projections from EARWIG, this is the data presented in Figure 5.7
- p, the number of delay events that occurred *per* day for the quantity of minimum daily temperature days within each regionally defined temperature range (causing the majority and most severe delays) evaluated from the cold delay data from the ADB and regionally representative weather station data (shown in Table 5.3)

Table 5.3: Defining p (the probability of a delay event happening on a day within the regional temperature ranges) in equation (5.2), for each region

Region	Number of raw ADB data points in “temperature range” column (a)	Quantity of cold days in “temperature range” from each regionally defined weather station column (b)	Mean number of delay events *per* day p equation (5.2) (p=a/b)
S	377	261	1.44
M	148	193	1.3
W	46	143	0.32
N	179	286	0.6

The evaluation of equation (5.2) from the data described produces new values for the x-axis in Figure 5.5, which represent the severity of delay events caused on the future projected ice and snow delay days, based on the ADB trends.

This process was performed for the Low and High emissions scenarios for all time series. Equation (5.1) was integrated to give the area under each regionally defined trend and the equation numerically solved with N from equation (5.2) in place of f_1 in equation (5.1) for the different values for future climate projections of d in equation (5.2).

The total costs of delays caused by ice and snow based on the future projected frequency of cold delay days, is shown in Figure 5.8. The costs are derived from the total delay minutes attributable to cold delay days (from the integration of the trends from Figure 5.5 and equation (5.1)) evaluated in relation to climate change projections from EARWIG) multiplied by the mean cost of a delay minute (£73.47, Burr *et al.,* 2006).

5.4 Results and Discussion

Climate change predictions show that future winters will become warmer, while the temperature ranges which cause the majority of - and most severe - ice and snow-related delays will remain similar in frequency in the coming decades. The south region is predicted to experience the largest reduction in ice and snow delay days. Figure 5.7 shows that for the south region the temperatures causing the majority and most severe ice and snow-related delays will half by 2080, according to the high emissions scenario. Whereas, in the north region the most damaging temperature range will have reduced by 20% by the 2080s high emissions scenario, it is also noteworthy that there is very little change in the regional temperature ranges for the north until the 2080s. According to future scenarios, ice and snow-related delay costs are not likely to reduce until 2080 in the north region under the high emissions scenario and by the 2050s in the west and midlands regions, under the high emissions scenario. However, predictions suggest a slow then growing decline across the emissions scenarios and time series in the cost of ice and snow delays in the south region in the latter time series under the high emissions scenario.

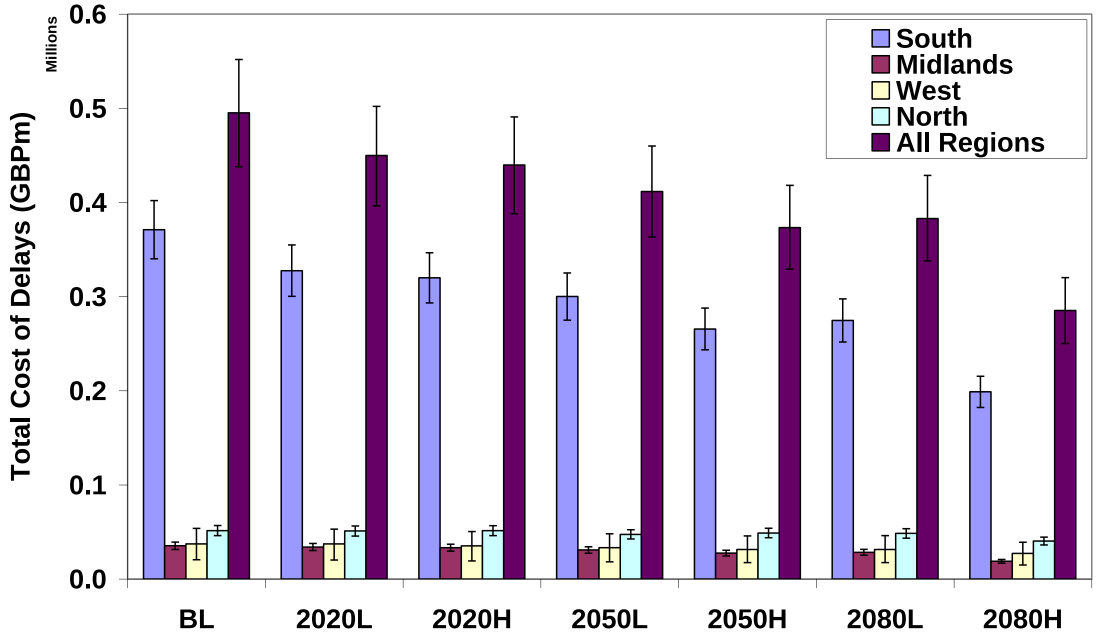


Figure 5.8: Ice and snow-related costs for the regional temperature ranges in Table 5.1

Despite the north region being the coldest region in GB, the south is more frequently and more severely affected by ice and snow-related delays. This is likely due to the extensive use of the conductor rail as a power source across the south. Although conductor rail infrastructure is present in the Mersey area (an area in the north region), only a very small percentage of the regional network as a whole is powered by this method. In addition, the majority of lines in the south are used extensively by commuters, on lines that operate near to capacity, which means that overnight ice formation affecting the morning commute can cause very severe delays. Relating back to the ADB data, the delay incident causing over 13,000 delay minutes in the south region occurred due to heavy snow in the cold winter 2008/2009, between a location in Sussex and Victoria station. Based on the average cost of a delay minute (£73.47) *per* delay minute (Burr *et al.,* 2008), that delay alone would cost around £962,000. From the annual costs in Figure 5.8 and Table 5.4, one incident of this magnitude would triple the annual cost of delays occurring on days when the minimum daily temperature is within the regional temperature ranges under the baseline scenarios. Nevertheless, this delay was associated with a very cold winter and so the severity of this delay cannot be considered “typical”, yet it represents what can occur during spells of adverse weather. The method used to establish trends in the data meant that very extreme data points like this one contribute to the trends but do not define them.

Table 5.4: Total costs of ice and snow-related delays occurring when the minimum daily temperature is within the regionally defined temperature ranges

Time series, emissions scenario	trend minus variation[4] (£k)	Annual cost (£k)	trend plus variation (£k)	~% reduction from baseline cost
BL	440	500	550	NA
2020L	400	450	500	10
2020H	390	440	490	12
2050L	360	410	460	18
2050H	330	370	420	26
2080L	340	380	430	24
2080H	250	290	320	42

The temperature range at which the majority and most severe delay events occur varies slightly for all regions. It is believed that the slight variation is due to both the location of some of the representative weather stations and the nature of the infrastructure in each region. Although the railway network across GB is fundamentally the same (with the exception of the south region which is powered mostly by conductor rail), some areas may be treated slightly differently to alleviate the types of temperature delay they are most prone to. Variation in the temperature range seen to cause the majority and most severe ice and snow related-delays (Figures 5.1 and 5.2) may also be due to the location of the

[4] The variation is defined from the regression statistics from the regionally defined trend lines, Figure 5.3

weather station; although considered generally representative, there may be some aspects of microclimate that vary from the rest of the region. For example, the midlands region experiences the peak of the majority and most severe delays on colder days than any other region. This may be because the weather station is at a location that has a particularly cold microclimate compared with the majority of the rest of the region, an issue that would not have shown so obviously when analysing the heat-related delays with data from the same station. The midlands is almost entirely landlocked, meaning that it is prone to colder weather without the tempering effects of the sea. For this reason and because of the vital cross-country links through the midlands, it may also be that infrastructure in the midlands is treated more regularly to alleviate the effects of potentially harsher winters. In contrast, the south region which has a large proportion of conductor rail appears to be prone to severe and frequent delays at warmer temperatures than other regions (Figures 5.1 and 5.2). Again, this could be due to the location and topography of the area that the representative weather station is in. However, this trend is more likely to be caused by ice formation on the conductor rail at temperatures a little above 0°C.

Relating back to the ADB, for all regions the most severe incidents were caused by snow, which is in keeping with the findings in Smith (1990). Smith (1990) also states that in mid-winter the punctuality of services is 6-7% below that of the rest of the year, furthermore, punctuality was seen to reduce at temperatures of around +2°C, an ambient air temperature threshold which is reached every other day during the average winter. There is an increase in delays at around 1°C to 2°C, evident from the rise in frequency of cold-related delays in Figures 5.1 and 5.2.

Also it has been recorded in studies and in anecdotal evidence that ice forms on the rail head and conductor rail at ambient air temperatures up to +2°C. Cold weather can affect a wide area; ice can form wherever the temperature is low enough, meaning that large areas of the network can be simultaneously affected by cold weather, whereas other adverse weather conditions cause localised damage and delays. Furthermore, the effects of an area of cold weather will affect a region with denser track more than a region with sparse track. The south region has the densest track and has conductor rail infrastructure that can be badly affected by ice formation. Operating at or near capacity also causes knock-on delays in the south, exacerbating the effects of a delay that in another region may not have been as serious.

Tension cracks are a cold-related delay that can cause serious damage and delays as well as being a major safety hazard. It was hoped that tension cracks could be analysed against the temperature on the day crack-related delay incidents were recorded. However, like buckled rails they seemed to be recorded under different descriptions, such as damaged or deformed rail. As with buckled rails, tension cracks can vary in severity from a complete break in the rail detectable through wrong side track circuit failures, to faults which propagate and weaken over time. The type of crack and severity of delay could all contribute to the delay incident description. They may not be directly caused by cold weather but they can still be a symptom of it. Cracked rails are very rarely recorded in the ADB as being related to cold weather, and on inspection it was difficult to derive any patterns from rail-related delay data that corresponded with cold days. Nevertheless, from a subjective perspective on operations, the decrease in the extremely cold temperatures should result in a decrease in the propagation of tension cracks. According to predictions this will be most prevalent in the south of GB. However, with the increase in extremely high summer temperatures and the decrease in extremely cold winter temperatures, considering a new SFT for CWR is likely to be an option. This would rebalance the incidents of buckled rails and tension cracks to an appropriate and manageable level. To reduce buckles through changing the SFT is likely to increase the incidence of cold-related tension cracks. Based on future temperature profiles and spatial analogies of SFT practice in other European countries, a new SFT and maintenance regime is recommended in Chapter 6.

Through the course of this research there has been relatively little literature on how cold weather affects the railway network in GB, including data to form a temporal analogy. Consequently, there is no data available to offer a comparison with the costs quantified in this Chapter. The costs presented in Figure 5.8 and Table 5.4 cannot be considered definitive for this reason. However, the magnitude of the reduction in the cost is demonstrative of the effects of future climate predictions.

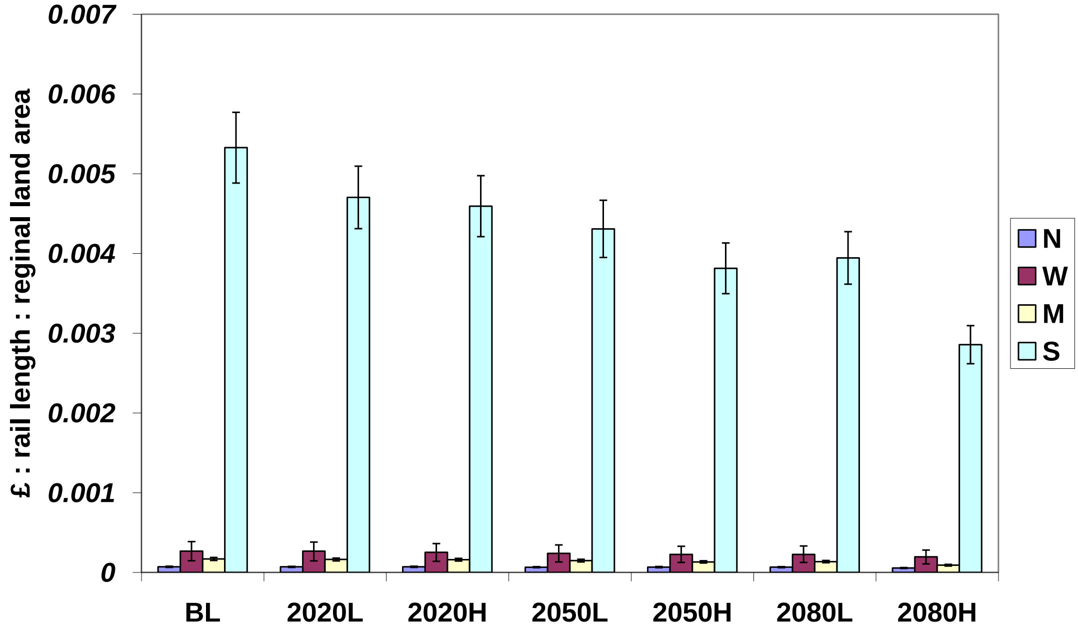


Figure 5.9: Costs as a ratio to the length of rail and the area of each region (from Table 4.5 in Chapter 4)

The heavy skew on the south trend curve caused by very severe delays in the region was very different to the trends for the other three regions. This discrepancy makes the normalised results shown in Figure 5.9 even more significant (the network length and region area used to calculate the cost ratios are in Table 4.5). The costs caused by ice and snow-related delay minutes are projected to decrease more significantly in the south as winter temperatures increase. However, the south region is predicted to remain the region most affected by ice and snow delays, furthermore, current and future predicted trends show that more trains will be operating meaning that the severity of future delays is likely to be worse. This effect will be reflected in operations for all regions due to the expansion of the future network, however it is likely to be more critical around London and other main centres. Furthermore, where there are bottlenecks in the network the effects of delays can be intensified. Birmingham New Street station is an example where operations at busy times are already at or very near capacity. There are essentially four routes in and out of the station that carry local and national services, unexpected delays (50% of which can be caused by weather in winter (Smith, 1990) in and around the station can cause severe delays both for the West Midlands and have severe subsidiary delays for the rest of GB.

Thompson and Parry (1997) estimated the cost of operating a fleet of 20 de-icing trains at £3 million. The potential costs of not de-icing in the South East could rhetorically be infinite; there is no way of knowing the cost of delays with no de-icing. Considering the scale of the costs of baseline delays caused by ice and snow in the south region of the UK, a cost of 3 million appears a cost effective investment. The south region is the region projected to experience the greatest decrease in ice and snow related costs, therefore it may be appropriate to reduce the fleet of de-icing trains and/or the quantities of de-icing spray used and still see a reduction in delays caused by ice and snow. Strategies for coping with ice and snow should remain in place to ensure effective use of de-icing facilities.

5.5 Future Mitigation and Maintenance

The impacts of ice and snow are predicted to reduce assuming the network infrastructure and operations regimes stay the same. Reduced financing for mitigation and treatment of ice and snow may be appropriate in the long-term future. However there are other aspects of future operations that need to be considered. Short-term trends suggest that traffic and demands on the network will increase (Network Rail, 2008) which will exacerbate the impact of delay incidents.

In addition, the knowledge that there is a predicated reduction in cold-related delays on UK rail infrastructure could cause complacency. A reduction in preparedness could also cause an extremely cold winter - equivalent to the cold winter 2008/09 - to cause equally severe or worse delays. Furthermore, a poor improvement record would reduce public confidence in railway transport and a bad reputation for the railway network could cause revenues to drop.

In order to understand the effects of colder winters compared with "normal" winters, it would be advantageous to compare the delays incurred in winter 2008/09 with other years from the ADB data provided. However, winter 2008/09 is the only complete winter available in the new data and although it was appropriate to mix the old and new ADB data, comparing the two versions is not viable. Firstly, in the old version of the ADB, delay events were recorded according to the new standards (formerly Rail Track standard RT/E/C/18 302), secondly, the delay incidents in the new version are stored in different, reason specific groups, whereas ice snow and cold related delays had to be filter extracted from sections of the old ADB, not all sections were available and one of the lessons learned from analysing the heat-related delays was that delays could be stored in a variety of ADB groups and thus were not available for the analysis. Finally, the years being analysed in the ADB represent a changing period for UK railways, in 2002 Network Rail took over from Rail Track, the sections of the ADB made available before this show a vastly reduced quantity of delays being recorded. Over the following years the improvement in the quantity and quality of recorded data in the ADB appears to improve, particularly with the introduction of the new monitoring and recoding system. Thus it is difficult to compare winter 2008/09 with other years because the data recorded across the decade is too variable and would not wholly demonstrate climatic variability rather organisational cultural change, improved diligence and policy change.

The delays in the south region are a significant proportion of nationwide cold-related delays (Figure 5.9), meaning that mitigation and treatment of ice and snow-related delays should continue. The less affected regions are likely to require continued mitigation against ice and snow delays in the foreseeable future. Improving or continuing good practice in mitigation and treatment of ice and snow-related delays will exacerbate any weather-related reduction that may be experienced due to predicted future temperature profiles. The research conducted by Network Rail to reduce the effects of cold-related impacts is likely to continue to be cost effective investments, in view of predicted cold days not significantly reducing in the 2020s or 2050s.

Figure 5.7 shows the number of days causing most ice and snow-related delays are predicted to halve by 2080. However, the railway network is affected by a range of cold-related delays, which are prevalent at a variety of low temperatures. Ice and snow-related delays from the ADB are most prevalent at temperatures of ~-2°C to ~ +1°C, which is in keeping with evidence, showing that pneumatic tyres on an icy surface have least resistance at around 0°C (Figure 5.3) and that ice forms on the rail head at temperatures up to ~1°C to 2°C. The temperatures around 0°C is an ambient air temperature range that is at the peak of the Gaussian distribution for minimum daily winter temperatures at baseline, meaning that of the spread of minimum daily temperatures they occur most frequently. This is corroborated by Smith (1990), which states that a minimum daily ambient air temperature of 2°C occurs on average every other day in winter months, the temperature at which punctuality begins to be affected. So although winters are predicted to become warmer the temperatures that cause the most frequent and severe ice and snow-related delays are not predicted to change in the near future or very dramatically.

Although costs have been produced, due to the nature of the data inputs these costs should be considered illustrative, rather than definitive of situations that could arise due to future projections of anthropogenic climate change.

CHAPTER 6

A NEW STRESSING REGIME FOR THE FUTURE RAILWAY NETWORK

This Chapter presents how countries around the world stress their rails to cope with the annual temperature extremes each respective network is exposed to, compared with GB climate and railway network. This information is used along with UK future temperature profiles to make recommendations for maintaining and stressing GB network in the future.

6.1 Background: Stress Free Temperature in GB

The importance of good quality track, ballast and substructure in reducing the risk of rail buckles is discussed in Chapter 2. This section expands on that information to build a better understanding of the structure of GB network relating to SFT and buckle management.

CWR in GB is stressed to a SFT of 27°C. The most common method of stressing rails in GB is using hydraulic tensors. Short lengths of CWR rails (<180m with adjustment switches, which are diagonal gaps that allow transition between sections of CWR and from CWR to jointed rail) are laid when the rail temperature is between 21°C and 27°C. Hunt (1994) explored the option of increasing the SFT used in GB by 5°C and concluded that the disadvantages of increasing the SFT would outweigh the positive outcomes. Ryan and Hunt (2005) conducted a review of literature and practice both from GB and elsewhere and concluded that, as with the findings in Hunt (1994), there was no evidence to show that the SFT in GB should be changed. Hunt (1994) also concluded that identifying and tackling individual problems was more appropriate than a blanket nationwide approach. This included considering a higher SFT in areas prone to rail buckles due to higher summer temperatures to combat the 3°C to 5°C rail temperature loss of SFT due to the “rolling out” effect on track in the first months after installation (Ryan and Hunt, 2005). The rolling out effect is the process of the newly-stressed and laid track moving laterally, which is caused by the movement and a readjustment of the ballast support around the sleepers, resulting in a loss of tension.

The true SFT of GB network is more likely to be around 22°C to 24°C rail temperature, due to the “rolling out effect. The nature of “rolling out” results in the network being stressed at a SFT less than the intended 27°C. Furthermore, influences such as reduced ballast cohesion and degraded sleepers can all contribute to reduce SFT in one or both rails of the track, which averages out across both rails. Ultimately, the SFT of the railway network in GB is likely to be lower than the prescribed SFT leaving the rail more susceptible to the influences of high temperatures

Rails that have a SFT less than 21°C rail temperature are re-stressed before the onset of higher summer temperatures. Equally, if rails are found to be above the maximum desired SFT of 27°C they are also re-stressed to a lower SFT. If a rail is more than 3°C greater than the SFT of 27°C rail temperature then it is re-stressed as a priority. VERSE is the non-destructive method of assessing the SFT in rails used by Network Rail. The method requires ~30m of rail to be unclipped from the sleepers, a load is applied to the rail and the SFT is calculated based on the rail temperature and the rail reaction to the load (Vortok International, 2007).

According to supplier product data the mean accuracy of VERSE measurements is ± 0.2°C, with a standard deviation of 1.3°C (Ryan and Hunt, 2005). Consequently, it can be considered that the SFT in GB is essentially within an approximate range of 21°C to 27°C rail temperature, providing the network is extensively checked at regular increments. In order to make predictions and recommendations for appropriate future practices it is necessary to consider the existing practices in other countries.

6.2 Stress Free Temperature in Other Countries

The range of SFT in Europe, the USA and the cooler states of Australia are examined in this section in order to put GB stressing regime in context and to make recommendations for future SFT in GB (see Table 2.1). Ryan and Hunt (2005) examine a number of European countries and the USA. There is one aspect of the USA's approach to stressing CWR that GB could consider, which is having a range of SFT that are applied based on local rail usage and climate, essentially the same approach as one of the recommendations made in Ryan and Hunt (2005). The general aim in the USA is a target SFT rail temperature range of 90°F to 110°F (32°C to 43°C) but it can be as low as 50°F (10°C). Although the range of temperatures experienced in GB is not as extreme as in the USA, having a higher SFT for the warmer regions and lines/routes prone to buckling than the cooler areas could be a useful means of balancing the risk of buckles and broken rails across the network.

Table 6.1: SFT for CWR in a variety of countries (Ryan and Hunt, 2005; Hunt 1994)

Country / region	SFT (°C)
UK	27
France	25
Germany	23 ± 3
Spain	27
Switzerland	25
Austria	20 - 25
Ireland	23
Holland	25
USA	(10) 32 – 43
Australia	38 ± 5 (ARTC 2009)

GB has a higher SFT than all European countries in Table 6.1, except Spain. This is remarkable when considering how the countries' average maximum summer (Figure 6.1) and average minimum winter temperatures (Figure 6.2) compare.

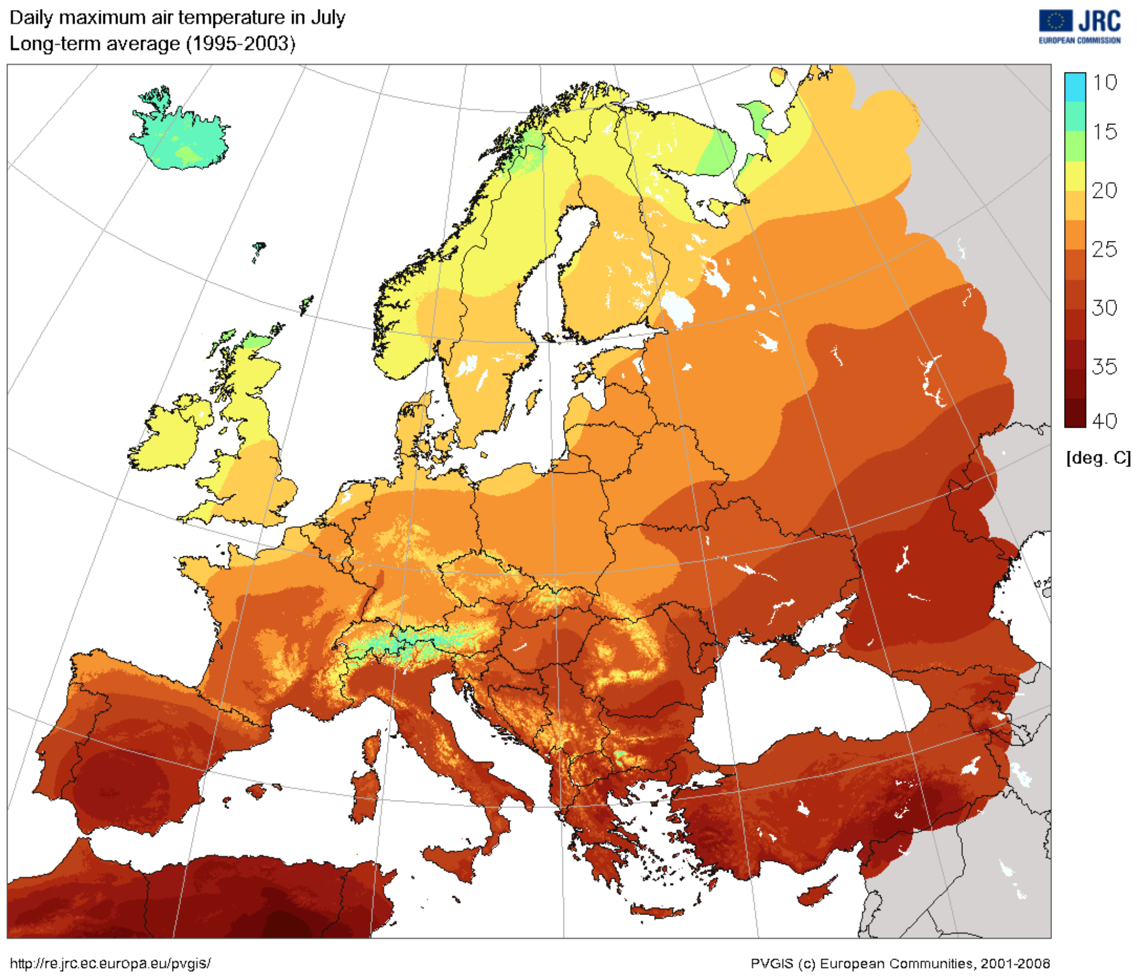


Figure 6.1: Mean maximum daily temperature in July across Europe PVGIS © European Communities, 2001-2008 (Huld *et al.,* 2006)

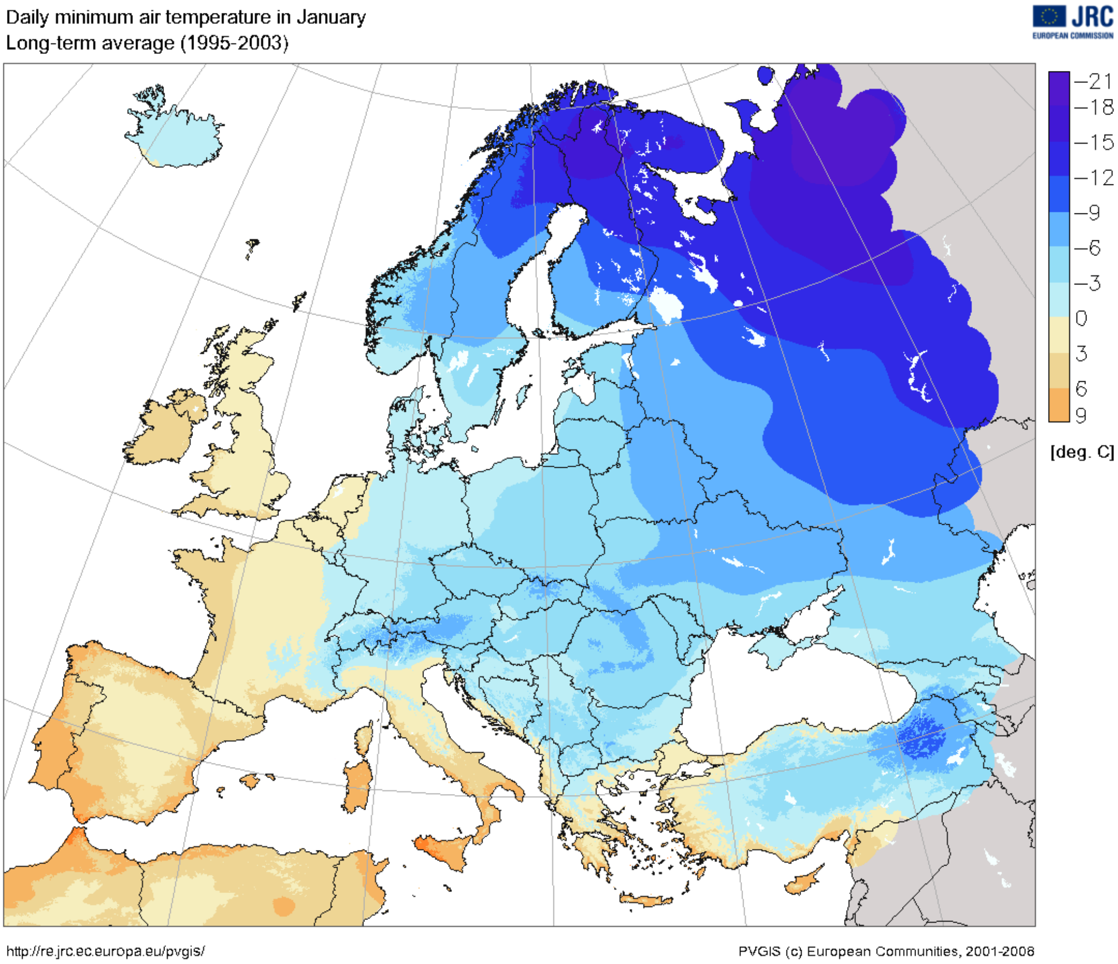


Figure 6.2: Mean minimum daily temperature in January across Europe PVGIS © European Communities, 2001-2008 (Huld *et al.,* 2006)

GB climate is generally temperate all year round owing to the tempering qualities of the Atlantic Ocean and Gulf Stream. In comparing GB network SFT with the Spanish network SFT, there are a number of unknowns, such as the tolerance of the Spanish rail operator to wrongly stressed rails. It is unclear whether 27°C (rail temperature) has a ± tolerance or if it is the maximum SFT, as with GB, or the minimum desirable SFT. However, the information in Table 6.1 suggests that GB is operating with a higher SFT than is perhaps necessary. This is corroborated when considering where GB SFT lies in relation to the maximum and minimum temperatures in GB, compared with Spain, France and Germany (Figure 6.3).

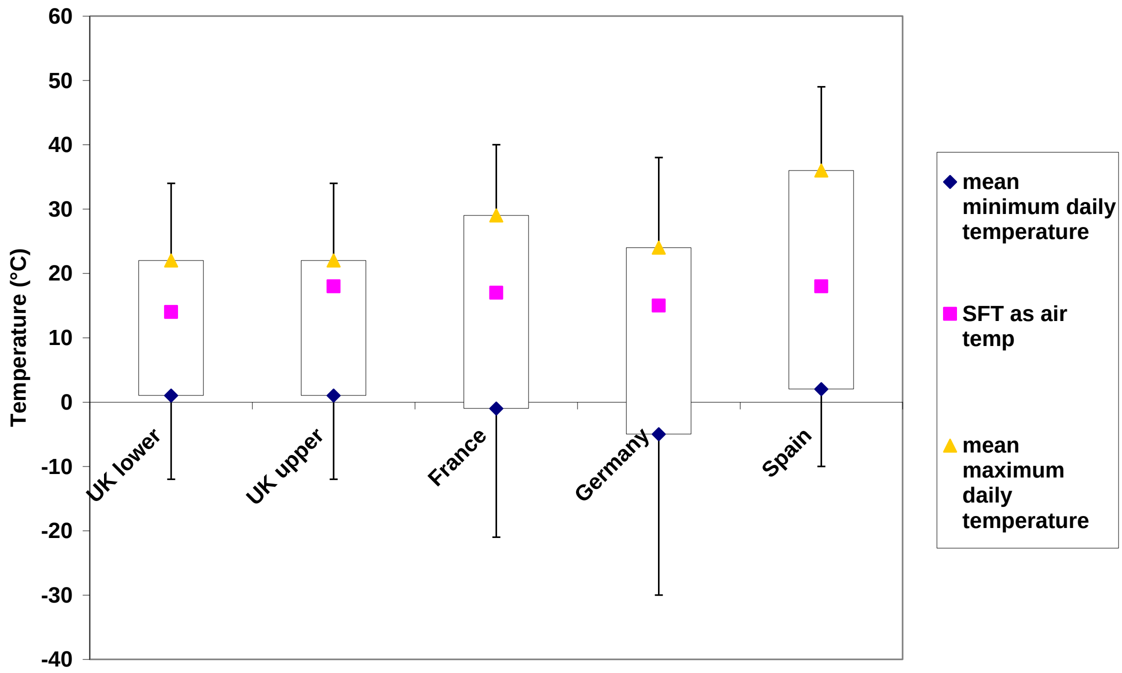


Figure 6.3: Box and whisker plots demonstrating how the SFT of GB (upper and lower tolerable SFT range), France, Germany and Spain corresponds with the extreme temperature profiles in the respective countries

The mild winters and temperate summers experienced in GB are evident from Figure 6.3. What is also evident is the disparity of the SFT in GB compared with the extremities of temperatures, in contrast with the other three countries. With such mild winters GB SFT can be higher than France and Germany as it is does not have to protect against the threat of recurrent and potentially very cold snaps. Cold-related tension cracks and rail breaks behave in many ways like rail buckles; they occur spontaneously. It has been observed by Igwemezie (2007) in the USA that weakened rails crack on the first cold snap of the new winter, similar to buckle harvesting as the highest summer temperatures are reached. Dislocations, cracks and flaws in the micro structure of steel rails can propagate when the material is at tensions well below the yield stress of the material, particularly with the force of a passing train (Igwemezie, 2007).

Having good quality rails, which are appropriately stressed, is the best protection against tension rail breaks. A rail is rarely replaced unless a break or crack has been identified, meaning that rails are used to destruction – an approach which is also favoured in Germany (Ryan and Hunt, 2005). Buckled rails, on the other hand are avoided through both appropriate stressing *and* ensuring quality track bed and substructure. Table 2.1 demonstrates the importance of quality track bed in improving the lateral resistance that increases the temperature at which buckles may occur. Integral infrastructure like track bed and substructure are costly and time consuming to replace, and the cost of time (or delay minutes) is intensified when replacing infrastructure on major lines and routes because of the passenger delay minutes associated with large numbers of trains full of commuter and business travellers. Preventative measures such as ensuring vital infrastructure is well maintained are likely to ultimately save money and reputation from reducing the incidence of cracked and buckled rails, as well as other fatigue-related damage and delays.

Maintaining a higher SFT is a cheap and more easily monitored method of reducing the risk posed by heat buckles. According to Table 2.1 if UK infrastructure was of a high standard then there should be a very low risk of buckles and associated ESR under current climatic conditions in GB. Considering that the temperatures that cause buckles are predicted to increase according to UKCIP02 predictions, improving the quality of track bed to alleviate heat buckles should become a long-term priority. The following section explores the options for future infrastructure, including the SFT, in order to keep rail buckles and cold-related tension cracks at an appropriate level.

6.3 Future Weather, Maintenance Regimes and Stress Free Temperature

Future climate change predictions state that summers will be hotter and winters will be warmer. The predicted change in the hottest summer days and coldest winter days is influential in determining the SFT of CWR for future climate scenarios. In addition, the difference between the hottest days and the coldest days is important. The SFT is an optimal temperature at which minimal damage is caused by both the hottest and coldest days. The evidence in Figure 6.3 suggests that the SFT in GB is higher than is conventional in other countries for two reasons. Firstly, GB experiences mild winters, thus there is less risk of rails cracking under a higher SFT. Secondly, it may be that the track bed infrastructure in GB is in a worse condition than infrastructures in equivalent European countries and setting a higher SFT helps reduce the risk of buckles without extensive and expensive track bed renewal.

In order to assess an appropriate approach to future CWR stressing the same temperature parameters as shown in Figure 6.3 have been calculated from EARWIG-simulated data for the three time series and the low and high emissions scenarios. The regional temperature parameters were plotted along with the upper (27°C) (Figure 6.4) and lower (21°C) (Figure 6.5) SFT limits, as equivalent ambient air temperatures (from equation (2.1) (Hunt, 1994)). All temperatures are on the same scale.

The upper limit SFT of 27°C (rail temperature) appears to remain an appropriate SFT right up to the 2080s under the high emissions scenario. This assertion is based on the evidence from Figure 6.3 and the approach taken by France, Germany and Spain in balancing the SFT with temperature variation. However, if the level of quality of track bed continues to be as it is at present, 27°C (rail temperature) is unlikely to be a high enough SFT. If GB approached the problem as it does presently and increased the SFT to reflect the existing method, it may be that cold-related tension cracks could become more prevalent. The increase in hot summer days is predicted to be greater than the increase in cold winter days. A wider spread of temperatures means that relying on a higher SFT to overcome heat buckles leaves the network more susceptible to cold-related tension cracks. Improving the quality of the track bed reduces the risk of rail buckles, thus the SFT could be kept at 27°C (rail temperature) and continues to be an effective stressing regime.

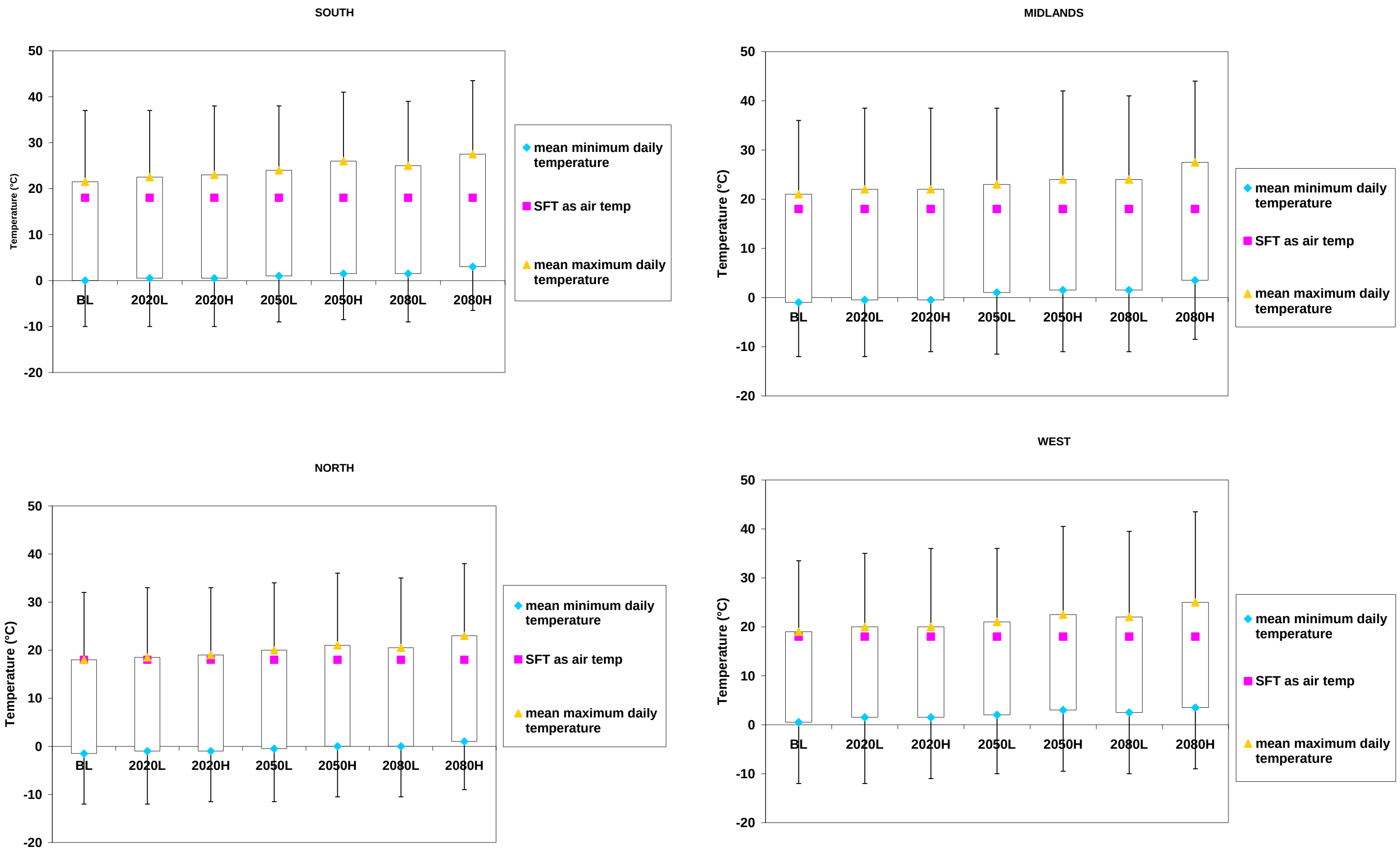


Figure 6.4: Future temperature change by region, compared with the current SFT of 27°C (equivalent air temperature)

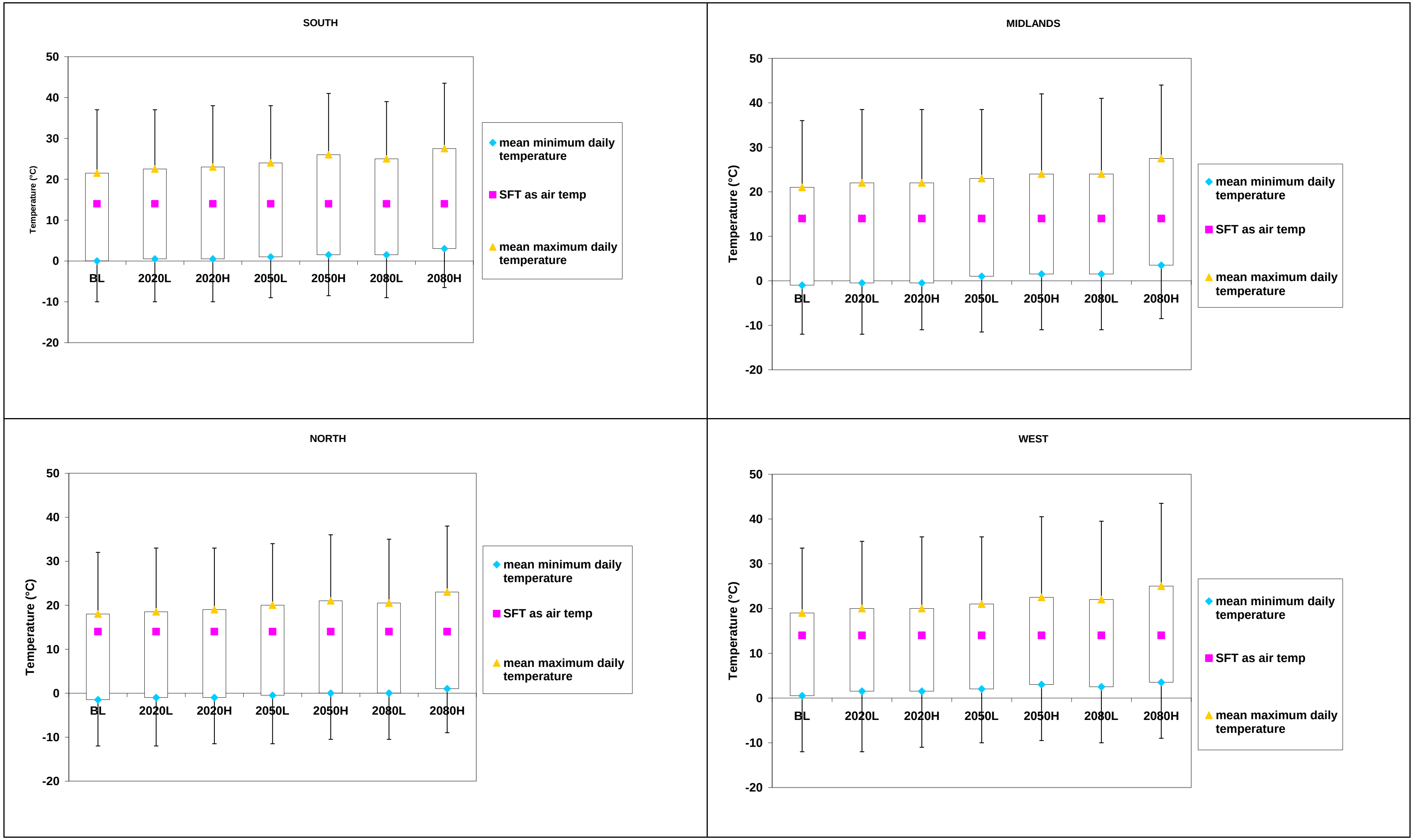


Figure 6.5: Future temperature change by region, compared with the current SFT of 21°C(equivalent air temperature)

In reality, much of GB's CWR is stressed less than a SFT of 27°C. A lower SFT will not aid in protecting from rail buckles on track that is in poor condition, under future climate scenarios (Figure 6.5). Relating to Table 2.1 track stressed at 27°C (rail temperature) in poor condition is monitored and considered being in the stages of becoming at risk of rail buckling at ~25°C (ambient air temperature). Track stressed at 21°C (rail temperature) and in poor condition will be at the same risk but at lower ambient air temperatures. For GB network to continue to have sections of track stressed at the lower limits of the currently acceptable SFT, will leave the track vulnerable to buckles under predicted future climate scenarios, particularly if the quality of track support is not improved.

6.4 Recommendations for Future Stressing and Maintenance

The changes predicted in the 2020s under the range of emissions scenarios and the 2050s under the low emissions scenario show a change in high temperature days that is larger than the increase in extremely cold days, thus increasing the range of temperatures that GB network is exposed to. Presently GB SFT relies on the temperate climate and narrow range of temperature extremes to stress to a higher SFT to reduce the risk of heat-related buckles and maintain an acceptable level of cold-related tension cracks. Future predictions suggest that this method is going to become more risky further into the time series and under the high emissions scenario. An appropriate course of action is to steadily invest in improved track and track bed infrastructure, which will reduce the risk of buckles from more hot days whilst also keeping cold-related tension cracks at an appropriate level by not increasing the SFT. The timescale of future climate predictions is long and although most railway infrastructure is robust and has a lengthy operational life, the timescales are appropriate for cost-effective improvements made in the normal life cycle of infrastructure.

Ryan and Hunt (2005) recommended that the range of SFT could be reduced from the bottom up, particularly in view of measuring techniques now being accurate within 1°C. Taking this action, together with the introduction of track bed improvements, will reduce the risk of buckles further and improve the predictability and reliability of the network, whilst also increasing the lower SFT in accordance with an increase in low winter temperatures. In order to combat the rolling out effect it may also be suitable to stress the network slightly higher than 27°C (rail temperature) to ensure that once the track is stabilised the SFT is not significantly lower than 27°C.

Figure 6.6 shows how the regional temperature profiles of regions of GB compare with the baseline temperature profile of Spain. GB in the 2080s under the high emissions scenario is predicted to undergo a more dramatic increase in hot days than the other time series and emissions scenarios considered in this study. However, the increase in maximum daily temperatures under future scenarios does not put the hottest days in GB at the same level with the hottest days in baseline Spain. On the other hand British winters are predicted to become marginally milder than baseline Spanish winters. However, the geography of GB may still dictate that cold snaps caused by winds from the North Sea could cause very cold days, most likely colder than cold snaps in Spain.

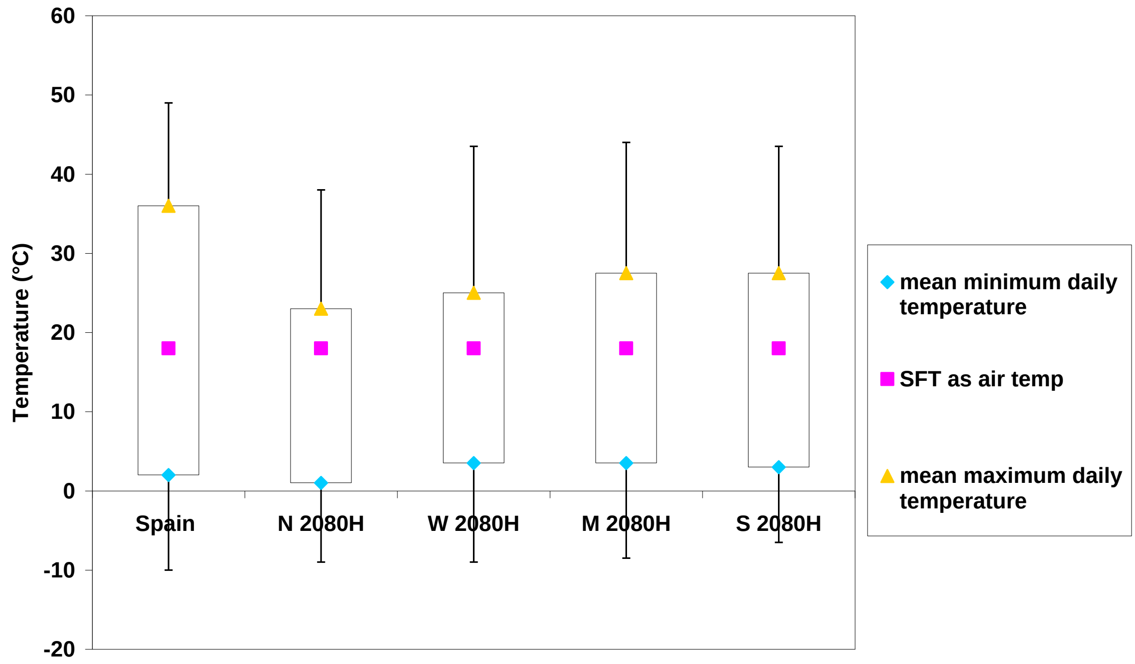


Figure 6.6: UK temperature profile and SFT (27°C) in the 2080s under the high emissions scenario, compared with baseline temperature profile of Spain and SFT (27°C)

The evidence from Figures 6.3 to 6.6 suggests that there is little cause for an increase in the SFT of GB railway network. However, narrowing the range that is tolerable for the SFT is likely to be an effective change in the 2020s and 2050s, in conjunction with steady improvements in the quality of track bed and substructure. For the 2080s, particularly under the high emissions scenario, maintaining a consistently high quality track and track bed with a narrow margin of a SFT close to 27°C are key measures to alleviate heat-related buckles and keep cold-related tension cracks at an appropriate level. In order to maintain a SFT close to 27°C, it is likely that stressing to a higher SFT, around 29°C to 31°C (rail temperature), will overcome under-stressing due to “rolling out”. Maintaining good quality track and track bed, particularly good quality ballast, will improve the lateral resistance vital in preventing rail buckles and longitudinal resistance that will reduce the rolling out effect of pre-stressed rail. Timing maintenance to ensure track is not stressed at higher limits before winter, in poor quality track bed or under-stressed before summer will contribute to smooth operations under more challenging climatic conditions.

Temperature profiles in the midlands, west (particularly the South West) and the south regions are similar. The north region on the other hand has cooler hot days than the other regions and it is likely that in cold snaps the north region is exposed to the coldest weather. Conversely, under baseline weather conditions the hottest days are experienced in the south region, which is predicted to continue under future climate change. Ryan and Hunt (2005) recorded that the USA apply different SFT to areas prone to extremes of temperature. The difference in the temperature ranges in GB is small compared with the USA. Thus, actively stressing some areas differently to others based on temperature-related rail damage is unlikely to be necessary. Nevertheless, monitoring the SFT of areas known to be hotspots for temperature damage and maintaining these areas accordingly will help to eliminate disproportionate damage caused at micrometeorological hotspots.

Although it is important to maintain an appropriate SFT, track geometry is vital to mitigating rail buckles. The two are nevertheless inherently linked and having good quality track geometry, adequate and good quality ballast will all contribute to maintaining the SFT (maintained through longitudinal ballast resistance) and keeping lateral resistance when the rail is in compression on hot days, which can lead to rail buckles. In short, the maintaining track bed to a high quality will reduce the risk of buckles because there is longitudinal resistance maintaining the SFT and lateral resistance supporting the sleepers when the rail is in compression. Good track geometry also reduces the initiation and propagation of rail cracks by removing rough ride which creates areas of high pressure at the wheel/rail interface. These cracks can be made worse and develop as cold related tension cracks. Lubrication of canted track and at curves can also aid the reduction of stress cracks in rails and ease the residual stress in the rail and to gauge from flange contact on the rail edge that can be the trigger for a rail buckle. This is particularly true of sections of track that carry heavy loads.

Network Rail have begun to use GIS to monitor the geographical location of potentially damaging weather fronts in relation to the network. Although this process is still in its infancy there is the potential to extend this tool to include many more aspects of the network and the weather systems that affect it. With regards to buckling and cracked rails, the following could be included to help improve understanding:

- Monitoring the quality of the track;
    - A chronology of maintenance regimes performed
    - What maintenance is required and when (this would highlight routes that are due maintenance if there is adverse weather predicted
- Identifying hotspots for particular track based faults;

- Identification of potential causes, micrometeorological or infrastructural (for example, ballast pumping can often re-occur at the same location several times, even after maintenance)

The identification of vulnerable locations can aid in the more accurate enforcement of ESR, thus reducing unnecessary delays caused by managerial decision making as with the hot summer 2003 where the quality of much of the track was unknown.

CHAPTER 7

CONCLUSIONS

GB railway network is stressed to a SFT of 27°C (rail temperature) in order to keep cold-related tension cracks and heat-related rail buckles at a tolerable level. Heat-induced rail buckles can be costly and damaging; they can cause derailments (Figure 2.1) and cost up to £1million to repair (Thornes, 2002). Hot days also create delays through line-side fires, expanding overhead lines, equipment overheating, thermal comfort issues and ESR, which are enforced when there is a risk of heat buckles occurring (Table 2.1). Cold-related delays can be caused by the presence of ice and snow on the infrastructure. Cold-related tension cracks and breaks in rails can be caused by pre-stressed CWR contracting in cold weather. The adverse effects of weather can be costly to GB railway network through both damage to infrastructure and consequent delays but also in the actions taken to mitigate and maintain against weather-related delays.

Climate change is predicated to alter the temperature profile of the climate in GB, which in turn will have an impact on the infrastructure and operations of the railway network. The aim of this thesis has been to determine if a new stressing regime for continuous welded rail would be an appropriate adaptive response to predicted future temperature profiles in GB. This has been achieved though the following objectives, outlined in Chapter 1.

1 *Quantifying the effects of hot weather on infrastructure and operations on GB railway network*

Eddowes *et al,.* (2003) is a seminal text in identifying the effects of climate change on the railway network. One of the key recommendations in this work was identifying the need to quantify the changes. Metroeconomica (2004) identifies that in order to quantify climatic impacts there must be a quantifiable unit that represents the change in frequency and severity of the impacts of adverse weather. The quantifiable unit came in the form of delay minutes from Network Rail's alterations database. In order to assess the impacts of hot days only, the ADB was filtered to extract delays relating to heat (like heat ESR and rail buckles). Each incident was assigned a region (north, south, midlands or west) based on the recorded location in the ADB. Each region was allocated a regionally representative weather station from which maximum daily temperatures were taken and assigned to the regional delay data by the recorded date of the incident. Although it is a very raw form of data the ADB provided reliable trends that describe how hot days affect operations on the railway network. Heat-related delays like heat ESR, equipment overheating and rail buckles were all analysed and buckled rails were also analysed separately. It was found that buckled rails cause the most delay minutes *per* single delay event than any other heat-related delay. The overall severity of all heat-related delays and buckles increase with the maximum daily temperature. A similar process was applied to winter related delays from the ADB.

2 *Quantifying the effects of cold weather, ice and snow contamination on infrastructure and operations*

The approach used to quantify the impacts that cold weather, ice and snow have on the railway network was similar to that used for heat related delays. The ADB was filtered for delay incident descriptions which included reasons like cold, ice and snow. The incidents were divided by region based on the location description and the minimum daily temperature on the date of the incident was assigned from the regionally representative weather station. Trends in the frequency and severity of delays showed that the majority and most severe delays occurred in an ambient air temperature range of around +1°C to -2°C. The ADB delay data occurring on days within a regionally defined temperature range - causing the majority and most severe delays - were used to describe how cold weather affects the railways. The trends were negative power curves showing that there are a high number of minor delays and a small number of very severe delays, with a sliding scale in-between.

3 *Fiscally quantify the impacts that future summer and winter temperature profiles may have on infrastructure and operations*

The trends generated in satisfying objectives *1* and *2* are considered representative of GB railway network operational reaction to adverse weather. In order to analyse the effects of future projected weather patterns the Environment Agency Rainfall and Weather Impacts Generator (EARWIG) was used. The generated climate change data was applied to the trends from the ADB to quantify the delay minutes caused by future heat, cold, ice and snow. Based on simulated EARWIG data it was found that the frequency of heat-related delay days is predicted to increase and so is the frequency and severity of heat-related delay events. The temperature range that causes the majority and most severe ice and snow-related delays is not predicted to reduce dramatically until the 2050s and 2080s under the high emissions scenario. The quantifiable unit – the delay minute – was converted into a financially quantified amount from the mean cost of a delay minute - £73.47 (Burr *et al.,* 2008). Although this cost is likely to be considerably more in some areas (urban/commuter lines) of the country and probably less in others (rural lines), the nationwide nature of the study means that a national average cost is adequate. The north region incurred the highest costs for heat-related delays, whereas the south region incurred the highest costs for cold-related delays.

The network in the south region is predominantly powered by conductor rail and the conductivity of the rail can be insulated completely by the presence of ice. The south region is also a region that operates close to capacity on many lines, often causing a delay to be longer and affect more trains than in other regions. Having higher costs associated with heat delays in the north - the coldest region is an unexpected result. However, this is also the largest region. In order to assess the relative severity of temperature-related delays in each region the predicted future costs were normalised by the area of the region and the length of rail in each region.

The railway network in each region was mapped using GIS. The area of the regions and the length of rail contained within each were recorded from the data in the maps. This data was then used to normalise the costs incurred due to hot and cold-related delays; £: density of rail. The south region is affected more by the cost *per* kilometre of rail *per* kilometre squared of land for both heat, and ice and snow-related delays. Despite being the warmest region in GB, ice and snow-related delays cost more here than anywhere else. Normalising the results served to demonstrate the “true” impact ice and snow-related delays have on the south region. For the heat-related delays the north region was the region most affected. However, the north region is the largest region by a considerable amount and from normalising the results the south region was shown to experience the highest cost and impact by the density of rail than any other region. Heat-related delays are predicted to worsen in all regions; ice and snow-related delays are predicted to decline slowly in the south region until the 2080s under the high emissions scenario and marginally in the other regions. Delays in winter months caused by the presence of ice and snow on infrastructure are not predicted to decrease considerably under future climate scenarios because the temperature range that causes the majority – and most severe – delays is not predicted to change dramatically.

Although costs have been produced, due to the nature of the data inputs these costs should be considered illustrative, rather than definitive of situations that could arise due to future projections of anthropogenic climate change.

4 *Make recommendations for changes in future network infrastructure and operations in a warmer climate based on evidence from spatial analogies and quantified changes in temperature related delays.*

The frequency and severity of rail-related, heat-induced delays is dependent on the quality of the track (including the SFT), track bed and substructure. The frequency of hot days causing delays is predicted to increase; furthermore extremely hot days in the future are predicted to be hotter than they have been for baseline summers. The extremely hot summer 2003 is predicted to become a "normal" summer by the 2050s under the high emissions scenario. There are two main approaches to reducing the risk of heat-related delays and buckles: firstly, to have an adequate SFT that is an appropriate balance between the hottest and coldest days the network is likely to be exposed to; secondly to make sure that the track is good quality, that it is well supported by good quality ballast and that the ballast is evenly laid on firm and even subgrade. Ensuring that both these conditions are met should prevent the frequency and severity of heat-related buckles and ESR from increasing, despite the predicted increase in hazardously high temperatures.

Ice and snow-related delays are predicted to experience only minor reductions across GB. The most significant reduction is predicted to be experienced in the south - the region that incurs more cost due to ice and snow delays than any other. It is recommended that the mitigation work currently carried out to alleviate the effects of ice and snow should continue, yet it is likely that there will be a steadily decreasing demand for mitigation. Settled snow causes the most severe winter delays, UKCIP02 have predicted an increase in winter precipitation which could result in increased instances of snow fall, however, only if conditions are right, particularly if the temperature is low enough for water to freeze.

The increase in temperature of hot summer days is greater than the increase in temperature of the coldest days. The SFT of the future railway network in GB must continue to alleviate both hot and cold delays for a wider range of temperatures. However, in comparing the range of temperatures experienced in other European countries, GB has a relatively temperate climate. GB also appears to operate with an high SFT of 27°C, compared with 25°C in France, 23°C (±3°C) in Germany and 27°C in Spain (all rail temperature). The Spanish railway network is exposed to a wider range of temperatures and to temperatures far higher than are experienced in GB. The reality of GB SFT is that it is between 21°C and 27°C (rail temperature). To alleviate future hot and cold rail-related delays it has been recommended that GB railway network considers tightening this range from the bottom up. By the 2080s under the high emissions scenario it may be necessary to have 27°C (rail temperature) as the minimum SFT. However, from reviewing the SFT and ambient air temperature range in Spain compared with the predicted future temperatures for GB, there is no evidence to suggest that a SFT higher than 27°C (rail temperature) would be required, even in the 2080s under the high emissions scenario. To moderate the risk posed by dangerous, expensive and damaging rail buckles it is going to be vital to ensure the quality of track is a more predictable asset to rely on.

The subsidiary benefits of having good quality and well-supported track will be evident in reduced damage at the wheel/rail interface and improved durability of rails, including the propagation of cold tension cracks initiated by faults in the rail, which are often caused by rough ride. Not increasing the SFT and improving the quality of track across GB will reduce the instances of both cold-related tension cracks and heat-related buckles in the future. Furthermore, having more reliably stressed CWR and uniformly higher quality track bed will reduce the need for ESR enforced due to unknown or low track quality (Table 2.1), which was an operations issue in 2003. The recommended changes can be made within the natural life cycle of the existing infrastructure and prioritised where infrastructure is old, inadequate or where temperature-related damage hotspots exist. With the predicted increase in passenger numbers and demand for a reliable and efficient railway network, it is strongly believed that the changes made in due course will be cost effective and lead to a stronger reputation and service for the future of UK railways.

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APPENDIX 1:

Table A1.1: Summary of information from the four regionally representative weather stations

	North region	West region	Midlands region	South region
Station name:	Longton	Yeovilton	Waddington	Heathrow
County:	Lancashire	Somerset	Lincolnshire	Greater London
SRC id:	12282	1302	384	708
Grid reference (OS):	SD 483257	ST 549231	SK 987652	TQ076767
Station start date:	01/01/1973	01/01/1964	01/01/1946	01/01/1947
Station end date:	Current	Current	Current	Current

Table A1.2: Details of errors and missed records for midlands regionally representative weather station, Waddington.

Start date	End date	Remark type	Remark
07-08-2009	10-08-2009	QUALITY CONTROL	DCNN 2423: GRASS MIN DATA SUSPECT. DELETED AND SET TO VERSION 0 IN MIDAS. INC 340623 REFERS.
07-06-2009	08-06-2009	MISSING DATA	WIND ID 242301: ALL HCM

			WIND DATA MISSING. INC 332437 REFERS.
31-05-2009	01-06-2009	MISSING DATA	WMO 03377 : ALL WMO SUNSHINE & RADIATION DATA UNAVAILABLE.INC 331420 REFERS.
25-05-2009	26-05-2009	MISSING DATA	WMO 03377 : ALL WMO SUNSHINE & RADIATION DATA UNAVAILABLE.INC 330794 REFERS.
21-11-2007	23-11-2007	QUALITY CONTROL	WIND ID 242301: DIRECTION STUCK ON 240. SET TO V0 IN MIDAS. INC 253922 REFERS.
05-07-2005	10-07-2005	QUALITY CONTROL	DCNN 2423 : DUE TO FAULTY SENSOR ALL 30CM SOIL TEMP READINGS DELETED FROM MIDAS.INC 159765 REFERS.
15-02-2004	16-02-2004	QUALITY CONTROL	DCNN 2423: INCOMPLETE DAY OF RADIATION VALUES.WHOLE DAY DELETED.

05-11-2003	06-11-2003	QUALITY CONTROL	WMO 03377: INCOMPLETE DAY OF RADIATION VALUES.WHOLE DAYS VALUES DELETED AND SET TO VERSION 0
13-07-2003	15-07-2003	QUALITY CONTROL	WMO 03377: RADIATION VALUES DELETED DUE TO INCOMPLETE DAY.AVAILABLE VALUES SET TO VERSION 0
02-11-1996	Current	DATA ROUTE	GAUGE 142002 : DATA FROM SAWS OR SAMOS
30-05-1996	Current	OBSERVING PRACTICE	24 OBS/DAY
29-05-1996	Current	MISSING DATA	NO DAILY DATA : CLOSED 8/1953-5/1955; 7-8/1968. DATA FOR SCAMPTON SUBSTITUTED
20-02-1996	Current	IDENTIFIERS	142002 1995-**** 142001 1946-****

Table A1.3: Details of errors and missed records for south regionally representative weather station, Heathrow.

Start date	**End date**	**Remark type**	**Remark**

11-11-2008	11-11-2008	MISSING DATA	WMO 03772: ALL OBSERVATION DATA UNAVAILABLE.INC 306134 REFERS.
26-08-2008	27-08-2008	MISSING DATA	WIND ID 511305: ALL WIND DATA MISSING. INC 288685 REFERS.
04-05-2008	05-05-2008	MISSING DATA	WMO 03772: ALL OBSERVATION DATA UNAVAILABLE.INC 274589 REFERS.
26-02-2008	27-02-2008	MISSING DATA	WMO 03772: ALL OBSERVATION DATA UNAVAILABLE.INC 265721 REFERS.
19-02-2008	20-02-2008	MISSING DATA	WMO 03772: VARIOUS OBSERVATION DATA INTERMITTANTLY UNAVAILABLE.INC 263594 REFERS.
16-01-2008	17-01-2008	MISSING DATA	WIND ID 511305 : ALL WIND DATA MISSING. INC 260791 REFERS.

07-01-2008	08-01-2008	MISSING DATA	WIND ID 511305: ALL WIND DATA MISSING DUE TO LOCKED WIND ISU. INC 259793 REFERS.
08-11-2007	09-11-2007	MISSING DATA	WIND ID 511305 : ALL WIND DATA MISSING. INC 252294 REFERS.
29-07-2007	30-07-2007	MISSING DATA	WIND ID 511305 : ALL WIND DATA UNAVAILABLE DUE TO LOCKED WIND ISU .INC 240940 REFERS.
27-05-2007	29-05-2007	MISSING DATA	WIND ID 511305 : ALL WIND DATA UNAVAILABLE .INC 233807 REFERS.
21-04-2007	23-04-2007	MISSING DATA	WIND ID 511305 : WIND ISU LOCKED : INC 229292 REFERS.
03-04-2007	04-04-2007	MISSING DATA	WMO 03772: ALL OBSERVATION DATA UNAVAILABLE.INC 227292 REFERS.
06-03-2007	07-03-2007	MISSING DATA	WMO 03772 : ALL OBSERVATION DATA

			MISSING FROM OBS.INC 223985 REFERS.
29-11-2006	30-11-2006	MISSING DATA	WIND ID 511305 : ALL WIND DATA UNAVAILABLE .INC 212936 REFERS.
17-12-2006	08-11-2006	MISSING DATA	WIND 511305: COMMS PROBLEMS
23-10-2006	09-10-2006	MISSING DATA	WIND 511305: COMMS PROBLEMS
19-09-2006	20-09-2006	MISSING DATA	WMO 03772: ALL OBSERVATION DATA UNAVAILABLE.INC 204109 REFERS.
17-09-2006	19-09-2006	MISSING DATA	WIND ID 511305 : ALL WIND DATA UNAVAILABLE .INC 203643 REFERS.
28-07-2006	29-07-2006	MISSING DATA	WIND ID 511305: COMMS PROBLEMS
01-09-2006	06-09-2006	MISSING DATA	WMO 03772 : ALL WIND TEMP & MSLP DATA INTERMITTANTLY MISSING FROM OBS.INC 201973 REFERS.

30-08-2006	31-08-2006	MISSING DATA	WMO 03772 : ALL WIND & RADIATION DATA MISSING FROM OBS.INC 201826REFERS.
27-08-2006	29-08-2006	MISSING DATA	WMO 03772 : ALL OBSERVATION DATA MISSING FROM OBS.INC 201530 REFERS.
12-08-2006	13-08-2006	MISSING DATA	WIND ID 511305 : ALL WIND DATA UNAVAILABLE .INC 200130 REFERS.
08-08-2006	08-08-2006	MISSING DATA	WMO 03772: ALL OBSERVATION DATA UNAVAILABLE.INC 199528 REFERS.
27-03-2006	28-03-2006	MISSING DATA	WMO 03772: ALL OBSERVATION DATA UNAVAILABLE.INC 186847 REFERS.
04-03-2006	05-03-2006	MISSING DATA	WMO 03772 : ALL OBSERVATION DATA UNAVAILABLE.INC 184407 REFERS.

30-12-2005	30-12-2005	MISSING DATA	WIND ID 511305 : ALL WIND DATA UNAVAILABLE .INC 177630 REFERS.
27-12-2005	28-12-2005	MISSING DATA	WIND ID 511305 : ALL WIND DATA UNAVAILABLE .INC 177630 REFERS.
26-11-2005	28-11-2005	MISSING DATA	WIND ID 511305 : ALL WIND DATA UNAVAILABLE .INC 174425 REFERS.
17-11-2005	18-11-2005	MISSING DATA	WIND ID 511305 : ALL WIND DATA UNAVAILABLE . INC 173555 REFERS.
01-05-1969	31-12-1969	QUALITY CONTROL	WIND 511301: DATA CORRUPTED IN ORIG DIGITISED RECORD; DATA MAY BE ASSIGNED TO INCORRECT DATE ORIG DATA IN ARCHIVE
01-01-1969	31-12-1969	QUALITY CONTROL	WIND 511301: MANY DDD & FFF DATA CORRUPTED IN ORIGINAL DIGITISED RECORD; COR SCRIPT RUN 2002 ORIGINAL DATA IN

			ARCHIVE
02-05-1997	01-09-1997	MISSING DATA	RAIN ID 247536 WADRAIN: NO DATA IN MIDAS FOR ~ 4 MONTHS CDB OR PAPER RECORDS MAY BE AVAILABLE
11-09-2002	Current	INSTRUMENTATION	MK6 WIND ANEMO TOWER AT NGR 508436.1736 EAST 175536.8963 NORTH BASE ELEVATION 22.76M MAST HEIGHT 10.38M
02-11-1996	Current	HISTORICAL NOTES	GAUGE 247536 : RAIN RECORDER CHARTS RETAINED IN TECHNICAL ARCHIVES
30-05-1996	Current	OBSERVING PRACTICE	24 OBS/DAY
20-02-1996	Current	IDENTIFIERS	247536 1947-**** 247537 1988-**** / SSER

Table A1.4: Details of errors and missed records for west regionally representative weather station, Yeovilton.

Start date	**End date**	**Remark type**	**Remark**
19-09-2009	21-09-2009	MISSING DATA	WMO 03853 : ALL

			OBSERVATION DATA MISSING.INC 345084 REFERS.
16-05-2009	18-05-2009	MISSING DATA	WMO 03853 : ALL OBSERVATION DATA MISSING.INC 329882 REFERS.
14-05-2009	15-05-2009	MISSING DATA	WMO 03853 : ALL OBSERVATION DATA MISSING.INC 329733 REFERS.
01-02-2009	02-02-2009	QUALITY CONTROL	WMO 03853 : WET BULB/RH SENSOR SUSPECT- WET BULB & DEW POINT SET TO VERSION 0.INC 317218 REFERS.
22-12-2008	06-01-2009	MISSING DATA	WMO 03853 : ALL AUTOMATIC VISIBILITY & CLOUD DATA MISSING . INC 311846 REFERS.
20-09-2008	22-09-2008	MISSING DATA	WMO 03853 : ALL AUTOMATIC VISIBILITY DATA MISSING . INC 291987

			REFERS.
16-08-2008	18-08-2008	MISSING DATA	WIND ID 867302: ALL WIND DATA MISSING. INC 287580 REFERS.
18-11-2006	21-11-2006	MISSING DATA	WMO 03853 : ALL WMO SUNSHINE & SLOAR RADIATION DATA UNAVAILABLE.INC 211488 REFERS.
22-11-2006	04-11-2006	MISSING DATA	WIND 867302: COMMS PROBLEMS
29-09-2006	02-10-2006	MISSING DATA	WMO 03853 : ALL OBSERVATION DATA UNAVAILABLE.INC 204901 REFERS.
18-08-2006	22-08-2006	MISSING DATA	WMO 03853 : ALL AUTOMATIC CLOUD DATA MISSING . INC 200696 REFERS.
05-07-2006	20-07-2006	QUALITY CONTROL	RAIN ID 401004 : DUE TO BLOCKED/FAULTY TBRR ALL HOURLY AND 12 HOURLY RAINFALL DATA

			DELETED FROM MIDAS.INC 196600 REFERS
13-03-2006	14-03-2006	QUALITY CONTROL	WMO 03853 : WET BULB DRY - WET BULB & DEW POINT SET TO VERSION 0.INC 185299 REFERS.
22-10-2005	23-10-2005	QUALITY CONTROL	DCNN 8673 : INCOMPLETE DAY OF RADIATION DATA. AVAILABLE DATA SET TO VERSION 0 IN MIDAS.
25-09-2005	26-09-2005	MISSING DATA	DCNN 8673 : INCOMPLETE DAY OF RADIATION VALUES.AVAILABLE DATA DELETED.
20-08-2005	21-08-2005	QUALITY CONTROL	DCNN 8673 : INCOMPLETE DAY OF RADIATION VALUES.AVAILABLE VALUES SET TO VERSION 0.
11-08-2005	15-08-2005	QUALITY CONTROL	DCNN 8673 : INCOMPLETE DAY OF RADIATION VALUES.AVAILABLE VALUES SET TO VERSION

			0.
13-08-2005	18-08-2005	MISSING DATA	WMO 03853 : ALL 10CM SOIL TEMP UNAVAILABLE. INC 163834 REFERS.
18-06-2005	05-07-2005	MISSING DATA	DCNN 8673 : ALL RADIATION DATA UNAVAILABLE . INC 157710 REFERS.
18-06-2005	19-06-2005	MISSING DATA	WMO 03853 : ALL OBSERVATION DATA MISSING . INC 157710 REFERS.
19-03-2005	21-03-2005	QUALITY CONTROL	DCNN 8673 : INCOMPLETE DAY OF RADIATION VALUES. AVAILABLE VALUES SET TO VERSION 0 IN MIDAS.
29-08-2004	30-08-2004	QUALITY CONTROL	DCNN 8673: INCOMPLETE DAY OF RADIATION VALUES.AVAILABLE VALUES SET TO VERSION 0
14-08-2004	15-08-2004	QUALITY CONTROL	DCNN 8673: INCOMPLETE DAY OF RADIATION

			VALUES.AVAILABLE VALUES SET TO VERSION 0
12-08-2004	13-08-2004	QUALITY CONTROL	DCNN 8673: INCOMPLETE DAY OF RADIATION VALUES.AVAILABLE VALUES SET TO VERSION 0
17-04-2004	18-04-2004	QUALITY CONTROL	DCNN 8673: INCOMPLETE DAY OF RADIATION VALUES.AVAILABLE VALUES SET TO VERSION 0
13-03-2004	14-03-2004	QUALITY CONTROL	WMO 03853: INCOMPLETE DAY OF RADIATION VALUES.WHOLE DAY DELETED.
06-03-2004	08-03-2004	QUALITY CONTROL	WMO 03853: INCOMPLETE DAY OF RADIATION VALUES.WHOLE DAY DELETED.
21-02-2004	22-02-2004	QUALITY CONTROL	DCNN 8673: INCOMPLETE DAY OF RADIATION VALUES.WHOLE DAY DELETED.
17-01-2004	18-01-2004	QUALITY CONTROL	DCNN 8673: INCOMPLETE

			DAY OF RADIATION VALUES.WHOLE DAY DELETED.
16-11-2003	17-11-2003	QUALITY CONTROL	WMO 03853: INCOMPLETE DAY OF RADIATION VALUES.WHOLE DAYS VALUES DELETED AND SET TO VERSION 0
09-06-2003	Current	INSTRUMENTATION	WMO 03853: RADIATION AND SUNSHINE SENSOR INSTALLED
02-01-1995	01-01-1996	MISSING DATA	RAIN ID 401005 WADRAIN: NO DATA IN MIDAS FOR ~ 12 MONTHS CDB OR PAPER RECORDS MAY BE AVAILABLE
02-01-1964	01-10-1964	MISSING DATA	RAIN ID 401005 WADRAIN: NO DATA IN MIDAS FOR ~ 9 MONTHS CDB OR PAPER RECORDS MAY BE AVAILABLE
18-10-1999	Current	SITE INFORMATION	SSER SITE WAS AT GRID REF 3551E 1237N AND

			ELEVATION 18M
02-11-1996	Current	DATA ROUTE	GAUGE 401004 : DATA FROM SAWS OR SAMOS
30-05-1996	Current	OBSERVING PRACTICE	4 OBS/DAY TO 31/12/1976; 24/DAY ONWARDS
14-12-1995	Current	ASSOCIATED RAINFALL	Rainfall for 1995-**** gauge 401003; for 1995-**** gauge 401004
14-12-1995	Current	ASSOCIATED RAINFALL	Rainfall for 1964-1995 gauge 401005; for 1987-**** gauge 401006 elevation of these gauges 18metres
02-11-1996	Current	HISTORICAL NOTES	GAUGE 401005 : PAST EVAPORATION DATA AVAILABLE CEASED NOW
02-11-1996	Current	HISTORICAL NOTES	GAUGE 401005 : PAST HOURLY TABULATIONS AVAILABLE CEASED NOW
02-11-1996	Current	HISTORICAL NOTES	GAUGE 401005 : RAIN RECORDER CHARTS RETAINED IN TECHNICAL ARCHIVES
02-11-1996	Current	DATA ROUTE	GAUGE 401005 : DATA

			RECEIVED BY MAG. TAPE OR FLOPPY DISK

Table A2.5: Details of errors and missed records for north regionally representative weather station, Longton.

Start date	**End date**	**Remark type**	**Remark**
02-06-1987	01-07-1987	MISSING DATA	RAIN ID 571405 WADRAIN: NO DATA IN MIDAS FOR ~ 1 MONTH CDB OR PAPER RECORDS MAY BE AVAILABLE
02-09-1986	01-10-1986	MISSING DATA	RAIN ID 571405 WADRAIN: NO DATA IN MIDAS FOR ~ 1 MONTH CDB OR PAPER RECORDS MAY BE AVAILABLE
02-01-1973	01-06-1973	MISSING DATA	RAIN ID 571405 WADRAIN: NO DATA IN MIDAS FOR ~ 5 MONTHS CDB OR PAPER RECORDS MAY BE AVAILABLE
02-11-1996	Current	DATA ROUTE	GAUGE 571405 : DATA ROUTE THROUGH WATER AUTHORITY

APPENDIX 2:

RAILWAYS, WEATHER, CLIMATE AND CLIMATE CHANGE – ARTICLE IN RAILWAY STRATEGIES MAGAZINE

01/11/2009 | Channel: Infrastructure

LEE CHAPMAN and KAY DOBNEY review the influence that the weather can have upon railway infrastructure and means of mitigating or adapting to these effects, both now and in the future

The wrong kind of leaves or the wrong kind of snow; an excuse which is familiar and frustrating, both as a commuter and as an operator for GB rail network. The effects of weather are part of the day-to-day operations of the railways (Table 1). Generally, the impacts of adverse weather are controlled through close monitoring and mitigating actions, such as emergency speed restrictions to reduce the risk of a buckled rail and anti/de-icing conductor rails to prevent poor conduction connection on cold days.

Increased numbers of hot days	• Increased railway buckling • Expansion/buckling of bridges • Increased heat exhaustion of maintenance and operations staff. • Overheating of engines and line-side equipment
Decreased numbers of cold days	• Reduced winter maintenance costs for rail (e.g. overhead line and third rail de-icing) • Improved working conditions for personnel in cold environments
Increased heavy precipitation	• Rail submersion • Increased landslides and undercutting
Seasonal changes	• Changes in timing of: o Leaf-fall for railways o Winter maintenance regimes
Drought	• Navigation problems on inland waterways
Sea level change	• Localised problems, e.g. storm surges
Extreme events	• Localised flooding • Wind damage to pantographs / infrastructure • Fallen trees blocking lines

Table 1: Impacts of weather and climate on the railway network

The Intergovernmental Panel on Climate Change is 90 per cent certain that human activity is causing climate change. Much of this is caused by a dependence on fossil fuels which when burnt release damaging greenhouse gases such as carbon dioxide. Transport as a sector accounts for 26 per cent of these emissions with cars and planes being the main culprits. This summer has seen the launch of the first set of UK probabilistic climate change scenarios (UKCP09). Predictions are made for several emission scenarios (or storylines) as well as for various time periods over the next century. The way in which we deal with predicted climate change can be largely sub-divided into two approaches: mitigation and adaptation.

Mitigation

Mitigating the effects of future climate change will require a reduction in carbon-intensive activity and the railway network is well placed to contribute to a more sustainable future. Realistically, future greenhouse gas emissions are unlikely to reduce significantly in the foreseeable future. According to predictions, this promises a legacy of change to which many businesses will have to adapt, and the railway network is no different. Rail transport is thought of as a ‘green’ form of transport (particularly electric rail which is non-polluting at source); indeed, national rail services produce around half the greenhouse gases per passenger kilometre than a medium-sized diesel or petrol car and compares even more favourably to

short-haul and domestic air travel. Unfortunately, any changes that are made to mitigate the impacts of climate change take a long time to make any difference to the climate (up to 100 years). Hence, in the shorter term there is a need to adapt to the new climate.

Impacts and adaptation

Climate change will increase the magnitude and frequency of the problems highlighted in table 1. One high profile impact of climate change is sea level rise. The line that runs through Dawlish along the south Devon coast is currently a hotspot where the sea wall can be topped by stormy high seas. Future predictions suggest an increase in sea level and an increase in frequency and severity of storm surges. A storm surge strong enough to top the barrier on the River Thames in London would have disastrous effects on all aspects of the City, including rail transport. Many coastal power stations in GB have their fuel or by-products transported by rail.

More extreme downpours in winter could cause more frequent and severe incidents of flooded track, scour at the base of bridges and wash away earthworks. Ageing and silted drainage could lead to more frequent and severe floods. In addition, earthworks that are original infrastructure or that have had trees removed could collapse.

Storms and high winds cause debris to be blown onto the line which damages trains and can even cause derailments. The OLE can be damaged and wind can cause poor conduction connection and damage the pantograph.

A subsidiary impact of storms is an increase in the number of leaves dropped in autumn. When damp leaves are squashed by passing trains on the railhead they form a slippery Teflon-like layer. This layer causes poor railhead adhesion which causes station overruns and wrong-side track circuit failures, potentially leading to SPADs. Climate change will affect the timing and extent of the autumn season and its associated problems.

Overall, specific adaptation measures are required to secure the future safe operation of the railway network. In some cases these can be straightforward and inexpensive, in other cases the problems are multi-faceted and require complex strategies to overcome.

Case study Temperature Change – Costs and Consequences

Hot weather causes track to expand and in extreme cases can cause rail buckles. Continuously welded rail (CWR) is pre-stressed to a stress-free temperature (SFT) of 27˚C rail temperature. Track in poor condition can be prone to rail buckles at lower temperatures than track in good condition because of inadequate ballast support; emergency speed restrictions (ESRs) are enforced when there is a risk of buckles. To reduce the risk of buckles, well maintained track, adequate ballast and substructure are vital. Climate change is predicted to cause more frequent hot days; a summer equivalent to the extremely hot summer of 2003 is predicted to become a one-in-five-year summer by 2080 under the worst-case emissions scenario.

The costs of future heat-related delays on GB network have been estimated to increase from an average year currently costing £9 million to an average year in 2080 costing £13 million. An extreme summer, the future equivalent of the hot summer of 2003, could cost up to £23 million. These costs do not include materials or labour, the total cost of a buckled rail has been estimated up to £1 million.

Warmer winters are likely to cause fewer ice and snow-related delays and tension cracks in CWR on extremely cold days. It has been shown that the temperatures that cause the majority and most severe ice and snow related delays are around >-2°C and <1°C. This may be because ice is more slippery when it is warmer, also that more delay days occur in this temperature range because it is the most frequently experienced minimum daily temperature range across GB. These critical ranges of temperatures are not anticipated to decrease in frequency until the 2050s of current climate change predictions.

The severity and frequency of extremely cold days is predicted to reduce, consequently so will cold-related tension cracks. With a predicted increase in extremely hot days and decrease in extremely cold days, it may be pertinent to change the SFT of CWR for the future network; this would make the rails more resilient to buckles on hot days and keep tension cracks at an appropriate level. The Australian network is set to a SFT of around 40°C. Although this may always be too high for GB, considering a rise that is in keeping with future temperature profiles could save money by reducing dangerous rail buckles and the associated delays.

FUTURENET

The University of Birmingham has just commenced a project entitled FUTURENET which will investigate how GB transport system will change in terms of design and usage over the next 50 years. The project will investigate the impact of weather and climate on the hard infrastructure of roads and railways (adaptation) as well as summarise likely changes in usage, travel behaviour and technology (mitigation). The aim is to make recommendations as to how to increase the resilience of future transport networks to climate change.

In summary, climate change will cause many future challenges for running a safe and efficient railway. Although there is much research required to fully identify and adapt to the effects of climate change, planning to adapt to these changes now will allow infrastructure to be managed and maintained efficiently in the future.

Variation of buckling incidents with temperature

Temperature change – costs and consequences

Dr Lee Chapman is a Roberts Research Fellow at the University of Birmingham focusing on the impact of weather and climate on the built environment. Lee has developed forecast models for both the road and rail industry. Recent research is now focused on improving the resilience of the transport network to the effects of climate change.