QUANTIFYING THE VULNERABILITY OF GB RAIL TO TEMPERATURE AND PRECIPITATION IN ORDER TO IMPROVE RESILIENCE

by

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ABSTRACT

Creating a more resilient railway network is crucial to national socioeconomic performance. GB's railways are considered to be a resilient transport network when compared with other modes of transport. However weather and seasonal events can be attributed as the cause of 12% of train delays, on average. There are already well-established areas of research into specific relationships between railway assets and weather hazards which have been directed by industry experts, giving a fragmented overview of the resilience of railway assets to weather.

The research presented in this thesis has developed a systematic, methodological approach which challenges the preconceived ideas of the impacts of weather on railway infrastructure. In principle, the analysis integrates historic railway infrastructure fault data with high resolution weather data, accounting for location whilst considering the exposure frequency of assets to different weather types. The methodology developed takes a novel, data-driven approach which highlights challenges for Network Rail regarding data quality. This approach has made few assumptions about the relationships between temperature and precipitation and the significant railway asset categories identified. As a result, this analysis has not only supported existing understanding through further interrogation of fault events but has identified assets which have previously been overlooked but are affected by weather hazards.

The approach developed provides a scalable and tractable foundation which can easily be employed by railway infrastructure managers, such as Network Rail, to calculate useful asset fault rate thresholds which can be utilised to inform decision making processes regarding asset maintenance and operations. In addition, the results of the analysis have been used to inform recommendations particularly for Network Rail as the Infrastructure Manager but also for the wider railway industry stakeholders to support progress towards a resilient railway for future mobility. This is of particular importance when viewed within the context of future climate change.

Key Words: *Railway Infrastructure, Extreme Weather, Weather Resilience and Climate Change Adaptation*

DEDICATION

As an engineer, a scientist and a woman, I must acknowledge the women who have previously forged a path through STEM subjects. They demonstrated that women may not belong only in the kitchen, but they may also belong in labs, in the field and as part of teams of researchers, working towards great things. Therefore, this thesis is dedicated to those women in STEM, whose endeavours have, in part, afforded me the opportunity to undertake this level of education and research. I am sure, if she were here, my own grandmother would be astounded.

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I am very grateful to have been guided through this research by my supervisors, Dr Andrew Quinn and Dr David Jaroszweski, their knowledge and advice have been invaluable and their patience immeasurable. Thank you both.

I must also thank many colleagues within the School of Engineering and Birmingham Centre for Railways Research and Education. In particular, I must thank Prof Clive Roberts, Steve Mills and Dr Jenny Illingsworth, who have all been tremendously supportive and encouraging as I transition from student to staff at the University of Birmingham. Additionally, thanks go to the inhabitants (prisoners) of F59B who have made this experience at least marginally more bearable. Some of which, I hope may be lifelong friends. Thanks especially to Simon, sorry, Dr Simon Hodgkinson, for being a constant source of support and amusement for the duration of this experience.

Finally, I must thank my long-suffering parents, without whom, I would not be here, my siblings Helen and George, who I hope will not be too put out by calling me Dr Fisher, and my best friend, Kathryn, who has tolerated so much.

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Term	Definition
°C	Degrees Celsius - Unit of Temperature
Δ	Greek alphabet Delta signifying change
%	Percentage
£	Pounds sterling or GBP
3rd Rail	Third Rail provides electricity for traction power for trains.
ADB	Alterations DataBase
CCA	Climate Change Adaptation
CCS	Command, Control and Signalling
CP	Control Period - five-year periods which structure NRs planning and investment e.g. CP5 2014-2019
DEFRA	Department for Environment, Food and Rural Affairs
DfT	Department for Transport
ELR	Engineer's Line Reference
ESR	Emergency Speed Restriction
E&P	Electrical and Power
EWAT	Emergency Weather Action Team
FCAD	Failure Cause Detail Action – FMS attribute
FMS	Fault Management System
FMS Suffix	Fault event label
FOC	Freight Operating Company
FUTURENET	Future Resilient Transport Networks
GB	Great Britain
GIS	Geographic Information System
IMDM	Infrastructure Maintenance Delivery Manager
LC	Level Crossing
LCE	Level Crossing Equipment
LNW	London Norther Western
METEX	NR's GIS based decision support tool which enables analysis of gridded observed weather data and rail data
NCRF	No Clear Relationship Found
NR	Network Rail
NRF	No Relationship Found
NSA	Not a Significant Asset
OHL	Over-Head Line
OLE	Overhead Line Equipment
ORR	Office of Rail Regulation

Term	*Definition*
OS	Ordnance Survey
POE	Point Operating Equipment
PPM	Passenger Performance Measure
PW	P.W. or P-Way refers to the Permanent Way
RAM	Route Asset Manager
RDG	Rail Delivery Group
RSSB	Rail Safety and Standards Board
S&C	Switches and Crossings
SFT	Stress Free Temperature
Sig	Short for Signals
SPAD	Signal Passed At Danger
SPS	Signalling Power Supply
TC	Track Circuit
Tel	Telephone or Telecoms
Telecoms	Telecommunications
TfL	Transport for London
TOC	Train Operating Company
TP	Traction Power
TPWS	Train Position Warning System
TRaCCA	Tomorrow’s Railway and Climate Change Adaptation
TRUST	Train Running System
TSI	Technical Specification for Interoperability
WRCCA	Weather Resilience and Climate Change Adaptation
UHI	Urban Heat Island
UK	United Kingdom
UKCIP	United Kingdom Climate Impact Projections
UKCP	United Kingdom Climate Projections

CHAPTER ONE: INTRODUCTION

1.1 Background

Creating a more resilient railway network is crucial to the socioeconomic performance of Great Britain (GB) (McNaulty et al., 2011). Demand on railway networks in Europe and the United Kingdom (UK) is increasing as governing bodies move towards more sustainable transport policies, for example reducing carbon emissions through a modal shift away from roads towards greener modes. This should be achieved through a 50% shift in medium-distance passenger and longer distance freight journey's to rail or waterborne modes by 2050 (European Commission, 2011). To facilitate this, rail infrastructure will need further investment to add adequate capacity to existing railway networks.

GB's railways are considered to be a resilient transport network when compared with other modes of transport (Eddowes et al., 2003; Zanni et al., 2017). However, over the eight years preceding the winter of 2013/14, weather and seasonal events could be attributed as the cause of 12% of train delays on average (Network Rail, 2014b). The UK experiences a temperate maritime climate, so temperatures are usually moderate, but the UK also experiences extreme weather events (Beniston et al., 2007). The most notable example of the effect of extreme weather events on railway infrastructure in recent years, is the collapse of the Dawlish Sea Wall in early 2014. Stormy seas, combined with a high tide destabilised the track, leading to a two month line closure, while the track was reinstated (Dawson, 2012). The cost to the railway industry has been estimated to be in the region of £45m, however this does not consider the cost to the economy caused by the extended suspension of services (Network Rail, 2014c).

Following the events of the winter of 2013/14, the Department for Transport (DfT) conducted a review of transport resilience in the UK (Department for Transport, 2014). Consequently, the GB Infrastructure Manager, Network Rail (NR) have increased their efforts to address weather related risks to their infrastructure, both now and in the future. Primarily, this has been conducted through the development of a Weather Resilience and Climate change Adaptation (WRCCA) strategy (Network Rail, 2014b).

The relationships between weather and rail assets are complex and to date understanding of the root causes of the effects of weather events is limited (Network Rail, 2014b). To complicate matters further, it is predicted that future climate change will have negative impacts on existing infrastructure (Department for Transport, 2014). To create a transport network that is resilient to the impacts of future climates, current understanding of how weather hazards effect GB's railway network needs to be further developed. (Nolte and Rupp, 2011).

1.1.1 Vulnerable Railways

The railways in GB remain operational through the combined input of a number of different infrastructure assets. However, if one or more railway assets have reduced functionality or completely fail, operations are compromised, and the effects of weather are often to blame. Hazardous weather conditions can have negative consequences for railway infrastructure, but this is only possible if the asset, or one of its components, is susceptible to, or inadequately protected against, the effects of the weather hazards. For example, sections of track which are not raised and have inadequate or poorly maintained drainage have little protection from the impact of sustained rainfall once the ground is saturated. This can result in a hazardous amount of water accumulating on the railway line, flooding, the implementation of Emergency Speed Restrictions

(ESRs) and ultimately line closures. In this instance the track is susceptible to flooding as it is inadequately protected from its effects. To put it simply, a susceptible asset subject to the effects of hazardous weather can potentially be adversely impacted causing disruption to the operation of the railway network (Dijkstra et al., 2014). In this instance the operation of the affected section of the network could be described as vulnerable to the impacts of hazardous weather (Pant et al., 2014a); this relationship is illustrated in Figure 1.1.

Figure 1.1: Relationships between weather hazards and transport infrastructure.

The vulnerable operation of a railway network can refer to the operation of the whole network, a particular section or a single asset, and the vulnerability of a single asset contributes to the overall vulnerability of the network. The relationships between the risks to individual infrastructure assets from climate variables and the associated risk to the operation of other systems is illustrated in Figure 1.2 (Chou, 2015). However, in order to mitigate these risks, the mechanisms behind them need to be understood. Quantification of the effects associated with the interaction of a multitude of weather hazards and their effects on a multifaceted railway network could be achieved through modelling these relationships (Department for Transport, 2014).

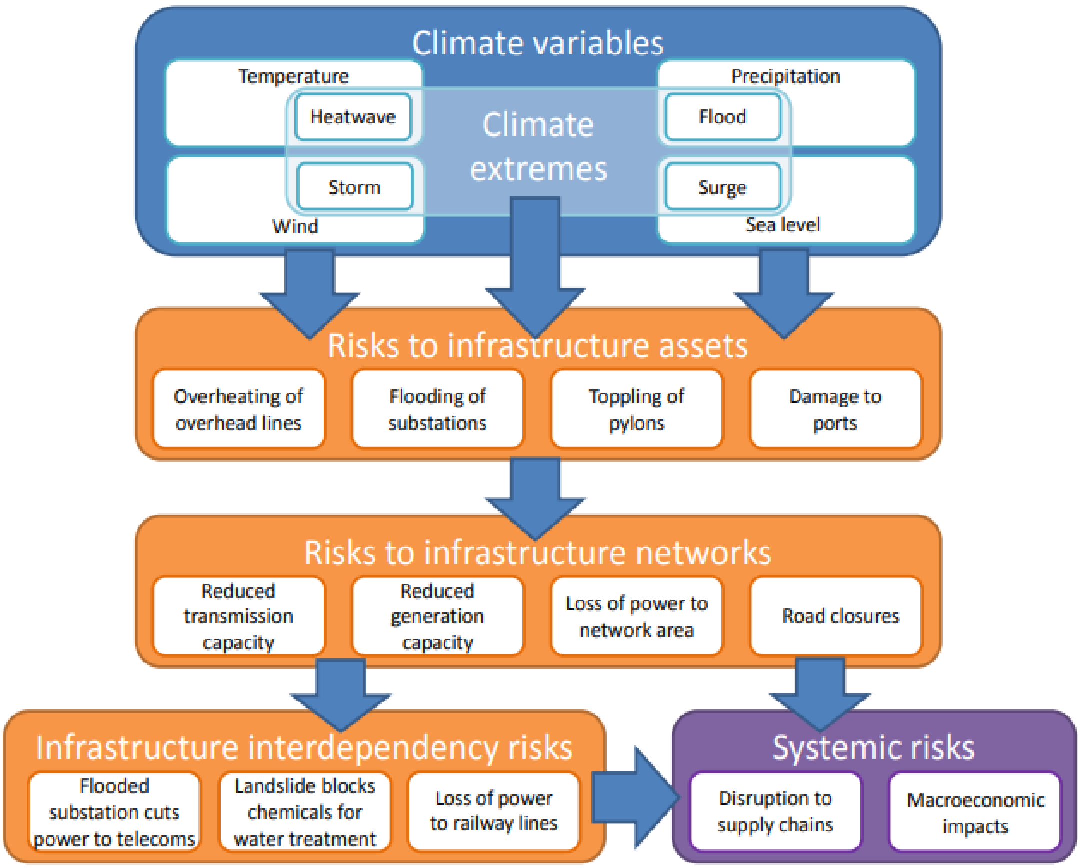

Figure 1.2: Overview of the climate change risk assessment framework for infrastructure (Chou, 2015).

1.1.2 Network Rail: The Role of the Infrastructure Manager

GB's railway network, which includes 20,000 miles of track and other infrastructure, such as bridges, tunnels, signalling equipment etc. is owned and managed by NR who are responsible for ensuring that it remains operational .GB's rail network accommodates 22,000 passenger trains and 700 freight trains every day, transporting on average 4.4m passengers and 11% of GB's freight (Department for Transport, 2014).

NR's operations are regulated by the DfT as well as the Office for Rail and Road (ORR) and the Rail Safety and Standards Board (RSSB). NR is primarily funded by the UK government, while their main customers are the Train Operating Companies (TOCs) and the Freight Operating Companies (FOCs). The TOCs and FOCs rely on NR maintaining and improving the railway network and its infrastructure so that they can operate train services as outlined in the timetables they have agreed. As the network operator, NR works closely with the TOCs and FOCs to manage disruption, including that caused by extreme weather. To support and facilitate this, there are several cross-industry processes and fora, led by the Rail Delivery Group (RDG), which bring together the principal operators to set overall policy. The governing structures outlined here are in place to ensure NR's operations are conducted safely whilst returning value for the taxpayer.

1.2 Creating a Resilient Railway in GB

GB's national transport infrastructure consists of various networks, systems and assets, which together deliver services to citizens and businesses, and support the environment, the economy and social well-being. It is therefore crucial that the railway network's operations are resilient to the negative effects of external drivers such as hazardous weather. However, *operational* resilience is, in the most part, dependent on the *physical* resilience of NR's railway infrastructure assets.

Infrastructure asset owners and operators are all faced with different challenges and so there is no single approach to improving resilience (Cabinet Office, 2011). Resilience can be achieved by considering the four factors shown in Figure 1.3. In this work, resistance and reliability are the aspects of physical resilience while redundancy and response and recovery are considered to be related to the operational resilience of a system. The physical resilience of railway infrastructure assets can be defined as the ability of their various components to anticipate, absorb, adapt to or rapidly recover from disruptive events (Cabinet Office, 2011). The operational resilience of a network refers to the

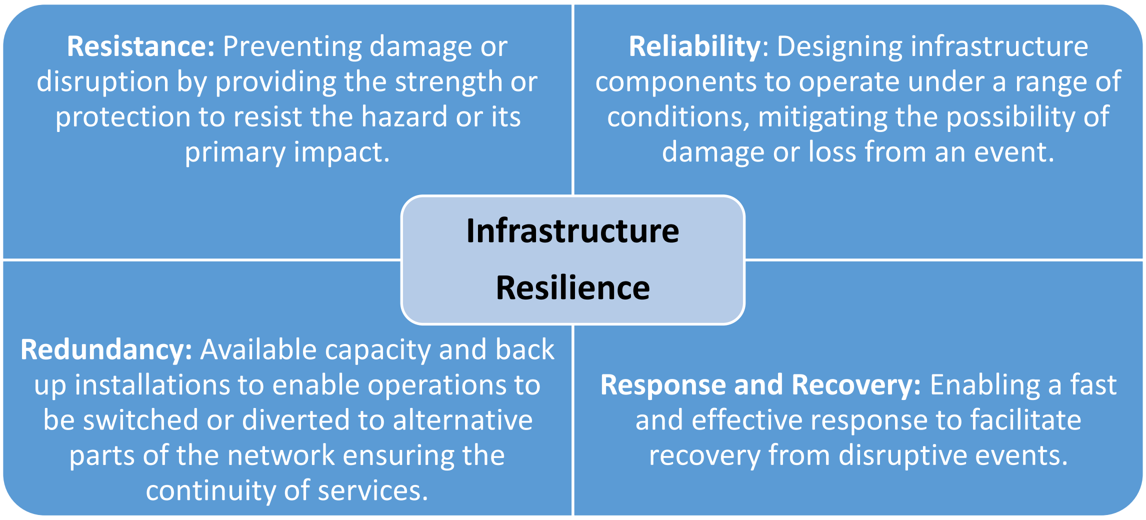

Figure 1.3: The four components of infrastructure resilience (Cabinet Office, 2011).

robustness of its individual components, the ability of a network to resist the impacts of asset failures, and the ability of that network to quickly return to normal operation (Quinn et al., 2017).

In response to the disruption caused by the storms and widespread flooding in the UK over the winter of 2013/14 the DfT has been exploring methods to create more resilient transport networks. The DfT's recommendations for improving the UK's transport resilience directly addresses NR, a major stakeholder and one of the largest asset managers in the UK. The DfT have outlined that achieving improved network resilience is crucial for NR's success and continued operation of a GB rail network for future mobility (Department for Transport, 2014).

Transport resilience has been described by the DfT's recent review of transport resilience in the UK as a transport network's ability to withstand the impacts of extreme weather, to continue operation and to recover promptly from its effects (Department for Transport, 2014). In addition to similar aspects to those outlined in Figure 1.3, the DfT recognises the role of communications with the users and managers of transport networks as a crucial tool for minimising the impact of disruption on journeys. By engaging with customers disruption may be managed by informing users to adjust their journey or infrastructure managers can use their feedback to inform decision making (Department for Transport, 2014). Within this work the management of demand or passenger flows is considered to be part of managing the operational resilience of the transport system by creating and controlling redundancy in the network. It's possible that a greater understanding of the impacts of weather on infrastructure will help inform the way that customers are informed about disruption and how to change their journey's. By achieving a greater knowledge of the relationships between weather variables and the railway's physical infrastructure assets, the magnitude of the effects of weather on railway network operation can be better understood. Therefore, strategic and informed decisions can be made effectively, reducing associated costs of and increasing the resilience of the operation of the network to adverse weather effects.

The process of creating a resilient transport network is outlined in Figure 1.4. The process is underpinned by understanding the vulnerability of assets and their criticality to the operation of the rest of the system. Following these, a network resilience analysis can be conducted to understand the network's ability to return to normal when the operation of an individual asset or section of the network are compromised. Next, interventions can be investigated, their costs evaluated, and suitable intervention measures can be enforced. Once in place, these mitigating measures can be evaluated by completing this iterative process again. The steps described above from the process shown in Figure 1.4 are also used in other frameworks and processes developed for the purpose of creating resilient systems (Ferranti et al., 2018; Marteaux, 2016a; Leviäkangas et al., 2011; Quinn et al., 2017), where no two are the same. The words used are often different as there is no single definition for these terms as this depends on the application. Additionally, the order of these processes can vary from model to model and are often looked at independently or in an alternate sequence. Figure 1.4 illustrates and explains the interpretations referred to in this research as this is considered to be the systematic process to ensure that each step is reliably informed, beginning with a vulnerability assessment.

Conducting vulnerability assessments of assets is increasingly important as transport infrastructure managers are taking action to ensure their networks are resilient to the effects of future climate change. If weather related incidents continue to cause 12% of delays across the railway network this can be equated to an average annual cost of £80m to NR for the same period (Department for Transport, 2014). Therefore, despite

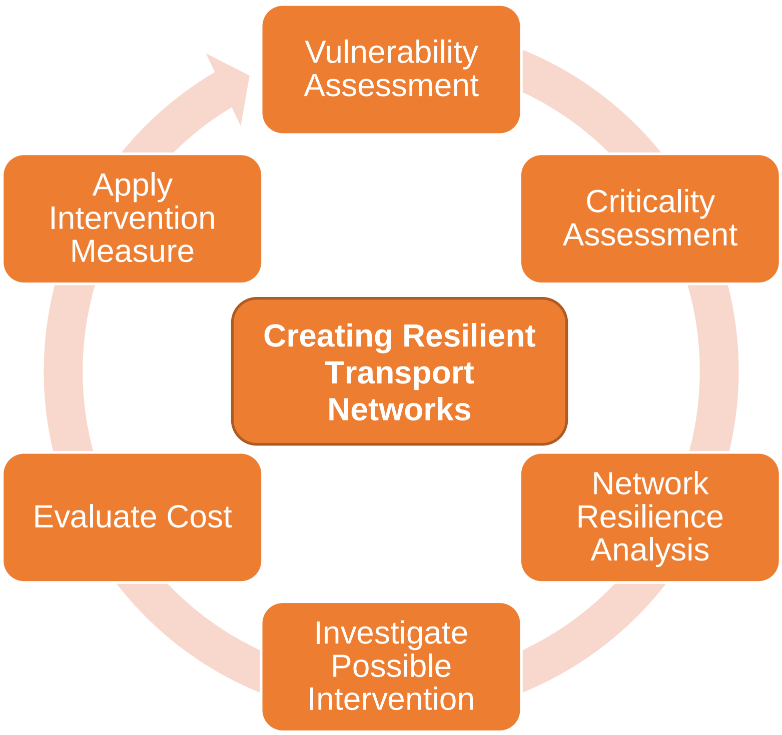

Figure 1.4: Overview of the iterative process leading to the creation of a more resilient transport network.

its relative resilience, the current operation of GB's railway network is still significantly at risk from hazardous weather, compromising the network's resilience and creating financial losses for NR. The level of resilience of a network can be quantified based on the cost of recovery from a disruptive incident, whether financial, or in terms of loss of service/duration. Therefore, the creation of a network which is operationally resilient is linked to the minimisation of these factors. GB's railway network is a mix of both legacy and new infrastructure assets, with varied geological, hydrological and meteorological environments (Network Rail, 2014b). These characteristics of GB's railway network create many challenges to achieving resilience as they each interact with hazardous weather in different ways.

1.3 Hazardous Weather

Weather becomes hazardous when it begins to have adverse impacts on people, property or the environment. Hazardous weather does not have to be extreme, but extreme weather is often hazardous. There is no definitive way to define extreme weather as it varies geographically across the world, its continents and regions therein. Within climate research, extreme weather is characterised using "extremes indices", a variety of measures to determine to what extent and in what way a particular weather event is considered to be extreme (Zhang et al., 2011). Broadly, extreme indices are determined based on their rarity (i.e. occur with a relatively low frequency), intensity (i.e. have a large magnitude relative to the norm) or severity (i.e. result in large socioeconomic losses) (Beniston et al., 2007).

1.3.1 Impacts of Hazardous Weather on GB Rail

All types of weather are sometimes hazardous when experienced in regions where the population, human or otherwise, are ill prepared for their effects. It is not feasible to be protected from all meteorological events at any single location, therefore it is necessary to concentrate on the types of hazardous weather events that frequently occur in the region concerned, in this instance the climate of the UK or more specifically GB.

An overview of the known weather impacts on the operation of the railways has been produced by NR and is shown in Figure 1.5. This has been produced using delay minutes attributed to unplanned delays under the Schedule 8 Delay Minute data which has been recorded as caused by weather effects (Network Rail, 2019e). The purpose, benefits and challenges of recording Schedule 8 Delay Minute data are discussed in Section 2.4. The weather categories in the figure are listed in the legend and are each discussed in this section. It is important to note that both subsidence and flooding are attributed to precipitation weather or coastal effects.

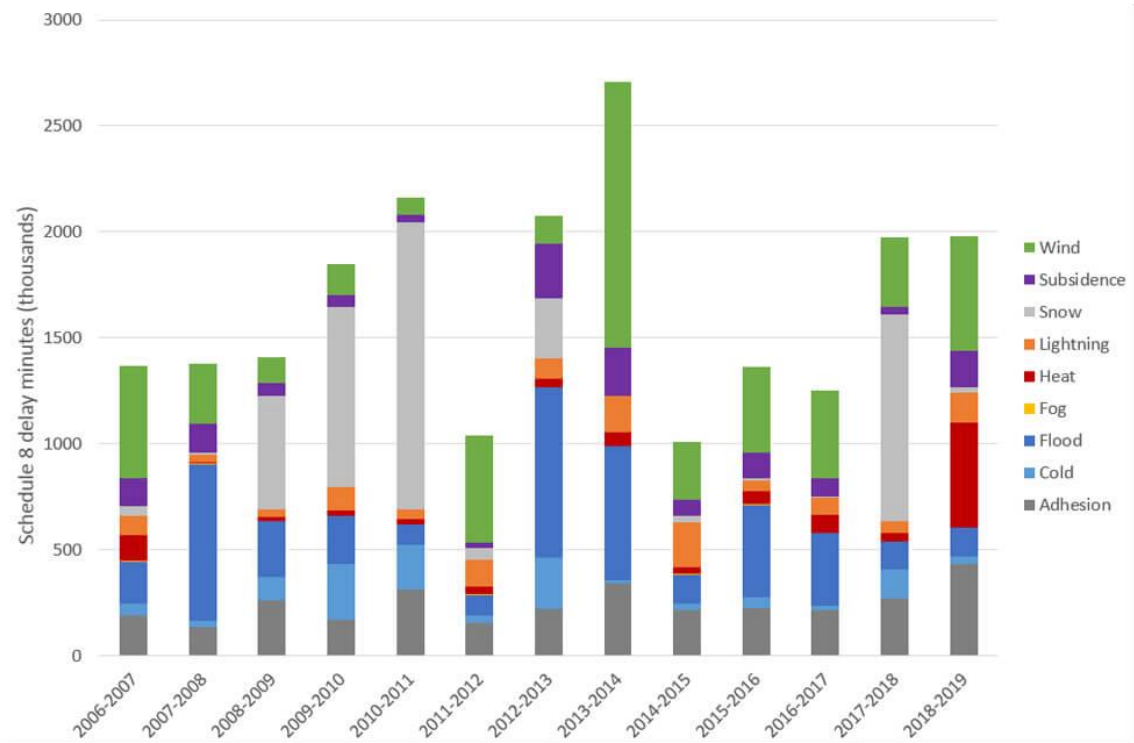

Figure 1.5: Network Rail Schedule 8 delay minutes attributed to weather related causes (Network Rail, 2019e).

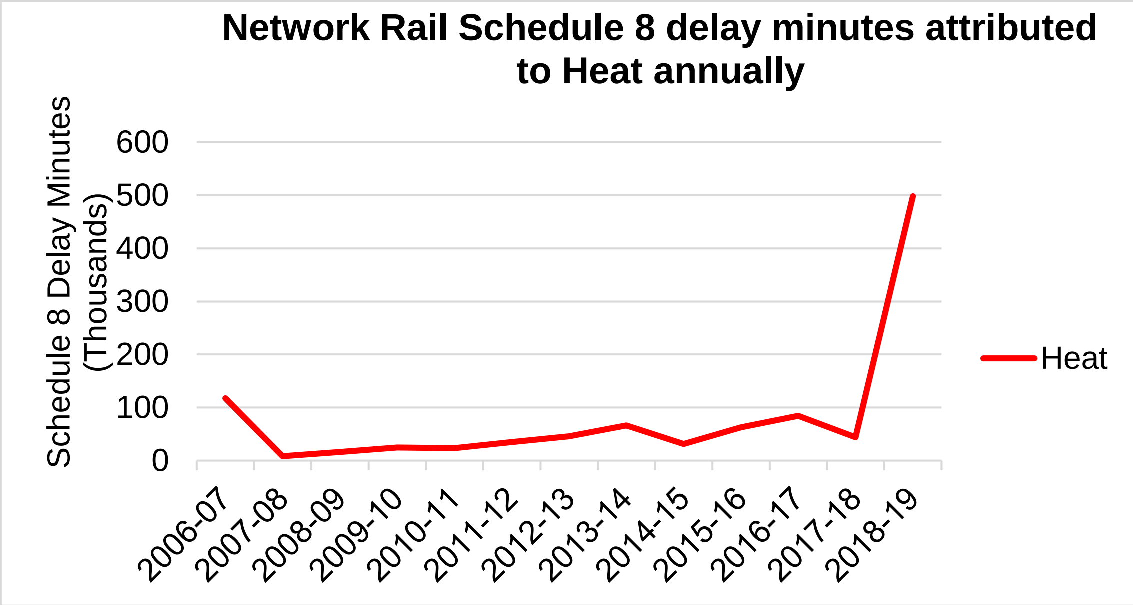

Figure 1.6: Number of Schedule 8 delay minutes attributed to heat annually (Network Rail, 2019e).

1.3.2 Temperature

Both high and low temperatures can have negative effects on a wide variety of railway infrastructure assets. While the research regarding the effect of colder temperature is limited, there is plenty of literature that investigates the impact of the hazards caused by higher temperatures (Chapman et al., 2008; Ferranti et al., 2016a; Dobney et al., 2009; Hooper and Chapman, 2012; Palin et al., 2013).

1.3.2.1 Heat related infrastructure faults

There are a great variety of impacts of high temperatures on railway infrastructure however, much of this literature has focussed specifically on the impact of heat on track assets alone (Dobney et al., 2010), the effect on urban areas (Chapman et al., 2013) or the effect on the south-east. In the latter case this is as it is generally exposed to the highest temperatures in the UK (Ferranti et al., 2016a). In the last 12 years the impact of high temperatures on the operation of the railways has been relatively low compared to the impacts of other weather hazards, perhaps as a result of changes made by NR. This is with the exception of 2018-19 as shown in Figure 1.6.

A particular problem caused by higher temperatures is that of rail buckling, which currently costs NR £9.2m per annum. This cost however is projected to double by 2080 (RSSB, 2015b). GB's railways feature continuously-welded rail as standard, and these are prestressed to withstand high temperatures that are commonly experienced in the UK. A rail may buckle when continuously-welded track is exposed to high compressive forces, such as those caused by the expansion of the metal rails during high temperatures. The rail will suddenly deform when the compressive forces overcome any lateral resistance. Rail is particularly susceptible to this deformation if the track is poorly maintained or incorrectly pre-stressed (Dobney et al., 2009). Rail buckling is not spontaneous however, as it is usually additional loading from a train that triggers a rail to buckle. By lowering the lateral forces experienced by the track, ESRs reduce the possibility, even when exposed to high temperatures, of a rail buckling (Hooper and Chapman, 2012). The temperature of the rails can vary greatly from the ambient air temperature, with rail temperatures roughly 1.5 times that of the air. Therefore, ESRs are enforced when the air temperature is greater than 27°C, this is the Stress Free Temperature (SFT) applied when rails are laid (Dobney, 2010). As a rail buckle may cause a derailment this is a safety critical concern where the delays caused by enforcing ESRs are preferable to the possible consequences of derailment (Dobney et al., 2009; Hooper and Chapman, 2012).

In addition to rail buckling, heat is known to effect Overhead Line Equipment (OLE). Thermal effects cause OverHead Lines (OHL) to expand and sag, this is managed through tensioning mechanisms which are either automatic or manual. Newer auto tensioned OLE are designed to operate at equipment temperatures up to 38°C and will automatically adjust the tension of the OHL to allow for thermal expansion. If OHL are allowed to sag this can lead to poor contacts between train pantographs and OLE or possibly dewirement, disrupting the power supply to rolling stock (Palin et al., 2013). Failures can cause serious issues as delays propagate across the railway network, the effects of which can be greater in urban areas where there is less timetable redundancy and the network is more congested (Chapman et al., 2013). This is particularly concerning as urban areas experience generally higher incidence of OHL sag faults as a result of urban heat island effects (Ferranti et al., 2016a).

Thermal expansion may affect other railway infrastructure assets, but these relationships have yet to be identified in the literature. As railway infrastructure technology develops there is an increasing dependence on electromechanical equipment. It is well known that electrical equipment can overheat, leading to equipment failure and even electrical fires. Overheating lineside equipment is a known problem (Palin et al., 2013) however the relationship between ambient air temperatures and the temperatures of lineside equipment has not been investigated to date (Ferranti et al., 2016a).

1.3.2.2 Cold weather impacts

The impacts of cold weather on railway infrastructure is understood much less than the effects of heat. In fact, the effects of cold temperatures on infrastructure or operation of the railways is often neglected from the literature, this is despite it having a roughly equal impact on railway operation, as shown in Figure 1.7.

As with heat, it is known that cold also impacts the material behaviour of track. In heat metal expands, in cold temperatures they contract causing tension cracks (Wang et al., 2012). In addition, low temperatures are known to freeze equipment, and when coupled with moisture the formation of ice can impair traction (through reduced

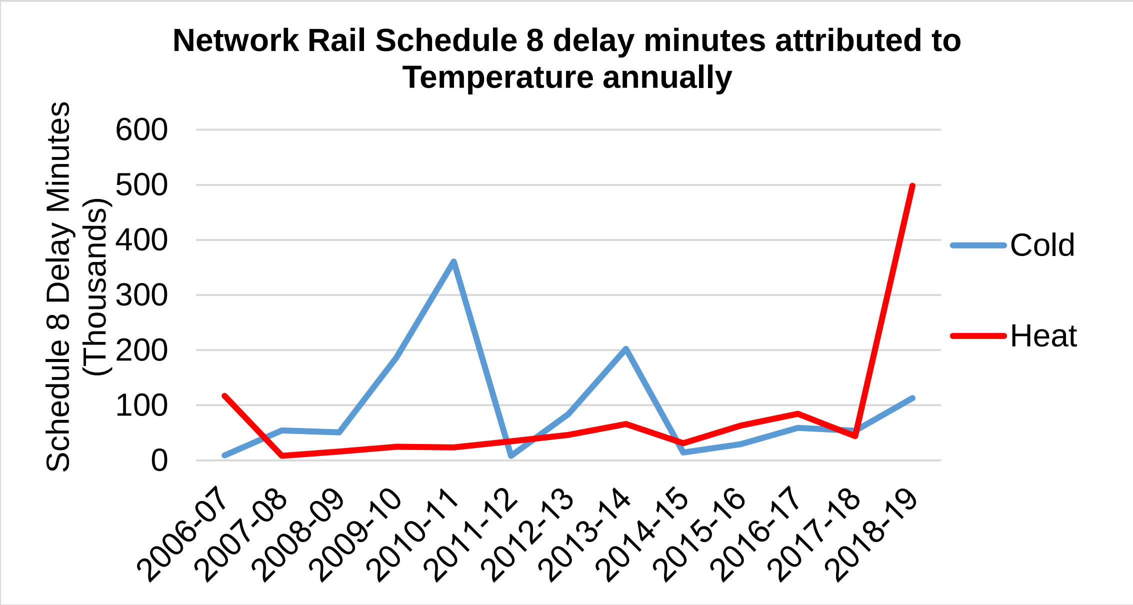

Figure 1.7: Comparison of the number of Schedule 8 delay minutes attributed to heat and cold annually (Network Rail, 2019e).

friction), power supply from OLE or third rail, and be a danger to passing trains when icicles form in tunnels (Eddowes et al., 2003). This is a frequent occurrence as illustrated in Figure 1.7, despite the fact that many railway infrastructure assets are designed to prevent the effects of cold temperatures, often through heated components, such as heated points. However, little literature has investigated the effects of low temperatures and their impact on railway operation.

1.3.3 Precipitation

Precipitation can cause a variety of hazardous weather, from rainfall through to snow. However, the presence of water can have a number of different impacts on railway infrastructure, whether as moisture, water ingress, flooding or ground saturation and consequent subsidence. Although the presence of excess surface water may not be related to weather, i.e. a burst water main, these are isolated incidents whereas precipitation is a frequent occurrence in the UK. The impact of weather hazards related to precipitation on the railways, as recorded by NR, are shown in Figure 1.8.

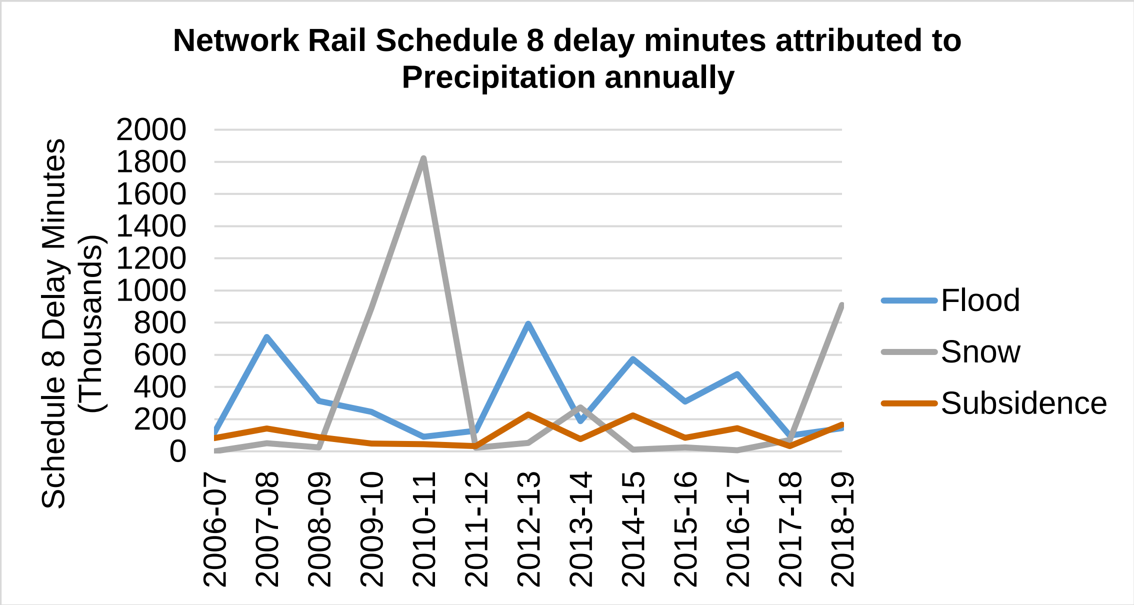

Figure 1.8: Comparison of the number of schedule 8 delay minutes attributed to precipitation related weather hazards annually (Network Rail, 2019e).

1.3.3.1 Flooding

The railway network is engineered to protect infrastructure assets from flooding, this may include raising assets or providing adjacent drainage systems. This is crucial, as flooding can impact the operation of the railways in many different ways, for example by blocking railway lines when flood water rises above the height of the rail head. Additionally, flooding also disrupts electrical systems such as the running rails and effects the stability of track support structures through ballast washout. It has also been identified that there is a high risk of cascading failure where flooding of power substations leads to operational failure on the associated section of the railway network however this is an area of limited research (Ferranti et al., 2016b).

Intense rainfall will also be more frequently experienced in GB under future climates. Therefore, the impacts of precipitation which have previously been outlined, will also happen more frequently with more dramatic effects (Jenkins et al., 2009). However, this does not account for the influence of antecedent weather events on the extent of the impact of extreme rainfall events which may occur in any season, not just winter. Where intense rainfall follows a period of steady rainfall, permeation of already saturated ground is not possible resulting in pluvial flooding which can reduce the stability of earthworks.

1.3.3.2 Subsidence

Precipitation and a lack of precipitation can both cause issues for the stability of earthworks. Earthworks become vulnerable to subsidence after substantial rainfall, when embankments and cuttings adjacent to the railway lines experience fluctuation in pore water pressures. When there is a lack of precipitation and higher temperatures earthworks may become desiccated, leading to cracks appearing on the surface of cuttings and embankments. When these fissured earthworks are infiltrated by excessive rainfall they can become unstable or experience slope failures (Network Rail, 2018b). Although vegetation can help control ground water levels and roots can help stabilise earthworks, deciduous vegetation can negatively impact the railways as leaves on the line can contribute to adhesion issues, this is exacerbated under high winds (Bíl et al., 2017).

The collapse of embankments can block the line with debris which can derail passing trains. As this is a safety critical issue there has been much research into slope stability, and based on the outcomes of these studies NR have employed embedded sub-surface monitoring for their most critical geotechnical assets. Through the use of remote failure detection technologies and train-borne monitoring NR aim to assess the condition of geotechnical assets and ultimately to prevent earthworks failures. Analysis of the data returned enables NR to take preventative measure to restore the condition of earthworks so that they are less susceptible to the effects of periods of high rainfall or drought (Network Rail, 2018b).

1.3.3.3 Snow/Hail

The combination of low temperatures and precipitation results in a wide variety of weather conditions; sleet, snow and hail in particular. These can affect visibility for train drivers (Li et al., 2006) but also have serious impacts on railway infrastructure. Although there are many components that have been designed to reduce the impact of snow on railway operations such as point heaters, there is little in the way of research regarding the specific impacts of snow on railway infrastructure. This is surprising considering the large proportions of delays attributed to the effects of snow in the winters of 2010/11 and 2018/19 as shown previously in Figure 1.8. The key concerns regarding snow are drifts forming and blocking the line as well as snow compacting causing blockages in equipment such as points. Hail can cause similar problems when compacted, forming solid ice which blocks points and other equipment, as well as causing damage when it strikes assets. These challenges, for predominantly mechanical assets, have faced the rail industry for some time (Champion, 1947) and despite less frequent episodes of snow and cold weather in the UK they evidently still cause a significant amount of delays. However, the impacts of both snow and hail are difficult to measure at any specific place on the railway, and this is particularly true for localised hazards, such as snow drifts. As a result, the impacts of these weather hazards are not considered in this research.

1.3.4 Storms

Storms are extreme in magnitude, often combining both wind and precipitation, with some storms also exhibiting lightning, or in colder temperatures, snow or hail. Storms typically affect GB for between 24 hours and up to 72 hours depending on the weather patterns experienced, as this is the time it takes a weather system to move across GB. Storms contributed to the extreme weather events experienced over the winter 2013/14 and are a regular occurrence in GB. Some research has been conducted regarding the impact of storms on transport networks (Johnson, 1996; Jaroszweski et al., 2015; Dawson, 2012) and this often explores the development of the meteorological conditions with the aim of creating a timeline of the conditions experienced. Such timelines have recently been coupled with train delay minute data and road traffic data to explore the development of events on the 28th June 2012 (Jaroszweski et al., 2015). Despite their frequency and serious impact on railway infrastructure, storms will not be explicitly explored in the research as they are discrete, individual events.

1.3.4.1 Wind

Not only does wind affect the stability of rolling stock (Baker et al., 2009) but it also has negative impacts on railway infrastructure. Wind particularly affects OHL and their contact with train pantographs which can lead to dewirement. As well as the direct effects of wind on railway infrastructure assets another key issue is trees falling onto the line (Fu and Easton, 2016). Not only will a fallen tree block the route, but it may also bring down the OHL or other equipment with it. In addition, wind indirectly damages railway infrastructure by moving a wide array of debris trackside which can affect many different asset types (Baker et al., 2010).

Wind has significant and wide-ranging effects of wind on transport infrastructure wind speeds vary greatly even over short distances particularly in urban areas, where the built environment influences the strength and direction of wind. This makes analysis of the effects of wind on transport infrastructure very complicated affecting the degree of certainty of future predictions of wind in a geographical area. Projections of future wind speeds and storminess remains an area of continued research as existing models have significant levels of uncertainty due to the complexities of this particular area. Existing models have not identified any significant trends regarding future storminess and therefore the impact of wind has been determined to be less important than other weather variables at this stage in the research (Fung et al., 2018).

1.3.5 Coastal Effects

As an island nation many areas of GB are negatively impacted by coastal effects, with high tides or high winds causing high waves. This can be hazardous to railway infrastructure as was quite dramatically proven in 2014 when parts of the Dawlish sea wall collapsed into the sea after being relentlessly battered by high waves. The severe overtopping led to the line being closed to rail traffic, so fortunately there were no causalities except for Isambard Kingdom Brunel’s historic infrastructure. Although this was a particularly catastrophic event, this section of the railway is closed roughly every 10 years as a result of the effect of coastal elements on the structural integrity of this line (Dawson, 2012).

As well as impacts in the South West, the railways of North Wales and the North East of England also experience coastal effects (Sibley et al., 2015; Jaroszweski et al., 2015). Although coastal effects can have a catastrophic impact on coastal lines, the number of railway sections affected represent only a small proportion of the mainline network. Therefore, this hazard has been excluded from consideration for the main body of this research, as inclusion while developing a methodological approach may distort the output due to the specific nature of this hazard and its impacts. However, it may be possible to apply the findings of this research to this type of hazard in the future.

1.3.6 Combinations of weather hazards

Railway infrastructure is often affected by the combination of weather hazards. A line side fire for example, may not explicitly be the consequence of high temperatures; other causes include arson and accidental events, where the latter is more likely when prolonged high temperatures have led to vegetation desiccation along the railway line. This demonstrates that it is not just the role of temperature that creates a greater risk of lineside fires, it is also the role of precipitation, or indeed the lack of precipitation (Eddowes et al., 2003). There are many other hazards caused by the combinatorial effects of weather hazards. It is the intricacies of these processes that complicates analysis, but through their identification it can be highlighted that the railways are affected by hazards that are a result of a combination of weather variables (Department for Transport, 2014). This research will not explicitly focus upon the combinatorial effect of different weather variables, however by looking at more than one variable it is hoped that this research may be able to highlight suspected combinatorial effects for further research. In addition, the output of this research may be able to support future research in the analysis of such weather scenarios.

1.3.7 Antecedent weather

The role of antecedent temperatures in the phenomenon known as buckle harvesting, where the previous maximum temperature for the season has been exceeded prompting rails to reach their yield point and buckle, is well understood (Dobney et al., 2009). Buckle harvesting has been the subject of a number of research projects due to its highly critical nature and increased likelihood under future climates if adjustments to infrastructure are not made to accommodate these changes. This research however targets only one asset type, ignoring other railway asset types which may experience similar relationships with antecedent temperature.

The only other asset type where antecedence has been considered is earthworks assets, where research has investigated the impacts of different rainfall patterns on the stability of slopes and the likely impact of future climate change (Clarke and Smethurst, 2010). The relationships between earthworks and precipitation have been discussed in Section 1.3.3. However, it is possible that the antecedence of weather variables may have more impacts than are currently known, the inclusion of antecedent weather variables in this research will support the identification of these unknown relationships. This is beneficial as the identification of antecedent relationships will help inform decision making processes such as weather event preparations or creating more resilient asset renewal schemes.

1.4 Susceptible Infrastructure

As has been established in the previous sections, GB's railways are exposed to numerous types of hazardous weather. However, these are only problematic if railway infrastructure assets are susceptible to their effects. Individual assets may perform very differently even when exposed to the same weather conditions, this may be because of an asset's age, condition, or design. These attributes directly impact an asset's susceptibility to the effects of hazardous weather (Quinn et al., 2017).

Much of GB's mainline railway network was constructed over 150 years ago, this poses the somewhat unique challenge of addressing issues resulting from legacy infrastructure. A prime example of this issue is the railway cuttings and embankments, which were constructed to reduce the track gradients, thereby enabling early trains to achieve these inclines (Department for Transport, 2014). However, modern design standards for these geotechnical assets have improved significantly since many of the first routes were constructed. Subsequently, modern earthworks have much shallower shoulder gradients and are much more stable as a result. For example, GB's first High Speed section of railway, HS1, completed in 2004 has been designed and maintained to modern design standards. This route experienced no earthworks failures during the winter of 2013/14. Comparatively the rest of the network experienced a number of embankment failures, but fortunately few derailments as shown in Figure 1.9. The negative impact of adverse weather on legacy rail embankments is undeniable, with around 170 embankment slips across the rest of the GB network.

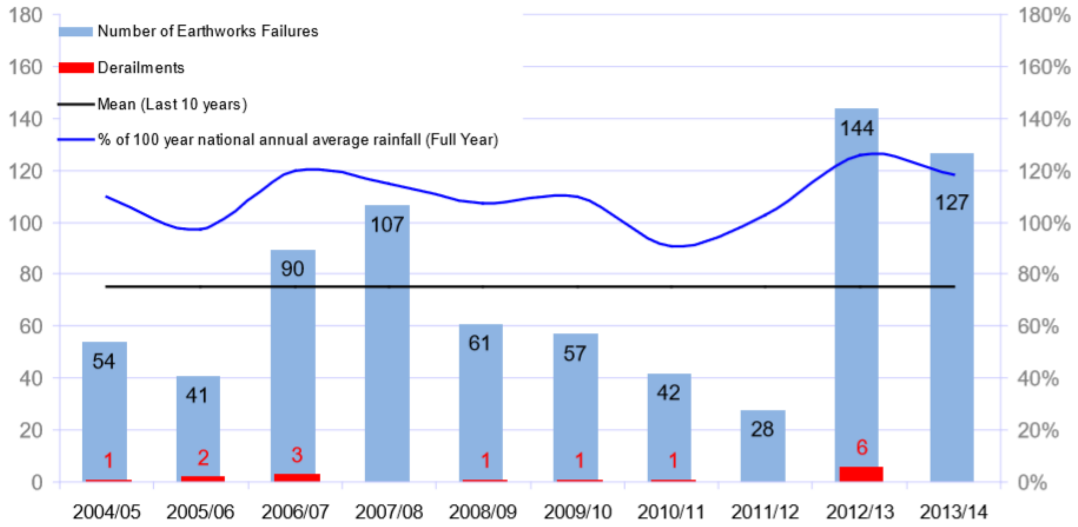

Figure 1.9: Relationship between annual average annual rainfall and embankment slips (Department for Transport, 2014).

In addition to the susceptibility of earthworks to the effects of rainfall, there are a number of other known relationships between key weather variables and different railway infrastructure types these can be seen in Table 1.1. In addition to these direct

Table 1.1: The impacts of weather hazards affecting GB's railway infrastructure assets (Source: (Marteaux, 2016a))

Weather Hazard	***Susceptible Infrastructure and Impact***
High Temperatures	Track buckling OHL sag Overheating electrical equipment Lineside fires Track circuit failures Expansion of moving parts
Low Temperatures	Track blocked by snow drifts Blocked/Frozen points Ice formation on 3rd rail Ice formation over the line (i.e. inside tunnels) Rail cracking Freeze-thaw damage to earthworks and sleepers Tree fall due to snow loading Track circuit failures at level crossings due to road grit
High Precipitation	Earthworks failures/landslides Bridge Scour Flooding Water ingress causing signalling and other electrical failures Power failure due to water contact with 3rd rail Track circuit failures
Low Precipitation	Earthworks failures due to desiccation Soil shrinkage of foundations for equipment such as OLE Lineside fires Electronic equipment failures in low humidity Earthing faults due to poor earthing with dry ground

relationships it is important to note that if a susceptible asset fails it may cause other assets to fail too. This is dependent on the cause and effects of a specific failure mechanism for a particular asset. For example, if a drainage system is overwhelmed because it has a blockage this may cause flooding, destabilising track and affecting signalling systems or negatively affect some other railway assets (Usman et al., 2015).

1.5 GB Rail and Future Climate Scenarios

Despite the implementation of mitigation measures for climate change around the world, the consensus is that the climate is still warming, and this has been indicated by changes in aspects of the global climate and supported by the consistency of

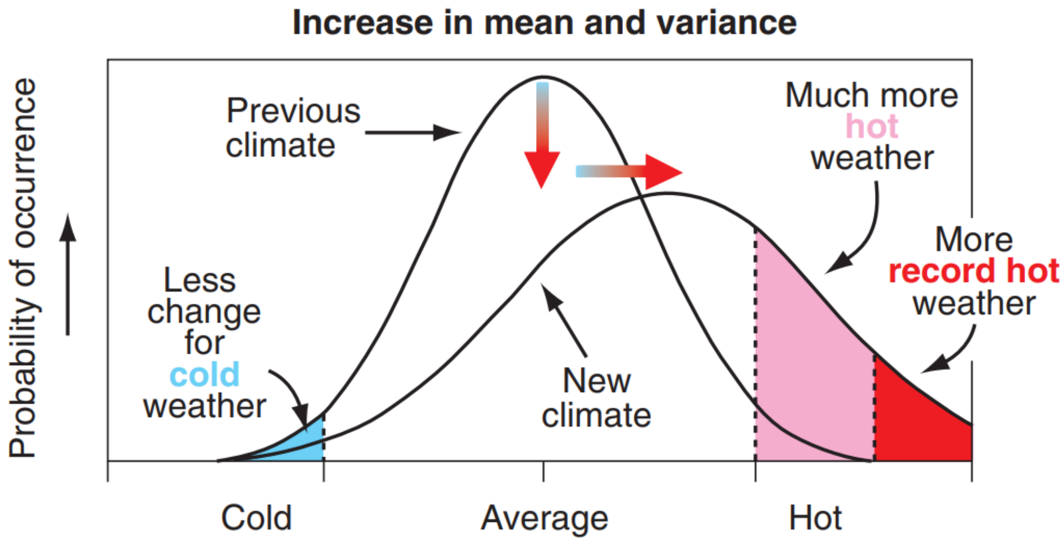

Figure 1.10: The increase in mean and variance of temperatures as a result of climate change (Folland et al., 2001).

observations (Stocker et al., 2013). Average mean temperatures are projected to increase whilst also becoming more variable as illustrated in Figure 1.10. The expected increase in global temperature will increase the amount of moisture held by the atmosphere, resulting in an increase in the frequency of precipitation events, particularly extreme ones (Stocker et al., 2013). The steady realisation that changes in climate cannot be prevented entirely through mitigation of emissions has prompted decision makers to consider ways to reduce the impact that future climates will have upon society. However, the consideration of the impact of climate change on railway infrastructure was considered a novel perspective as recently as 2010 (Baker et al., 2010).

Action is being taken to adapt the built environment to be resilient against the possible effects of climate change. Climate models have been utilised to help further understanding of the role of weather in many sectors, however there are inherent uncertainties associated with modelling natural processes like climate. Obtaining reliable results is particularly difficult when modelling at a localised scale as there are intricate relationships between the climate and local environments, whether natural or engineered (Daly et al., 2009; Carter, 2011).

Current understanding of the climate and how it may change in the future is relatively good in comparison to existing knowledge regarding the possible effects of climate change on the railways in GB or indeed the effects of current weather conditions. It has long been established that the operation of the railways will be significantly impacted by climate change and in order to adapt the system appropriately to the hazards it may create in the future, the extent to which these hazards impact on the railway must first be established both for future and current climates. This can only be achieved by improving understanding of how weather hazards currently affect GB's railway network, but even that is a complex question formed of many components (Dijkstra et al., 2014). Tackling this challenge is crucial to creating a resilient railway system which will remain operable in the future, even under future climate scenarios where extreme weather events are predicted to become a more frequent aspect of the UK's climate (Stocker et al., 2013). Although the impact of future climates is outside of the scope, this research is conducted within the context of informing future understanding of the impact of climate change on railway infrastructure.

1.6 Research Context: A Resilient Railway for Future Mobility

So far, this chapter has outlined the current impacts on GB's railway network however, it is important to consider the wider context. Existing infrastructure may be replaced as technologies advance and the effects of a future climate may be different to the effects of the climate currently experienced in GB (Baker et al., 2010). At present, NR have identified that the effects of high temperatures are far reaching, whilst earthworks are the most susceptible to the effects of precipitation (Network Rail, 2014b), but will this remain the case in the future?

In 2019 the UK Parliament declared a climate emergency (BBC, 2019) and this has two key implications firstly, that policy in all industries including transport, will be aiming for net zero carbon emissions by 2050 (Environmental Audit Committee, 2016), and secondly that the UK Parliament acknowledges that the climate is changing (Stocker et al., 2013). As a low carbon mode of transport, it has been recognised that there is a significant role for rail in the reduction of emissions within the transport sector, including a shift of freight transport to more sustainable modes than roads, such as rail or waterborne (European Commission, 2011). Therefore, it becomes even more crucial that the future railway network in GB is resilient to impacts of future climates.

In order to combat the effects of hazardous weather on railway assets, both now and in the future railway infrastructure must be resilient to the effects of hazardous weather. NR has recognised this, particularly following the widespread damage to their mainline network following the winter of 2013/14. As a result they planned to invest £328m in drainage maintenance and improvements over the course of Control Period 5 (CP5) and increased their spending on track drainage works alone, by £120m from CP4 to CP5 (Department for Transport, 2014).

Greater investment is expected to strengthen the resilience of railway assets against the adverse impacts of hazardous weather; however, can increasing expenditure be effective without a quantified and in depth understanding of railway asset failure caused by hazardous weather? At present much of the existing literature focusses upon a few types of assets under specific conditions or conducts high level network wide impact analysis. Within NR much of the existing knowledge is tacit, which is unhelpful when the effects of corporate memory loss are an issue NR is currently trying to mitigate through a greater focus on data-driven analysis of the effects of weather on their infrastructure and operations (Network Rail, 2014b).

The qualified effects of broad weather categories were previously listed in Table 1.1. However, without an improved understanding of how weather currently negatively impacts railway infrastructure assets, then infrastructure will not be adequately protected against the effects of future conditions resulting from climate change. If suitable action is not taken the risk to the railway network will increase as illustrated in Figure 1.11. This figure from NR shows how the current critical threshold for railway infrastructure assets will more frequently be surpassed under future climates leading to an unacceptable level of risk to infrastructure and railway network operations. It is

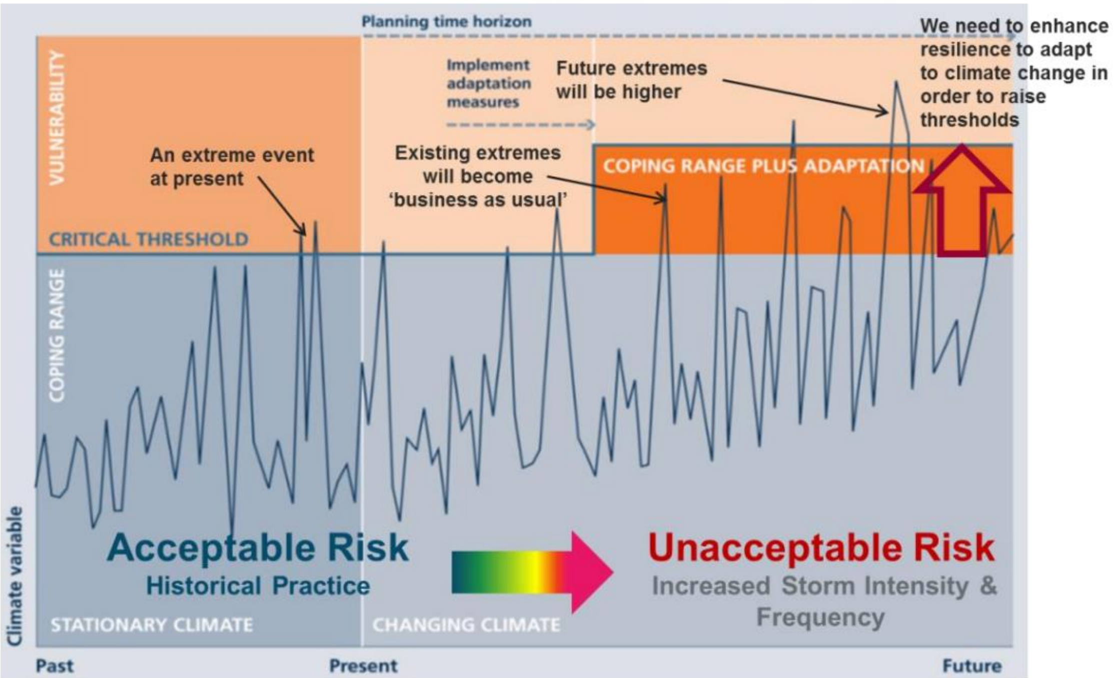

Figure 1.11: A changing critical threshold for vulnerability, for present and future climates (Network Rail, 2017b).

therefore crucial that this critical threshold is raised through improved resilience of infrastructure and network operations (Network Rail, 2017b).

A transport network may only become resilient if the effects it is resisting, or overcoming are well understood. At present there is not an adequate understanding of the scientific and engineering principles behind weather related faults to ensure that investment in infrastructure is effectively targeting assets that are susceptible to the effects of weather hazards. In addition, current understanding is not consistent or a quantified understanding of incidence and causation (Marteaux, 2016a), consequently this research aims to contribute to this whilst also highlighting actions for stakeholders from DfT through to Route Asset Managers.

1.6.1 Aim

This research aims to develop a systematic, methodological approach to assess the vulnerability of railway infrastructure assets susceptible to the effects of hazardous weather.

A systematic, data-driven approach challenges the existing status quo of established areas of focussed research, facilitating the identification of the currently overlooked railway assets which are affected by weather hazards. By achieving this aim this research will expand existing knowledge of the relationships between weather variables and railway infrastructure assets, informing decision making processes and asset management strategies.

1.6.2 Objectives

This aim will be achieved by completing the following objectives:

1. Review existing methodologies and industry practice used to investigate the relationships between weather and railway infrastructure assets to inform the development of a novel and systematic methodological approach.
2. Identify and interrogate significant relationships between weather variables and railway assets by utilising the methodological approach developed.
3. Establish known weather thresholds and produce improved thresholds, outlining how they address current knowledge gaps and validate the output of this analysis.
4. Critically evaluate the methodological approach developed and the results found, outlining areas for further development and future research needs.
5. Illustrate how the developed methodology can be practically applied to inform operations, asset management and associated decision-making processes in addition to further recommendations for associated stakeholders.

1.7 Outline of Thesis Structure

This thesis presents the work conducted to meet the objectives outlined in the previous section and thereby achieve the aim of developing a methodological approach to investigate the relationships between railway infrastructure faults and weather. **Chapter Two** presents a review of current practice within NR compared with existing academic research and introduces the role of operational thresholds and previously identified knowledge gaps. The second chapter continues by evaluating the methodologies that have been employed by existing academic research as well as the quality of data sources utilised. Consequently, the direction of enquiry is presented.

The methodological approach developed is explained in detail in **Chapter Three**, including the data sources that were utilised and the process that was employed to conduct this research. An application of the developed methodological approach is presented in **Chapter Four**. This chapter begins by outlining the definition of the significant weather variables and asset groups and how their significance was identified. The subsequent sections in **Chapter Four** each highlight the relationships between the significant asset groups and the key weather variables investigated, with some in depth analysis of interesting results. The causes and implications of these results are discussed in **Chapter Five** which explores the wider context of these findings whilst recommending how this work can inform the direction of future research and improve current stakeholder practices. In addition, the discussion chapter will also present recommendations for the railway industry in order to create a railway network. This work concludes in **Chapter Six** which establishes how the work presented addresses each of the objectives established in this chapter followed by an overview of key recommendations for key railway industry stakeholders. Following the final chapter, the references and any appendices referenced in the text can be found.

CHAPTER TWO: REVIEW OF EXISTING METHODOLOGIES

2.1 Overview of Existing Methodologies

As the aim of this research is to develop a systematic, methodological approach to assess the vulnerability of railway infrastructure assets susceptible to the effects of hazardous weather, it is necessary to evaluate existing methodologies. Broadly, this chapter reviews current weather impact guidance and strategies within the rail industry alongside the relevant academic literature. The academic literature explored includes, but is not limited to, multimodal transport networks (Dijkstra et al., 2014; Nokkala, 2014), interdependencies between different types of infrastructure (Hodgkinson, 2018; Palin et al., 2013) and methods applied to different infrastructure assets all together e.g. Power (McColl et al., 2012).

The review begins by exploring NR's current practice regarding asset management relating to weather resilience and climate change adaptation. This includes the methods employed by NR to measure the operational performance of the railway network, including operational and failure thresholds. These thresholds have previously been evaluated during the Tomorrow's Railway and Climate Change Adaptation (TRaCCA) research project (Marteaux, 2016b). This review highlighted challenges and knowledge gaps to be addressed by future research. Therefore an awareness of these gaps is necessary to ensure that the methodology developed in this work robustly overcomes some of these challenges whilst contributing to the current knowledge and filling in some these gaps.

To support the exploration of NR's current practice regarding the management of weather impacts and the effects of climate change. This chapter also presents alternative or complimentary methodologies and approaches utilised within existing research. Specifically, this chapter presents alternative measures of operational performance and the use of thresholds within both NR's current practice and those utilised to facilitate academic research relating to the effects of weather hazards. In addition, the approaches and data utilised in NR's WRCCA framework will be compared with others used in current research projects. This review and evaluation of existing practice and methodologies will enable the identification of the relevant understanding needed to inform the whole process of delivering resilience and therefore inform a novel methodological approach to create a resilient railway network.

2.2 Railway Operations and Performance

In order to effectively deliver its duties the railway network is split into a number of "Routes", these Route Businesses are devolved in order to ensure that the specific needs of the different regions of GB are being met and that the daily operations of the entire network are managed effectively. Although many of the strategic policies are driven by the "Corporate Core" of NR, the devolved Route Businesses conduct their own strategic planning and operations. As with all businesses, NR has shifted their route structure a number of times, most recently in June 2019, from nine to five Routes. The routes referred to in this research are the previous ten as shown in Figure 2.1.

As a national infrastructure manager, NR has a number of methods by which they manage weather related risks and associated impacts to the operation of the railway network. These includes asset management tools, operational standards, guidance, policies, and alert systems. The methods may apply to routes, sections and individual assets where the risk presented by weather impacts is high (Network Rail, 2014b).

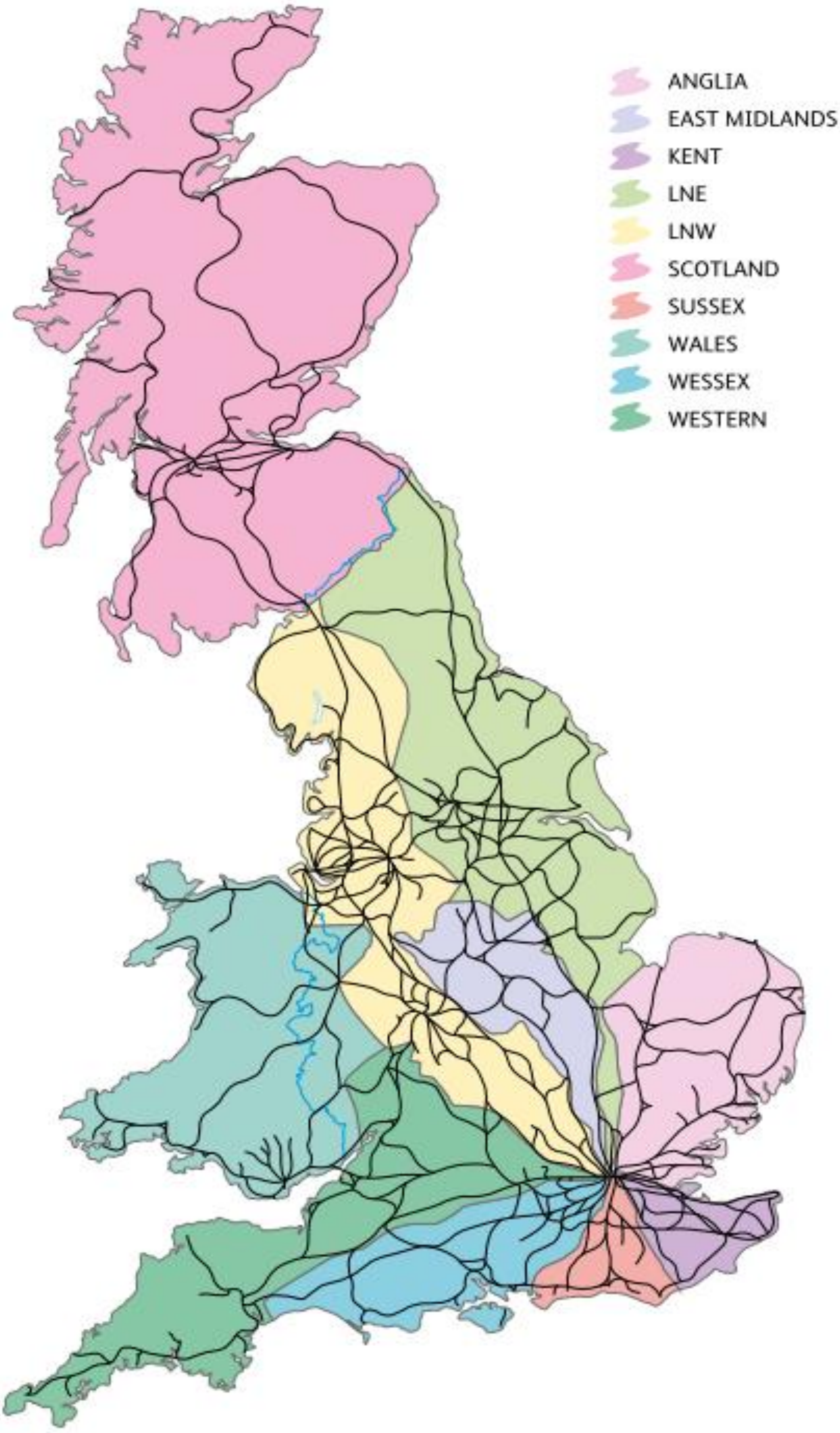

Figure 2.1: A map of Network Rail's devolved Route Businesses (Network Rail, 2015).

As part of their Asset Management Strategy NR have a Fault Management System (FMS) for reporting and recording faults affecting railway infrastructure assets. Reporting faults enables those that need urgent attention to be reactively dealt with, while those that are not urgent then feed into NR's maintenance operations. FMS is managed at Route level, reported faults are attributed to the assets affected and assigned to a Fault Team who will resolve the issue (Network Rail, 2019b).

2.3 Operational response to extreme weather events

Natural disasters and extreme weather can have far reaching impacts on transport networks, stretching across whole continents, as was the case in 2010 when air traffic in Northern Europe was grounded following the eruption of the Icelandic volcano Eyjafjallajökull (BBC, 2010). This event prompted the EU to investigate how transport networks can be more resilient to the effects of natural disasters and extreme weather. The EU funded "Management of Weather Events in Transport system" (MOWE-IT) project aimed to support transport network operators, authorities and passengers. Current best practices were highlighted and further tools and methodologies were developed, culminating in mode-specific guidance documents to support decision makers, that were disseminated at stakeholder workshops (MOWE-IT, 2014).

NR's operational response to the impact of extreme weather is undertaken by NR's Extreme Weather Action Team (EWAT), who manage train services when weather warnings are active. These changes to the number of train services impact the Passenger Performance Measure (PPM) which combines both the punctuality of train services as well as their reliability. The fluctuation of PPM for different weather conditions each year is illustrated further in Figure 2.2 (Network Rail, 2020b). EWAT

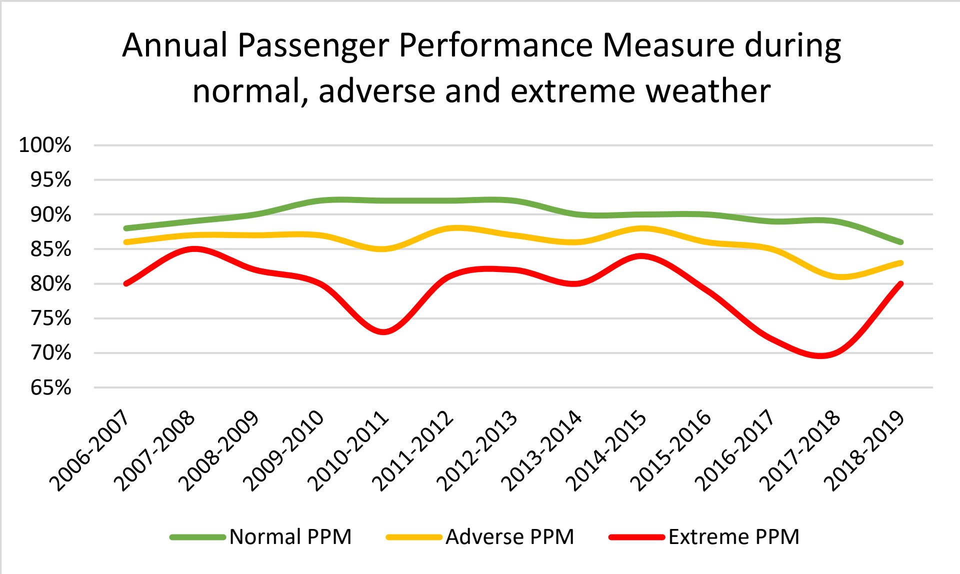

Figure 2.2: The fluctuation of PPM for different weather conditions (Network Rail, 2020b).

Table 2.1: Network Rail's Weather Condition Categories (RSSB, 2014).

Weather Condition Category	***Percentage of PPM***
Normal Weather	>93%
Adverse Weather	>88%
Extreme Weather	<88%

decision processes use definitions of 'normal', 'adverse' and 'extreme' weather conditions and acceptable PPM ranges shown in Table 2.1, however it is not clear how these weather condition categories are derived.

The EWAT predominantly uses weather variable thresholds in order to keep the railways operating and minimise the impact on the timetable. In addition, weather forecasts and real-time weather alerts prompt NR's operational responses. These may include temporary speed restrictions, deploying teams to monitor, manage or protect at-risk assets or when necessary close lines. NR uses a Flood Warning Database, the Washout and Earthflow Risk Mapping tool and for high risk assets, asset specific Remote Condition Monitoring (RCM) equipment in place (Network Rail, 2014b).

NR's operational responses are directed from route level control centres or teams, whilst planned asset maintenance is also managed at route level. In addition to the individual challenges that arise from each route's unique geography and asset portfolio, the way that these assets are maintained may also differ depending on the Route's available resources and strategic priorities. These differences in asset management result in assets with varying levels of resilience against the effects of weather. This was demonstrated in the winter of 2013/14 when very little disruption was experienced on the London Underground, despite only 45% of their network being protected from the elements by being in tunnels (TfL, 2019). This is compared to a number of landslips which were experienced on the main line network which is managed by NR, unlike the London Underground, which is managed by Transport for London (TfL) (Department for Transport, 2014).

The resilience of the London Underground network to the impacts of the 2013/14 winter weather has largely been attributed to more effective vegetation clearance programmes and improvements in drainage maintenance conducted by TfL. This demonstrates that the asset management strategies employed by TfL enabled the London Underground to be more resilient to the effects of the extreme weather experienced during this period (Department for Transport, 2014). However, it must also be noted that TfL's network is a compact urban network that predominantly operates passenger services, while by contrast NR's network is nationwide, featuring coastal routes and a variety of different lines, and with traffic patterns including high speed freight traffic. Regardless, it is evident that the asset management challenges faced in different areas of the country, different networks or even different sections of the same network often face individual and unique challenges (Network Rail, 2017b).

2.3.1 Methods used to explore extreme weather events

One approach that has been used to investigate and expose failure mechanisms of railway assets has been to explore extreme weather events which have a specific temporal range, where the scale of the weather experienced is extreme, and where the impacts are severe. This has been applied to heatwaves (Ferranti et al., 2018), storms (Johnson, 1996; Jaroszweski et al., 2015) and extreme winter weather (Ludvigsen and Klæboe, 2014). This method has been applied using many different types of weather data, including weather radar (Jaroszweski et al., 2015), gridded observations (Fu and Easton, 2016) and meteorological station observations (Johnson, 1996). While, focusing solely on extreme events is limiting in terms of the number of weather types that can be explored (one cannot investigate a drought and a flood in the same spatiotemporal boundary), this approach does offer the ability to look at the effects of a combination of weather variables (Jaroszweski et al., 2015), antecedent weather variables (Ferranti et al., 2018) and the impacts on multiple types of asset, or multiple transport modes (Jaroszweski et al., 2015). For example, studies using this approach have investigated the effects of both wind and precipitation (Jaroszweski et al., 2015), the impact of phenomena such as rail buckle harvesting (Ferranti et al., 2016a) and the impacts on multi-modal transport networks (Jaroszweski et al., 2015). In the case of the combination of weather variables it is particularly important to understand when any one of the weather variables does not reach the levels which trigger alerts and warning systems, but still may cause damage because it is combined with another type of weather. This is possible through investigation of the principle components which have exerted the primary impacts during weather events but investigating individual events in this manner can prove difficult (Fu and Easton, 2016).

Investigating the complex weather scenarios of extreme weather events with fault reports alone is difficult as they are subjective and often inconsistent. However, it is important to remember that these records are not kept for understanding the cause of delays, but instead for attributing culpability for Schedule 8 payments, as explained in the next section. However, consideration of the effects of combinations and antecedence of weather can be crucial to understanding the causes and mechanisms of asset failures. Therefore, it is valuable to take a holistic approach when investigating the relationships between faults and weather scenarios (Jaroszweski et al., 2010).

2.4 Operational Performance Metrics

When the railway network is fully operational, all of the train services timetabled reach their final destinations, including all of the stations along the associated routes, at the times scheduled in the timetable. When timetabled services are disrupted this can be planned or unplanned. Planned disruption takes the form of agreed alterations to the timetable, this usually occurs to allow NR to undertake engineering works. The TOCs and FOCs are reimbursed for their losses through what are known as Schedule 4 Payments. For unplanned disruption the Schedule 8 Payment scheme applies. Where the cause of disruption is found to be a failure of infrastructure or due to the impacts of weather, NR compensates TOCs and FOCs for losses. However, when NR's maintenance routines improve asset condition and therefore service reliability above an agreed level of punctuality the TOCs and FOCs make payments to NR to acknowledge their increased revenue and to incentivise continued good performance from NR (Network Rail, 2019j). To calculate Schedule 8 scheme payments, performance is measured using the Public Performance Measure (PPM) which combines punctuality and reliability. Since April 2019 PPM has been calculated accounting for both delays and cancellations. A cancelled service is a train that completes 50% or less of its planned route. A ‘half cancellation’ refers to services that fail to stop at one or more of the planned station stops, for example an early termination. In addition, the delays that are considered to calculate the PPM are delays beyond a reasonable tolerance at each station call for the planned route. This acceptable tolerance is measured in delay minutes, the responsibility for which is distributed between TOCs, FOCs and NR. NR is held responsible for delays caused by infrastructure failures and external causes such as trespass and weather.

The Tomorrow's Railway and Climate change Adaptation (TRaCCA) project, funded by RSSB, investigated the future resilience of the railway network in the UK and highlight any vulnerabilities (Marteaux, 2016a). As part of TRaCCA, the various metrics used by the GB railway industry, the international rail industries, and for other industries such as Highways, Energy and Water, were evaluated (TRACCA, 2016).The GB rail PPM, Schedule 4 and Schedule 8 costs featured in this study amongst other metrics. It was noted that there are no GB rail metrics that directly link to the impact of weather, as they focus on cost, safety, punctuality, asset condition, fatalities and accidents. Although these are all necessary and useful, many of these current metrics (without further disaggregation) do not enable rail operations managers or decision makers to investigate their operational performance or to make informed decisions regarding the impact of weather on railway assets. Despite this, both delay minutes and incidence figures have been used (sometimes together) to explore the relationships between weather and physical railway infrastructure assets. It is also difficult to conduct valuable analysis from data sets that have not been collected for the purposes of understanding relationships with weather. This difficulty lies within the lack of integration of core asset data sets with weather variables and the lack of recording even the perceived role of weather as the cause. However, there are other challenges to overcome when using these metrics (RSSB, 2016), for example, if the priority is to inform strategies for greater resilience of the railways, then what is the most appropriate measure?

2.4.1 Using Delay Minutes as a Metric

Delay minutes are used to incentivise train operating companies to ensure their trains run on time, with levies and fines issued as a consequence of poor performance, as described in the previous section. This is not the only cost of delayed trains; delays propagate throughout the network and passengers do not reach their destinations as planned, which has a further financial cost to the wide economy (Jaroszweski et al., 2015). Attributed delay minutes are a good reference for use when determining the impact of delays and understanding their impacts on the train timetable, enabling calculation of the financial cost of delayed trains, either to the TOCs or to the economy. As a result, delay minutes have been utilised in a number of studies that aimed to analyse the impact of different weather variables on railway operations or infrastructure (Dobney et al., 2010; Ferranti et al., 2018; Fu and Easton, 2016; Jaroszweski et al., 2015). However, utilising delay minutes to determine the impact of extreme weather limits the scope of the analysis to faults that have impacted the service of a train, and consequently have a direct economic cost to the railway industry. This type of metric excludes events resulting in the cancellation of services or faults that may have occurred when no services were due to run (i.e. overnight) (RSSB, 2016).

Although the impact of weather on train services is of interest to the TOCs, NR as the infrastructure manager, and to the wider public, the use of delay minutes as a proxy for impact does not enable a reliable analysis of the root causes of the faults. If a fault has not impacted the operation of services this does not mean it has not happened, or that its cause could not be attributed to the adverse effects of weather. Additionally, using delay minutes for the analysis of railway faults will reflect the effect of delay propagation. Incidents that occur in the south east, and central London in particular, cause a greater number of delay minutes, indicating that the scale of the effect of such incidents is greater on the operation of the network in urban areas. The greater interdependencies within these high density urban networks result in more delay minutes per incident, and more propagation across the network (Ferranti et al., 2016a; Jaroszweski et al., 2015). Incidents that occur in these congested sections of the railway network therefore also have a greater economic cost to NR, TOCs and FOCs (Network Rail, 2017b). Consequently, this highlights that the measure used when considering the effects of incidents reflects the research priorities, whether this be the impact of incidents on the delays across a network or the cost of incidents to NR.

Delays are recorded in the Alterations Database (ADB). The reporting of faults and consequent logging in the ADB usually relies on the interpretation of either the fault reporter or the responding infrastructure maintenance teams to attribute the fault as weather related. If a fault has not been attributed as weather related it is not subsequently considered when delay minutes are used as a metric. The accuracy of attribution depends on the reporting party's understanding of the cause of a fault, and although suitable for the analysis of heat-related track buckling faults (Dobney et al., 2010), this type of methodology overlooks any faults where a direct relationship with weather but is as yet unknown or is poorly documented.

In summary, utilising the ADB and Schedule 4 and 8 payments can improve understanding of the risks associated with the impact of climate change on GB's railway infrastructure. In addition, this type of methodology can inform the creation of frameworks to manage risk and the resources needed to improve the resilience of the railway network (Baker et al., 2010). However, this approach is only suitable when considering the operational resilience of the railway network and the consequent costs of weather and climate change impacts.

2.4.2 Using Fault Incidence as a Metric

Another less common approach to determine relationships between weather and fault events, is to analyse weather-related fault incidence. It is this approach that is used in NR's Route WRCCA plans, where NR have outlined their route vulnerability assessment methodology, which itself was based upon the methodology developed by *Dobney et al., 2010.* NR's WRCCA Strategy and route WRCCA plans are explored in detail in Section 2.6. NR are moving away from subjective evaluations and towards data-driven assessments, to improve their understanding of failure rates, thresholds and how these change. The results of this type of assessment, which identifies assets that are sensitive to the impacts of weather, are illustrated in Figure 2.3. This assessment has been conducted internally however and no results of the vulnerability assessments have been published (Network Rail, 2014b).

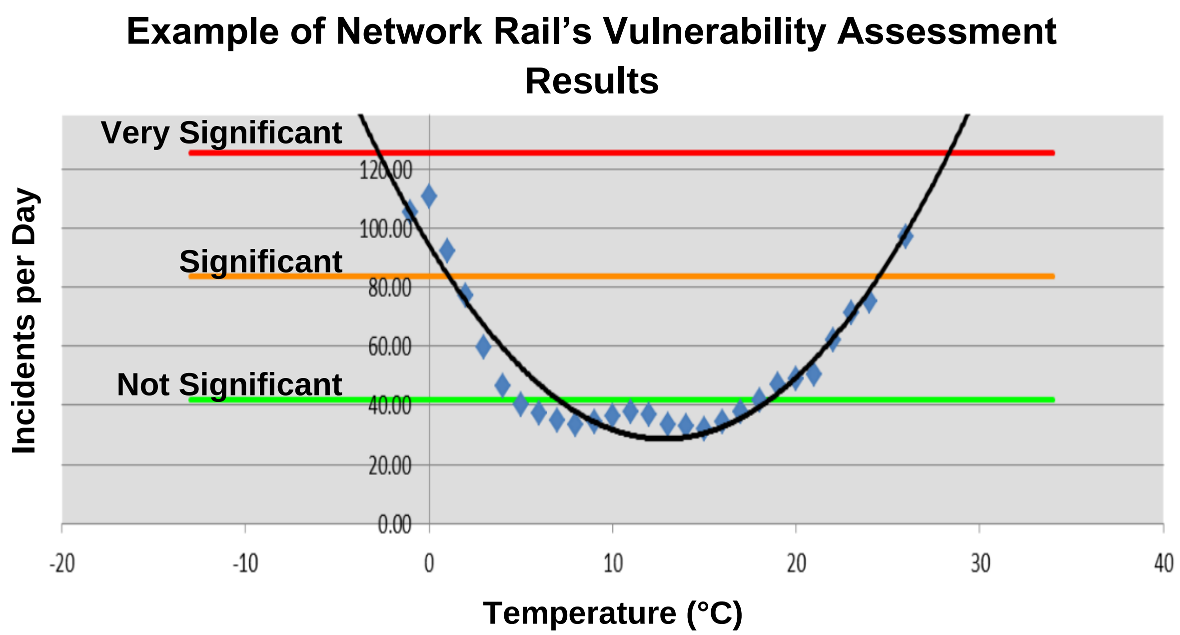

Figure 2.3: An example of Network Rail's asset failure and weather analysis (Network Rail, 2014b).

Other research has utilised fault incidence to conduct analysis of the vulnerability of railway assets to weather variables, including heat (Ferranti et al., 2018) and wind (Fu and Easton, 2016). However, none of these methodologies have considered the frequency of exposure to weather events of a specific magnitude, and subsequently determined the relationship between incidents and the rate of exposure to this scale of weather event. This approach could be harnessed to assess the physical resilience of railway infrastructure assets to the effects of weather. In addition, the analysis of incident rates enables the identification of thresholds at the point where operation begins to be significantly impaired, due to the effect of weather on railway infrastructure. These relationships have been leveraged to inform operational thresholds to facilitate appropriate operational responses.

2.5 Operational Thresholds

In order to trigger a response to extreme weather events or to measure operational performance it is helpful to use thresholds. If thresholds are exceeded or if an unacceptable level of delays are experienced, NR can deploy more resources to mitigate the impact of hazardous weather on the operation of the railway, impose ESRs or cancel services (Network Rail, 2017b). For example, NR deploy heat watchmen when the air temperature is 39°C, however depending on the track condition this figure may be lower and even as low as 16°C (Network Rail, 2012). In addition, if floodwaters pass the bottom of the railhead, speed restrictions of 5mph are applied, if they pass the top of the railhead trains will not run (RSSB, 2015a). Operational thresholds are often used to measure many different aspects of the performance and the operational resilience of the railway network. The thresholds are informed by a range of measures, including the design limits of assets, likelihood of derailments and other safety incidents or the threshold at which a significant number of failures occur.

2.5.1 Existing Thresholds

A number of projects reviewed existing thresholds for the impact of hazardous weather on railway infrastructure (Leviäkangas et al., 2011). The initial phase of the TRaCCA project identified a number of areas where existing knowledge and research could be improved. This resulted in the production of an overview of knowledge gaps regarding climate change and the GB railway, consisting of four sections:

- Gaps in operational threshold analysis of railway systems
- Gaps in knowledge about impacts on the rail network
- Gaps in knowledge about procedures, risk mitigation and solutions
- Gaps in design thresholds, standards and other research (RSSB, 2014)

TRaCCA's evaluation of existing thresholds in Figure 2.4, Figure 2.5 and Figure 2.6, identify areas for improvement in order to develop accurate and reliable thresholds which inform the resilient operation of the railway network in GB. Each column in these summary tables shows the different areas considered, which will be discussed (working from left to right) in this section. Beginning with the Technical Specification for Interoperability (TSIs) and asset ‘subsystems’.

2.5.1.1 TSIs and Railway Asset Subsystems

The operational threshold values present the information originating in those TSIs which relate to physical railway infrastructure assets (rolling stock and passengers are not considered here). Although these infrastructure categories form a standardised classification, this does not directly correlate with those used by NR. Similarly, the list of railway systems is not exhaustive and has been formulated based on those assets that have been identified as ‘*important*’ by the authors and experts at stakeholder workshops. As a result, the outcomes must be considered as subjective.

2.5.1.2 Failure Thresholds

Of those systems that are represented in NR’s guidance and other literature, not all have defined operational thresholds for each of the weather variables considered. The absence of a failure threshold in the tables presented mean that there is no specified failure threshold relating to the particular weather variable and the railway asset concerned. However, this does not mean there is no relationship between the asset and the weather variable, but it does mean that there is no known relationship or that the relationship is too complex for linear thresholds. It is also important to note that these relationships are based upon frequency of incidence with reference to the average incidence rate. Within the review of NR’s standards, TRaCCA identified that the failure thresholds referred to by NR are defined as high (200%-300% average daily failures) and very high (>300% average daily failures) (RSSB, 2014).

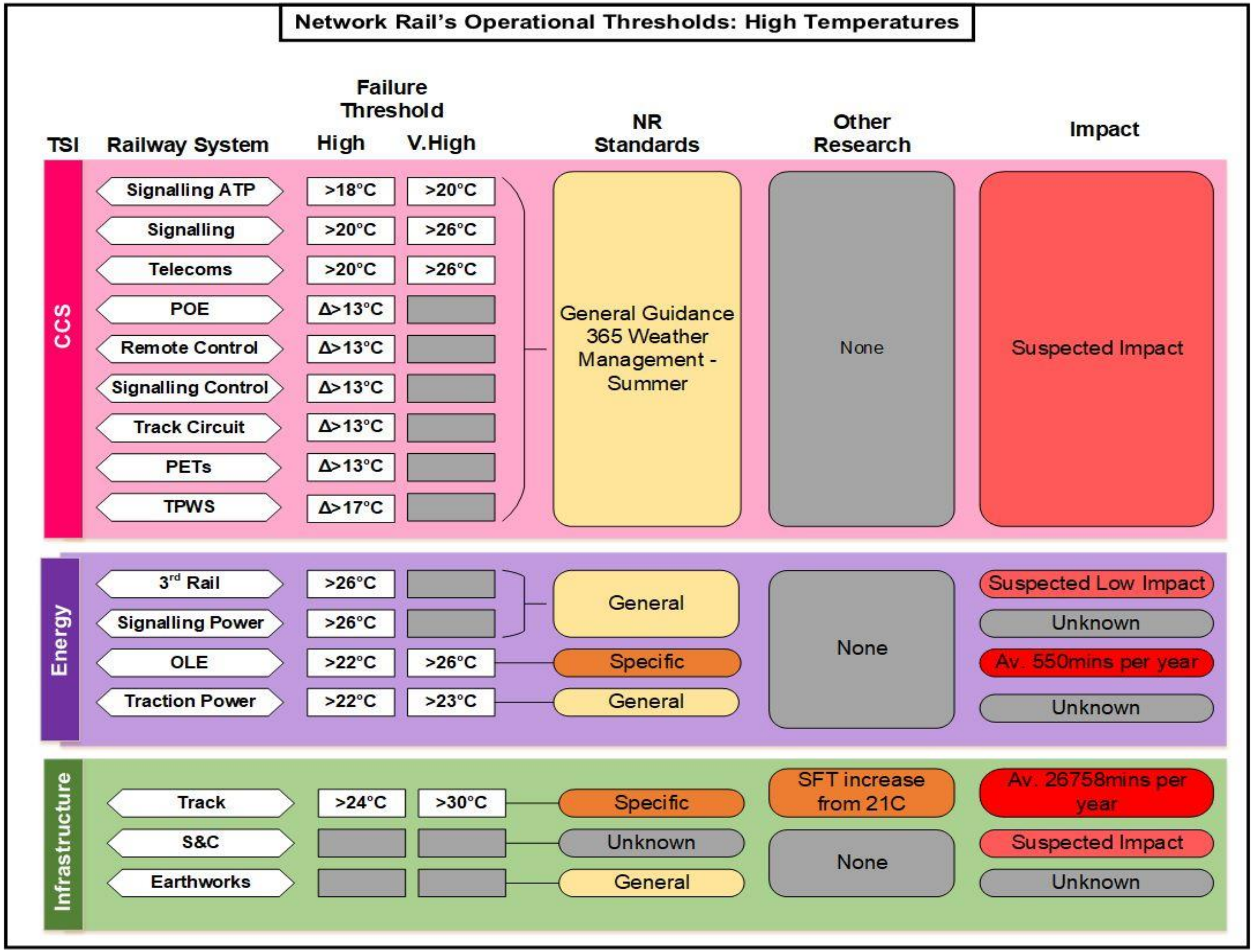

Figure 2.4: Summary of the gaps identified in the TRaCCA project in Network Rail's Operational Thresholds for High Temperatures for a selection of railway assets. Adapted from (RSSB, 2014).

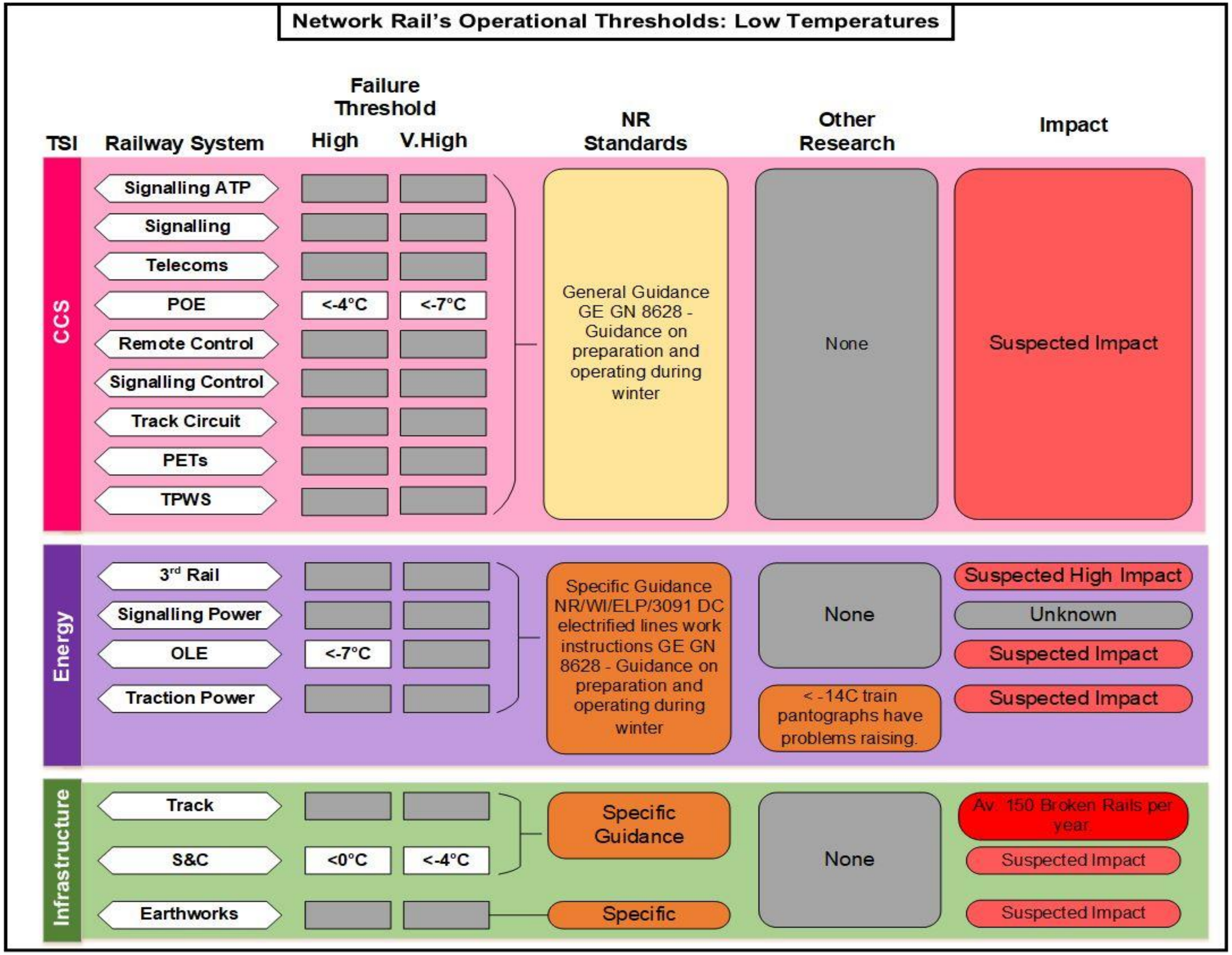

Figure 2.5: Summary of the gaps identified in the TRaCCA project in Network Rail's Operational Thresholds for Low Temperatures for a selection of railway assets. Adapted from (RSSB, 2014).

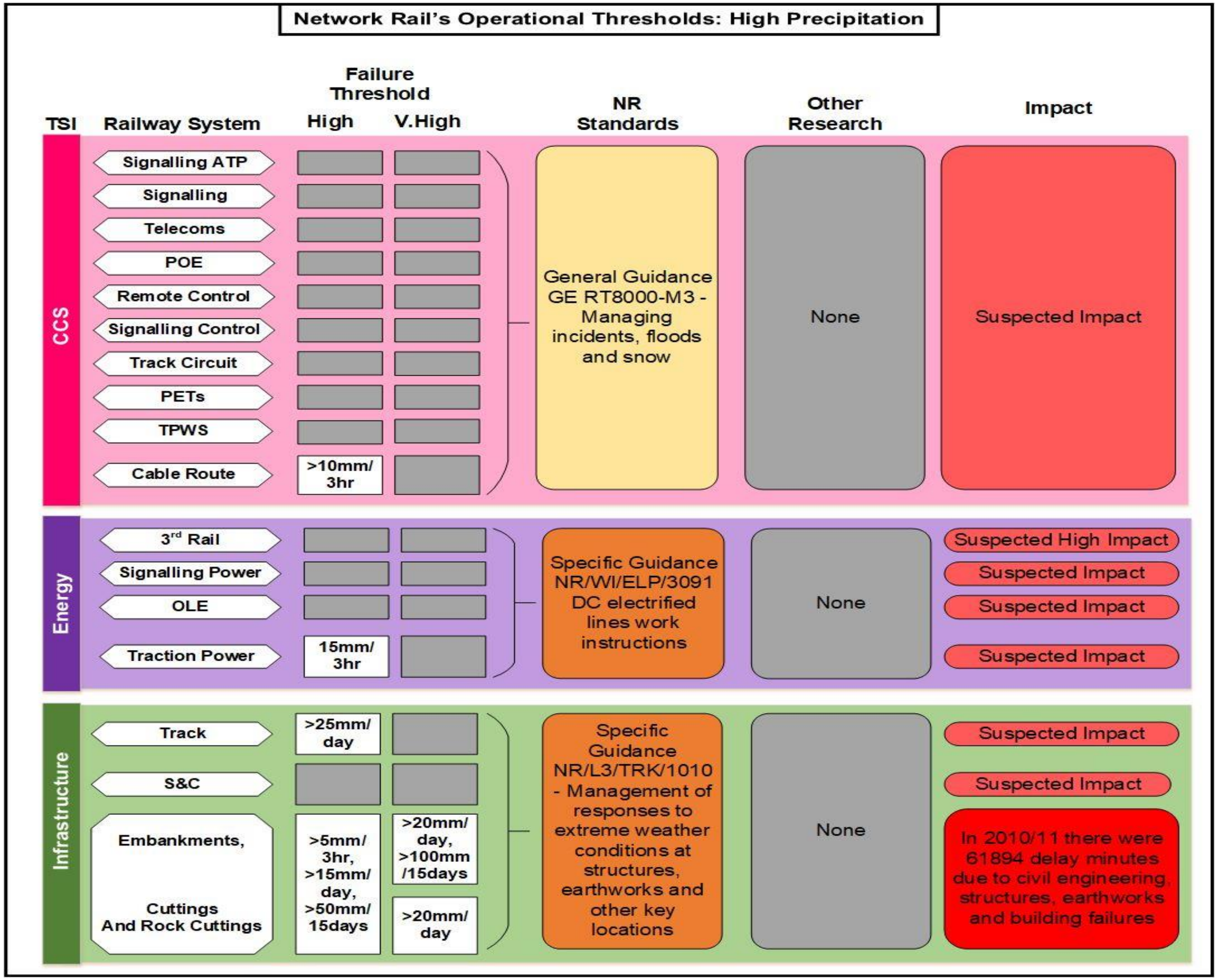

Figure 2.6: Summary of the gaps identified in the TRaCCA project in Network Rail's Operational Thresholds for High Precipitation for a selection of railway assets. Adapted from (RSSB, 2014).

2.5.1.3 Network Rail Standards and Other Literature

Overall Figure 2.4, Figure 2.5 and Figure 2.6 show that knowledge of the effects of different weather variables on railway infrastructure assets is not clearly represented in the policy and guidance which inform preventative actions even where there is a suspected impact. These gaps in the existing understanding of the relationships between weather and railway infrastructure assets need to be addressed if the national railway network is to adapt to future climates. However, it is also important to note that those operational thresholds that NR do enforce are often based on historic experience or tacit knowledge rather than a scientific understanding of engineering principles (RSSB, 2014). Even academic literature relies on workshops with industry experts, rather than data-driven analysis to identify those assets which are most impacted by the effects of weather (Palin et al., 2013). However, NR have stated that they are now focussing on data-driven approaches to obtain an objective understanding of how weather impacts railway infrastructure assets and the operation of the network (Network Rail, 2014b).

2.5.1.4 Impact on railway network operations

The absence of failure thresholds, guidance documents or other research does not preclude the absence of an impact on railway operations particularly as it is known that there are a number of relationships which are not fully understood at the moment. It has been noted in some literature that the data that NR has regarding these assets is underutilised for the purposes of conducting this type of academic research (Jaroszweski et al., 2015). The final column in Figure 2.4, Figure 2.5 and Figure 2.6 show the listed impacts for the TSI categories which have operational or failure thresholds relating to higher and lower temperatures, and precipitation. The impact of weather on some of these assets has been estimated relating to the number of faults, the delays they cause or the cost relating to these delays. There are a few of these relationships where the impact is unknown, however, many of these relationships have a suspected, but as yet unquantified, impact on the operation of the rail network. Despite this, NR have endeavoured to prepare for the impacts of climate change through the development of a WRCCA Strategy as discussed in the next section. By employing a WRCCA Strategy NR aim to create a physically resilient network. While, operational responses to adverse and disruptive weather will always be required in order to ensure the safety of those on the railway network, however protecting the railway against future changes and increasing resilience will reduce the need for an operational response in the future (Network Rail, 2014b). Regardless, the impact of future climates must first be understood before plans can be made to improve the resilience of national infrastructure networks.

2.6 Weather Resilience and Climate Change Adaptation Strategy

So far, this chapter has explored NR's practices regarding managing the effects of weather impacts on railway infrastructure, alongside a review of the current research around these topics and the methodologies used. In the previous chapter, the known effects of weather hazards on railway infrastructure were presented, highlighting the requirement for the impacts of climate change to be considered in order to create a resilient railway network for future mobility. Building on these outcomes, this section will explore NR's approaches to assessing the impact of climate change, alongside an evaluation of the methodologies of current research, to support the development of the methodological approach within this research.

NR's WRCCA Strategy aims to focus activity to improve the way that NR currently handle the risks associated with weather impacts and climate change in order to reduce the long-term impacts and costs associated with future climate change (Network Rail, 2017b). As previously discussed in Section 2.2, NR consists of the “corporate core” of the business and nine devolved Route Businesses. In order to ensure that the WRCCA Strategy is applied appropriately in each of the regions of the railway network a WRCCA Route Plan has been developed for each of the routes.

NR have recognised the need for a consistent approach across all of the devolved Route Businesses to effectively highlight and address issues with the WRCCA across the rail network. Therefore, NR have developed a framework to assess vulnerability and impacts, identify actions and review performance as shown in Figure 2.7. The WRCCA strategy forms part of this framework, which comprises of, a vulnerability

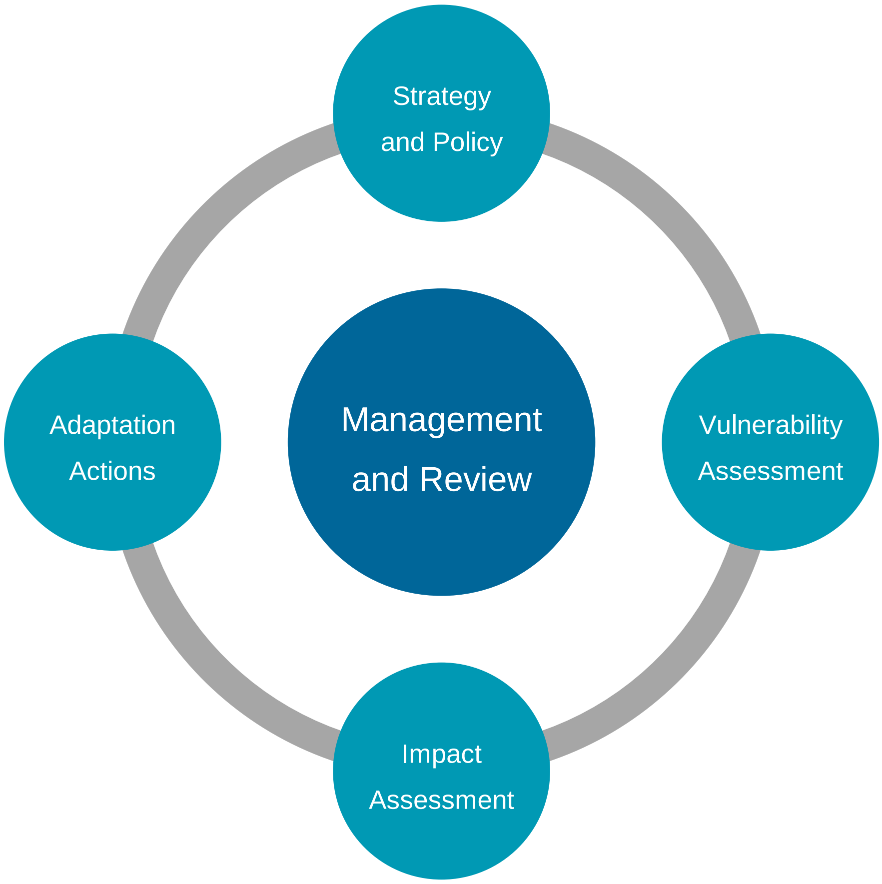

Figure 2.7: Weather resilience and climate change adaptation framework (Network Rail, 2014b).

assessment, impact assessment and a set of adaptation actions. The adaptation actions developed from this framework are presented in the route specific WRCCA plans to account for each of their individual challenges (Network Rail, 2017b). The remaining stages of the framework are discussed in the following sections alongside complimentary existing research and an evaluation of the various methods employed.

2.6.1 WRCCA Vulnerability Assessment

The WRCCA Vulnerability Assessments were produced by conducting a threshold analysis (as discussed in Section 2.4.2) using Schedule 8 delay minutes and costs. This was supported by an analysis of weather data to determine relationships between weather and railway infrastructure incidents. The WRCCA plans employed UK Climate Projections (UKCP) UKCP09 Gridded Observation weather data for this vulnerability analysis, as discussed in the next section. As an alternative solution, NR are also investigating the option of recording weather observations at locations along each route with their current trial in Scotland (Network Rail, 2014b). As part of their WRCCA planning, NR have deployed 102 weather monitoring stations across the Scotland route to provide real time weather observations. It is hoped that analysis of the observations provided by this will enable NR to base their decisions on data-driven analysis instead of experience, providing a more reliably informed response to weather events (Network Rail, 2014a). Following NR's assessment of current vulnerabilities this was expanded to consider future climate change vulnerability. This assessment was conducted using UKCP09 climate projections as discussed in Section 2.6.1.2, however other research has employed regional climate models or weather analogues to investigate the impacts of future climate change and so these approaches are also discussed.

2.6.1.1 Using Gridded Weather Observations

As the evidence of climate change and its impacts has increased over the last few decades the need to better understand the consequences and mechanisms causing Climate change has become apparent. As a result the UK Climate Impacts Programme (UKCIP) was established to address these issues (West, C.C. and Gawith, 2005). To better inform the UKCIP, UKCP have been produced by the Met Office Hadley Centre for Climate Science and Services (Perry et al., 2009) and published most recently in 2018 (Met Office, 2019b).

Output of UKCP09 included Gridded Observation Datasets for temperature and rainfall to facilitate the production of future climate projections (Perry et al., 2009). The UKCP09 Gridded Observation Datasets were produced using interpolation and regression analysis of historic Met Office weather station observations. The method used accounts for the effects of altitude, on coastal, urban and rural environments, and only includes land surface climate observations. This approach enabled the production of accurate regularly distributed values for temperature and precipitation variables (Perry et al., 2009). This format has the advantage of mitigating the issues that result from irregular distribution of weather stations, providing reliable climate estimates anywhere up to 40km from weather station locations which makes it suitable for a range of applications. The UKCP09 Gridded weather datasets are particularly useful for weather applications which include spatial analysis such as that regarding transport networks (Met Office, 2019a).

2.6.1.2 Using UKCP09

Previously, broad climate categories have been outlined in order to provide a framework for discussion of the most prominent effects the railway network will experience under future climates (Baker et al., 2010). These climate categories are listed below:

- Hotter, drier summers.
- Warmer, wetter winters.
- Increased frequency of extreme weather events.
- Increased coastal storminess and sea level rise.

This categorisation of the climate provides a useful basis for discussion of the likely future problems for the railway network resulting from climate change and even provides a crude attempt at approaching the concept of the effects of weather combinations. It should be noted that the categories do not include spatio-temporal aspects like antecedent weather events, or of extreme events that contrast with the usual climate experienced for each of the seasonal categories (e.g. intense summer rainfall). These issues cannot be completely separated as they are inherently related, both through meteorological science, as well as in the way that they effect the operation of the GB railway network and its diverse set of assets (Jenkins et al., 2009; Baker et al., 2010). Consequently, using broad weather or climate categories is too simplistic, particularly following the development of better tools to investigate the impacts of weather or climate change such as the outputs of UKCP09.

As future climate models have developed, their increased sophistication enables their application as part of numerical, statistical or physical models to identify the relationships between weather and national transport infrastructure assets. This is achievable as the UKCP09 provides the means to create sets of projected climatic data that can be used to statistically create future climate scenarios from current baselines.

By using this weather generator, quantification of the effects resultant from the interactions of a multitude of weather hazards and their effects on a multifaceted railway system can be achieved through numerical modelling of the underlying relationships (Department for Transport, 2014).

2.6.1.3 Using Regional Climate Models

Route WRCCA plans utilise UKCP09 to enable prioritisation of actions to improve the weather resilience of the railway network (Network Rail, 2014b). By analysing individual routes in isolation, NR intends to improve their knowledge of weather impacts on each route through identification of localised primary climate drivers, secondary impacts, and the vulnerability of assets to these impacts. Furthermore, NR intend to increase their understanding of the potential impacts of climate change on each route thereby informing the implementation of cost effective adaptation measures (Network Rail, 2014b).

The route WRCCA plans employ regional climate models to investigate what future climates for each route will look like. For example, the LNW Route considered projections from the two main regions the route passes through, the North West England and the West Midlands regions. The regional models enabled NR to estimate the future change in percentage of average monthly precipitation and future changes in temperature in degrees centigrade (Network Rail, 2014b). However, these results in isolation do not indicate the impact of climate change on the probability of asset faults.

Previously research has used approaches developed to investigate the impact of climate change on electricity networks (McColl et al., 2012) to investigate the impacts of climate change on railway infrastructure and operational processes. This approach utilised regional climate models to investigate the frequency of exceedance of existing thresholds by future weather patterns. Application of this methodology to the railway infrastructure of GB investigated a number of potential impacts, including thermal expansion of OLE, and the availability of windows of opportunity for track maintenance. This approach informed a number of recommendations to improve practices within NR which would support a greater resilience of railway infrastructure and operation, particularly relating to maintenance (Palin et al., 2013). Although drawing only on weather variables linked to temperature, similar approaches have been used to investigate the impact of future precipitation patterns on the failure of earthworks; in these cases, while the relationships are more complex, they have been validated by experimental results (Rouainia et al., 2009; Clarke and Smethurst, 2010).

2.6.1.4 Using Weather analogues

Another approach utilised to explore the potential impact of climate change on infrastructure is that of Weather Analogues. This approach uses examples of past weather events such as the heatwave of 2003, which is predicted to be 'normal' weather experienced in Europe in the future, as a model of future trends (Dobney et al., 2009). Alternatively, the experiences of countries that presently experience the weather predicted to be 'normal' in the future can be used as the basis of a case study. It should be noted that the use of analogues assumes that the current infrastructure networks being analysed are similar to what is expected to be the case in the future (Sanderson et al., 2016). Nevertheless, while there are inherent uncertainties with this approach, particularly regarding the use of present infrastructure networks to reliably reflect the developments in technology and infrastructure in the future, however, this approach does provide some insight into the impacts of future climates and the challenges that future climates may pose (Dobney et al., 2009; Baker et al., 2010).

2.6.2 WRCCA Impact Assessment

Following the vulnerability assessment, the next stage of each of NR's route WRCCA plans is the impact assessment. In this step, the performance impacts anticipated as a result of each route's projected future climate, including resultant increases or decreases in weather variable magnitudes and frequency, are presented. Next, the impacts of different groupings of weather variables are considered, highlighting the main asset classes which will be impacted by the change. The operational impacts on these vulnerable assets are then assessed and quantified using performance measures, enabling the identification of locations at high risk. In addition, NR were able to identify high risk areas for each route by utilising their Geographic Information System (GIS) based decision tool, known as METEX. Further assessment of these high risk sites was conducted to help identify the root causes of delays and resilience improvements that could be taken compared to those that are currently planned for the areas (Network Rail, 2014b).

The route WRCCA plans present a range of detailed incidents and projections for each route providing an informative overview of the key challenges that will need to be addressed (Network Rail, 2014b). It is important to note that these plans are often unique to specific locations in each route due to the combination of environmental factors that are experienced locally. A good example of this is Dawlish where the track is adjacent to the coastline, and despite being protected by sea defences these proved inadequate, as has been previously discussed (see Section 1.3.5). The socio-economic impacts of this weather event extensive and the closure of the railway line impacted the tourism industry, even in the off-peak season (Devon Maritime Forum, 2014). During periods of extreme weather, impacts can be felt nationally, as was the case during the winters of 2008/09, 2009/10 and 2013/14 (Department for Transport, 2010, 2014). Therefore, it is important to consider the spatial context of the impacts of weather on national transport networks as well as the socio-economic impacts, which are not reflected in the WRCCA plans.

2.6.2.1 Considering Spatial Context

Spatial analysis considers the environment adjacent to the railways, and is used to examine the risks associated with weather and its local effects on railway infrastructure at a given point on the network. This creates a reliable method with much more accurate results, especially as the hazards experienced over relatively small areas can be so diverse (Dijkstra et al., 2014). For example, hilly or mountainous regions experience relief rainfall; a railway in this environment will potentially be subject to increased flooding events both in terms of magnitude and frequency, particularly if the railway line is in a valley. However, the inclusion of this type of this spatial context in a detailed and accurate way requires the use of high-quality geographic asset data, which is the property of the infrastructure manager and is potentially sensitive.

Where access to NR's existing geographic models has been available, this has enabled a more detailed analysis of the impacts of weather variables. Where data has been provided, it should be noted that there have still been challenges regarding the quality of location data of incidents, particularly where these are referred to by railway specific geographic positioning measures which are not easily translated to conventional co-ordinate systems. Ambiguity of position can make the addition of supplementary data sources difficult, however, if these challenges can be overcome and the data sufficiently cleansed, analysis can provide an insight into the impact of weather and the subsequent spatial hazards. This methodology has previously been applied to inform vegetation management strategies based in the Anglia route depending on the location of different tree species are prone to causing rail incidents (Fu and Easton, 2016).

2.6.2.2 Assessing Socio-Economic Impacts

The operational resilience of multi-modal transport networks is the focus of the Future Resilient Transport Networks (FUTURENET) project which aimed to design a model to quantify the resilience of UK transport network infrastructure in the 2050s. This research defined resilience as pertaining to the transport networks ability to supply projected demand in the 2050s, and investigated ways to quantify this by undertaking travel behaviour surveys, considering future travel demand, including the influence of weather events and assessment of the effects of weather on asset deterioration (Dijkstra et al., 2014). By recognising the role of changing socio-economic factors such as attitudes towards sustainability, alongside a consideration of the meteorological conditions, FUTURENET allowed for a much broader range of influences on the transport industry than earlier studies, thus recognising the complex role of transport in society. A unified transport network model was established for analysis, however this broadened scope prevents a reliable assessment due to the complexities within this system of systems approach used (Dijkstra et al., 2014).

Part of planning for the future is understanding the projected costs associated with the effects of any future climate, including those that result from adapting legacy infrastructure to improve its resilience. Quantification of probable future costs associated with the impacts of future climates on the railway infrastructure has been undertaken in a number of different contexts to date. The effects of higher temperatures (Dobney et al., 2010), extreme weather events (Nokkala et al., 2012;

Sedlacek and Pelikan, 2010), and climate change (Dijkstra et al., 2014) have all been the subject of economic analysis. Each of these studies has taken a different approach to the analysis; *Dobney's* work on the impact of heat related rail buckling considered the frequency of future incidents used estimates of the associated Schedule 8 costs for the future scenarios (Dobney et al., 2010). However, this excluded the cost of the replacement and repair of buckled rails and associated damage to other assets (Palin et al., 2013). The analysis of the costs attributed to historic extreme weather events affecting railway infrastructure across Europe has been used for the basis of probabilistic future cost estimation (Leviäkangas et al., 2011; Nokkala et al., 2012). In addition, there may also be a cost associated with employing adaptation actions however, appropriate adaptation actions are an investment for the future resilience of the railway network.

2.6.3 WRCCA Actions

Following the assessments of asset vulnerability and impacts across the route, each route WRCCA plan presents the resultant planned actions to improve the resilience of the route. The target of these plans range from very high level aspects of the route infrastructure, guidance and policy, through to specific assets or equipment. The route WRCCA actions are broken down into two categories, firstly those actions which are in progress, planned with a completion date, or already ongoing activity. Secondly, come those actions which require further business case evaluation before they become part of the planned route actions. It should be noted that where plans have been completed, the actions listed in the route WRCCA plans have been criticised, as they do not account for the broad range of assets found to be affected by temperature. In addition, one route's WRCCA plan excludes one of the most significant asset failures, overheating signalling assets, which account for 60% of both cost and delay minutes between 2006-2013 for Anglia (Ferranti et al., 2016a). This highlights that the route WRCCA actions have not consistently considered the identified impacts of weather hazards and climate change.

2.6.3.1 Network Topology and Infrastructure Network Interdependencies

Adaptation actions can only be implemented in situations where the root cause of the asset failure is known. NR identify root cause understanding and analysis as necessary for each route to deploy cost effective control measures to ensure the resilience of each railway route. However, existing methods often fail to capture the specific root cause or failure mechanism of railway infrastructure faults related to weather, as this is often related to the underlying network topography. One approach that addresses this is the use of fault charts which can highlight the cause and effect of faults related to specific assets. While fault charts could potentially be a useful diagnostic tool, they have currently only been developed for track sub-grade failure. It is believed that if this approach was expanded to consider all infrastructure assets and their relationships with weather variables, this would play a key role in informing suitable adaptation measures to create a resilient railway network (Usman et al., 2015).

Identifying the root cause of a railway incident is particularly difficult when it involves additional infrastructure networks on which the railway is dependent e.g. power distribution networks (Pant et al., 2014b). Attempts have been made to model the dependencies of GB rail on the power network (Hodgkinson, 2018; Pant et al., 2014b), however existing research often simplifies the relationships between the assets of each infrastructure network. These studies that have attempted to rectify this however, have found that trying to understand historic incidents which are across infrastructure networks with different infrastructure managers and regulatory systems is not possible due to poor recording practices (Hodgkinson, 2018).

2.6.4 WRCCA Management and Review

Developing resilience assessment frameworks can support decision making processes regarding adaption of transport infrastructure for future social, economic or meteorological climates (i.e. for population growth, for privatised railways, for climate change or some combination) (Quinn et al., 2017). Within the route WRCCA plans both the physical resilience of infrastructure and the operational resilience of the railway network are explored. In each route WRCCA plan the management and review is conducted at both the corporate and route business level as well as the process for future review of the actions that have been presented in the plan. This demonstrates where the WRCCA plans sit within the wider governance of WRCCA challenges and risks at both the corporate and national level as well as at route level. The WRCCA plans require that policies, standards and monitoring are reviewed through the Safety and Sustainable Development Integration Plan, and that WRCCA action progress is to be reported every six months through the same mechanism.

2.6.4.1 Alternative Adaptation Frameworks

NR have made significant progress to ensure that consideration of WRCCA issues is integrated into their processes through the WRCCA Strategy and framework (Network Rail, 2017b). increasing pressure . There is ever increasing pressure for businesses to ensure that adaptation to climate change becomes business as usual, as the climate continues to change with no signs of slowing based on all scientific projections, and most recently in the UK the Committee on Climate Change has called for adaptation to be integrated into all government policy (Committee on Climate Change, 2020).

particularly for national infrastructure managers, as the risks associated with long term or significant failures have potentially serious ramifications. For the railway industry the UK National Audit Office estimated in 2008 that every minute a train is delayed costs the UK economy £73.47, which equates to roughly £98 when adjusted for inflation (National Audit Office, 2008).

A recent review of current best practice for adaptation frameworks for transport infrastructure managers and stakeholders at an international level was conducted during the RAIL Adapt Project. The role of both scientific based and decision centric approaches were considered in order to develop a flexible framework to support decision making processes for the implementation of adaptation strategies. The consultation resulted in a circular and iterative framework which enables evaluation of impact and performance improvements. In addition, this approach allows for the incorporation of new or updated information as knowledge expands. The resulting framework, shown in Figure 2.8, can easily be embedded into existing practice ensuring that '*climate adaptation actions become part of business as usual'*. Therefore, preparing transport infrastructure stakeholders to be resilient to future impacts of climate change (Quinn et al., 2018).

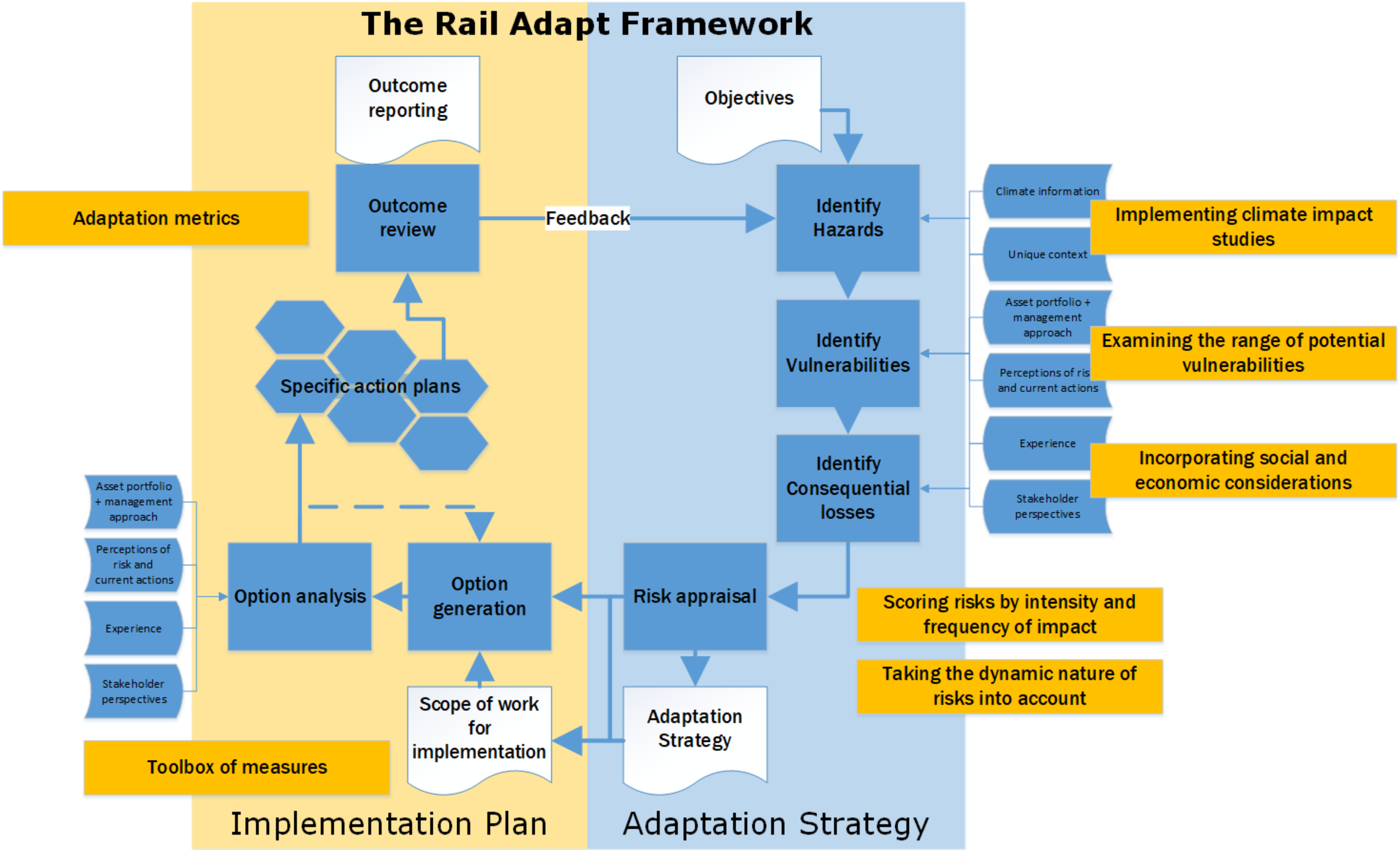

Figure 2.8: A framework for climate ready transport infrastructure, combining both an adaptation strategy and implementation plan (Source: (Quinn et al., 2018))

2.7 Chapter Summary & Proposal Justification

This chapter has reviewed NR's current practices regarding weather resilience and climate change adaptation processes whilst also considering methodologies that have been employed in current research. It has been found that NR's reactive processes are driven by threshold exceedance for daily operational resilience of the network. Similarly, measurement of operational performance is also conducted with reference to thresholds that relate to incident numbers, delay minutes or schedule 8 costs. Consequently, it would be appropriate for this research to support current practices by developing further thresholds, particularly as previous research has identified a number of gaps in current understanding of these thresholds (RSSB, 2014).

To support the development and improvement of existing thresholds the analysis undertaken will take the form of a deterministic analysis looking at past impacts of weather on the railway network. For the investigation of past events, the most appropriate weather data currently available are the reanalysed gridded observations provided by the Met Office, which provide the most reliable and greatest resolution data covering the railway network in GB. Additionally, both the impacts of temperature and precipitation should be explored to provide support for a broad range of existing thresholds. This should also include the whole range of both temperature and precipitation as well as antecedent measures to expand upon existing research.

Despite NR's preference for data-driven approaches, much of their existing research and that of others is led by expert opinion. Tacit knowledge of experienced stakeholders is very valuable for improving understanding of relationships however to ensure that research is effectively considering all possibilities it is the view of the author that the approach should be driven by data. It is important to note that data-driven in the context of this research does not include machine learning or artificial intelligence as is the case in certain fields but instead an objective approach led by the findings from data analysis rather than led by expert opinion. Therefore, this research will employ a systematic approach, led by data analysis to ensure there is no prior bias towards any existing approach, and to provide insight into previously neglected areas, relationships and failure mechanisms. This is particularly important as research to date has largely concentrated on specific, well understood climate variables, rather than other, more complex aspects of climate that have been less well explored despite their influence on the railway network being widely recognised. The main shortcoming of this simple identification is that it lists hazards without any clear basis for assessment of the effects of multiple hazards, cascading failure of infrastructure assets or consideration of factors like antecedent weather events (Dijkstra et al., 2014).

The review in this chapter has shown that commonly the measures applied to understand the impacts of weather hazards on the railways are the frequency of occurrence of an incident, the delay minutes experienced by the network, or a related financial measure. The measure chosen is dependent upon the aspects of the railways being analysed and the objectives of the analysis, therefore the measure used in any analysis needs to be carefully considered and the results of the analysis need to be viewed within this context (Dijkstra et al., 2014). Therefore, in order to both expand upon existing research whilst supporting the development of thresholds this analysis should focus on a range of asset categories and instances where they have failed as a result of the effects of weather hazards. To further improve upon current research the failure of assets should be considered relative to their exposure to weather variables.

Ultimately there is a need to draw together the individual threads of knowledge and understanding of the relationships between both weather hazards and physical railway infrastructure in order to begin to understand the behaviour of the woven fabric of the railway network as a national infrastructure. It is only once this is achieved that a robust and comprehensive approach towards creating a resilient railway network can occur by allowing targeted investment of resources to effectively improve resilience of the railway's physical infrastructure assets. The methodology of a systematic analysis of the vulnerability of railway infrastructure assets in terms of their rate of failure in relation to temperature or precipitation will be presented in the next chapter. This approach has been developed to compliment current practices and quantify further the relationships between key weather variables and railway infrastructure assets with the view to improve the resilience of the railway network in GB.

CHAPTER THREE: METHODOLOGY

3.1 Overview of Methodology Chapter

The previous chapter reviewed NR's current practice, and gave a summary of methodologies used in existing research to investigate the relationships between weather and railway infrastructure resilience. The previous chapter concluded with an overview of the key aspects of the approach this research will develop. This chapter presents the methodological approach to be followed in detail. The method is outlined in Figure 3.1, and the structure of the remainder of this chapter reflects its steps, beginning with the data sources employed and culminating in the completed vulnerability assessment.

3.2 Data Acquisition

NR's METEX database was made available as part of a strategic partnership agreement between the University of Birmingham and NR, providing fault event data for a five-year period from April 2006 until April 2011. The UKCP09 gridded observations for the climate variables presented in the next section, were obtained for the 5 years from the 1st of April 2006 to match the dates (as closely as possible) of the fault event data provided by NR. These datasets were utilised in order to facilitate the historic vulnerability assessment of the railway infrastructure assets which experienced faults over the five-year period. The next sections describe the content of the data sets and how they were handled in order to conduct the analysis.

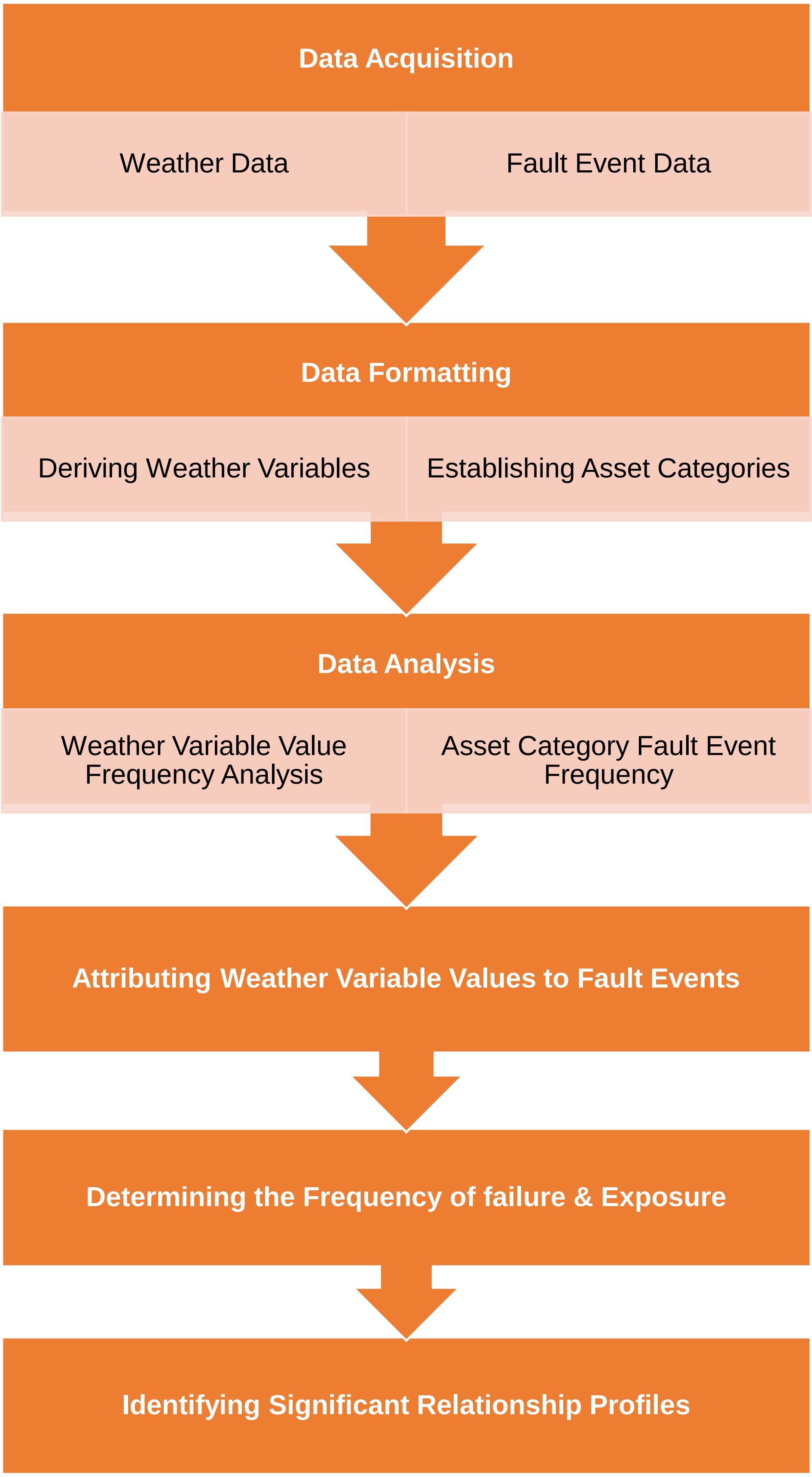

Figure 3.1: Outline of methodology and method chapter structure.

3.2.1 Weather Data

Chapter Two explored a variety of weather data sources used in existing analysis of the relationships between railway assets and weather hazards. It has been concluded that utilising UKCP09 gridded observations is the most accurate and reliable way of considering historic weather hazards affecting a national infrastructure network as described in detail in Section 2.6.1.1. Their creation was funded by the Department for Environment, Food and Rural Affairs (DEFRA) and are free to use for research under an Open Government License (The National Archives, 2019). The initial UKCP09 weather datasets acquired for this research have been extended to expose the more complex relationships between railway infrastructure assets and different types of weather, such as antecedent weather hazards. The mean daily temperature value has been excluded as this value did not add any additional insight after preliminary analysis. Therefore, the significant weather variables to be carried forward in the analysis of the results can also be seen in Table 3.1.

The maximum, minimum and daily precipitation totals will be included in the analysis as these quantify the weather experienced on the day of the fault event. The other weather variables listed are those derived from the original weather data, this includes the diurnal range and antecedent accumulation of precipitation which are already known to cause faults such as freeze thaw damage to concrete structures and flooding as discussed in Section 1.3.3. The derived weather variables were calculated for each of the grid squares with a fault event for each day over the time period considered. However, as the fault events are recorded for individual asset locations these two sets of data will need to be unified to find the weather occurring at the time and location of each fault event.

Table 3.1: UKCP09 Daily Gridded Observation Weather Variable Data (Met Office, 2019a) and consequent derived Significant Weather Variables.

Climate Variable	***Definition***
Maximum air temperature	Maximum air temperature measured between 0900 UTC on day D and 0900 UTC on day D+1 (°C)
Minimum air temperature	Minimum air temperature measured between 0900 UTC on day D-1 and 0900 UTC on day D (°C)
Diurnal range	Change in air temperature measured between 0900 UTC on day D and 0900 UTC on day D+1 (°C)
Precipitation	Total precipitation amount measured between 0900 UTC on day D and 0900 on day D+1 (mm)
Antecedent accumulation of Precipitation for a week	Total precipitation amount measured between 0900 UTC on day D and 0900 on day D-7 (mm)
Antecedent accumulation of Precipitation for a Month	Total precipitation amount measured between 0900 UTC on day D and 0900 on day D-28 (mm)

The initial datasets acquired for this research have been extended from 4 weather variables of interpolated reanalysed gridded observations to a total of 46 with integer values calculated for all of those that are continuous data. This was done to expose the more complex relationships between railway infrastructure assets and different types of weather, such as antecedent weather hazards. Predominantly the derived variables have been developed on a temporal basis, for example antecedence, diurnal ranges and averages for different periods were investigated. The additional derived weather variables are defined in Table 3.1. The derived weather variables were calculated for each of the grid squares with a fault event for each day over the time period considered. However, as the fault events are recorded for individual asset locations these two sets of data will need to be unified to find the weather occurring at the time and location of each fault event.

3.2.2 Railway Infrastructure Fault Data

The structure of the fault data accessed for this research can be seen in Figure 3.2. As this research is focussed on understanding the role of weather in causing faults to railway infrastructure the primary focus was upon the FMS data. However, some supplementary data was retained throughout the analysis to support further interrogation of individual fault events at a later stage, where necessary.

3.2.2.1 Defining Asset Categories

In order to better understand the effects of hazardous weather on physical railway infrastructure assets, the effect of weather across groups of similar assets was investigated. The recorded fault events cover a broad range of different asset types that collectively form NR's national railway network. As part of this analysis, fault events were grouped by the type of asset they impacted – the Asset Category.

The asset categories are based on NRs own asset classification so that these findings may be easily interpreted by the infrastructure manager. The asset categories were used to code each fault event so that relationships could be easily identified. The asset categories were assigned based on the Parent Asset Group and asset sub-group recorded (Appendix A). For example, the parent asset "Signalling" has an asset subgroup within it called "Point Operating Equipment". All of those faults listed within Signalling and Point Operating Equipment (POE) formed an asset category, which was then given a shortened title, therefore the asset category Signalling: Point Operating Equipment would become Sig POE.

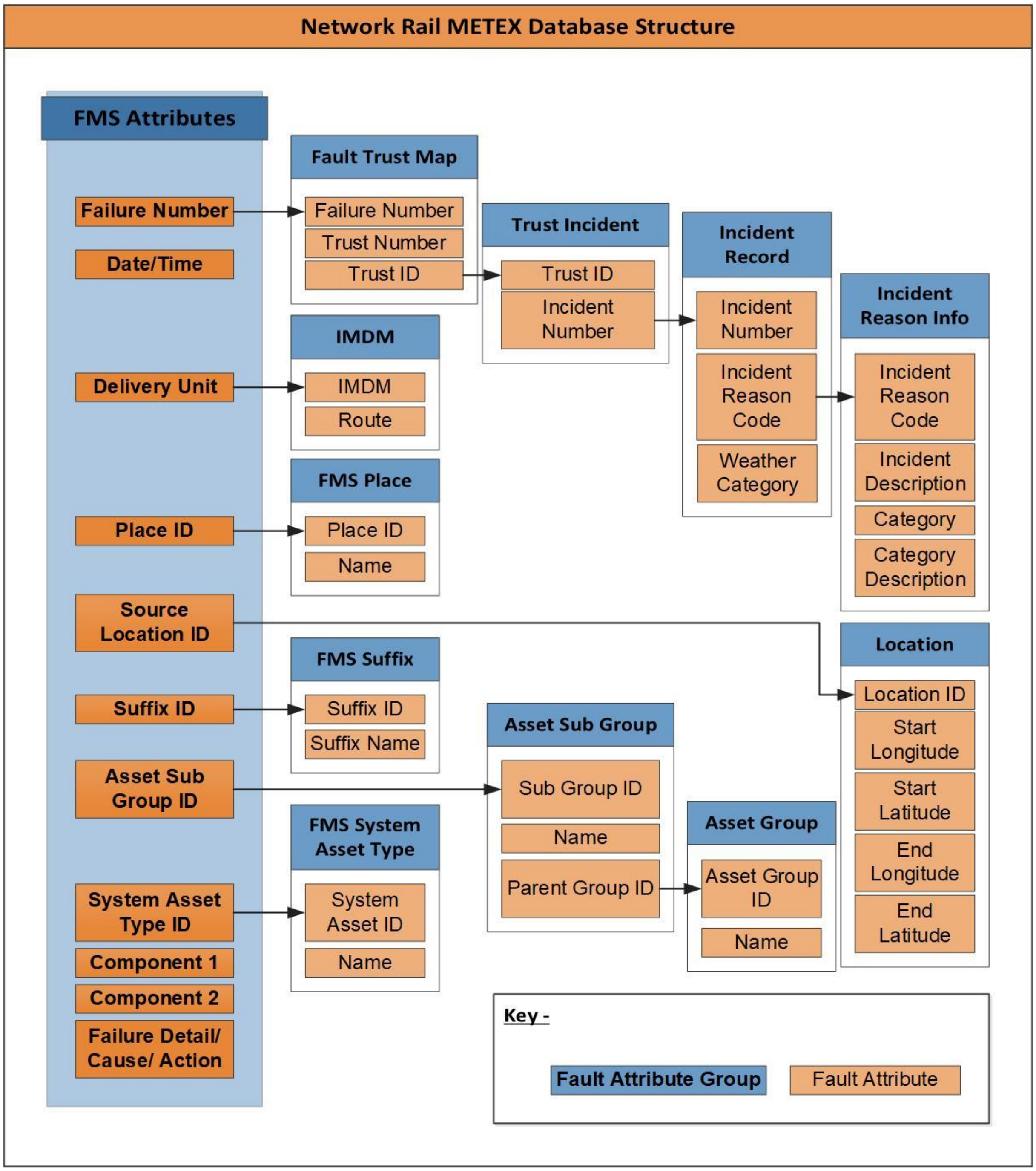

Figure 3.2: Diagrammatic representation of the FMS related data held within the METEX database and how data was compiled from a variety of datasets.

An initial analysis was undertaken, and it was found that there was not enough of a distinction between the different types of equipment within these asset categories. As a result a third parameter known as the “FMS Suffix”, which NR use to group asset types was used to further distinguish the asset categories (Network Rail, 2019b). To incorporate the FMS Suffix information into the coded asset categories a number was then added to the short name to indicate which FMS Suffix within the Asset category is attributed to a fault event. For example, those fault events with the FMS Suffix "Point Heating" sit within the Sig POE asset category and is the first FMS Suffix alphabetically and so the short name and number for these faults becomes Sig POE 1. Attributing each fault event to a particular asset category enabled the relationships between their failures and the weather at the time of the fault event to be analysed and correlations between types of asset and types of weather variable to be observed.

3.2.2.2 Supplementary Fault Data

Figure 3.3 outlines the four main datasets that were used in the analysis, and highlights the supplementary information that was retained to support further interrogation of the fault event records. Component 1 and Component 2 of the supplementary information table provide additional information about the equipment affected and sometimes record the cause of the fault. Of particular interest is the final column labelled as "Failure/Cause/Action/Detail" which will be referred to as the FCAD Attribute from this

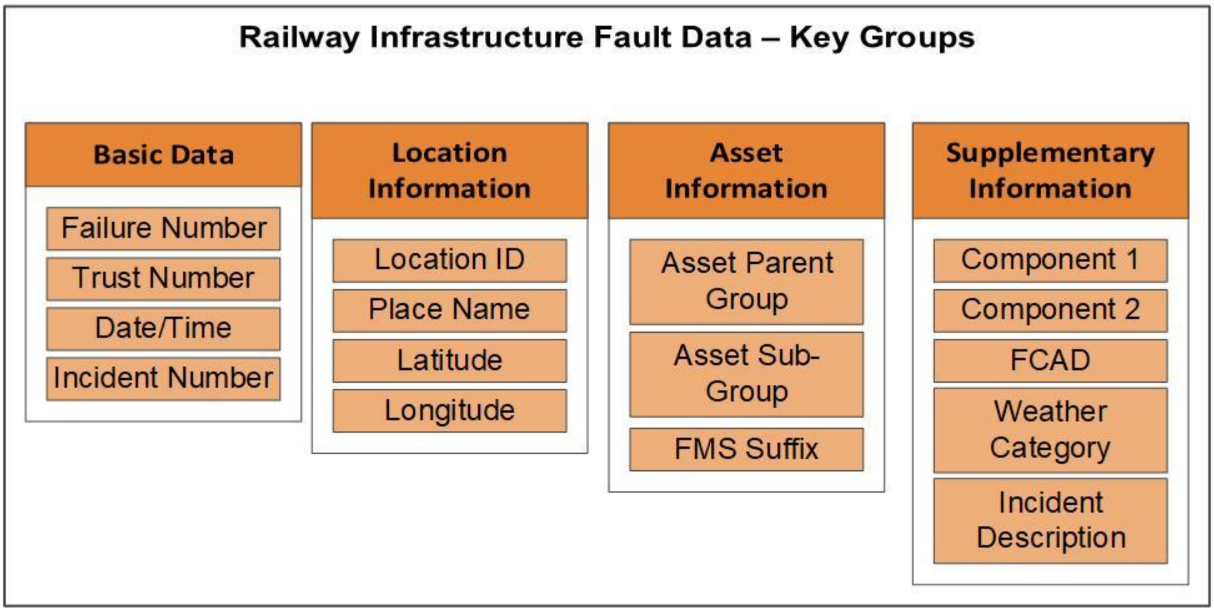

Figure 3.3: Railway Infrastructure Fault Data Groupings.

point forward. This last column is a free text column providing subjective data recorded by the person logging the fault. However, this is frequently not recorded and the text input is often in note form and therefore requires some level of interpretation.

The final two pieces of supplementary information are the weather category and incident description. These are only recorded to inform Schedule 8 payments, and as a result the Weather category has not been recorded for many of the faults reported, however this does not imply weather has not played a causal role in these failures. The weather category also fails to provide any specific detail of the magnitude of the weather event experienced, instead only including and only the type of weather experienced. Therefore, it was determined the weather category was unsuitable for this analysis compared to objective gridded observations of historic weather on the day of the fault.

3.2.2.3 GB Railway Network Routes

The analysis was conducted at Route level as this mirrors the level at which operational decisions are made. As discussed in the previous chapter, there may be some differences in operational practice between devolved Routes as they act independently within the structure of NR. Three routes have been used to facilitate the development of the methodological approach which can later be applied nationally in the future. Consequently, FMS datasets were prepared for three of NR's Routes which form part of the national strategic network, London North Western – North and South, and Wessex Routes, as shown in Figure 3.4.

The London North Western (LNW) route is split into two distinct sections, the south and the north, where LNW South covers the West Midlands, the West Coast Mainline between Birmingham and London Euston, and the Chiltern Line from Birmingham to

London Marylebone. LNW North covers the Merseyside region and the West Coast Mainline north of Birmingham. LNW has a total of 246.5m annual passenger journeys and 4500 miles of track, while Wessex has only 1300 miles of track but experiences a similar number of annual passenger journeys at 230m annually. If LNW is considered as two parts, the three routes have similar numbers of stations, level crossings and other associated infrastructure. All three routes are strategically important from both a passenger and freight rail perspective (Network Rail, 2019k, 2019g). The three routes also have geographic differences. The South East of the UK experiences a warmer, drier climate than the rest of the country, whilst the North West typically experiences cooler, wetter weather (Jenkins et al., 2009). Therefore, in the context of this research the differences in terms of climate experienced must be accommodated for, and their impact on findings minimised. This was achieved using the normalisation techniques discussed in Section 3.5.

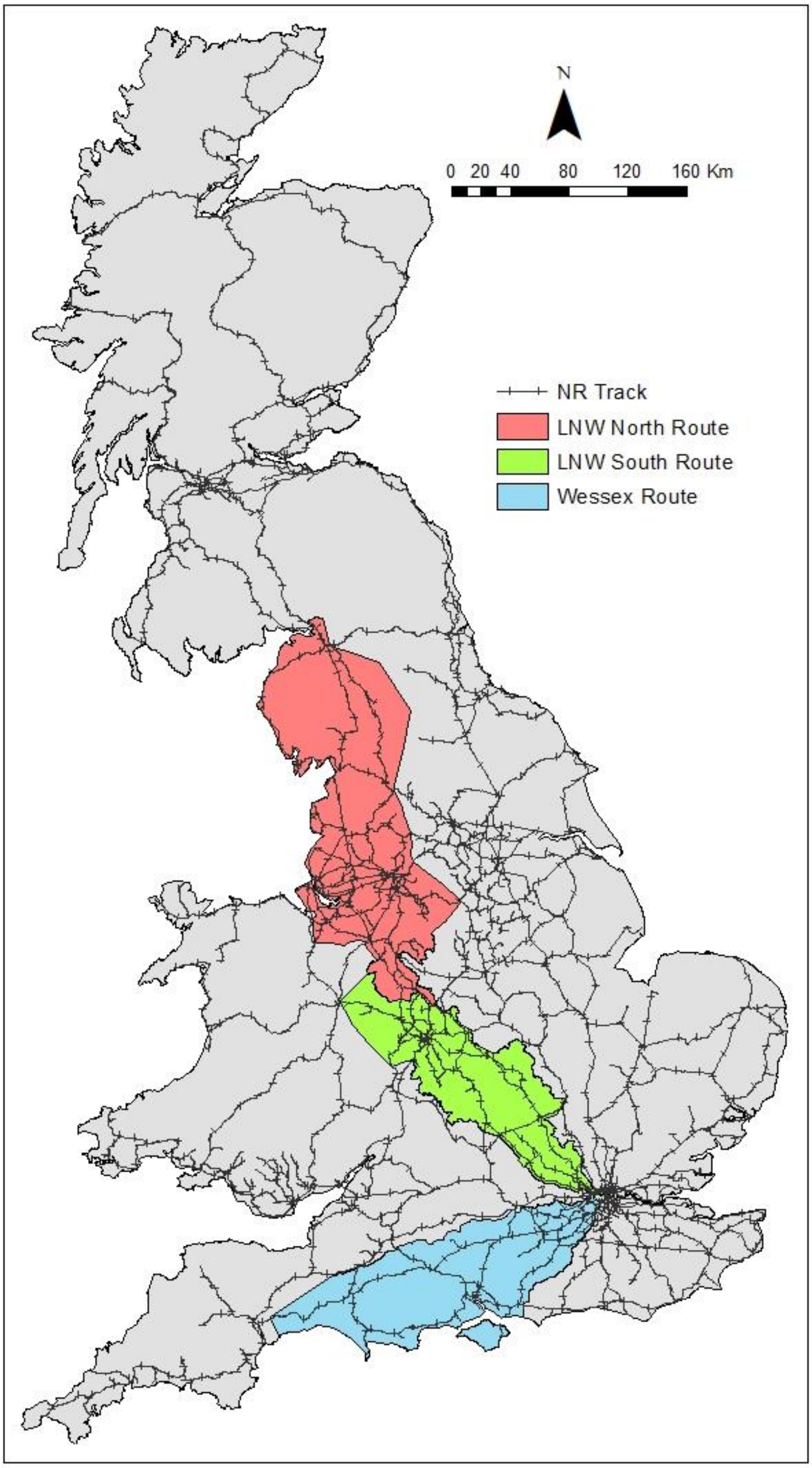

Figure 3.4: A map of Network Rail’s Routes which have been chosen for analysis.

3.3 Determining the Weather Conditions for Fault Events

In order to confidently attribute weather variable values to an associated fault event, two properties must be matched, the date and the geographic location. As the two datasets use different geographic coordinate systems, these needed to be unified so that the correct weather data can be matched with each fault event.

For each of the core weather variables (daily maximum, mean and minimum air temperature and total daily precipitation) a grid text file with space delimited values for each day of the five year time period was used. Each of the grid values is an estimate of the weather variable value at the centre of a 5km square area as illustrated in Figure 3.5. Previous research applying the gridded observations has also used a resolution of 5km or 25km for daily observations as this is a suitable level of accuracy available with this type of data. Each file contains all of the grid values for the whole of the UK's land mass and appears as a matrix. The location of each grid square can be identified using the Ordnance Survey (OS) National Grid (Met Office, 2016). The fault events are recorded with Engineer's Line references (ELR) and Latitude and Longitude coordinates. The OS National Grid coordinates were given new identifiers indicating where they appeared in the text file matrix, following this the fault event locations were

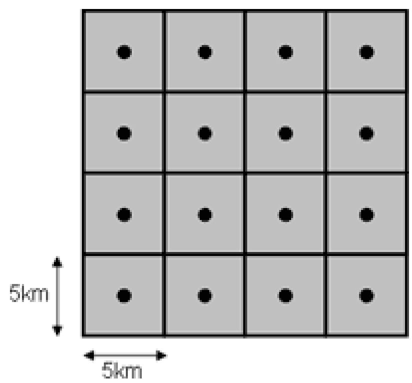

Figure 3.5: UKCP09 Gridded Observation Data Format (Met Office, 2016).

converted to this system. A list of grid squares and their coordinates for the three routes being analysed was then created.

Each of the gridded weather observation text files related to a specific day, with the complete set covering the five year period for which the FMS records were acquired. The process of matching the weather and fault data began by searching for the file with the relevant date for each fault event. Next, the weather data for each of the locations of the fault events occurring on that day were extracted and attributed to the fault event. This process was repeated for each of the core weather variables and completed using the code presented in Appendix B.

The railway lines for each route only pass through a small number of the total set of OS grid squares across the country, as demonstrated for two of the routes shown in Figure 3.6. To make the analysis easier, all of the unique coordinates for each route were identified and only the weather data from the matching grid squares was extracted from the raw datasets. Using this list of coordinates, or locations, all of the necessary weather variable data could be compiled for the dates of the five year period, beginning with the raw Maximum, Mean and Minimum Temperature values, and the Daily Total Precipitation measurements. Once the correct grid coordinates for each fault event's location had been found and the weather variables calculated, then the weather data for each fault event could be imported to the dataset. Once the additional derived weather variable values for each fault event are calculated (as outlined previously in Table 3.1) and allocated this facilitated the analysis of the relationship between the fault assets and the events' weather variables.

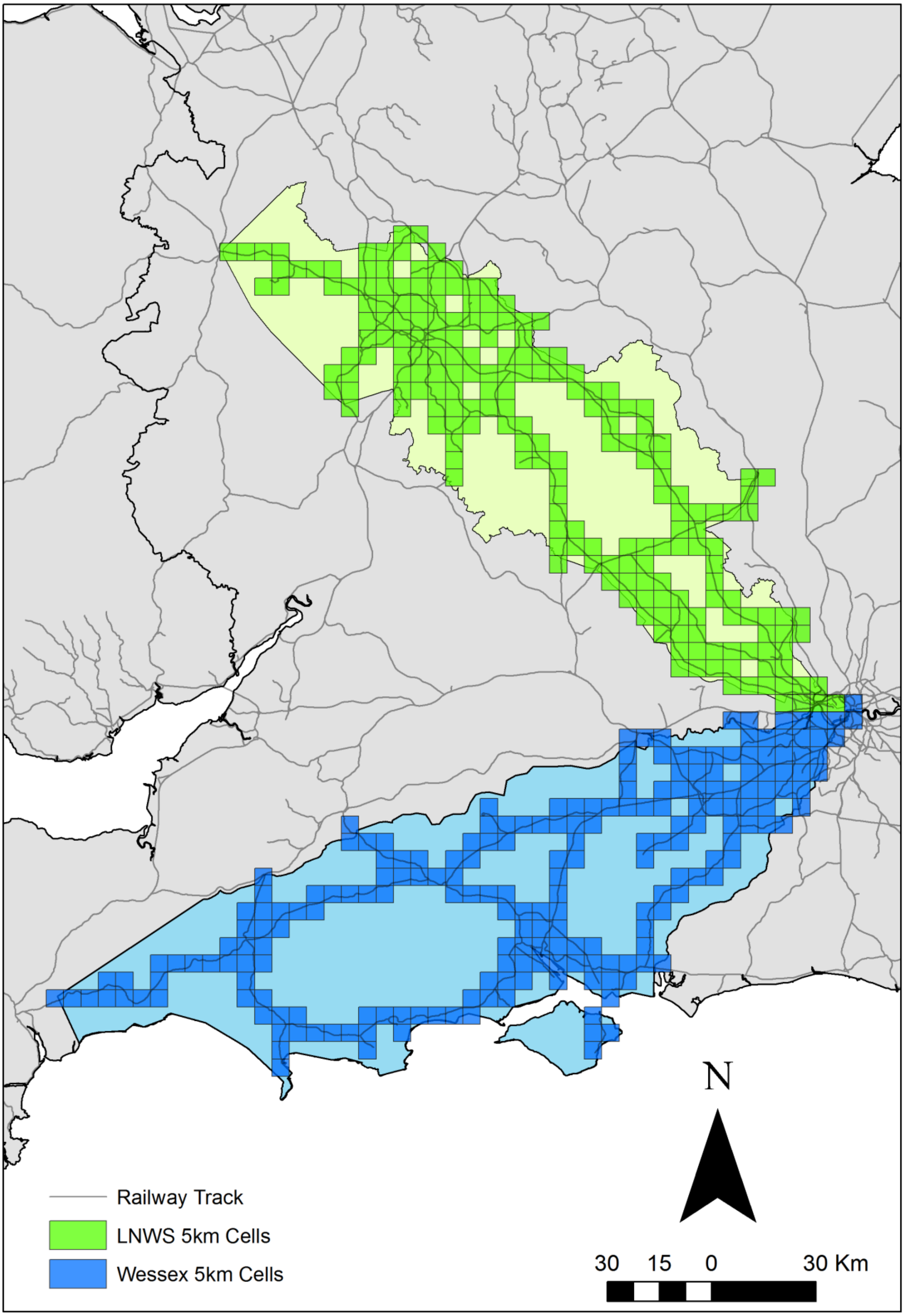

Figure 3.6: A Map of the LNW South and Wessex Routes and associated gridded weather observations cells.

3.4 Normalising the data: Determining the frequency of failure and exposure to weather conditions

The frequency of occurrence of a given weather variable value or weather scenario varies at different locations across the country. Therefore, the frequency of exposure to a given weather scenario will vary from location to location, and from asset to asset. For instance, the South-East of England more frequently experiences higher temperatures than the rest of the UK (Jenkins et al., 2009). To account for the differences in exposure frequency, and therefore enable a fair comparison of different regions of the UK, the data needed to be normalised. To normalise the data the frequency of fault events under one set of conditions can be divided by the frequency the location had been exposed to that set of conditions. For example, the number of faults in one location that have occurred when the daily maximum temperature is 26°C will be divided by the number of times that location was exposed to a maximum daily temperature of 26°C. By normalising the data, it was possible to establish the strength of the relationship between the weather variables and different asset fault types could be determined.

The frequency of fault events was determined by conducting counts of the total number of fault events for each asset category for each of the OS grid squares across the three routes. Similarly, the frequency of each weather variable value across the chosen routes was established by counting the occurrence of each weather variable value at each OS grid square location, these were stored as frequency tables using the code shown in Appendix C. The asset category fault frequency and the relevant weather scenario frequencies for each fault location were attributed to the fault event data. Following this, the asset category "weather related fault rate" was established and attributed to each fault event. The fault rate refers to the number of faults divided by the frequency of exposure to the same weather conditions.

3.5 Significant Relationships

To begin interrogating the role of hazardous weather in asset failure, those asset categories with a significant relationship between a weather variable and fault rate need to be identified. There will always be some number of faults that occur on some railway infrastructure so these cannot be avoided entirely however, the fault rate can help identify those instances that occur often and fail often, those that vary significantly from the usual fault rate. In addition, it is important that the whole sample of data is considered so that the results are not biased towards the current weather experienced most frequently and avoid unintentionally minimising the potential impacts of climate change in the future by excluding current extremes which may become the norm in the future. Therefore, it has been determined that statistical significance could be appropriately determined by utilising two different standard deviation thresholds which will highlight those scenarios with high and very high fault rates which are significant relative to the whole data set. To determine the significance of the fault rate, the first and second standard deviations were calculated for the relationships between each railway infrastructure category and each weather variable with continuous data. Where the fault rates for certain weather variable values are above the first standard deviation, the relationship with that weather variable value is considered to be significant. Similarly, where the second standard deviation is exceeded the relationship is considered to be very significant. This method therefore equates to an analysis of thresholds, which has been established as an operationally useful process.

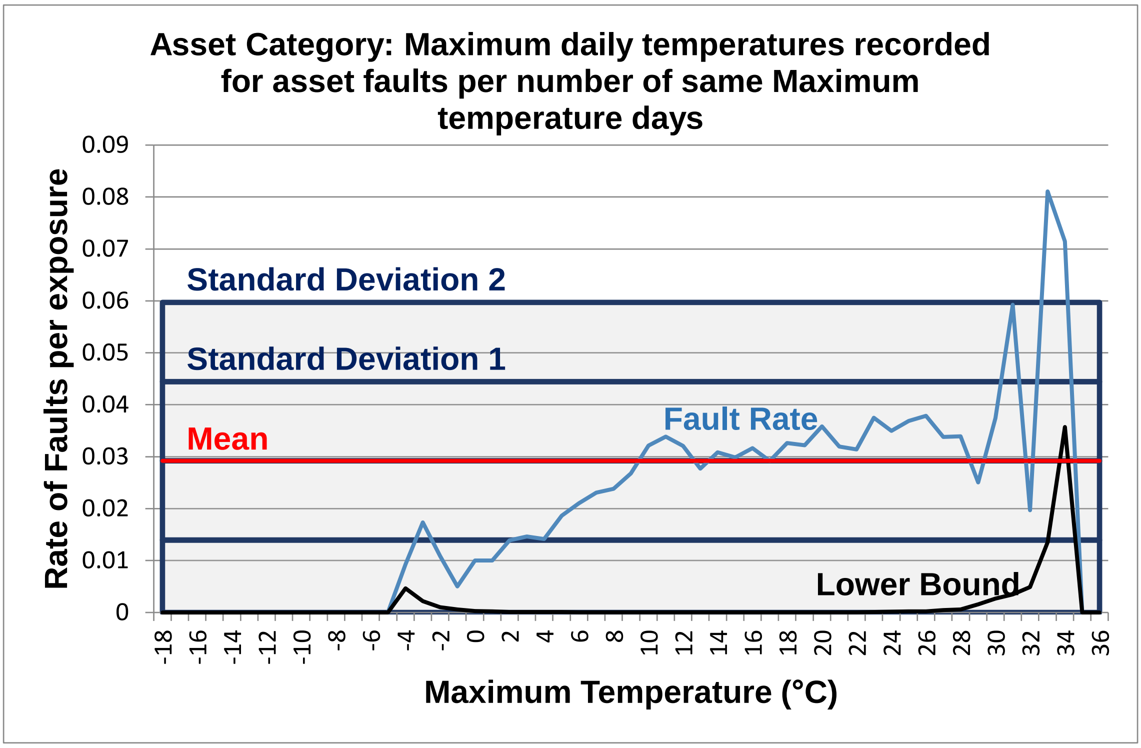

Figure 3.7: Example plot of the results. Showing the rate of faults for exposure of each weather variable value. The mean is shown as the Red Line whilst the Std. Deviations are shown in dark blue. The black line is the lower bound.

The results can be plotted as shown in Figure 3.7, making the relationship clearly visible. Anomalous data was excluded by adding a lower bound limiting line, the values of which are 1/the number of weather variable events. Including the lower bound line enabled the exclusion of events that had only happened once, and an idea of how frequently other events had occurred, allowing it to be determined whether peaks were true peaks or anomalies. On inspection, the relationship shown in this example figure is evident, the fault rate increases with the maximum daily temperature. The relationship threshold for the first standard deviation is 31°C and 33°C for the second standard deviation threshold. Although this is clear from looking at this single plot this process cannot be repeated manually for each asset category and each weather variable with ease. Therefore, those asset categories and weather variables with significant relationships needed to be identified. A method was therefore developed to not only identify those weather variables and asset categories with significant relationships but to also determine the type of relationship as well.

3.5.1 Relationship Profiles

The weather variable ranges were split into quartiles and the significant and very significant values identified for each weather variable as illustrated in Figure 3.8. By assessing which of the quartiles had significant values present, an overview of the asset relationships with different weather variables could be determined. From this, the significant relationships and the type of trend could be identified with ease, for example a significant value in only the last quartile (see Figure 3.8) would indicate a positive trend and could be classified as shown in Figure 3.9, with the classifications defined in Table 3.2. Once the relationship profiles were attributed, summary matrices were produced for each route, an example of such is shown in Table 3.3.

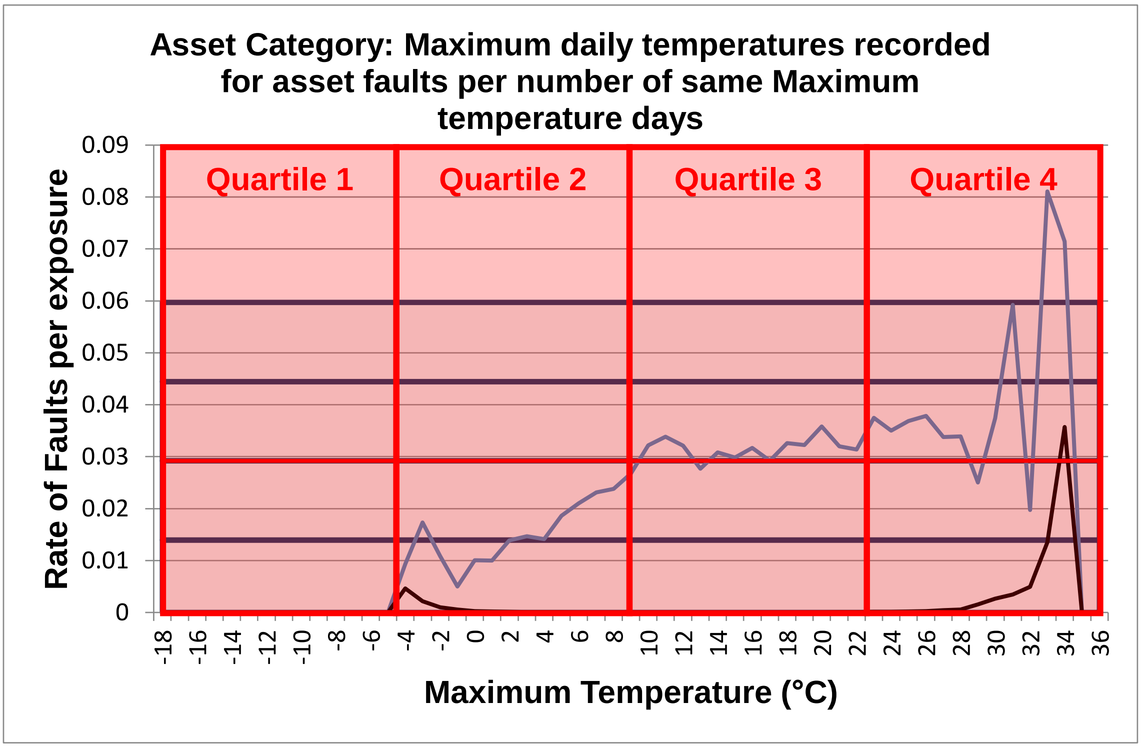

Figure 3.8: Illustration of how the weather variable range is split into quartiles to determine the relationship profile.

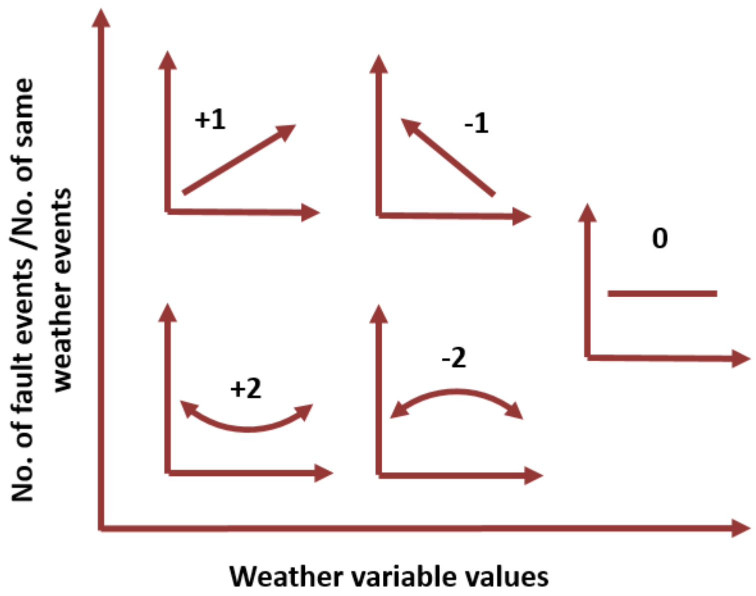

Figure 3.9: Fault and weather relationship profiles.

Table 3.2: An illustrative sample of the summary table categorising all relationships between each weather variable and asset type.

	Weather Variables			
Asset Types	1	1	1	-1
	0	0	0	0
	-2	-1	-1	2
	1	-1	0	2
	1	1	1	1
	0	-1	-1	0
	1	2	2	1
	1	1	2	1

Table 3.3: Relationship Classification Definitions.

Value	***Description***
0	No discernible trend
+1	Positive trend
-1	Negative trend
+2	Both high weather variable and low weather variable positive trends
-2	Both high weather variable and low weather variable negative trends

Finally, the significant asset categories that had been identified were interrogated further to verify the presence of relationships that have already been reported in the literature, thus validating this method. In addition, this would also enable the identification of previously unknown relationships not accounted for in the NR guidance, or unexpected relationships that suggest something contrary to existing literature. The results of this methodological approach and the significant relationships identified are discussed in detail in the next chapter.

3.6 Summary

Following the review of existing methodologies and the data sources they utilised in Chapter Two, a methodological approach was developed as detailed in this chapter. The resulting methodology allows for analysis of the effect of temperature and precipitation related variables (e.g. absolute temperature, diurnal range, total daily precipitation etc.) on railway infrastructure assets by deterministically highlighting relationships between these weather variables and different asset types (e.g. track, OHL etc.). In addition, a simple approach was developed to categorise the type of relationship between each asset and weather variables. The results of this analysis are presented in the next chapter alongside a commentary of any further examination of the fault event records to provide insights into the mechanism of failure, and the impact of weather hazards on railway assets.

CHAPTER FOUR: RESULTS

4.1 Overview of Results Chapter

This chapter begins by outlining the significant weather variables and asset categories identified through the application of the method presented in the previous chapter. The detailed results for each of the significant asset categories selected to be carried forward are then presented, and grouped into either Track asset categories, Signalling asset categories or Other asset categories. This chapter closes by presenting a comparison of the thresholds found by our method alongside the existing failure thresholds as presented in Chapter Two for each of the significant asset categories identified.

4.2 Significant Relationships

The aim of this research is to develop a methodological approach to assess the vulnerability of railway assets to the effects of hazardous weather, therefore it is not necessary or practicable to present results for all possible asset categories or weather variables experienced on the GB rail network or by extension for all resultant combinations of these. Consequently, this research focusses on those asset categories and weather variables that can be considered to be significant, as detailed in Section 3.2.1.

4.2.1 Significant Asset Categories

As the emphasis of this research is on the opportunities afforded by this approach, only those asset categories of significance will be presented in this results section. Previously those asset categories with less than 1% of the total faults for the routes were discounted on the basis that there were not enough fault events to reliably draw any conclusions. To ensure any anomalies are removed from the analysis this 1% threshold can also be applied to the average percentage of the faults across the three routes, these have been ranked in Table 4.1. It can be seen that when the average percentage of faults across the three routes falls below 2%, individual route asset fault percentages begin to fall below the initial 1% threshold. The fault event counts for each of the significant asset categories identified can be seen in Appendix D, this provides comparison between assets as well as the range across the routes. As a result, those asset categories with an average percentage of faults across the three routes above 2% are to be considered significant asset categories and carried forward for in depth analysis in this results chapter.

Sections 4.3 to 4.5 in this chapter present the results for each of these 11 asset categories which have been split into 3 asset groups based on their parent assets. Table 4.1 shows that three fall into the track asset group, 6 of the 11 asset categories form the signalling asset group and the remaining 2 assets are then attributed to the Other asset group. Following the presentation of results for the 11 significant asset categories these results are summarised and compared to the Failure Thresholds previously presented in Chapter Two.

Table 4.1: Ranked list of all asset categories that have an average across all three routes of above 1% of the total faults.

Rank	Short & Number Label	Short & FMS Suffix Label	Asset Category percentage of total route faults: LNW North	LNW South	Wessex	Average % of Faults
1	**Track Track 3**	**Track Track: TRACK (P.W)**	**16.44%**	**10.94%**	**19.23%**	**15.54%**
2	**Sig Sig 4**	**Sig Sig: SIGNAL**	**12.81%**	**12.00%**	**11.24%**	**12.02%**
3	**Sig POE 2**	**Sig POE: POINT OPERATING EQUIPMENT**	**6.87%**	**9.18%**	**6.37%**	**7.47%**
4	**UU 39**	**UU: NO EQUIPMENT**	**8.69%**	**7.75%**	**4.94%**	**7.28%**
5	**Sig TC 2**	**Sig TC: TRACK CIRCUIT**	**6.39%**	**5.46%**	**6.48%**	**6.11%**
6	**Sig LC 1**	**Sig LC: LEVEL CROSSING EQUIPMENT**	**4.02%**	**2.18%**	**7.68%**	**4.63%**
7	**Track S&C 1**	**Track S&C: POINTS (P.W)**	**4.45%**	**5.56%**	**3.28%**	**4.43%**
8	**Sig I 3**	**Sig I: PANEL / FRAME**	**5.10%**	**3.60%**	**2.91%**	**3.87%**
9	**Track Unknown 2**	**Track Unknown: BOUNDARY MEASURE**	**3.11%**	**1.94%**	**2.06%**	**2.37%**
10	**Sig TPWS 1**	**Sig TPWS: TRAIN WARNING SYSTEM**	**1.25%**	**1.97%**	**3.04%**	**2.09%**
11	**E&P TP 1**	**E&P TP: CIRCUIT BREAKERS**	**1.79%**	**3.00%**	**1.42%**	**2.07%**
12	Sig AC 1	Sig AC: AXLE COUNTER	0.73%	3.44%	1.48%	1.88%
13	UU 84	UU: TELEPHONE - SPT	1.42%	1.65%	1.04%	1.37%
14	Sig AWS 2	Sig AWS: TRAIN WARNING SYSTEM	0.77%	1.27%	1.76%	1.27%
15	Tel Tel 6	Tel Tel: TELEPHONE - SPT	1.24%	1.28%	1.08%	1.20%
16	Sig I 4	Sig I: SOLID STATE INTERLOCKING	0.42%	2.25%	0.91%	1.19%
17	E&P 3rd 2	E&P 3rd: TRACTION SUPPLY (THIRD RAIL)	1.71%	0.38%	1.45%	1.18%
18	Track Unknown 1	Track Unknown: ACCESS POINT	1.35%	1.40%	0.63%	1.13%
19	UU 83	UU: TELEPHONE - OTHER	1.08%	0.70%	1.32%	1.03%
~~20~~	~~UU 16~~	~~UU: CONCENTRATOR - VOICE~~	~~1.11%~~	~~0.87%~~	~~0.89%~~	~~0.96%~~

4.3 Significant Track Asset Faults

Faults relating to track assets include track buckling caused by higher temperatures (Dobney et al., 2010) and brittle rails caused by lower temperatures (Wang et al., 2012). It has been established in Chapters One and Two that track faults are relatively well understood, particularly with regards to the effects of high temperatures. Therefore, it is expected that the results of existing literature will be reflected in the results of this research, validating the methodological approach developed. Track is a Parent Asset Group and has a number of associated asset sub-groups and FMS Suffix Labels, which provide further detail about the assets. The full list of track asset categories can be seen in Table 4.2 which highlights the significant Track Asset categories: Track Track 3; Track S&C 1 and Track U 2, these will be referred to by their FMS Suffix label from this point onwards for clarity.

Table 4.2: A List of all Track Categories with those that are significant (as shown in Table 4.1) highlighted.

	Asset Sub-Group	FMS Suffix Labels	Short & Number	Full Asset Category Name
Parent Asset Group: Track	**S&C**	**Points (P.W)**	**Track S&C 1**	**Track S&C: Points (P.W)**
	Sign	Sign - Permanent	Track Sign 1	Track Sign: Sign - Permanent
	Track	Buffer/ End Stop	Track Track 1	Track Track: Buffer/ End Stop
		Rail Lubricator	Track Track 2	Track Track: Rail Lubricator
		Track (P.W)	**Track Track 3**	**Track Track: Track (P.W)**
		Traction Gel Applicator	Track Track 4	Track Track: Traction Gel Applicator
	Unknown	Access Point	Track U 1	Track Unknown: Access Point
		Boundary Measure	**Track U 2**	**Track Unknown: Boundary Measure**

4.3.1 Track (P.W.)

Fault events regarding track assets should be recorded under the asset category Track (P.W.), where P.W. stands for Permanent Way. The Permanent Way refers to the immediate area around the track resulting in a wide range of faults recorded in this asset category, which involve a variety of different assets. This may explain why this asset category has the greatest proportion of faults, averaging at 15.54% of total faults across all three routes. Investigating the additional Fault Event Equipment information held in the Component 1 & 2 attributes indicates that all faults attributed to the Track (P.W.) Asset category should be related to the track structure (Running Rail, joints, welds, rail fastenings etc.), the track substructure (Sleepers, ballast etc.) or the speed indicators, to name just a few key groups. However, many of the fault events have their Component attributes left blank whilst the FCAD attribute has details that relate to the component attributes. Despite the wide range of asset types there are still significant relationships between the key weather variables and Track (P.W.) Asset.

4.3.1.1 Temperature and Track (P.W.) Assets

The relationship profiles for key temperature variables for the Track (P.W.) Category can be seen in Table 4.3. These relationships are based on the individual route's thresholds of significance. The summary table for the asset category Track (P.W.)

Table 4.3: Relationship Profiles for Asset Category Track (P.W.) for Key Temperature Variables across all three routes.

Track (P.W.)		Temperature			
Route	**Fault Counts**	**Max**	**Min**	**Diurnal Range**	**Asset Category percentage faults**
LNW North	22439	1	1	0	16.44%
LNW South	11587	1	1	-1	10.94%
Wessex	14955	1	1	1	19.23%

shows that across all routes, there is a consensus that for higher daily maximum and minimum temperatures a significant number of faults occur. However, there is no consensus regarding the relationship between the diurnal range and Track 3 assets.

The relationship profile for Track (P.W.) and maximum daily temperatures is reflected in Figure 4.1 where there are significant peaks in the fault rate for higher temperatures. The overall fault rate for the three routes becomes significant once the ambient air temperature reaches 30°C, and then fluctuates between significant and very significant with each degree increase in ambient temperature. It is clear that there is also variation between each of the routes, for example, in Figure 4.1 for the maximum daily temperature of 33°C although the average fault rate across the three routes is 0.11,

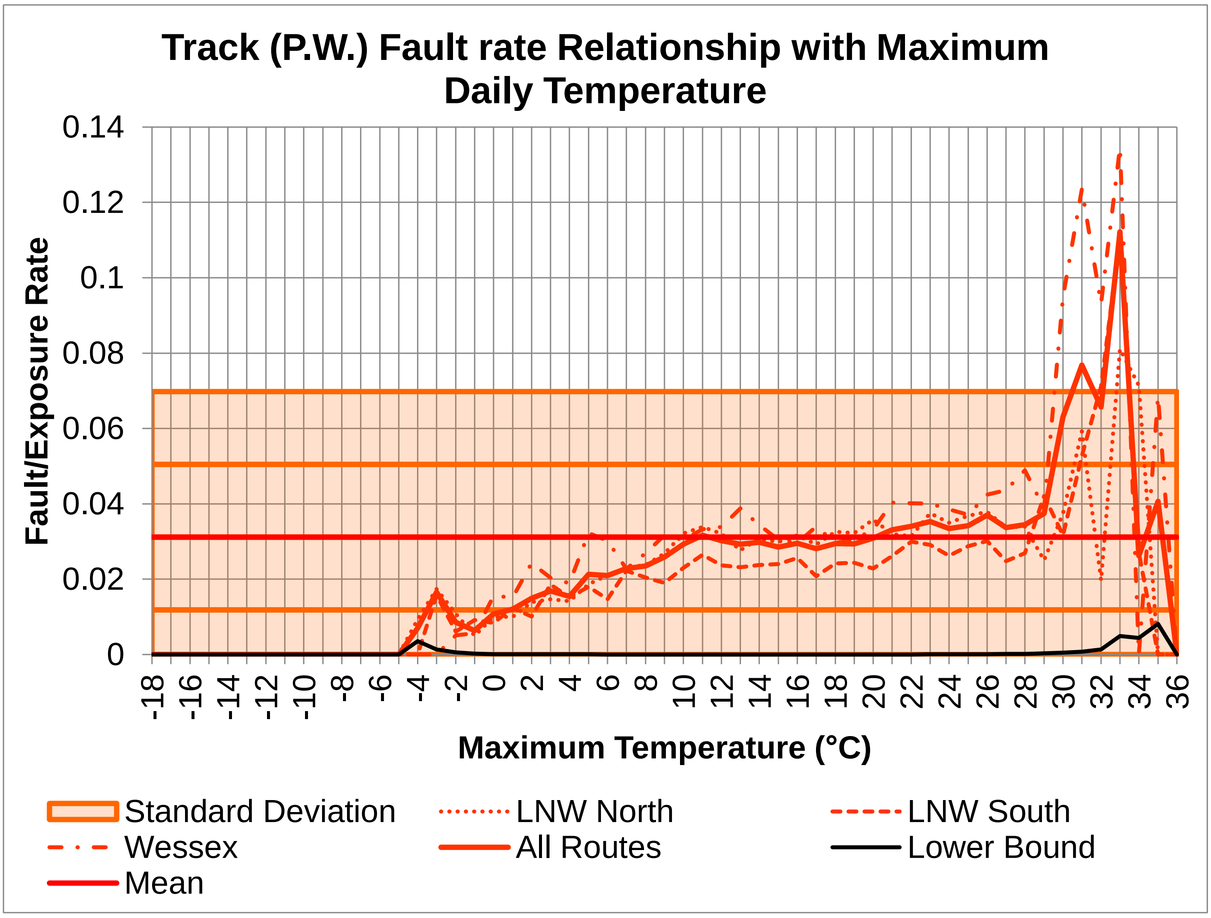

Figure 4.1: The relationship between the Daily Maximum Temperature and the Fault Rate for Track Assets, illustrating the relationships for each route.

the Wessex Route experiences a fault rate of 0.13, while LNW North is lower at 0.08. These variations can be seen in detail in the Table in Appendix E which lists the fault and weather event frequency for maximum temperature events greater than 19°C for Track (P.W.) across all three routes. From 19°C the fault rate across the three routes consistently passes the mean fault rate as can be seen in Figure 4.1.

There is a general trend between higher temperatures and the significance of the fault rate for Track (P.W.) assets. Across the three routes there is a significant fault rate for Track (P.W.) assets for air temperatures of 30°C or greater, becoming very significant for air temperatures greater than 31°C. The number of faults that contribute to these thresholds are shown in the table in Appendix E. There are 138 Fault Events that occurred when the daily maximum temperature was 30°C, while 99 Fault Events that occurred when the daily maximum temperature was 31°C. Therefore, these values reflect the significant fault rate threshold and would be suitable as operational thresholds for this asset category. It is important to note that this is the only relationship where the table of fault incidents has been listed. As discussed in Section 2.4.2 the usage of fault incidents counts does not account for the frequency of weather events which is why the method used in this analysis has been developed. However, it is important to present the basic statistics to ensure that there is confidence in the thresholds identified by this research.

The relationship profile for minimum temperatures is shown in Figure 4.2, however the peak at 20°C is reflective of the minimum temperature during the day that higher temperatures have caused faults, rather than the effects of low temperatures. This peak although seemingly an anomaly, is not excluded by the lower bound line. Further investigation of the fault event records showed that the reason for such a high fault

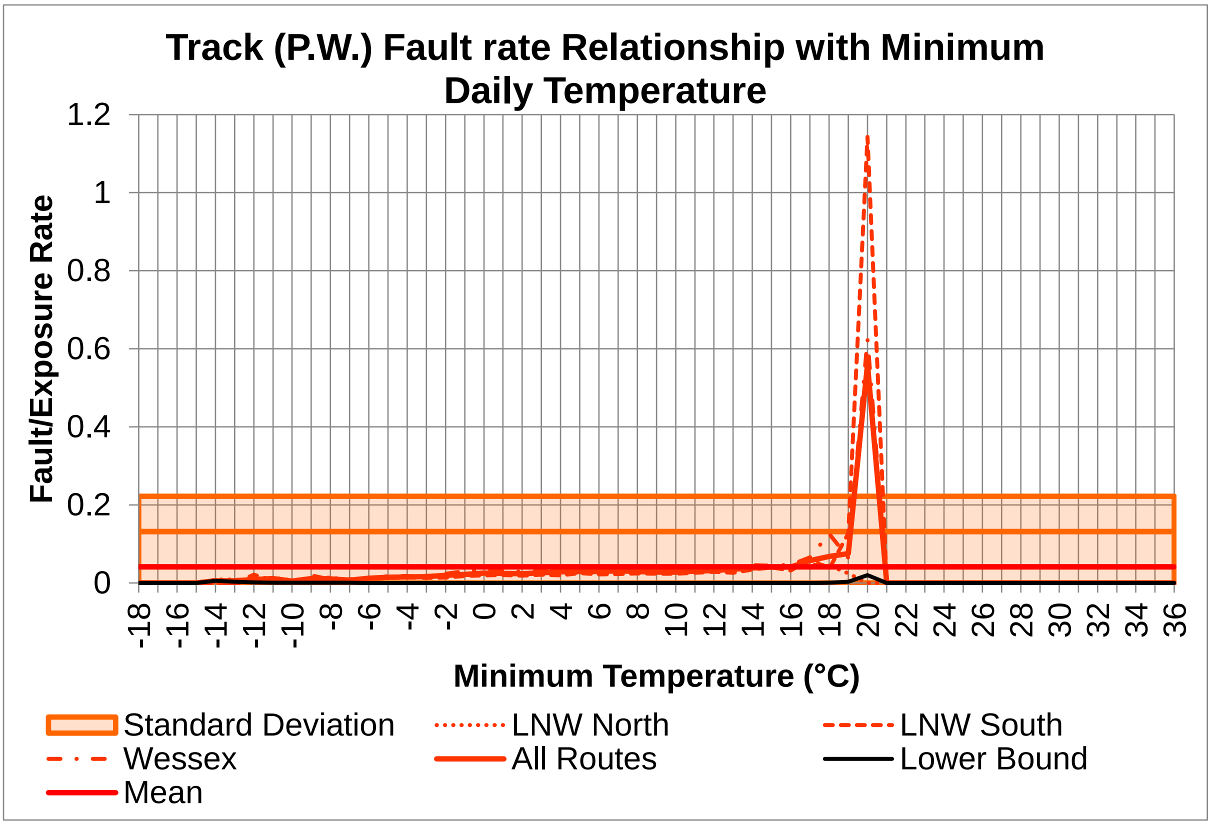

Figure 4.2: The relationship between the Daily Minimum Temperature and the Fault Rate for Track Assets, illustrating the relationships for each route.

rate is because multiple faults have occurred on the same day at this temperature as a result of coincidence rather than consequence.

Similarly, the fault rate shown in Figure 4.3 appears to be significant because a single event on one route has not been excluded by the lower bound line. Consequently, higher absolute temperatures are the dominant temperature variable relating to Track (P.W.) assets faults and there is no relationship with the diurnal temperature range or lower absolute temperatures.

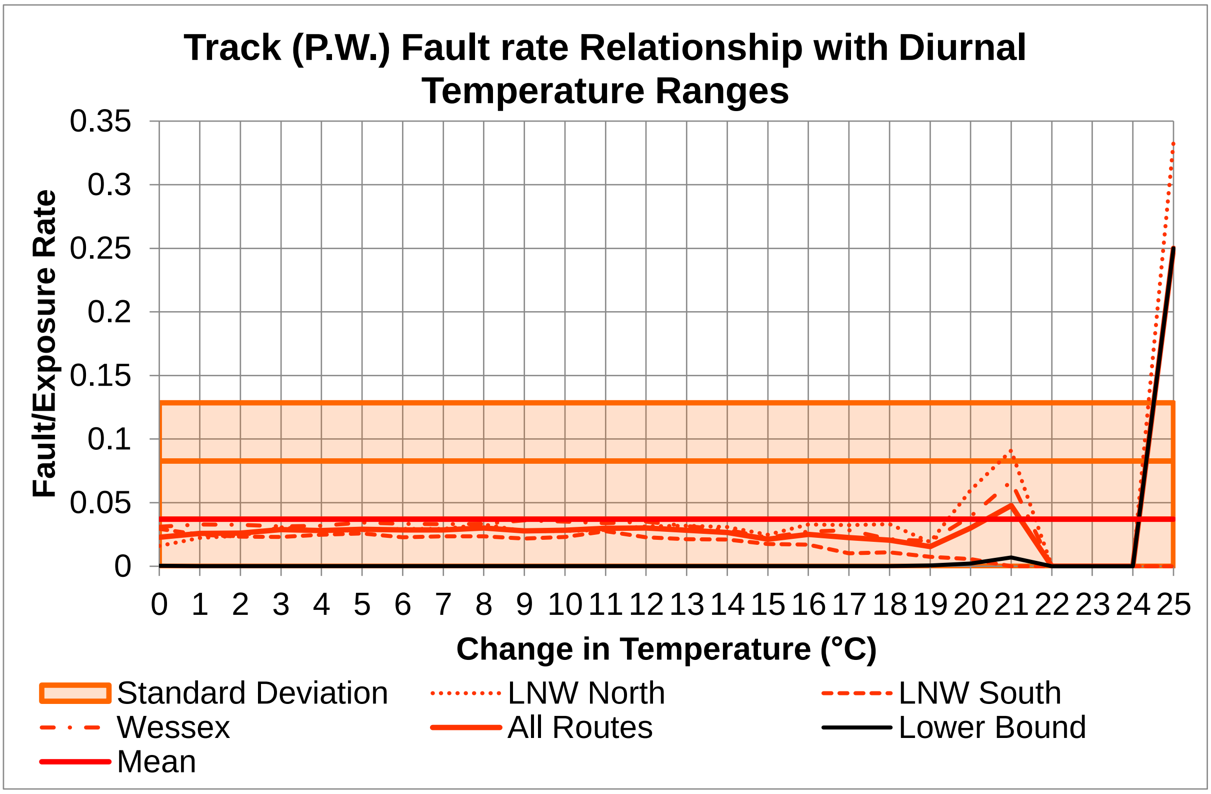

Figure 4.3: The relationship between the Diurnal Temperature range and the Fault Rate for Track Assets, illustrating the relationships for each route.

4.3.1.2 Precipitation and Track (P.W.) Assets

Throughout this chapter, the classification of the relationship profiles for precipitation weather variables are not presented. It was concluded that these did not accurately reflect the relationships found by investigating the fault rates and individual fault event records. The reasons for this omission are discussed in the critique of the methodology in Section 5.4.1 of the discussion chapter.

The Track (P.W.) fault rates for all three routes for daily precipitation can be seen in Figure 4.4 which shows there is no significant relationship across the three routes between Track (P.W.) and daily total precipitation. The peaks for Wessex are caused by single fault events that have not been excluded by the lower bound. This is because the daily precipitation totals here occurred more than once across the three routes and the lower bound only excludes weather events that have occurred once, and not fault events that have only occurred once. Any peaks that are not highlighted in the rest of this chapter are attributed to only a small number (<5) of Fault Events and are therefore not significant.

The individual fault events for those significant fault rate peaks, in Figure 4.4 for LNW South are listed in Table 4.4, which includes some additional information recorded with the fault records but not included in the analysis. Figure 4.4 shows that significant fault rates were experienced with a minimum of 39mm of precipitation recorded, however three of these fault events are in the same location (indicated by the place name) and occur on the same day. However, these fault events occurred at the Clunes Level Crossing in Scotland and therefore, are not situated in the LNW South route. These are not the only fault events recorded in error.

There are two fault events recorded forty minutes apart at Barnt Green, a station located just south of Birmingham. One of these faults indicates explicitly that there has been flooding caused by rain, however this incident has not been listed as a Severe Weather incident in the Train Running System (TRUST) used to record Schedule 4 and 8 incidents. This could mean that no trains were delayed or that the fault was minor causing no delays, but still important enough to report. The fault at Barnt Green occurred on the 20th July 2007 along with nine other faults on this date, as shown in Table 4.4. Six of the eleven faults events on this day have some reference to the effects of weather, flooding or drainage in at least one of the attribute fields. These fields contain supplementary information from the fault event records as shown in Figure 4.5.

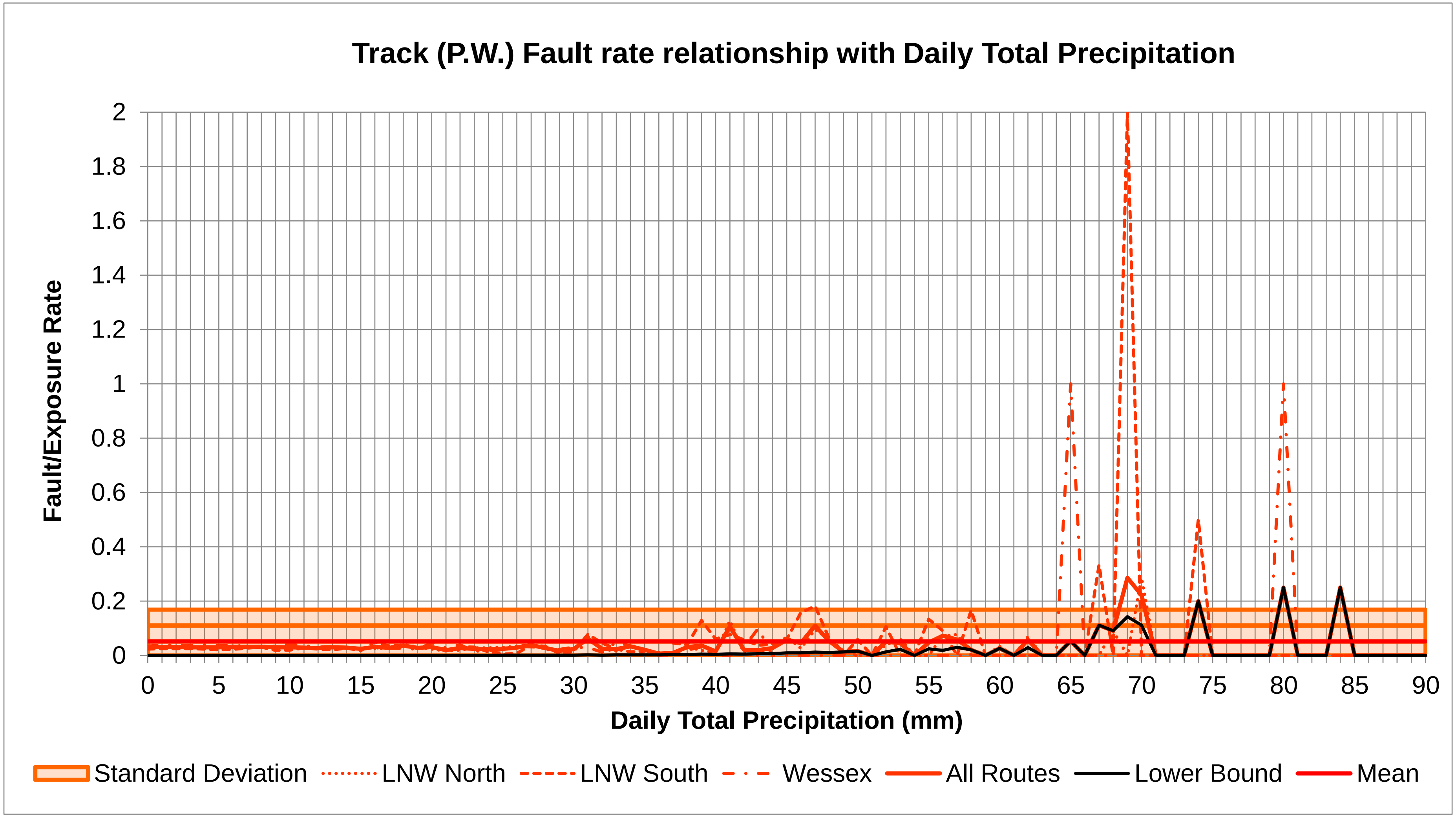

Figure 4.4: The relationship between daily total precipitation and the Fault Rate for Track (P.W.) assets, illustrating the individual and overall relationships for each of the routes.

Table 4.4: LNW South Track (P.W.) Fault Events with significant Daily Precipitation totals.

Fault Events:			**Route - LNW South**			**Weather Variable – Daily Precipitation**			
	Failure Number	**Date**	**Daily Precip. (mm)**	**Name**	**(X,Y)**	**Component 1**	**Component 2**	**FCAD**	**Incident Category Description**
Track (P.W.)	BCA319891	14/06/07	58	Moseley Tunnel	(121,192)	....	....	c/b had fallen over by the wind	
	BCA326117	**20/07/07**	**46**	**Lightmoor JNC**	(113,189)	**....**	**....**		
	BCA326101	**20/07/07**	**46**	**Pleck JCN - Darlaston JCN**	(119,190)			**Track flooding due to damaged culvert.**	
	BCA326078	**20/07/07**	**46**	***Whitacre JCN – Proof House**	(124,191)	**Rail Running**	**....**		**Severe weather**
	BCA326071	**20/07/07**	**47**	**Wood End**	(122,193)	**....**	**....**		**Other weather**
	BCA326045	**20/07/07**	**47**	***Birmingham International**	(129,194)	**Drainage**	**Culvert**		
	BCA326050	**20/07/07**	**55**	**Cradley Heath LC**	(120,192)				
	BCA326114	**20/07/07**	**55**	**Lye STN**	(120,192)	**....**	**....**		

Table 4.4: LNW South Track (P.W.) Fault Events with significant Daily Precipitation totals.

Fault Events:			Route - LNW South			Weather Variable – Daily Precipitation			
	Failure Number	**Date**	**Daily Precip. (mm)**	**Name**	**(X,Y)**	**Component 1**	**Component 2**	**FCAD**	**Incident Category Descripti on**
Track (P.W.)	BCA326 137	**20/07 /07**	**67**	***Hatton West JCN**	(123,198)			**Track flooding**	**Severe weather**
	BCA326 076	**20/07 /07**	**69**	**Barnt Green 1**	(120,195)	**Ballast**	**Ballast Ash**	**flood [Rain]**	
	BCA326 092	**20/07 /07**	**69**	**Barnt Green 1**	(120,195)	**....**	**....**		
	BCA326 098	**20/07 /07**	**74**	***Hatton West JCN**	(123,199)	**....**	**....**		
	BCA339 152	16/10 /07	47	*Claydon LNE JCN SB	(137,203)	Fencing	5 Wire	Broken wire ...	
	BCA379 231	28/07 /08	39	Clunes LC 160M 55C	(114,188)	Check Rail	Gauge Fault	Side wear	
	BCA379 233	28/07 /08	39	Clunes LC 160M 55C	(114,188)	Check Rail	Gauge Fault	Side wear	
	BCA379 236	28/07 /08	39	Clunes LC 160M 55C	(114,188)	Check Rail	Gauge Fault	side wear	
	BCA379 357	28/07 /08	39	Bloxwich	(120,190)	Ballast	Ballast Granite	Flood water.	Severe weather
	BCA464 162	01/05 /10	47	Northchurch Tunnel	(145,213)	Geometry - Top and Alignment	Inspected Fit For Purpose	Possible high ballast in the area.	Track Faults including Broken Rails

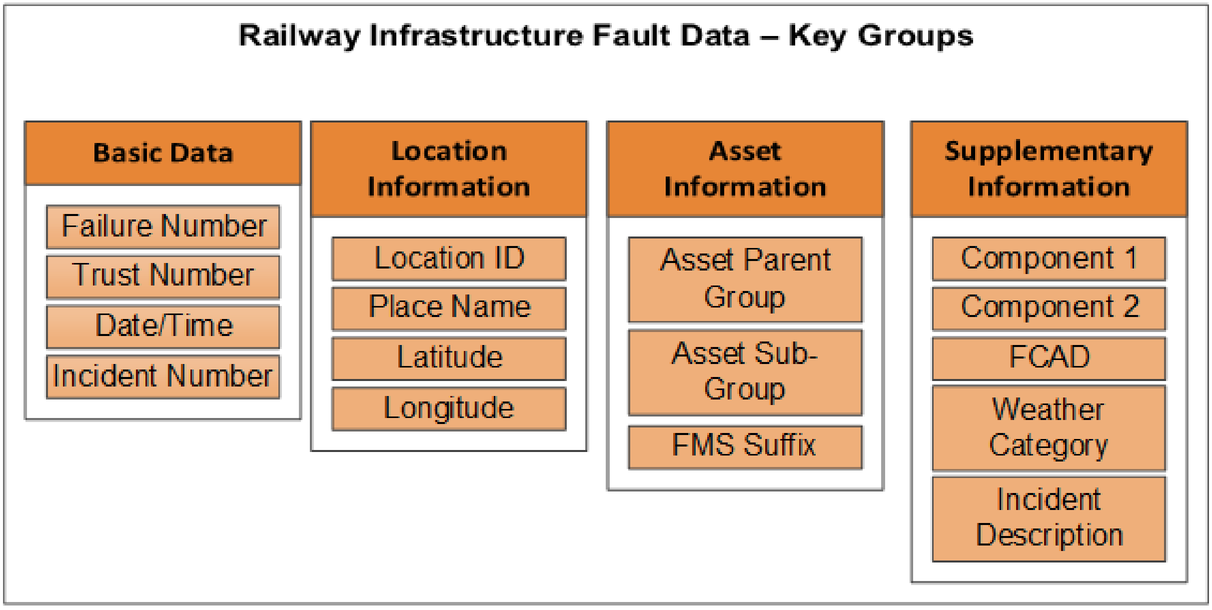

Figure 4.5: Railway Infrastructure Fault Data Groupings.

On the 20th of July 2007 intense rainfall was experienced for up to 18 hours across a large swathe of southern and mid-England from the Thames Valley to mid-Wales. These areas had already experienced greater than average rainfall throughout the preceding two months. However, the rainfall experienced on the 20th of July 2007 was extreme both in magnitude and impact. In many places the previously held records were broken as shown by Table 4.5. This led to widespread flooding as drainage systems were overwhelmed and the ground was saturated (Prior and Beswick, 2008). The events of the 20th of July 2007 were the result of an extreme weather event which has been identified during this approach, this may be useful for future applications of this methodology as discussed in greater detail in the next chapter in Section 5.5.1.2.

Track (P.W.) assets do have a significant fault rate intermittently across all routes with greater values of weekly accumulation of precipitation as shown in Figure 4.6. However, this is not enough evidence to draw a clear conclusion about the relationship between Track (P.W.) assets and this duration of accumulated precipitation. There is

Table 4.5: A selection of long period stations that set new daily rainfall records on 20th of July 2007 (Prior and Beswick, 2008).

Weather Station	National Grid Ref.	Rainfall 20th July 2007 (mm)	Previous highest daily rainfall (mm)	Date of previous Record	Earliest year of record
Sudeley Lodge (Gloucestershire)	SP(42)/039270	147.0	64.5	4 June 1985	1977
Pershore College (Worcestershire)	SO(32)/960447	120.8	67.5	24 Sept 1976	1957
Tewkesbury (Gloucestershire)	SO(32)/891337	119.0	70.6	10 July 1968	1961
East Shefford (Berkshire)	SU(41)/386738	110.6	51.3	10 July 1968	1964
Shipton Oliffe (Gloucestershire)	SP(42)/040186	107.5	69.3	24 June 2007	1974
Peasemore House (Berkshire)	SU(41)/461770	104.1	71.7	22 September 1992	1961
Brize Norton (Oxfordshire)	SP(42)/292067	100.2	70.9	10 July 1968	1968

a more consistently significant fault rate for the Wessex route, but this is for lower accumulation totals. This relationship is also reflected for the antecedent month's accumulated precipitation as shown in Figure 4.7 which shows that the accumulation of precipitation has a significant fault rate across the three routes for very low monthly accumulation values. This is because not only Wessex is affected by low levels of accumulated precipitation when the duration is extended from one week to a month. Showing that Track (P.W.) assets across all three routes are susceptible to the effects of month long droughts

Across the three routes the fault rate for higher values of accumulated precipitation across the month does not become significant until towards the end of the range presented in Figure 4.7. However, the relationship for LNW South is intermittently significant from values of 164mm upwards indicating that the infrastructure in this route

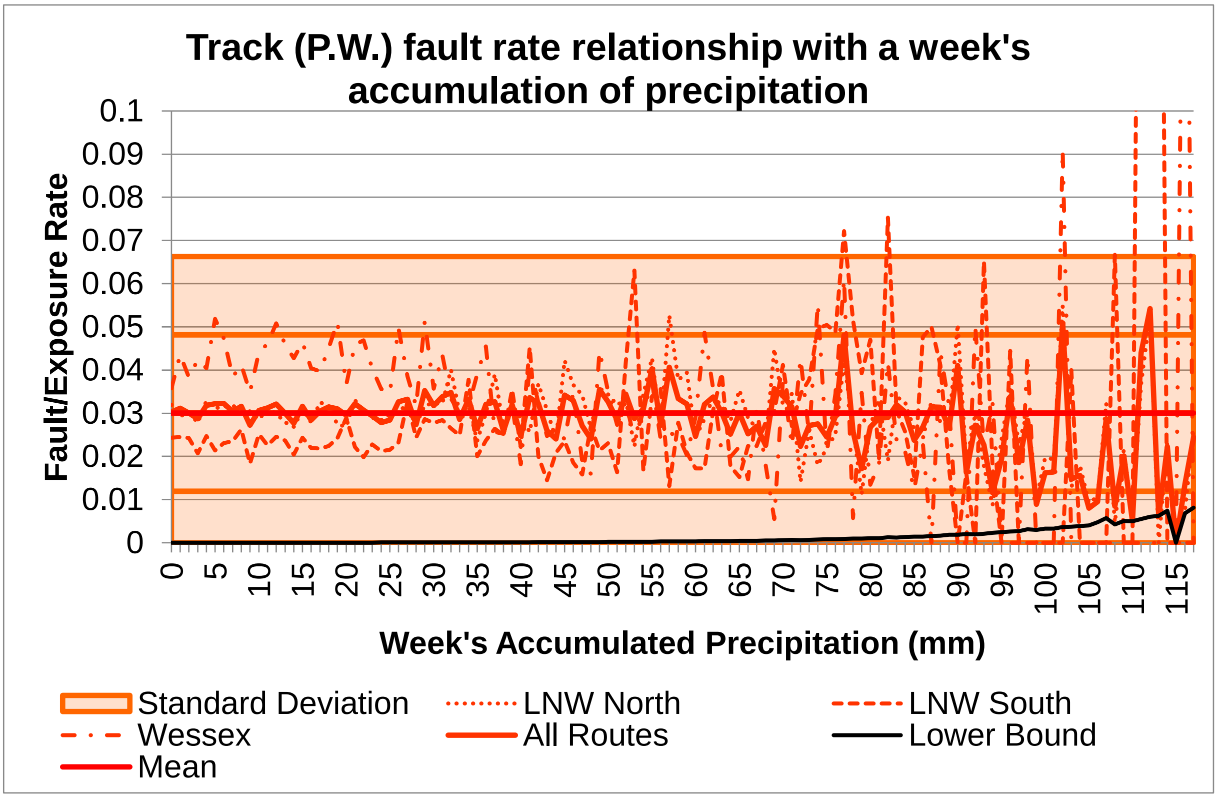

Figure 4.6: The relationship between a Week's precipitation and the Fault Rate for Track (P.W.) assets, illustrating the individual and overall relationships for each of the routes.

are less resilient to greater month's average precipitation. Due to the number of associated fault events it is beyond the scope of this research to interrogate these further as the analysis to determine indicated failure mechanisms would be too complex. In addition, although there are points where the fault rate becomes significant across the three routes for accumulated precipitation there is no observable trend..

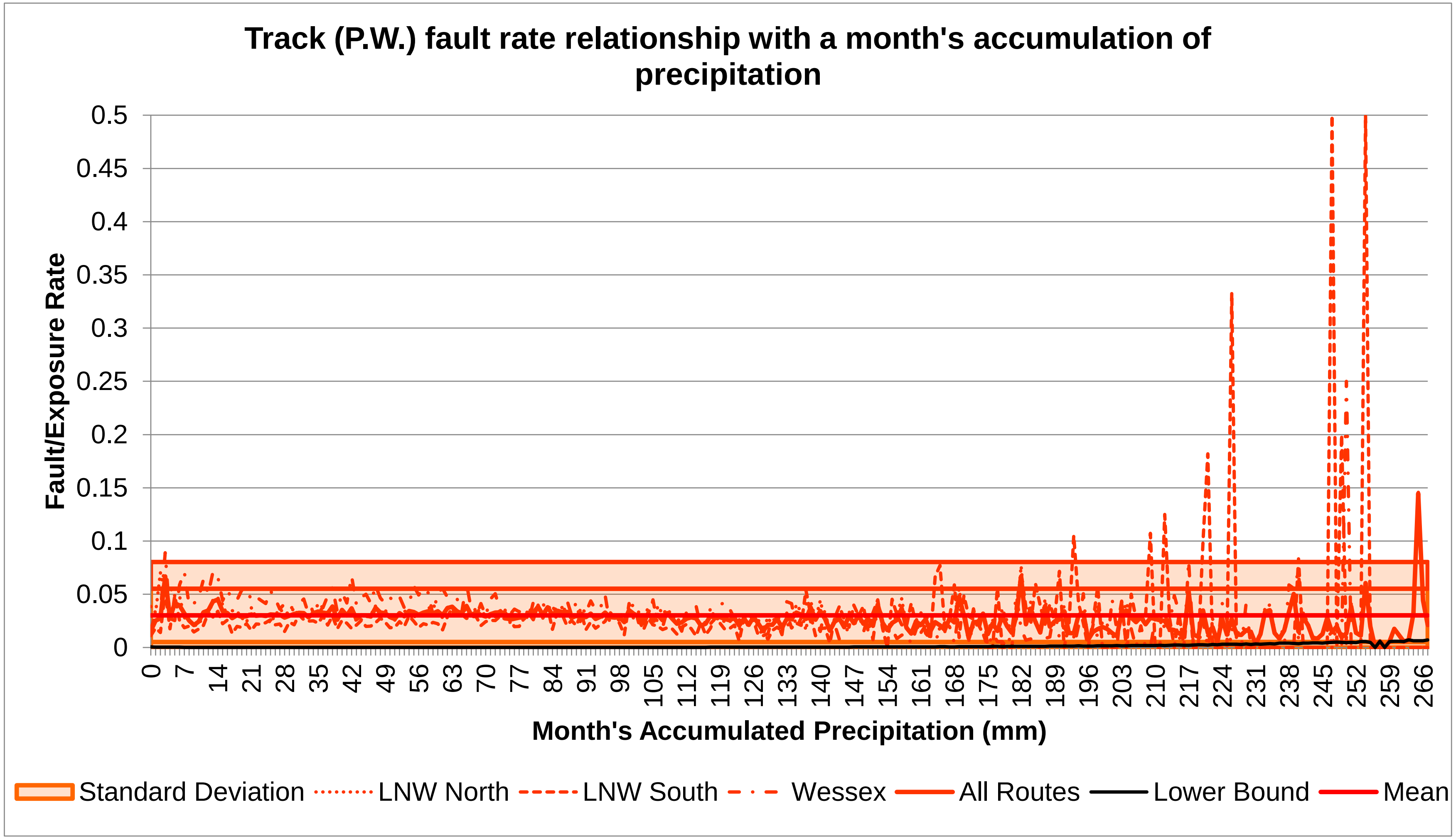

Figure 4.7: The relationship between a Month’s precipitation and the Fault Rate for Track (P.W.) assets, illustrating the individual and overall relationships for each of the routes.

4.3.2 Points (P.W.)

Points enable rolling stock to move from one set of tracks to another, which is integral to operating a multiline railway network efficiently. Points are made up of two distinct parts, Switches and Crossings (S&C) as illustrated in Figure 4.8. Switches change the rails that rolling stock are traveling on, or change the direction of the train, whilst crossings allow the flanges of the wheels of the train to pass through the intersection of two sets of rails. This assembly is made up of further components which are all included in the asset category Track S&C 1. Points are operated by signalling equipment which manages the traffic on the railway network, POE is discussed further in Section 4.4.2. Existing literature suggests that S&C are affected by cold temperatures especially when combined with precipitation (Marteaux, 2016a).

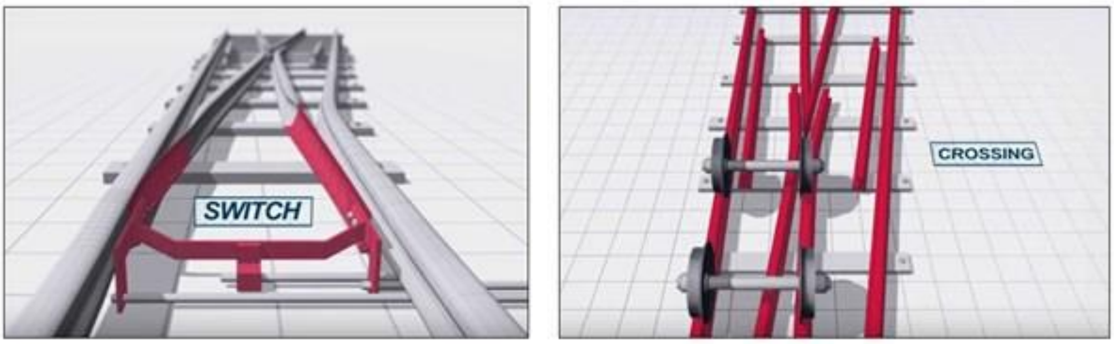

Figure 4.8: The Components of a Switch and Crossings Layout (Network Rail, 2017a)

4.3.2.1 Temperature & Points (P.W.)

The relationship profiles for Points and temperature can be seen in Table 4.6 which shows that there is largely consistency in the relationships with the exception of maximum temperatures for assets located on the Wessex route. For both sections of the LNW route lower temperatures are experienced when there is a greater number of point faults, increasing the fault rate. Significant fault rates occur when daily maximum and minimum temperatures are lower.

Table 4.6: Relationship Profiles for Points (P.W.) with Key Temperature Variables across all three routes.

Points (P.W.)		Temperature			
Route	**Fault Counts**	**Max**	**Min**	**Diurnal Range**	**Asset Category percentage faults**
LNW North	6079	-1	-1	-1	4.45%
LNW South	5885	-1	-1	-1	5.56%
Wessex	2552	2	-1	-1	3.28%

The fault rate relating to the maximum daily temperature in Figure 4.9, indicates a relationship between Points and lower temperatures, this is supported by the relationship that can be seen with the minimum temperature in Figure 4.10. Therefore, the overall fault rate for Points begins to increase for all routes for temperatures of 2°C and below, becoming significant at -4°C and very significant at -5°C.

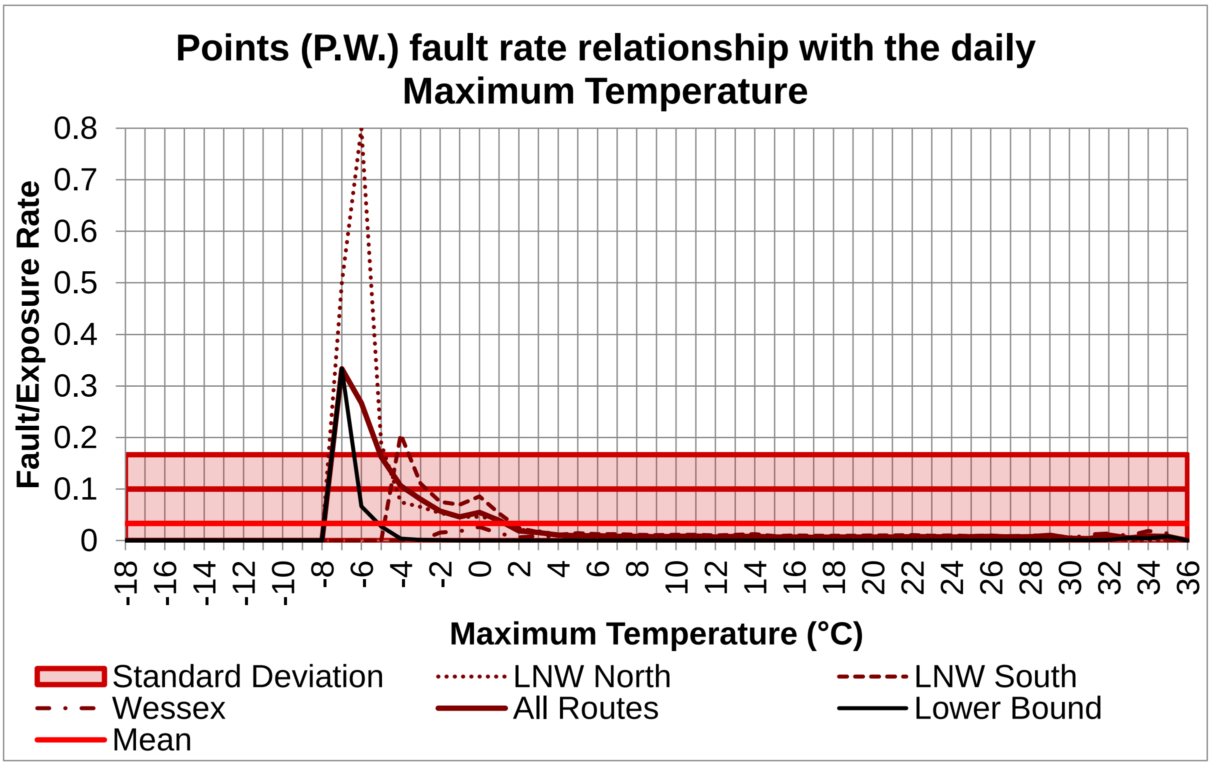

Figure 4.9: The relationship between the Daily Maximum Temperature and the Fault Rate for Points, illustrating the relationships for each route.

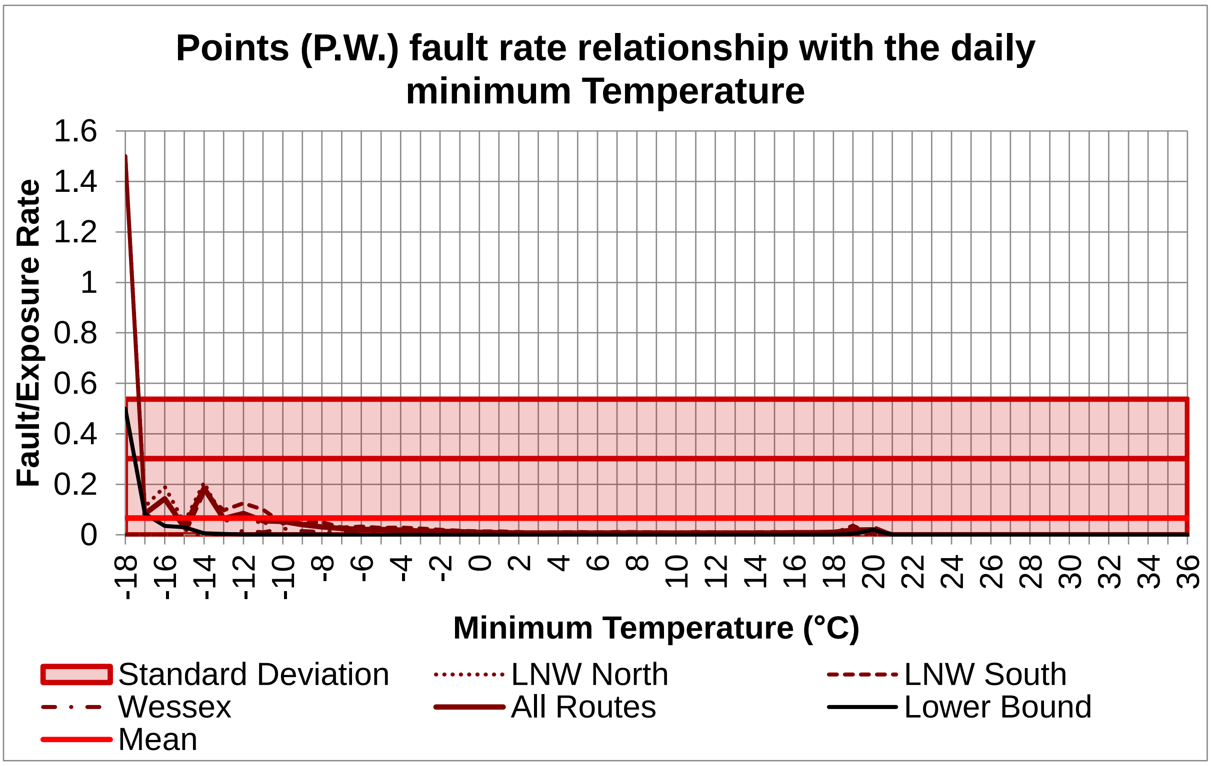

Figure 4.10: The relationship between the daily minimum temperature and the Fault Rate for Points, illustrating the individual and overall relationships for each route.

Both LNW North and South can be seen to have above average fault rates once the maximum daily temperature is zero or less as illustrated in Figure 4.9. For those LNW North faults where the maximum daily temperature is zero or below, 75% are attributed to weather. The fault counts for each category can be seen in Figure 4.11. 65% of these faults are specifically attributed to the effects of cold weather, illustrating the link between the temperature and the failure of the Points (P.W.). Further analysis shows that 86% of these faults are attributed to “Switch Rail Obstructions” and 83% of these can be attributed to weather and 71% to the effects of cold weather. The fault counts can be seen in Figure 4.12. There is a very clear relationship between switch rail obstructions caused by ice and snow as the result of lower temperatures and exacerbated when temperatures remain sub-zero for the whole day.

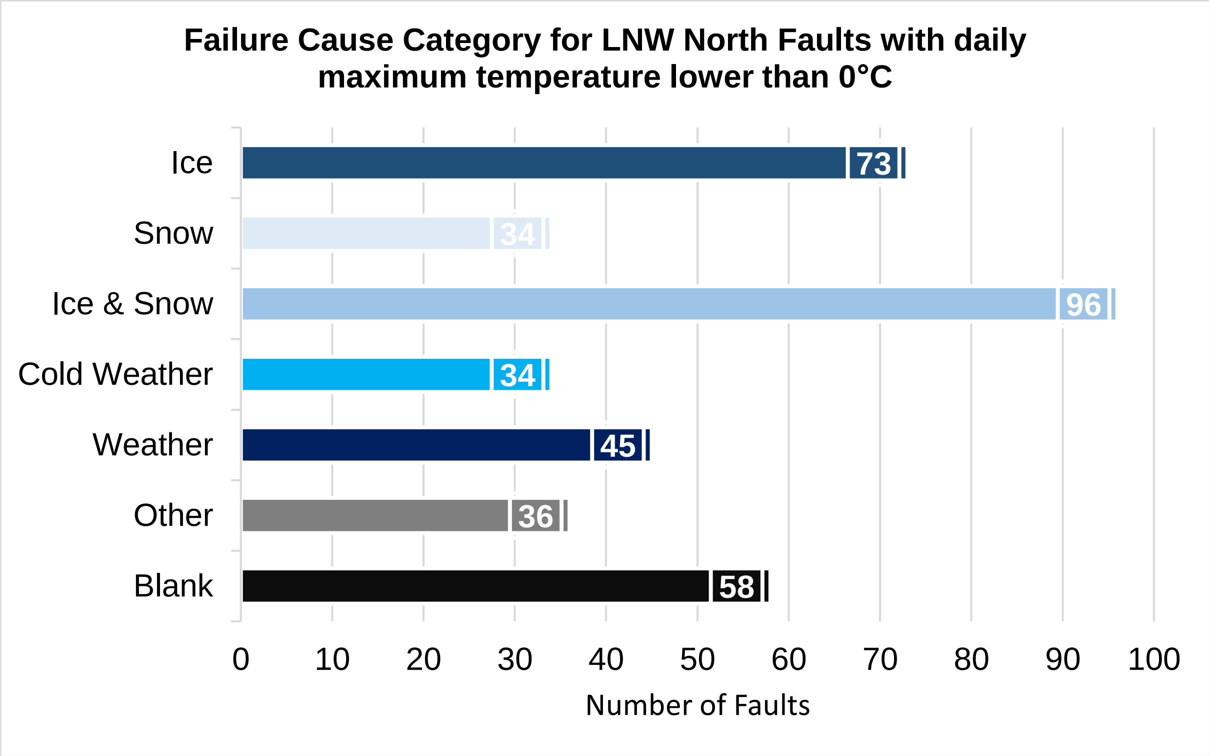

Figure 4.11: Final Column Category attribution for faults on LNW North with daily maximum temperatures equal to or below 0°C.

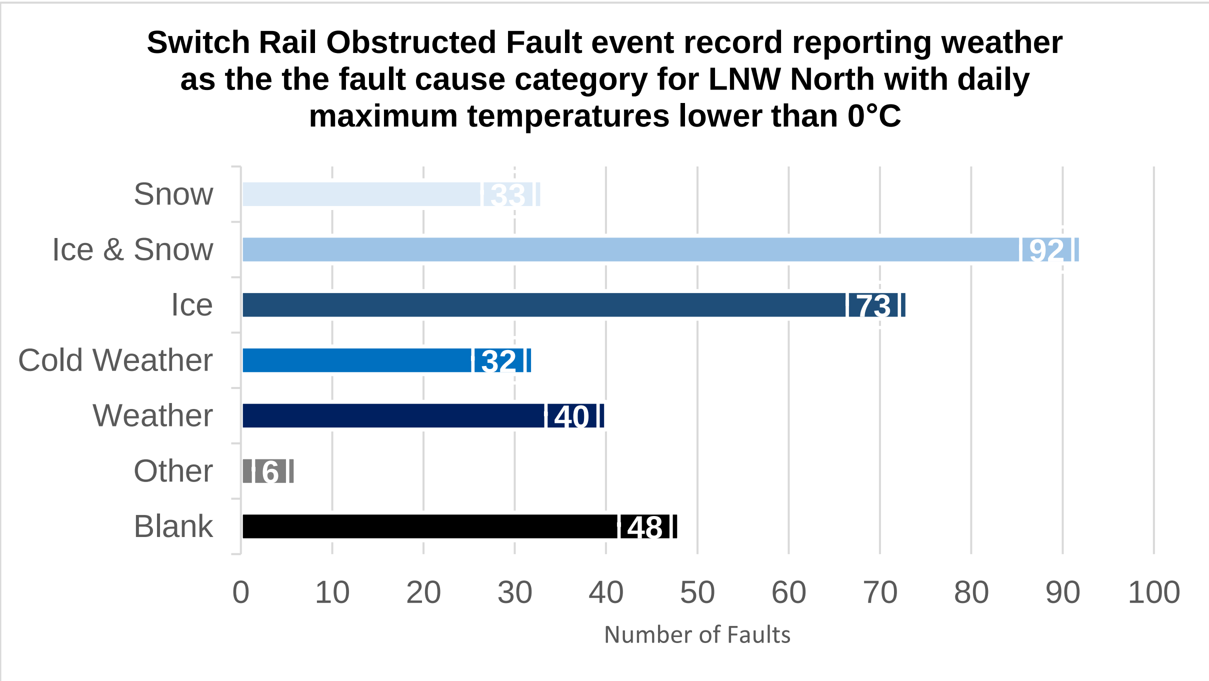

Figure 4.12: Percentages of Switch Obstruction faults for LNW North occurring with a daily maximum temperature of 0°C or below which have been attributed to weather.

Where the relationship profile for the Diurnal Range is -1, there are more fault events when the temperature does not change much over the course of a day. This is reflected in the relationships shown in Figure 4.13 where the fault rate is significant for diurnal ranges of 1 and very significant where there is zero change in temperature over the course of a day. These relationships suggest that the cause is not the magnitude of the low temperature but the duration for which sub-zero temperatures are experienced. This is the case for LNW North and LNW South, Wessex may not experience the same relationships because the number of faults for this route is comparatively low as was shown in Table 4.6. However, across the three routes there are 209 fault events contributing to the significant threshold for a diurnal range less than 2°C and 31 fault events contributing to the significant threshold for a diurnal range less than 1°C.

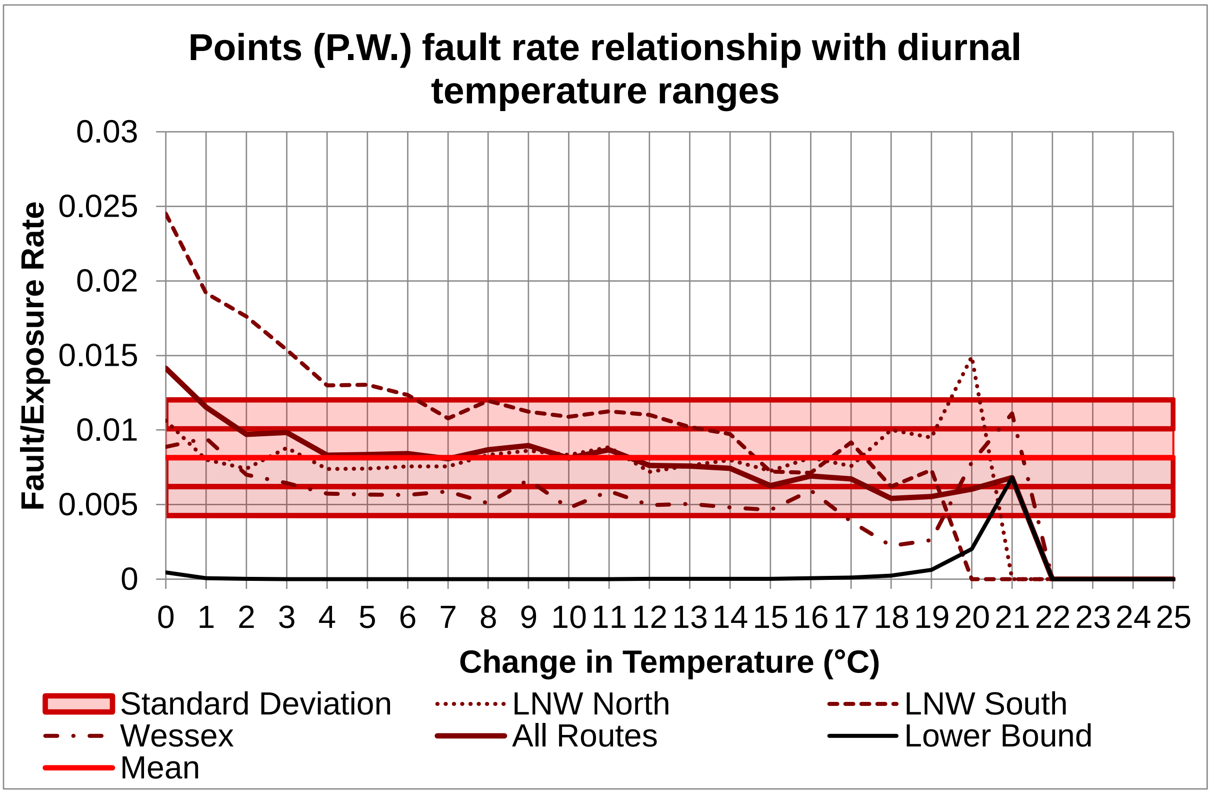

Figure 4.13: The relationship between the Diurnal Range of Temperature and Fault Rate for Points, illustrating the individual and overall relationships for each route.

4.3.2.2 Precipitation & Points (P.W.)

Regarding daily precipitation Points (P.W.) in the LNW South route are the only ones which experience significant fault rates as shown in Figure 4.14. The peak for LNW North is based on a single event, and the two peaks for Wessex are similarly based on single fault events. However, there is a total of 29 fault events that pass the significance thresholds for LNW South. None of the fault event records identify rainfall or flooding as their cause however, four fault events do mention snow, ice and frozen points indicating that there may be relationships between fault events and the combination of precipitation and low temperatures. This research hasn't conducted an analysis specifically on the combination of low temperatures and precipitation so this cannot be confirmed explicitly. Within these significant fault events there are no failure mechanisms indicated for precipitation and Points faults and no consistent trend throughout the fault events reported, despite the significance of the relationship.

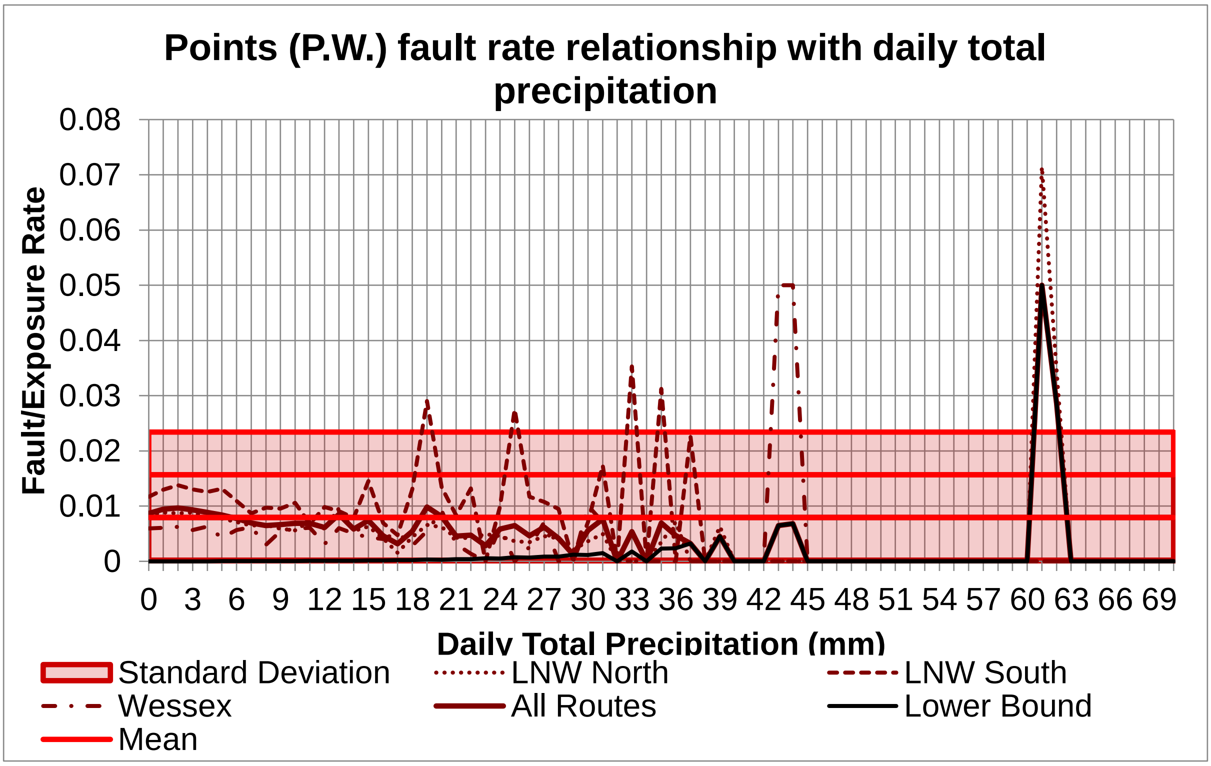

Figure 4.14: The relationship between daily precipitation totals and each route's fault rate for Points (P.W.) Assets.

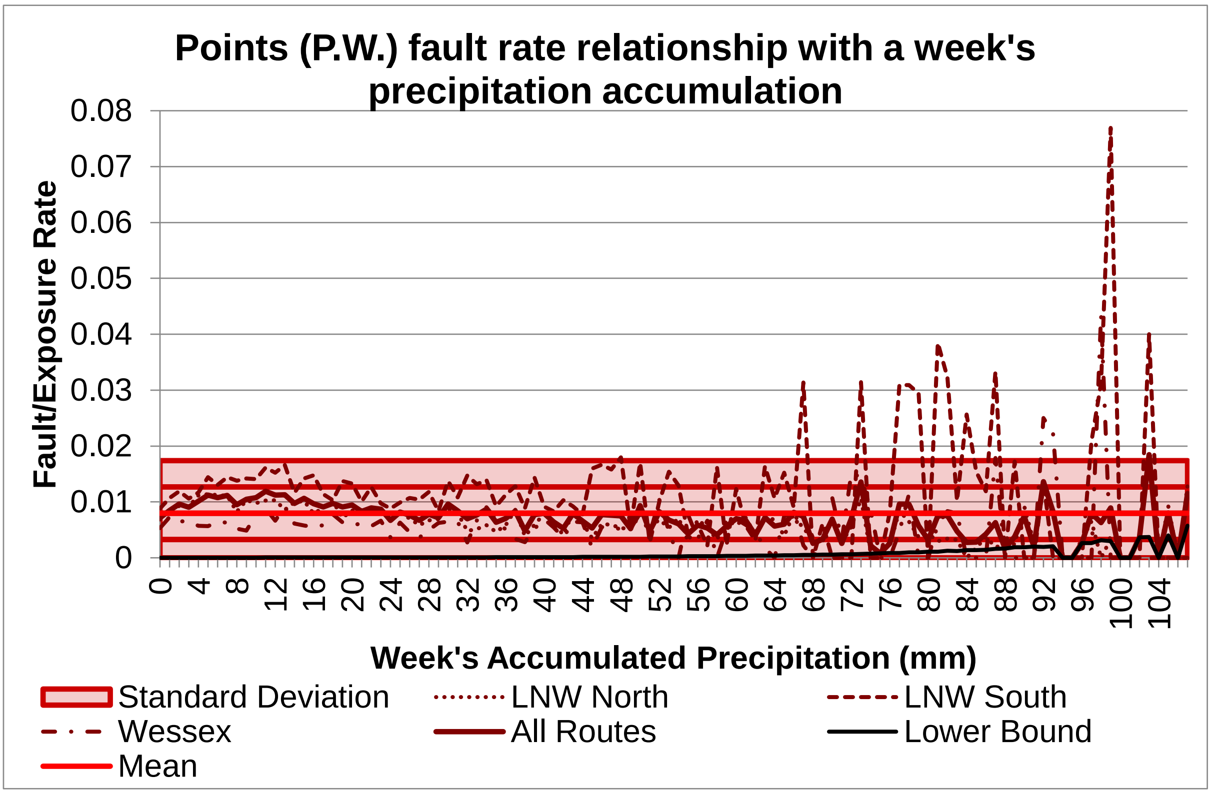

Figure 4.15: The relationship between the accumulation of precipitation for the week prior to faults and each route's fault rate for Points (P.W.) Assets.

There is no indication of a significant trend between Points and a week's accumulation of precipitation across all routes or for LNW North individually. Although Wessex has several significant peaks shown in Figure 4.15, these are caused by single fault events, low exposure frequencies or are unrelated based on the associated fault records. Contrastingly, LNW South experiences Points faults at a significant level consistently across the whole range of accumulated precipitation values greater than 4mm. A total of 2654 fault events can be considered as significant, however with such a quantity of individual events further extensive analysis would be needed to establish the role of weather which is beyond the scope of this research and has therefore been omitted.

Similar relationships are shown in Figure 4.16 for a month's accumulation of precipitation. As with the weekly accumulation of precipitation, Points (P.W.) assets for Wessex also have a few peaks which feature only a handful of events each. This is very small compared to LNW South which not only has many more significant peaks, but also these peaks include many fault events each. The peak with the greatest number of fault events is at a month’s accumulation of 71mm of precipitation where the count is 80 faults. This is in addition to a count of 79 fault events for Points (P.W.) assets for LNW South at a month’s accumulation of 20mm of precipitation prior to the fault event, which is considerably less precipitation. Both of these significant peaks fall within ‘normal’ weather scenarios, it should therefore be a concern that despite the steps taken to normalise this data for frequency of weather events there still remains a significant number of faults at these normal range values, but only for one route. This could highlight differences in the number of Points (P.W.) assets, the condition of the assets, differences in management or design of assets, particularly with regards to drainage or protection from water ingress.

Inspection of the individual fault events that contribute to these two peaks in Figure 4.16 for LNW South shows that in both cases snow and ice were the cause of the majority of the fault events, for the 20mm significant peak these faults happened during the December of 2010 when widespread snow affected the railway network (Prior and Kendon, 2011a; Department for Transport, 2010). The peak at 71mm of precipitation similarly has 32 faults attributed to the 02/02/09 where snow and ice were the cause of the Points (P.W.) faults. Many of these faults also occurred in the same location on the same day, which indicates why there is a significant peak at this value.

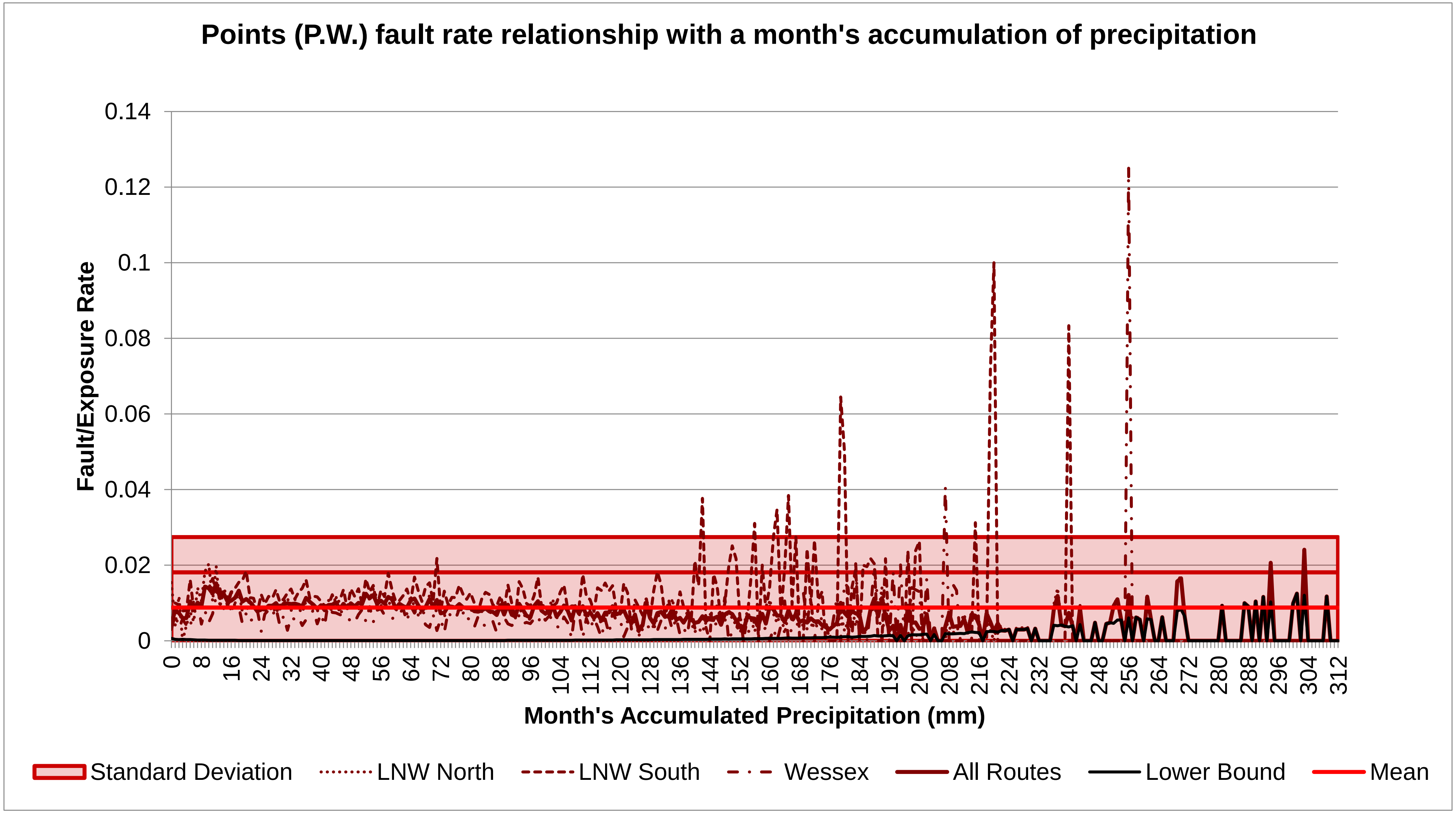

Figure 4.16: The relationship between the accumulation of precipitation for the Month prior to faults and each route's fault rate for Points (P.W.).

In this instance it can be concluded that the analysis of the fault rate for Points (P.W.) assets regarding the previous month's precipitation does not specifically show a strong relationship. Instead this indicates this measure has instead highlighted specific weather events that have caused many faults in a small spatiotemporal range (i.e. same day and same place). This is also reflected by many of the faults that contribute to the peaks for LNW North and Points (P.W.) assets regarding the previous month's accumulation of precipitation shown in Figure 4.16. These peaks appear at a month's accumulation of 9, 10 and 12mm which are in the normal range of weather. There is a total of 113 LNW North fault events for these values. Most of these fault events occur in December 2010, which experienced a long and heavy period of snowfall (Prior and Kendon, 2011a). Therefore, the relationship presented here may be less to do with the relationship between fault events for Points (P.W.) assets and more related to the extreme weather events that have occurred during the five years investigated. The winters of 2008/09 and 2010/11 are discussed in more detail later in Section 5.2.2.2.

LNW North is less affected by high quantities of accumulated rainfall over the course of the month prior to faults events. However, LNW South features consistently significant fault rates beyond a month's accumulation of 130mm of precipitation or greater. For Wessex this fault rate becomes consistently significant for Points (P.W.) beyond an accumulation of 183mm over a month. Although there are only 12 fault events for Points (P.W.) assets on the Wessex Route that contribute to the significant fault rate peaks there are 86 fault events for Points (P.W.) assets on LNW South which contribute to the significant fault rate peaks. Many of these faults indicate a fault due to a lack of lubrication, a few of these fault events also indicate the lubrication has been washed away as with the fault events for LNW South's Points (P.W.) assets.

It is therefore unclear whether the duration of rainfall or intensity of rainfall is the dominant factor in causing the washing away of lubrication, causing this type of fault with Points (P.W.) asset types. Alternatively, the cause may be unrelated to weather and instead due to poor lubrication routines during this period, or a combination of both factors. Despite the interesting complexities found within the detail of the relationships presented between Points and precipitation, there is no consistent and reliable relationship between the overall fault rate for Points (P.W.) and precipitation.

4.3.3 Boundary Measures

Any asset at the border between the railways and other land, with the purpose of protecting the railways and associated infrastructure from the trespass or damage caused by animals or humans, is known as a boundary measure. A fence, wall or other dividing structure may constitute a boundary measure. Boundary measures perform a crucial safety and security role as a railway infrastructure asset, preventing unauthorised access of people, animals and vehicles.

A significant proportion of the fault events across the three routes can be attributed to boundary measures, averaging at 2.37% of the total number of faults. One of NR's key objectives is to reduce animal incursion through improved boundary management. Possible causes have been identified by NR however there is little evidence that the effect of weather has been considered other than the mention of the effect of environmental factors on tensioned wire boundary measures (Network Rail, 2019f).

4.3.3.1 Temperature & Boundary Measures

The relationship profiles for boundary measures and key temperature variables can be seen in Table 4.7 which shows there is no consistent relationships across the routes. The maximum daily temperature often has a significant fault rate across the normal

Table 4.7: Relationship Profiles for Boundary Measures for Key Temperature Variables across all three routes.

Boundary Measures		Temperature			
Route	Fault Counts	Max	Min	Diurnal Range	Asset Category percentage faults
LNW North	4242	-2	-1	-1	3.11%
LNW South	2053	1	-1	2	1.94%
Wessex	1598	2	1	-1	2.06%

temperature range, particularly for LNW North as shown in Figure 4.17, therefore there is no specific relationship. In addition, there is no significant relationship between lower temperatures and the fault rates for boundary measures. However, there is a significant relationship between the fault rate and the diurnal range for boundary measures as shown in Figure 4.18. Across all three routes when there has been no temperature change there is a significant fault rate for boundary measures, however this trend is not the same across all three routes individually. Consequently, it is not clear if boundary measures have a significant relationship with temperature variables.

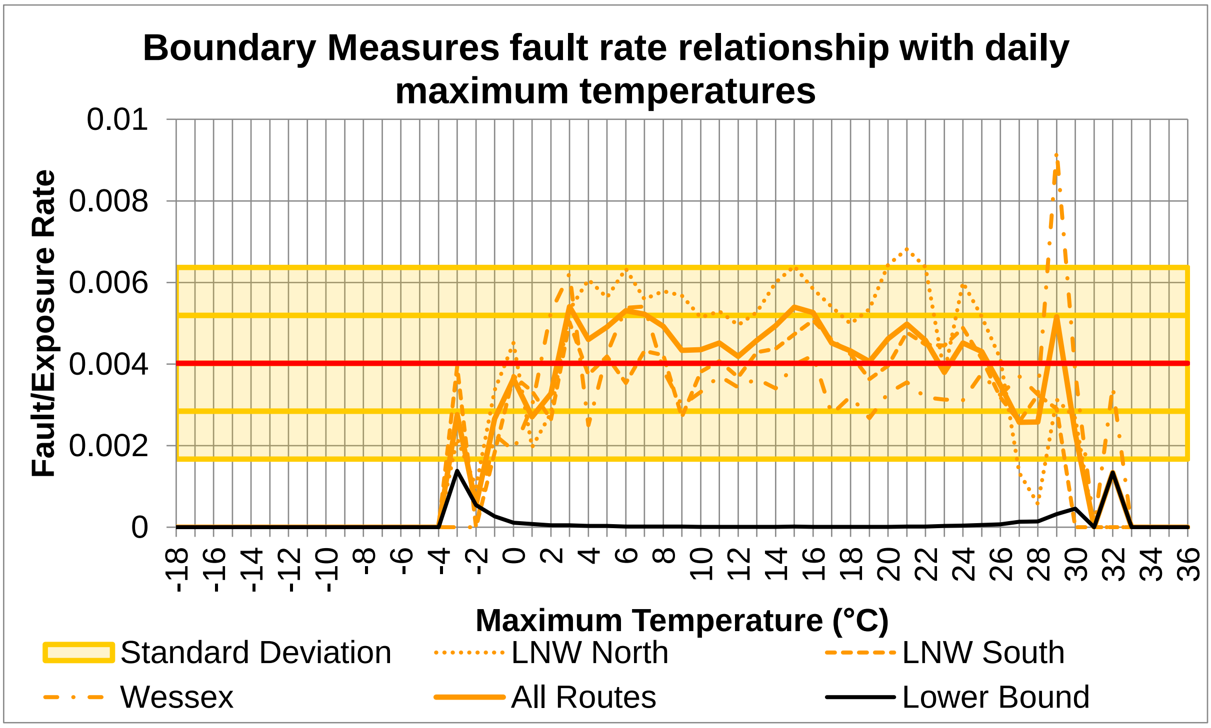

Figure 4.17: The relationship between the Daily Maximum Temperature and Fault Rate for Boundary Measures for each of the routes.

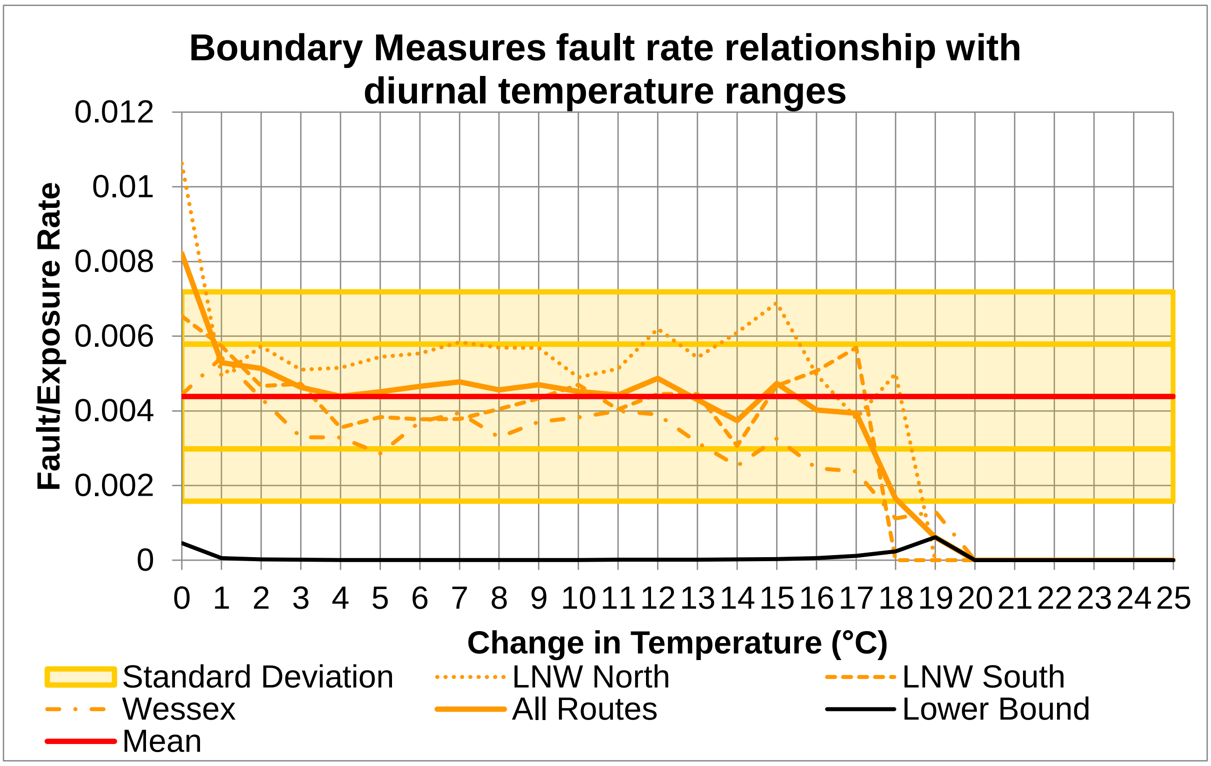

Figure 4.18: The relationship between the Diurnal Range of Temperature and Fault Rate for Boundary Measures, illustrating the relationships for each of the routes.

4.3.3.2 Precipitation & Track Boundary Measure

Overall, there is no relationship between total daily precipitation and the fault rate for boundary measures as shown in Figure 4.19. However, both LNW South and Wessex boundary measures have a significant and very significant relationship between higher daily precipitation totals above 30mm and the fault rate. Figure 4.20 shows that across the three routes there is a significant relationship with the fault rate for boundary measures and the week's accumulation of precipitation for amounts up to 20mm. Similarly, there is a relationship for a month's accumulated precipitation and a significant fault rate for boundary measures with less than 42mm as shown in Figure 4.21. The fault rate for both antecedent accumulation of precipitation is relatively low, but still significant, the fault rate for LNW North is the highest, and with very significant peaks for low weekly and monthly precipitation accumulation.

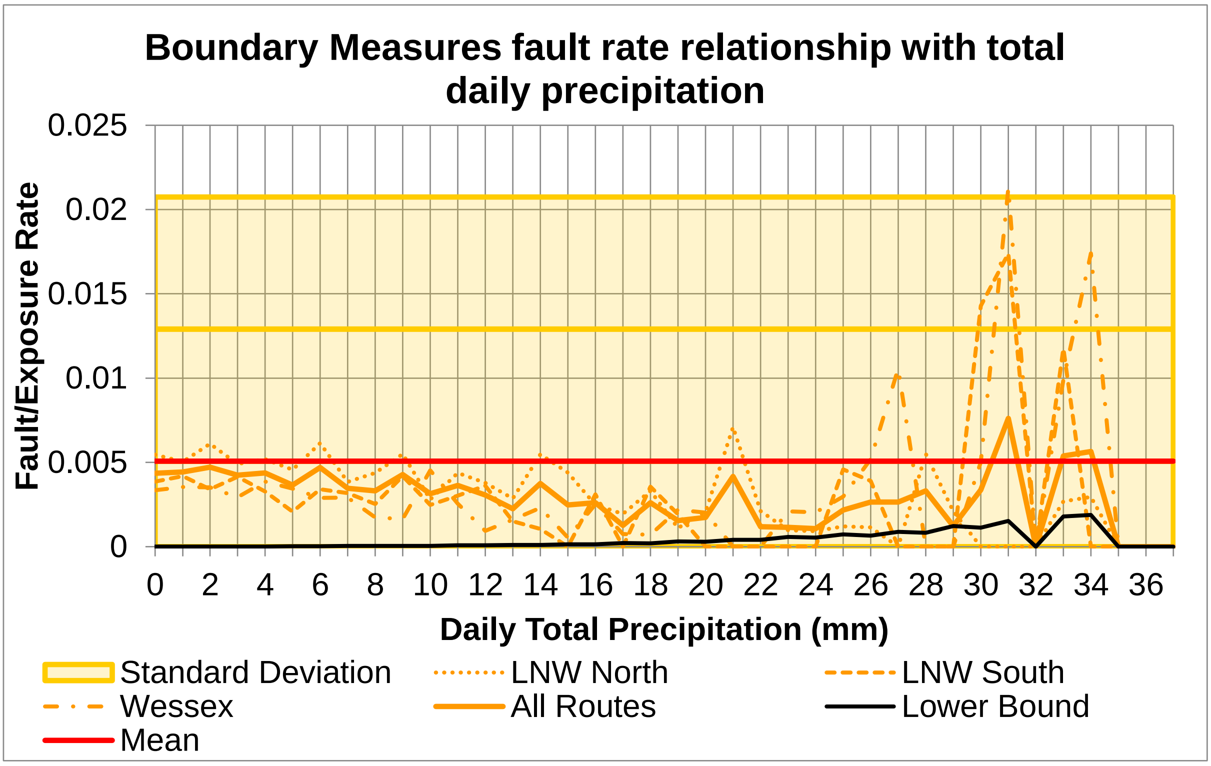

Figure 4.19: The relationship between daily precipitation totals and each route's fault rate for Boundary Measures.

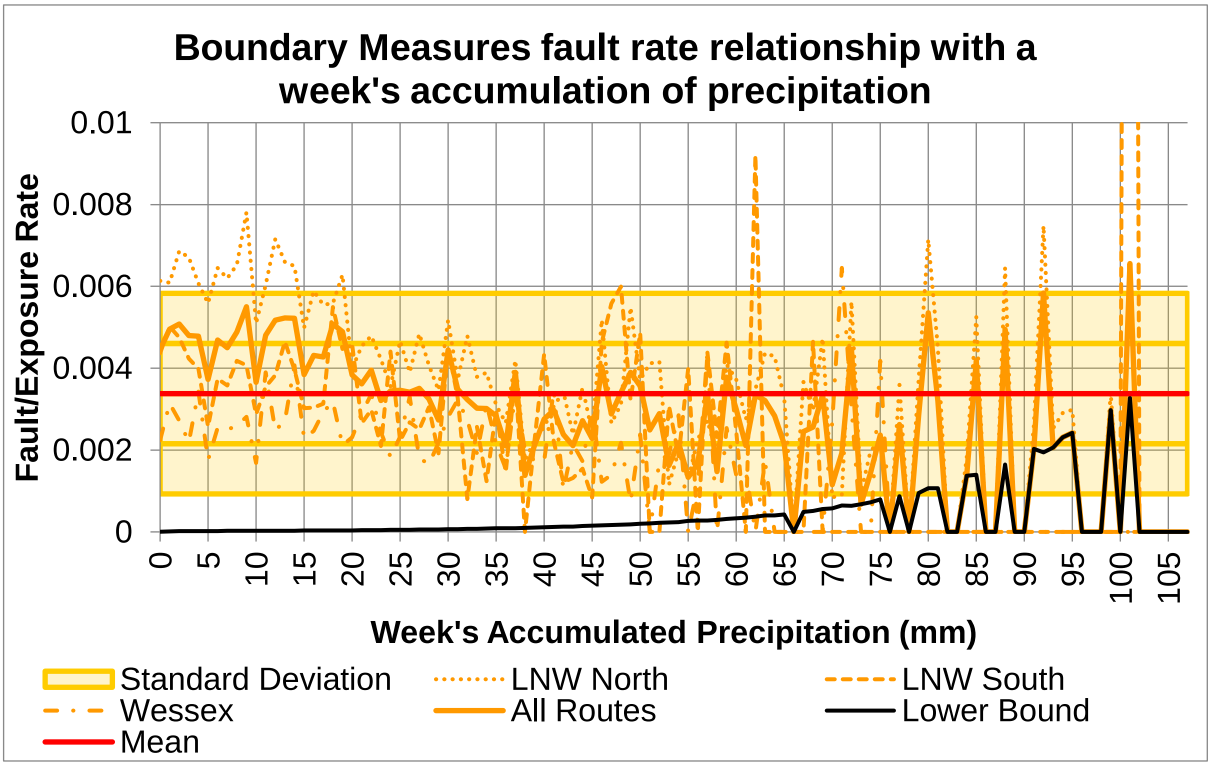

Figure 4.20: The relationship between the accumulation of precipitation for the week prior to faults and each route's fault rate for Boundary Measures.

Investigation of the individual fault records with a week's accumulation of 20mm or less precipitation showed that there were nearly 2500 fault event records contributing to these peaks and a similar number contributing to the peaks less than 42mm for a month's accumulation. However, due to the quality of the reporting it was not possible to determine if these were as a result of the impacts of weather. Component 2 for this asset category includes a categorisation of the fault cause, however in many cases this was made unclear by conflicting entries in the FCAD free text column. A few examples are shown in Table 4.8, illustrating the difficulty of assigning fault causation.

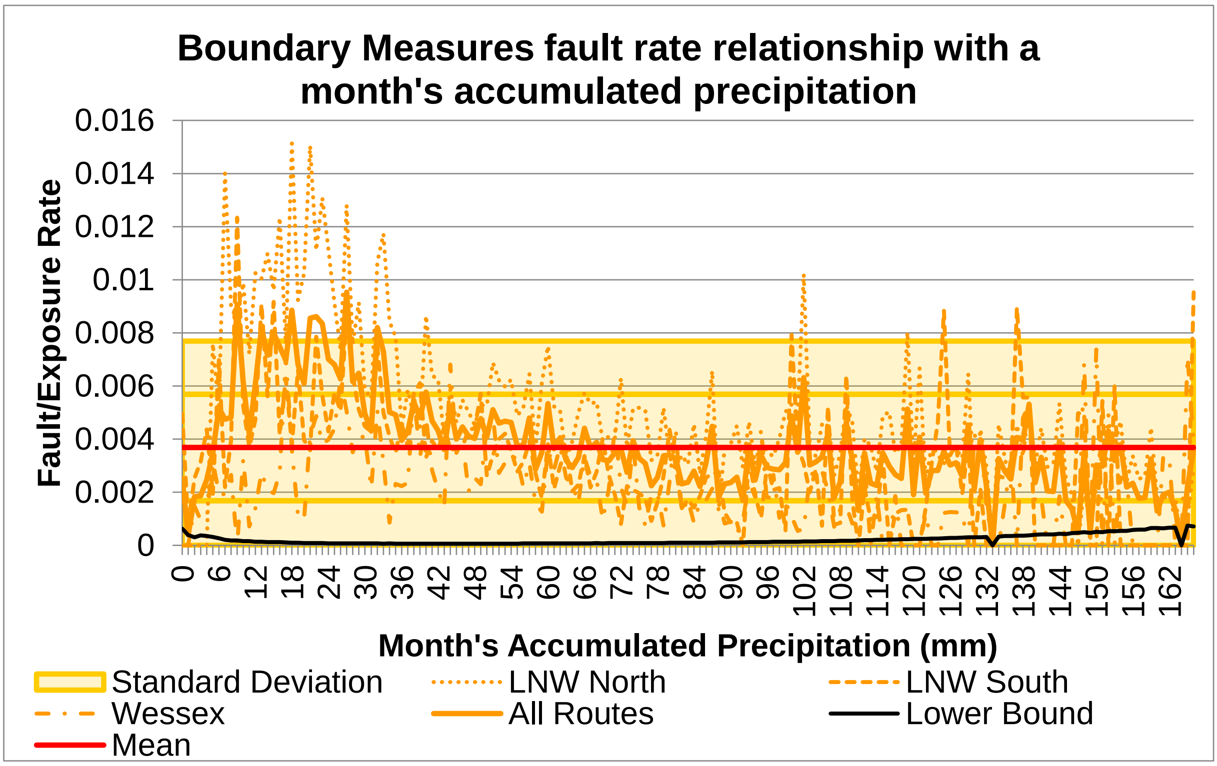

Figure 4.21: The relationship between the accumulation of precipitation for the month prior to faults and each route's fault rate for Boundary Measures.

Table 4.8: Example Boundary Measure fault event records, illustrating the difficulty of concluding the cause of fault events.

Component 1	Component 2	Failure/ Cause/ Action/ Detail	Possible causes
Fence – Post and Wire	Damage due to Accident - Gap	Stray animal. Tree had fallen on fencing and cattle pushed through	Treefall Wind Cattle Inadequate Fencing
Fence – Metal Palisade	Damage due to vandal/crime - Gap	Removed by the fire brigade to gain access to get to a lineside fire.	Fire Fire Brigade Vandalism Arson Heat Drought
Fence Post and Wire	Loose Wire/Components - Gap	Sheep on line	Inadequate fencing Deteriorated Fencing Sheep

4.4 Significant Asset Faults

A signal is a piece of infrastructure that indicates to trains when it is safe to proceed to the next section of track. All infrastructure relating to the operation of signals can be referred to as signalling infrastructure. In the literature review, existing knowledge regarding the effect of different weather variables on signalling assets was explored revealing that there is some knowledge of the impact of weather but there are no operational thresholds known for many of the assets that fall into this category (RSSB, 2014). However, it is known that overheating lineside equipment is an issue for railway infrastructure and should be considered in the design of new systems (Palin et al., 2013; Hirano et al., 2005). The lack of clarity on this matter is exacerbated by the mixture of new and legacy infrastructure in operation, ranging from mechanical semaphore signals through to more modern coloured light signals.

Signalling is a Parent Asset Group with a number of asset sub-groups and FMS Suffix Labels, of the significant asset categories identified those belonging to the signalling parent asset group are highlighted in Table 4.9. Of these asset categories, six feature in the eleven asset groups with the greatest average proportion of faults across the three routes as can be seen in Table 4.10 and highlighted in Table 4.9. The results for the significant signalling asset categories are presented in the following sections and will be referred to by their FMS Suffix Labels.

Table 4.9: Signalling categories with greater than 1% of at least one route's fault events. The significant Signalling Assets are highlighted.

Parent Asset Group	***Asset Sub-Group***	***FMS Suffix Labels***	***Short & Number***	***Full Asset Category Name***
Parent Asset Group: Signalling	AWS	Train Warning System	Sig AWS 2	Sig AWS: Train Warning System
	Axle Counter	Axle Counter	Sig AC 1	Sig AC: Axle Counter
	HABD	Hot Box Detector	Sig HABD 1	Sig HABD: Hot Axle Box Detector
	Interlocking	Interlocking	Sig I 1	Sig I: Interlocking
		Panel/Frame	**Sig I 3**	**Sig I: Panel/Frame**
		Solid State Interlocking	Sig I 4	Sig I: Solid State Interlocking
		Train Describer	Sig I 5	Sig I: Train Describer
	Level Crossing	**Level Crossing Equipment**	**Sig LC 1**	**Sig LC: Level Crossing Equipment**
	Point Operating Equipment	**Point Operating Equipment**	**Sig POE 2**	**Sig POE: Point Operating Equipment**
	Signalling	**Signal**	**Sig Sig 4**	**Sig Signal: Signal**
	TPWS	**Train Warning System**	**Sig TPWS 1**	**Sig TPWS: Train Warning System**
	Track Circuit	**Track Circuit**	**Sig TC 2**	**Sig TC: Track Circuit**

Table 4.10: Asset categories with average percentage of faults across all three Routes over 2%.

	Short & Number	FMS Suffix Label	Asset Category percentage of total route faults LNW North	LNW South	Wessex	Average % of Faults
1	Track Track 3	Track (P.W)	16.44%	10.94%	19.23%	15.54%
2	Sig Sig 4	Signal	12.81%	12.00%	11.24%	12.02%
3	Sig POE 2	Point Operating Equipment	6.87%	9.18%	6.37%	7.47%
4	UU 39	No Equipment	8.69%	7.75%	4.94%	7.28%
5	Sig TC 2	Track Circuit	6.39%	5.46%	6.48%	6.11%
6	Sig LC 1	Level Crossing Equipment	4.02%	2.18%	7.68%	4.63%
7	Track S&C 1	Points (P.W.)	4.45%	5.56%	3.28%	4.43%
8	Sig I 3	Panel/Frame	5.10%	3.60%	2.91%	3.87%
9	Track U 2	Boundary Measure	3.11%	1.94%	2.06%	2.37%
10	Sig TPWS 1	Train Warning System	1.25%	1.97%	3.04%	2.09%
11	E&P TP 1	Circuit Breakers	1.79%	3.00%	1.42%	2.07%

4.4.1 Signals

After Track (P.W.), the Signals group has the second largest proportion of fault events as shown in Table 4.10, which also shows that the percentage of fault events for this asset category is consistent across all three routes with an average rate of 12.02%. There are several types of signal, the traditional semaphore signal is still in operation on some parts of the network and indicate to a train driver by raising and lowering its position from the horizontal or stop position. Most signals are colour light signals which operate in a similar way to highway traffic lights, however Position Light Signals which display an arrangement of lights to instruct drivers are also present across the network. The shift over time from semaphore to colour light means modern signalling equipment is often made up of electrical components, where historically they were predominantly mechanical.

4.4.1.1 Temperature and Signals

Across the key temperature variables the relationship profiles are either 1 or 2 but are inconsistent across the three routes as shown in Table 4.11. These relationships are reflected in Figure 4.22 and Figure 4.23 for the maximum and minimum daily temperatures and in Figure 4.24 for the diurnal range. It can be seen in Figure 4.22 and Figure 4.23 that there are peaks at either end of their respective ranges, reflecting the relationship profiles for maximum daily temperature and for minimum daily temperature. Wessex does not pass the significant thresholds for maximum daily temperature for either higher or lower temperature ranges, although this route does pass thresholds for minimum daily temperatures. Both LNW North and LNW South pass the significant thresholds for higher and lower temperatures for both the daily maximum and daily minimum temperatures. This is a strong indication that signalling equipment is sensitive to both hot and cold weather.

Table 4.11: Relationship Profiles for Signals for Key Temperature Variables across all three routes.

Signals		Temperature			
Route	Fault Counts	Max	Min	Diurnal Range	Asset Category percentage faults
LNW North	17490	2	2	1	12.81%
LNW South	12708	2	1	2	12.00%
Wessex	8742	1	2	1	11.24%

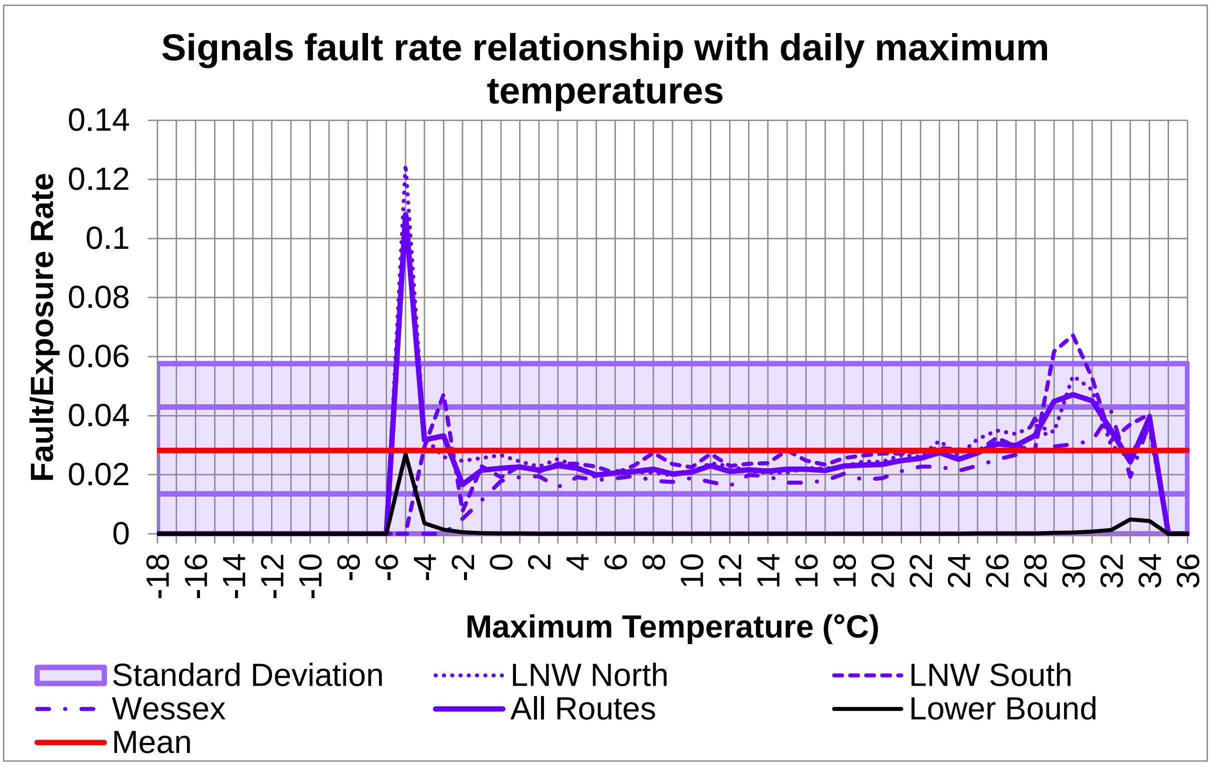

Figure 4.22: The relationship between the Daily Maximum Temperature and Fault Rate for Signal Assets, illustrating the relationships between each of the routes.

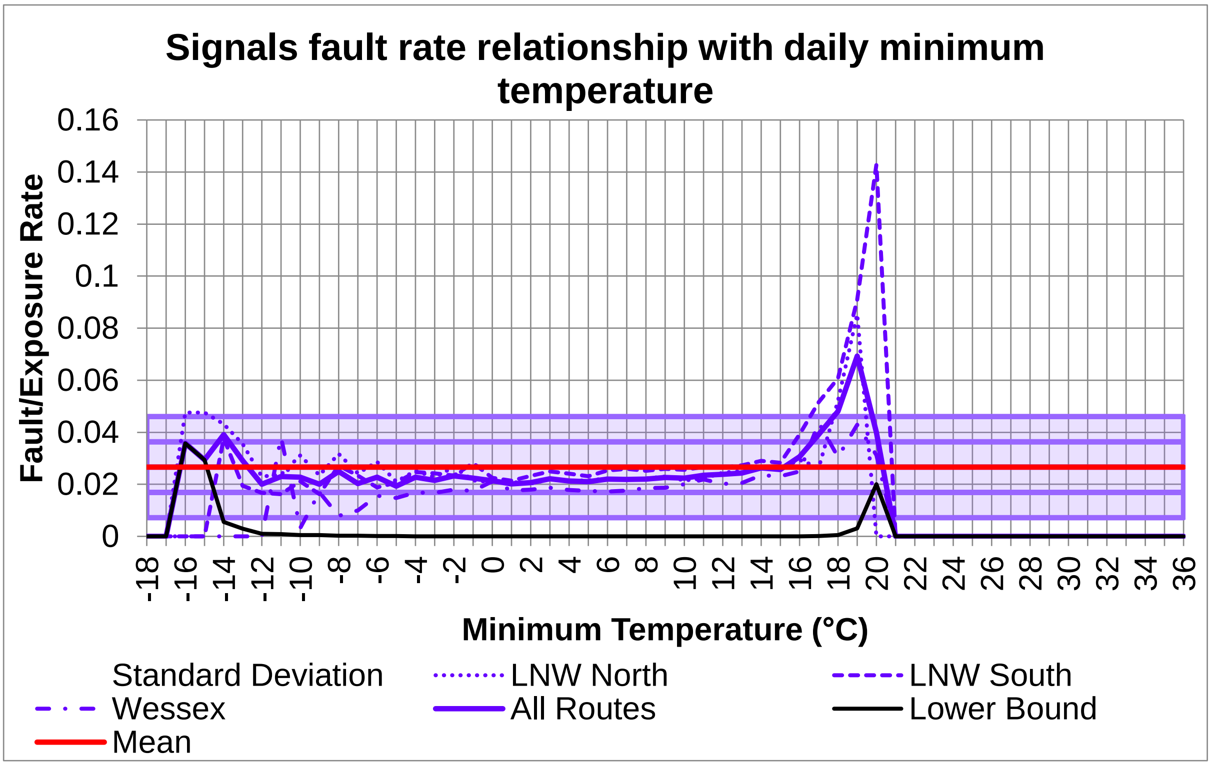

Figure 4.23: The relationship between the Daily Minimum Temperature and Fault Rate for Signal Assets, illustrating the relationships between each of the routes.

Only a handful of faults contribute to the peaks at the lower ends of the ranges, the individual fault event records indicate that weather, ice or sunlight are the cause of some of these faults. Contrastingly, the peaks at the higher end of the temperature range have just over 200 faults contributing to these significant peaks for LNW North and LNW South. However, there is no clear indication from investigating the individual fault event records that weather is the cause. This may be because there are relationships between weather and certain parts of the signalling equipment that are currently not well understood and therefore weather is not listed as a possible cause in the fault event data recorded. Further analysis would be needed to understand the cause of this relationship between high temperatures and signalling equipment.

With the exception of one peak for LNW South at a change of 0°C in Figure 4.24, the only peaks that occur are for higher diurnal range values and occur across all routes.

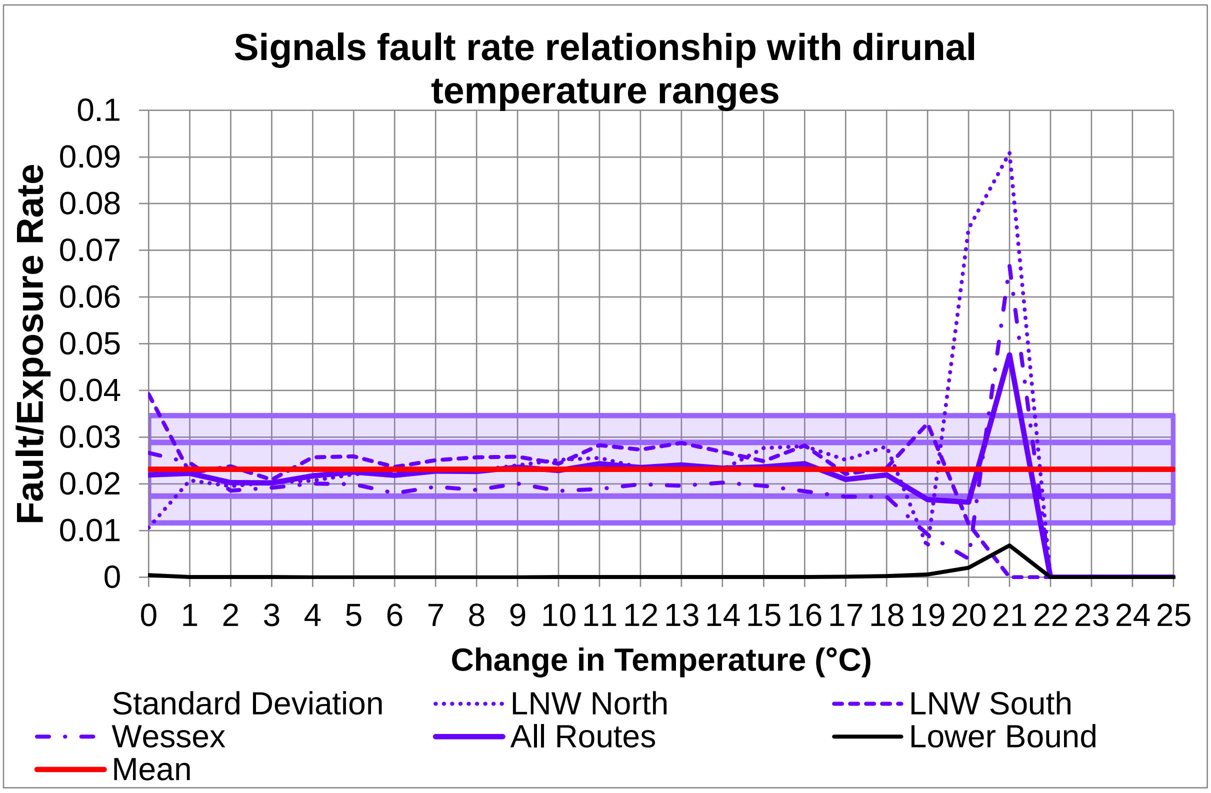

Figure 4.24: The relationship between the Diurnal Range of Temperature and Fault Rate for Signal Assets, illustrating the relationships between each of the routes.

For those faults for LNW South with a significant relationship with a diurnal range of 0°C there is no indication this is caused by weather following an investigation of the individual fault event records. From investigating the faults that contribute to the significant peaks at larger diurnal range values across all routes there is no consensus regarding the cause of the faults. Where detail is provided for these faults there are a small number that mention a few different weather factors as the cause of the fault including freezing, sunlight and heat. In addition, only 7 fault events contribute to the significant peak at a diurnal range of 21°C, this can therefore be discounted as there is not enough evidence to support a significant threshold. This may indicate that the diurnal range is not the cause of the fault but instead the absolute values are the weather variable that influence faults of signalling equipment.

The relationships with temperature for signals situated in each of the routes has been explored in detail. These individual relationships are broadly consistent with trends for higher temperatures across the three routes, with significant fault rates above 29°C. Overall the fault rate for signals experiencing colder temperatures becomes significant below -5°C. There is no overall relationship between signals and the diurnal range until the diurnal range becomes extreme at a range of 21°C, however there are not enough fault events contributing to this peak for it to be considered reliable.

4.4.1.2 Precipitation and Signals

LNW South experiences a significant rate of signal faults once the total daily precipitation is above 16mm and these fault rates then become very significant once daily precipitation exceeds 31mm as shown in Figure 4.25. Significant faults begin to occur for LNW North and Wessex at 39mm and 34mm of daily precipitation, respectively. However, LNW North and Wessex only have a significant rate of

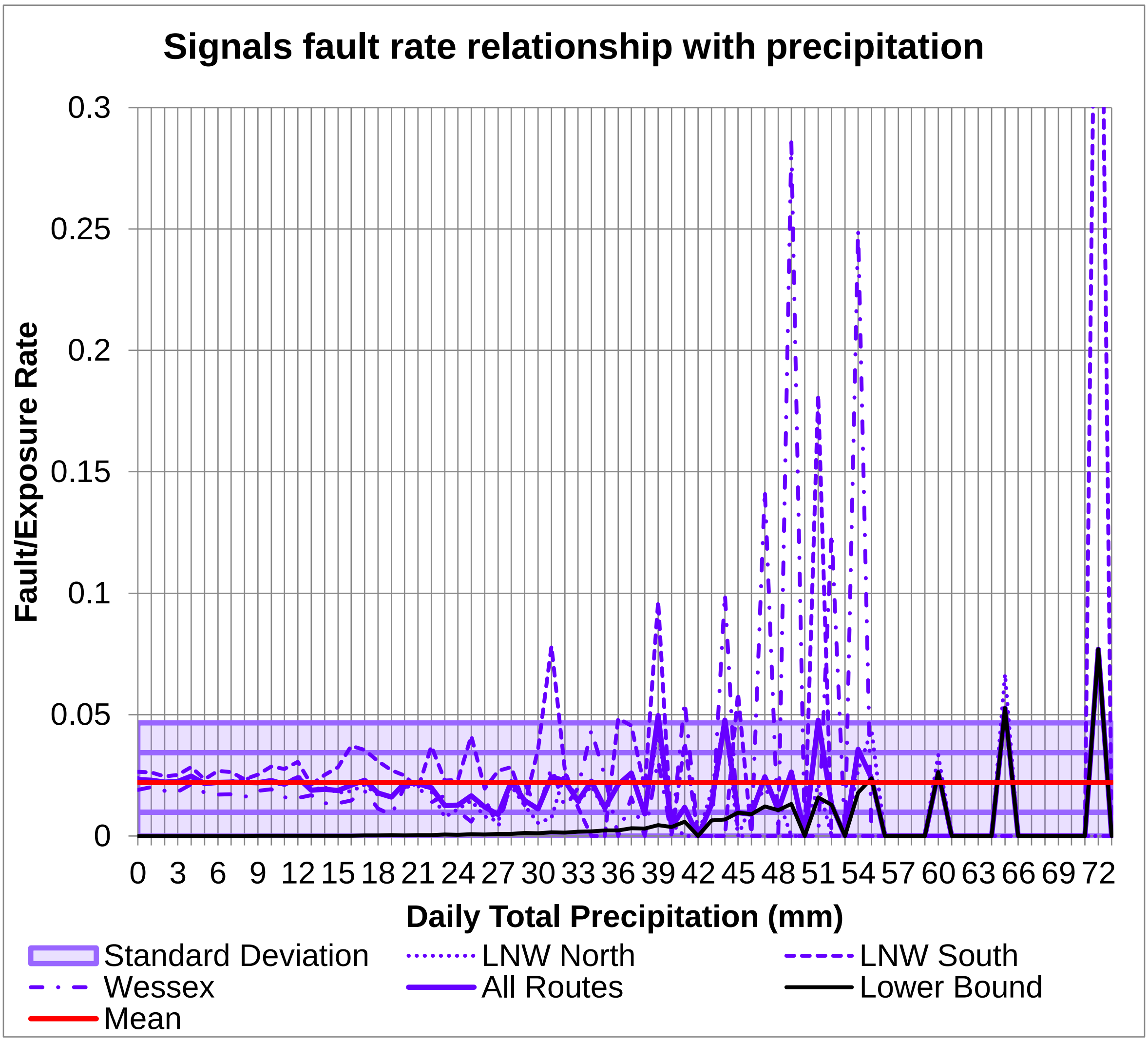

Figure 4.25: The relationship between daily precipitation totals and each route's fault rate for Signalling Assets.

signalling asset faults intermittently beyond the initial threshold for daily precipitation, unlike the consistently significant fault rates for LNW South.

Similar trends were observed for precipitation accumulation, however there are not enough fault events to identify a threshold with confidence. Considering the trends across the three routes, it may therefore be reasonable to draw an overall significant fault rate threshold at 39mm for daily precipitation. However, there are not enough fault events contributing to any of these peaks, nor is there enough consistency to conclude that there is a significant relationships between precipitation, daily or accumulated, and Signal asset faults with confidence.

4.4.2 Point Operating Equipment

Points have moveable switch rails which enable trains to change tracks at junctions. They are part of the signalling system and point failures cause signals to go to red to prevent trains from passing into unsafe sections of track as a failsafe system. Although they are primarily mechanical, Points are operated by digital mechanical point operating equipment (POE) and controlled either by levers or more recently by digital systems, where interlocking systems prevent trains from passing into unsafe sections of the railway network (discussed in Section 4.4.5).

4.4.2.1 Temperature and POE

It can be seen in Table 4.12 that the relationship profiles for maximum temperature and POE assets are the same across all routes indicating that both higher and lower maximum temperatures are related to a higher number of POE faults. However, the relationship profile for the Minimum daily temperature differs across the different routes. Higher diurnal ranges are related to a higher number of faults consistently across all routes.

Table 4.12: Relationship Profiles for POE assets for Key Temperature Variables across all three routes.

POE		Temperature			
Route	**Fault Counts**	**Max**	**Min**	**Diurnal Range**	**Asset Category percentage faults**
LNW North	9375	2	-1	1	6.87%
LNW South	9723	2	1	1	9.18%
Wessex	4949	2	2	1	6.37%

These relationships can be seen in more detail for the daily maximum and minimum temperatures in Figure 4.26 and Figure 4.27 respectively. Later in this section Figure 4.28 presents the detailed relationship for diurnal temperature ranges. Where the daily maximum temperature is above 29°C the fault rate for POE assets in LNW North and LNW South begin to become significant, while for Wessex the fault rate becomes significant at 31°C. With 54 POE fault events occurring across the three routes when the maximum temperature is 31°C this significant fault threshold can be concluded with confidence.

POE are also affected by lower temperatures as fault rates become significant when the daily minimum temperature is very low at -12°C or lower, as can be seen in Figure 4.27. However, Figure 4.26 indicates that the fault rate for POE assets becomes significant for maximum daily temperatures of -5°C or lower, this shows that these

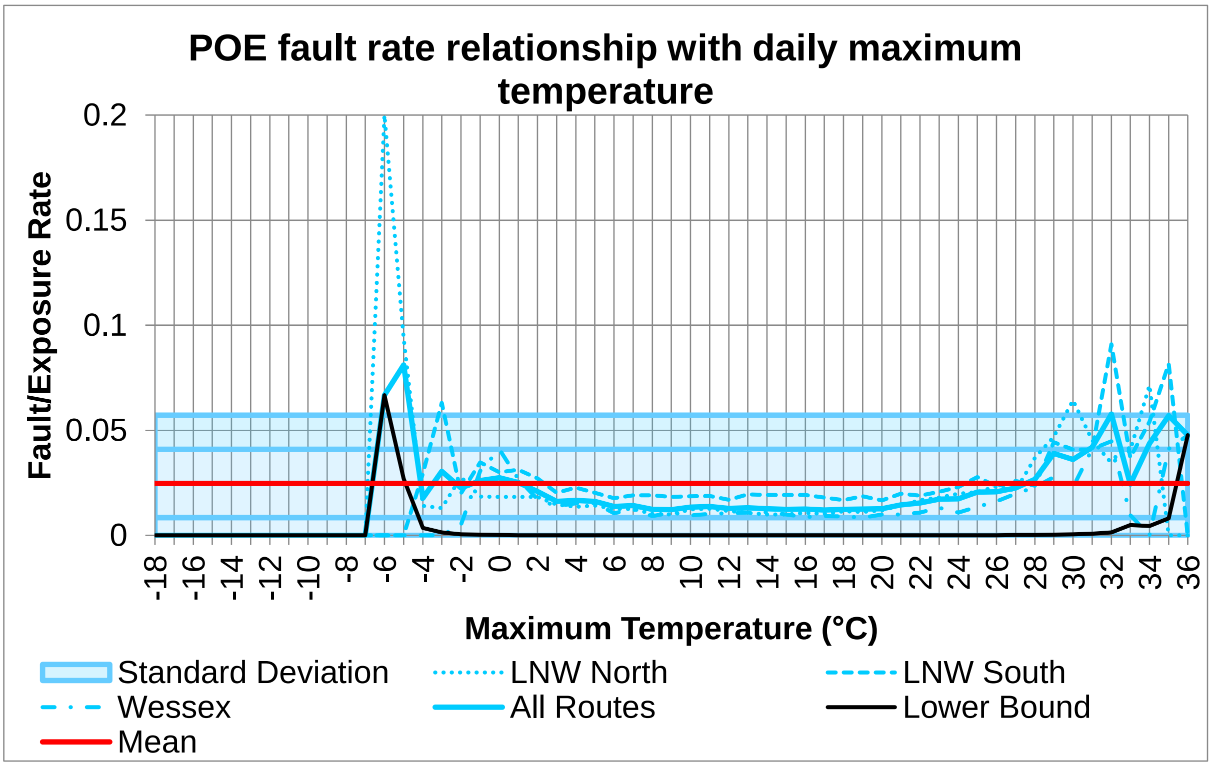

Figure 4.26: The relationship between the Daily Maximum Temperature and Fault Rate for POE Assets, illustrating the relationships between each of the routes.

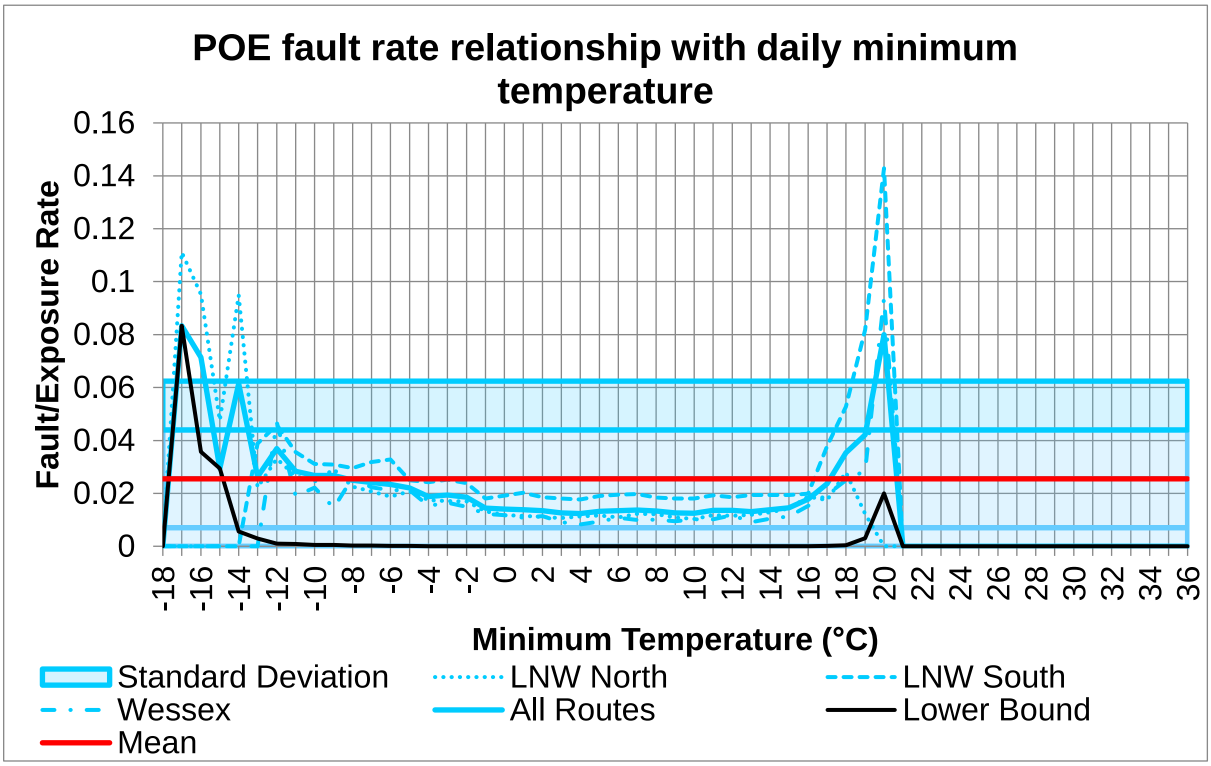

Figure 4.27: The relationship between the Daily Minimum Temperature and Fault Rate for POE Assets, illustrating the relationships between each of the routes.

assets are affected by lower temperatures not in the extreme range. However, this cannot form a significant threshold due to the low number of contributing fault events.

The fault rate relationship for POE with diurnal temperature ranges is shown in Figure 4.28, POE in the Wessex route are not significantly affected by diurnal range unlike LNW North and LNW South. Both of these routes have significant fault rates when the diurnal range is 16°C or greater. However, across the three routes the fault rate for POE becomes significant at a diurnal range of 17°C or greater. Investigating the fault event records for LNW South where the diurnal range was 17°C or greater, the maximum daily temperature was found to be 15°C or greater with increasing frequency as the maximum temperature increases as shown in Figure 4.29.

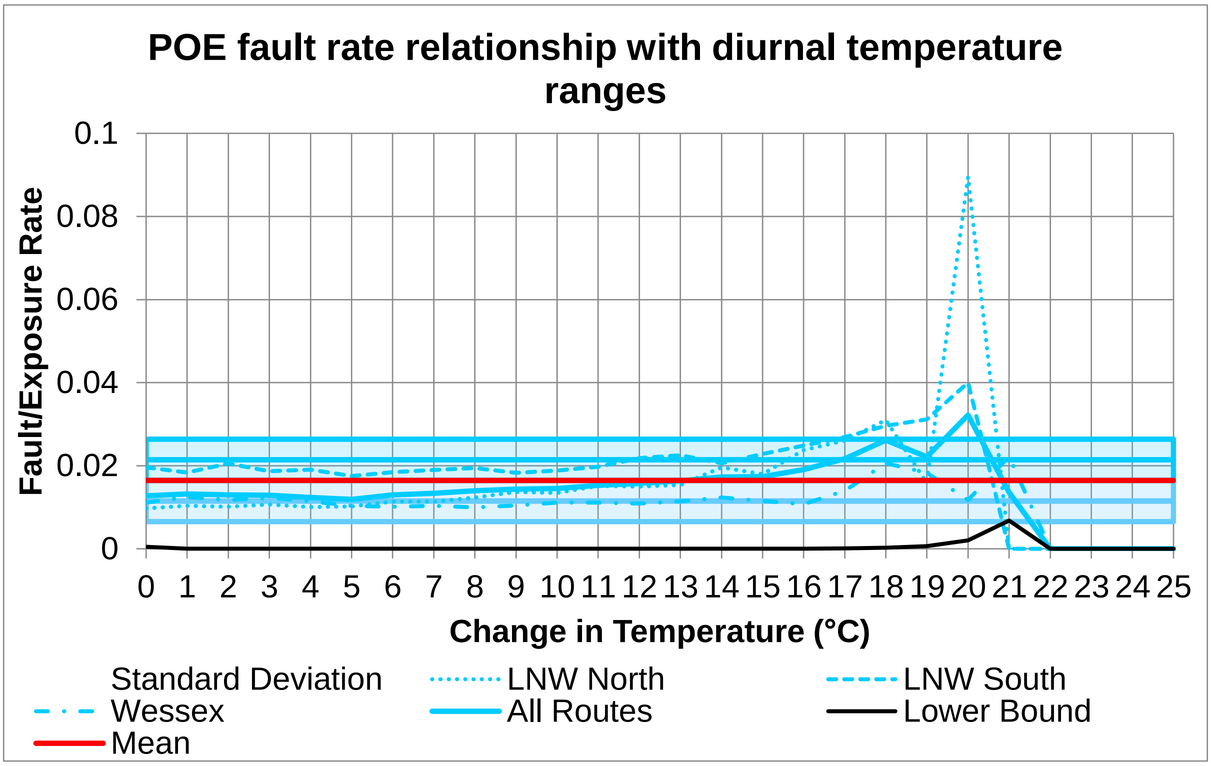

Figure 4.28: The relationship between the Diurnal Range and Fault Rate for POE Assets, illustrating the relationships between each of the routes.

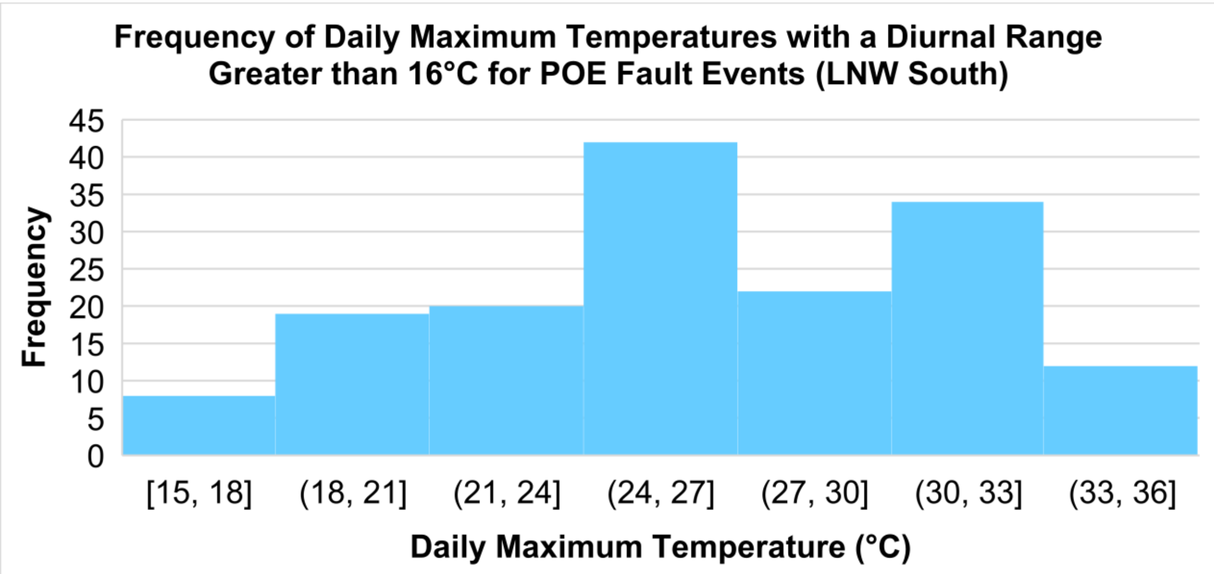

Figure 4.29: Frequency of Daily Maximum Temperatures where the Diurnal Range is greater than 16°C for POE Fault Events (LNW South).

4.4.2.2 Precipitation and POE

Overall the fault rate for POE in relationship to daily total precipitation is not significant until the 33mm point as shown in Figure 4.30 however there is no trend following this. There is no significant fault rate overall for POE assets with respect to the accumulation of precipitation according to Figure 4.31, however there are some peaks with a significant fault rate for LNW South. However, these peaks are not enough to determine a significant trend or relationship without further analysis of additional routes. The relationship graph for POE and the antecedent month's precipitation has been omitted as it does not show any additional relationships.

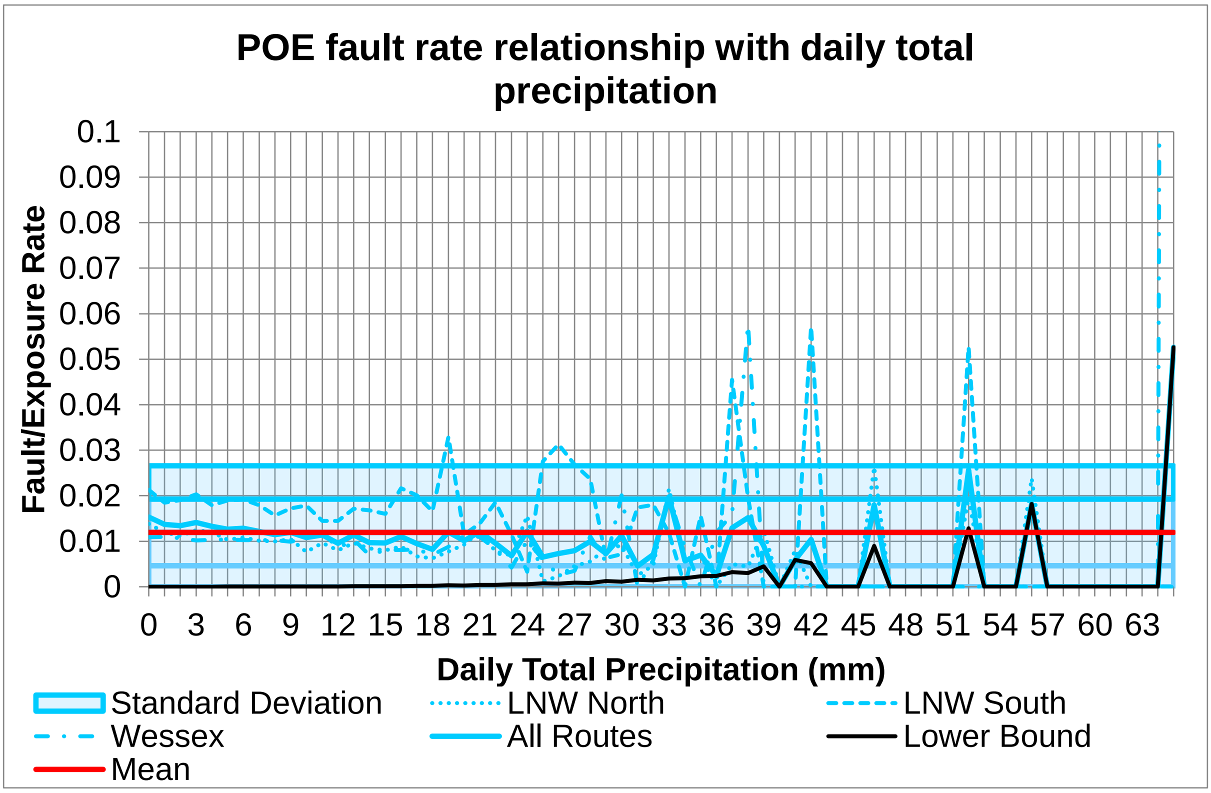

Figure 4.30: The relationship between daily precipitation totals and each route's fault rate for POE Assets.

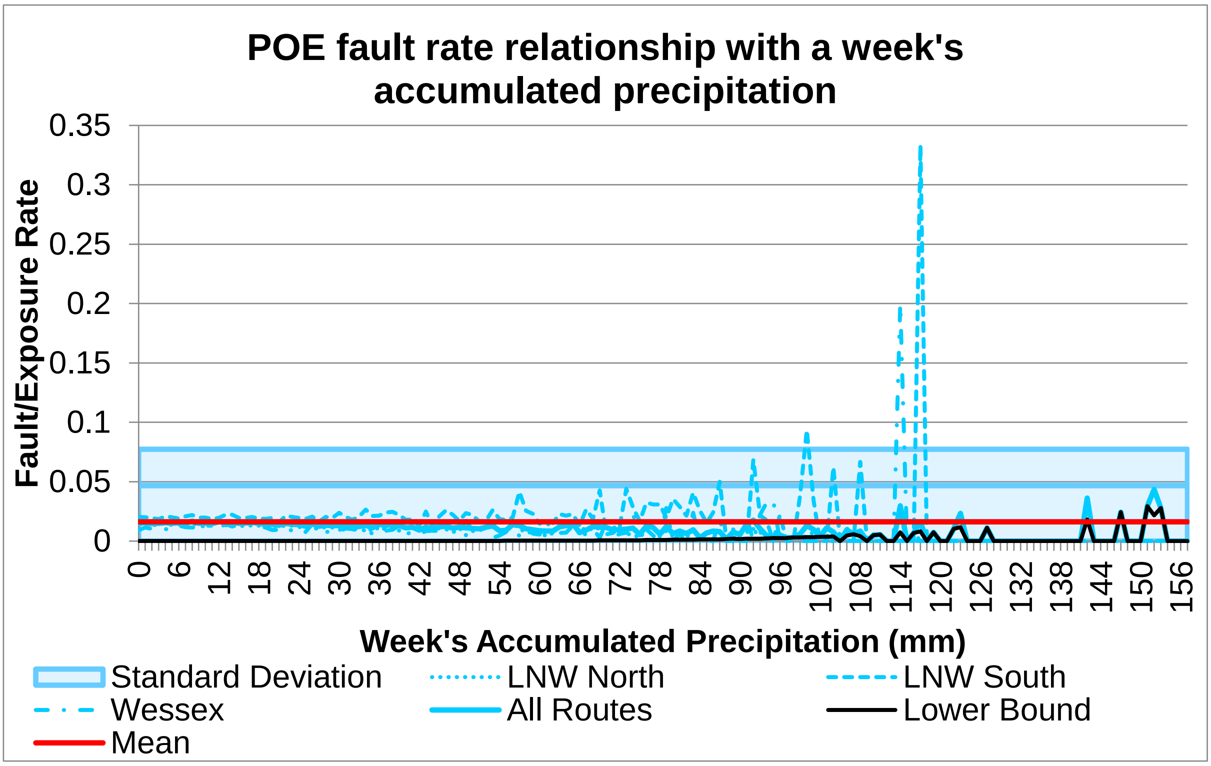

Figure 4.31: The relationship between the accumulation of precipitation for the Week prior to faults and each route's fault rate for POE Assets.

4.4.3 Track Circuits

Track circuits are used to detect when a train is present on a section of track. The device enables an electrical circuit to be completed when a train passes, connecting the two rails, this informs signallers of the position of trains on the mainline network (RSSB, 2018). Track circuit failures have already been linked to environmental conditions including local weather conditions and ballast contamination. Existing research has investigated the application of condition monitoring sensors for the purpose of effective fault detection (Chen et al., 2008). Further investigation has qualitatively identified the relationship between track circuit failures and temperature however no quantified relationships were identified as the linear regression method used was a simplification of the reality of incidents (Huang et al., 2017).

4.4.3.1 Temperature and Track Circuits

The relationship profiles for track circuits and temperature can be seen inTable 4.13, showing there is no consistency across the routes between the relationship profiles. These relationships are also shown in in Figure 4.32, Figure 4.33 and Figure 4.34.

There is no significant relationship between the temperature and the asset fault rate across the three routes. However, Track Circuit assets for LNW South experience a

Table 4.13: Relationship Profiles for Track Circuits for Key Temperature Variables across all three routes.

Track Circuits		Temperature			
Route	Fault Counts	Max	Min	Diurnal Range	Asset Category percentage faults
LNW North	8718	0	1	0	6.39%
LNW South	5776	1	0	1	5.46%
Wessex	5042	1	1	1	6.48%

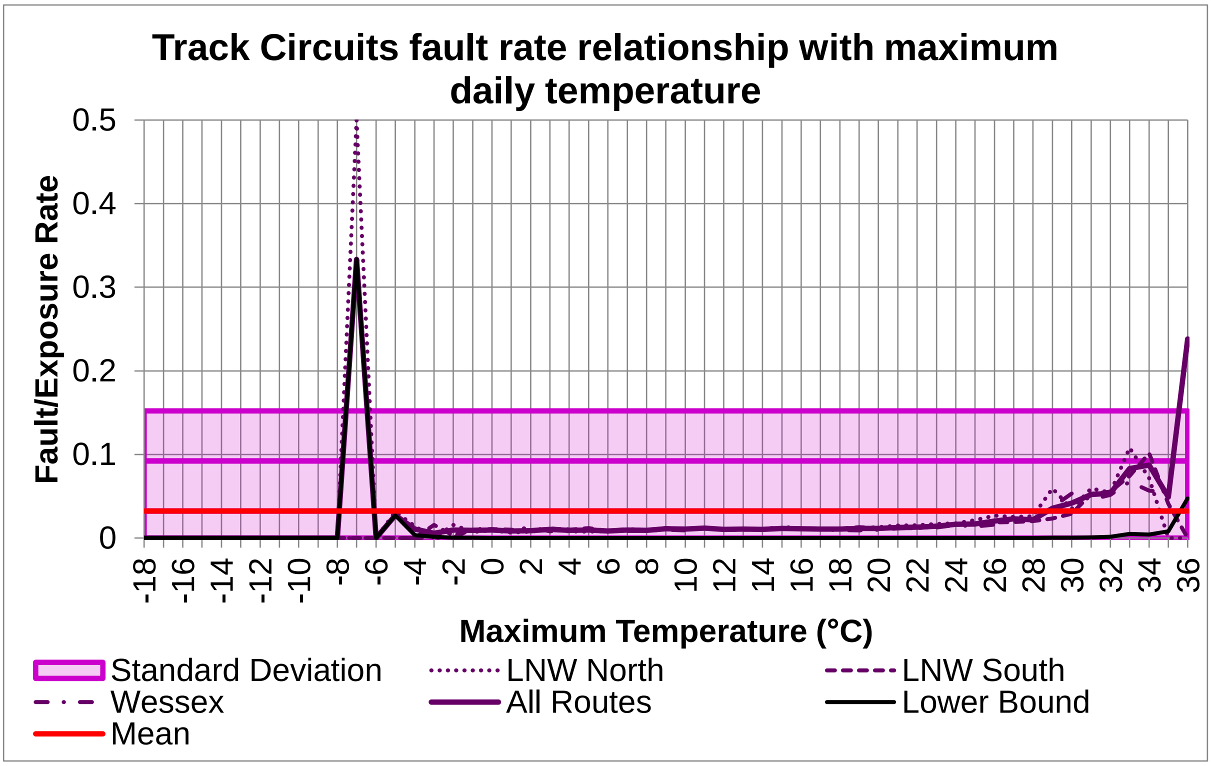

Figure 4.32: The relationship between the Daily Maximum Temperature and Fault Rate for Track Circuits, illustrating the relationships between each of the routes.

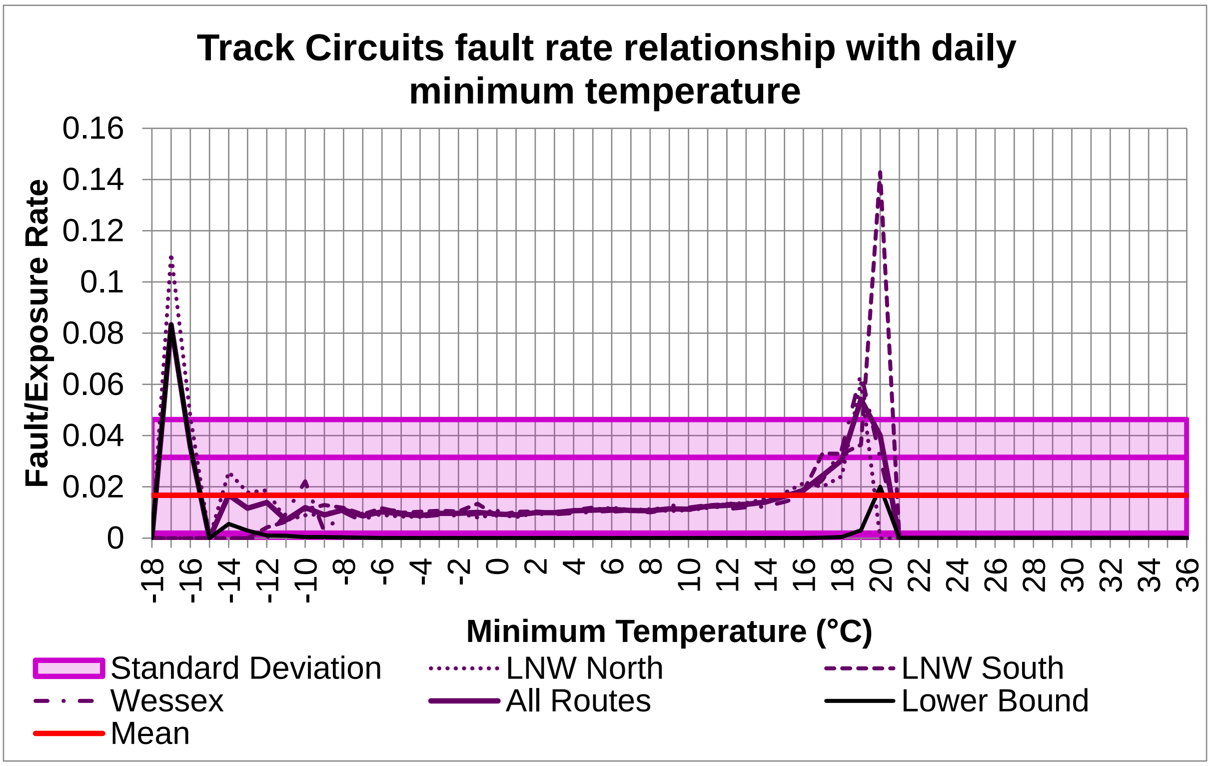

Figure 4.33: The relationship between the Daily Minimum Temperature and Fault Rate for Track Circuits, illustrating the relationships between each of the routes.

significant fault rate for temperatures greater than 30°C, as can be seen in Figure 4.32. There are 31 fault incidents that contribute to the significant peak at 31°C making this a significant threshold for the route. However, across the three routes the fault rate does not pass the threshold of significance.

There is no significant relationship found between track circuits and lower temperatures as shown in Figure 4.33. Track circuits are also affected by large diurnal ranges as can be seen in Figure 4.34, where there is no significant relationship until the diurnal range is 21. Although the fault rate across the three routes is significant, only Wessex experiences a significant fault rate for large diurnal ranges with 11 fault events contributing to this peak. It can be concluded that track circuit assets only have a significant relationship with large diurnal ranges, but without further investigation beyond the scope of this reason the precise reason remains unknown.

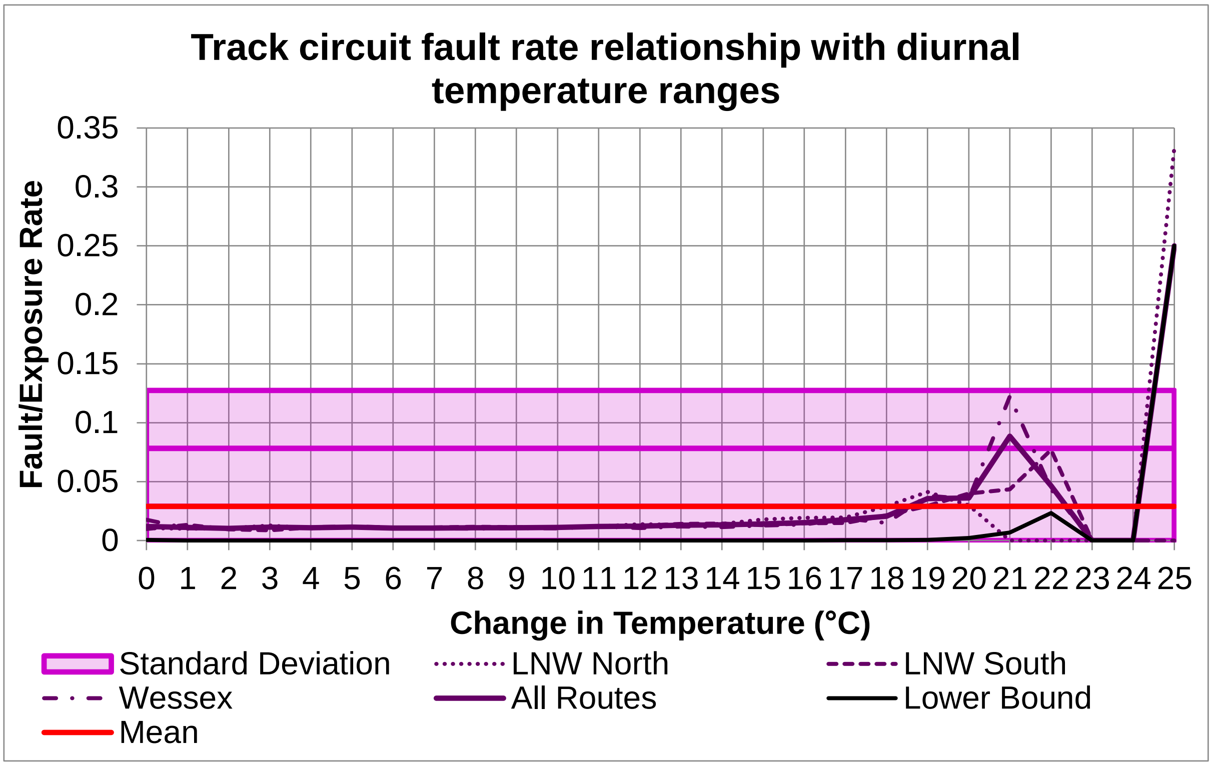

Figure 4.34: The relationship between the Diurnal Range of Temperature and Fault Rate for Track Circuits, illustrating the relationships between each of the routes.

4.4.3.2 Precipitation and Track Circuits

Across all three routes there is no significant relationship between daily precipitation and the fault rate of track circuit assets as shown in Figure 4.35. The track circuit assets in LNW South experienced significant and very significant fault rates intermittently above 37mm of daily total precipitation. However, these peaks only represent a small number of fault events (<5 fault events) therefore these peaks cannot be considered as indicators of the relationship between precipitation and track circuits with any certainty. These trends are also reflected regarding antecedent precipitation as shown in Figure 4.36, similarly there is an absence of a relationship with a month's accumulation therefore this figure has been omitted. Consequently, track circuits are not considered to be significantly impacted by precipitation variables.

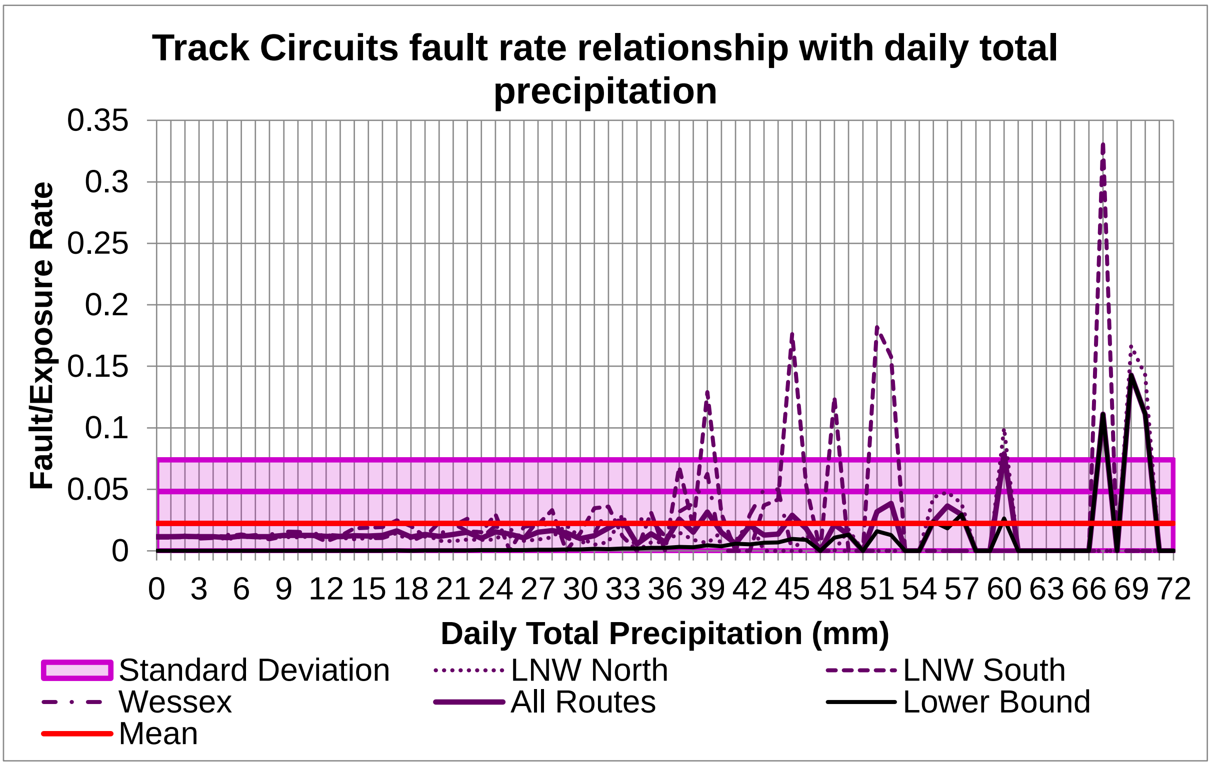

Figure 4.35: The relationship between daily precipitation totals and each route's fault rate for Track Circuit Assets.

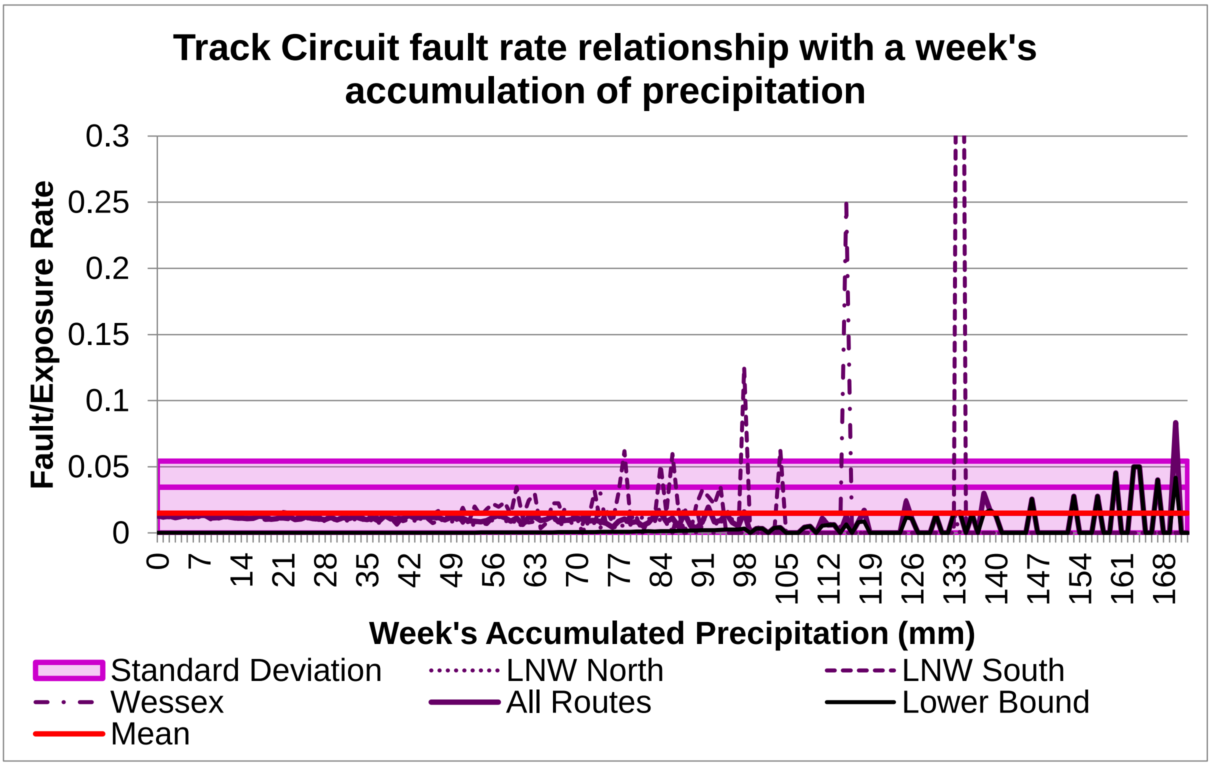

Figure 4.36: The relationship between the accumulation of precipitation for the Week prior to faults and each route's fault rate for Track Circuit Assets.

4.4.4 Level Crossing Equipment

Level Crossings (LCs) present a unique challenge in terms of managing both assets and safety. LCs form an interface between the railways, roads and pedestrian routes creating an environment of risk (Transport Committee, 2014b). This is a risk that has been recognised by the House of Commons Transport Committee, the ORR and NR. Despite GB's railways being some of the safest in Europe, the mainline network currently has around 6000 LCs in operation across GB (Network Rail, 2019d). In the 10 years preceding 2016, 93 deaths occurred at Level Crossings (ORR, 2016). As a result NR are committed to reduce the number of LCs on the mainline network and ensure that where possible no new LCs are introduced (Network Rail, 2019h).

Given that LCs are such a safety critical element of the railways, it is even more crucial that all of their associated assets do not fail as many of these are in place to prevent a risk to life. There is a vast array of assets present at LCs, all of which are included in this broad asset category, as indicated by the components listed against each fault event record. A selection of the Component 1's can be seen in Table 4.14, which reinforces the variety of equipment present at LCs and included in this asset category.

Table 4.14: A Selection of Component 1 attributed to Level Crossing Equipment Fault Events.

Audible Warning	CCTV Equipment	Hydraulic Unit
Barrier Boom	Crossing Lighting	Power Supply
Barrier Circuit Controller	Crossing Surface	Signage
Barrier Lifting Mechanism	Deflector Plate	Signalling Relay
Barrier Up Indicator	Equipment Protection	Surface Markings
Bell Alarm	Fencing	Traffic Lights
Cattle Grid	Gate Equipment	Transformer/ Rectifier
		Warnings/ Road Signs

4.4.4.1 Temperature and Level Crossing Equipment

The relationship profiles for Level Crossing Equipment (LCE) and temperature can be seen in Table 4.15, showing consistency in the relationship profiles within two of the routes but not across all the routes or temperature variables. LCE in the LNW North Route have significant fault rates for higher and lower temperatures, and higher and lower diurnal ranges, while Wessex LCE only have significant faults for higher temperatures and larger diurnal ranges. LNW South LCE however have a mixture of different profiles across the different temperature relationship profiles.

Table 4.15: Relationship Profiles for Asset Category Level Crossing Equipment for Key Temperature Variables across all three routes.

Level Crossing Equipment		Temperature			
Route	Fault Counts	Max	Min	Diurnal Range	Asset Category percentage faults
LNW North	5491	2	2	2	4.02%
LNW South	2303	1	-1	0	2.18%
Wessex	5971	1	1	1	7.68%

The relationships are shown in more detail in Figure 4.37, Figure 4.38 and Figure 4.39. Across the three routes the general trend suggests that fault rates increase with higher temperatures and diurnal ranges, with thresholds at daily maximum temperatures of 33°C and diurnal ranges of 21°C. The relationship between LCE fault rates and the diurnal range is fairly consistent for each route, however this also means that Wessex has a consistently very significant fault rate as shown in Figure 4.39. This is because the proportion of faults is much higher across the Wessex route than the others as confirmed in the final column in Table 4.15. The result has largely been dictated by the fault rate of one route, Wessex, therefore these conclusions cannot be drawn with certainty.

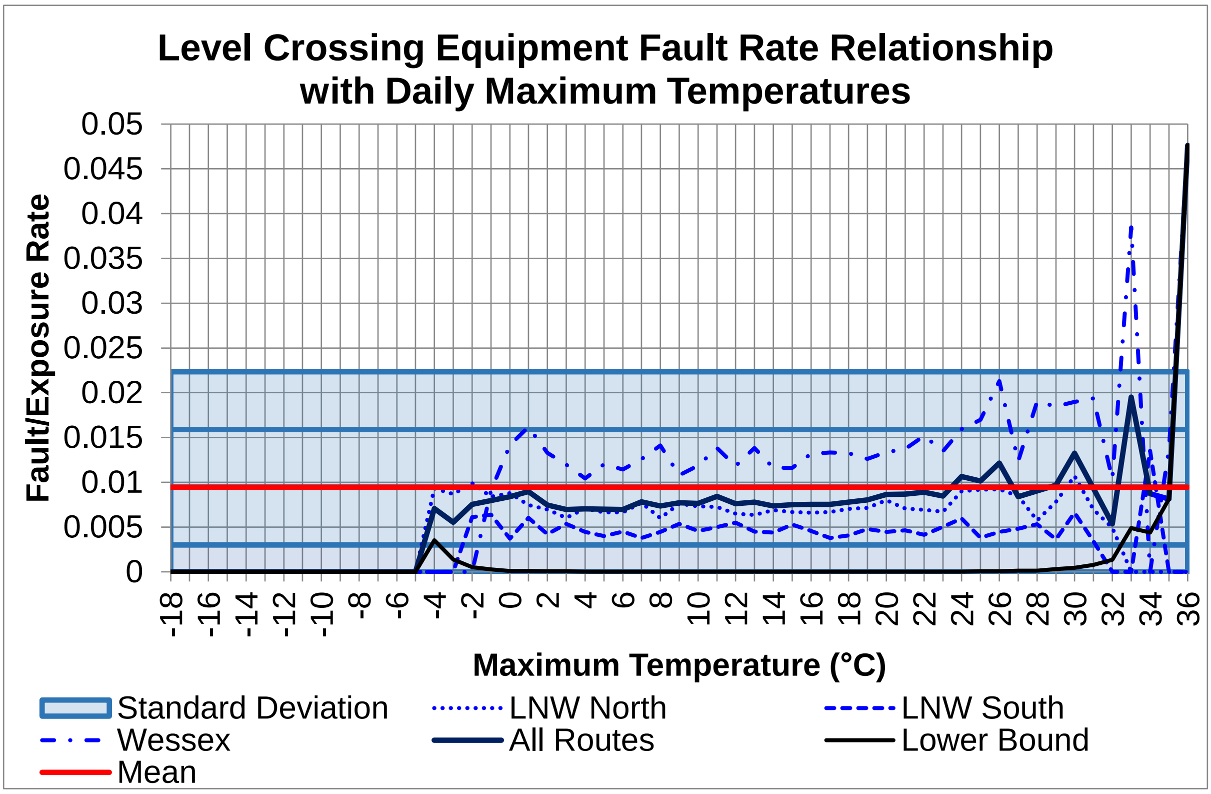

Figure 4.37: The relationship between the Daily Maximum Temperature and Fault Rate for LCE, illustrating the relationships between each of the routes.

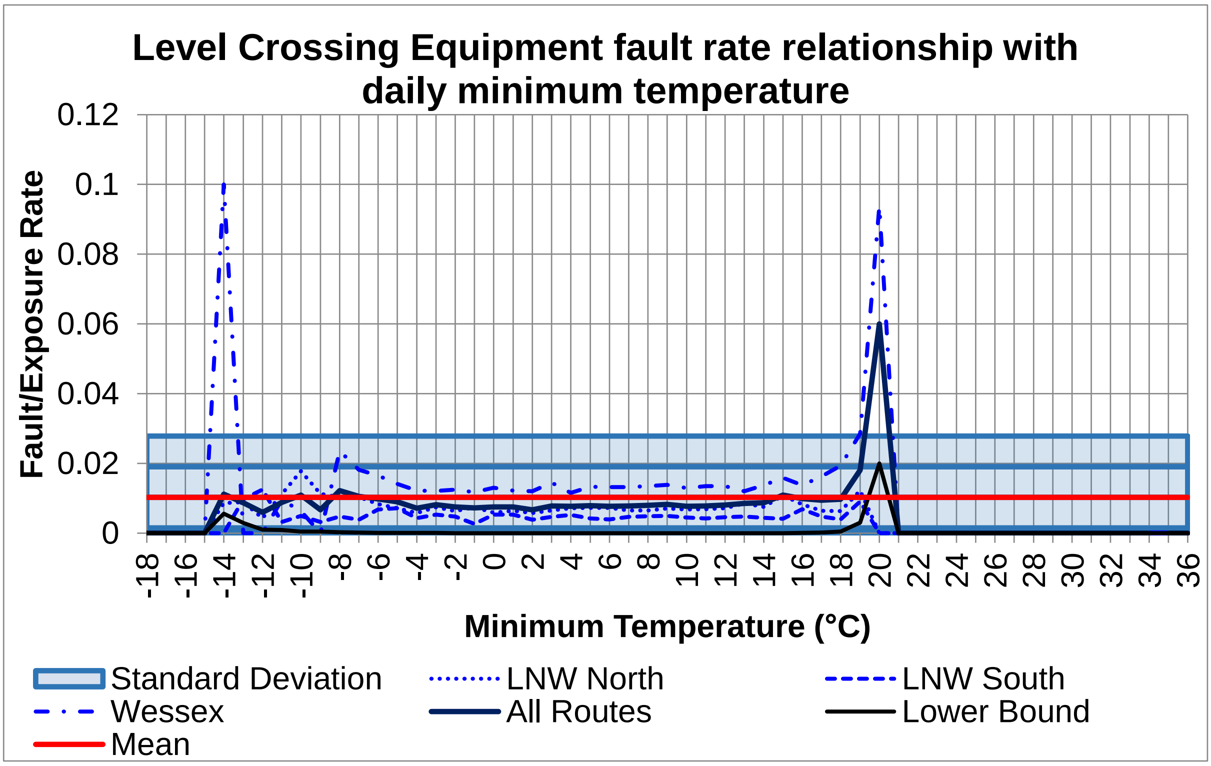

Figure 4.38: The relationship between the Daily Minimum Temperature and Fault Rate for LCE, illustrating the relationships between each of the routes.

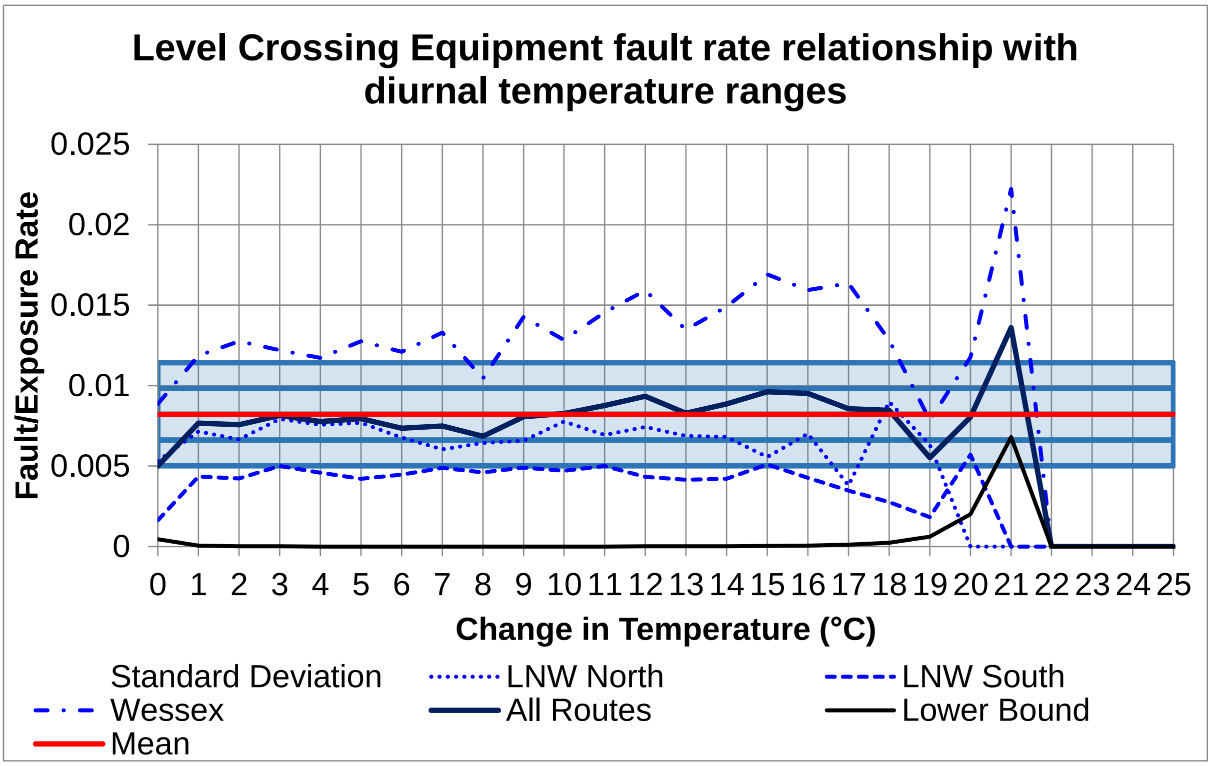

Figure 4.39: The relationship between the Diurnal Range of Temperature and Fault Rate for LCE, illustrating the relationships between each of the routes.

4.4.4.2 Precipitation and Level Crossing Equipment

Only LCE in Wessex have a relationship with precipitation or the accumulation of precipitation as shown in Figure 4.40 and Figure 4.41. Therefore, there is no overall relationship between precipitation and the fault rate for LCE. The large difference between Wessex and the other two routes could be for a number of reasons, the number of assets on each route, the fault recording strategy or the maintenance regimes. Alternatively, the relationship could be confirmed by conducting further analysis of additional routes across GB. However, from these results it is not possible to identify an operational threshold for LCE and precipitation across the three routes.

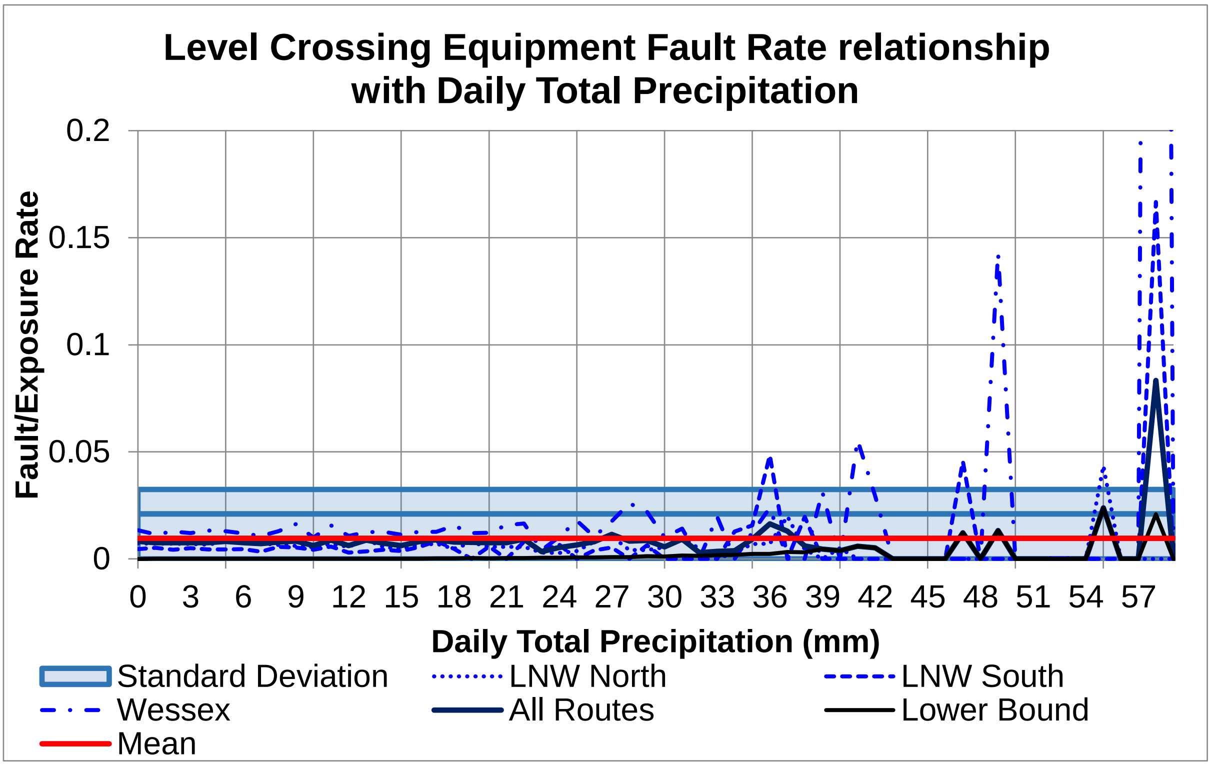

Figure 4.40: The relationship between daily precipitation totals and each route's fault rate for Level Crossing Equipment.

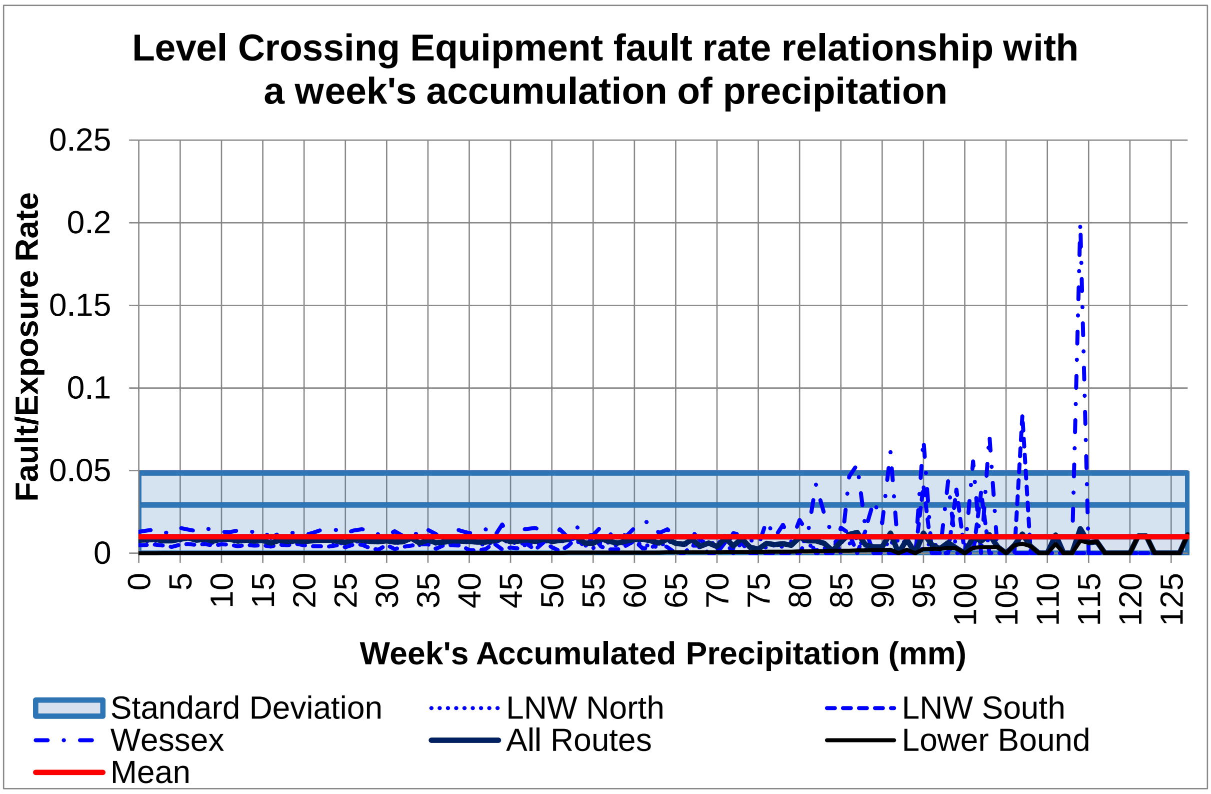

Figure 4.41: The relationship between the accumulation of precipitation for the Week prior to faults and each route's fault rate for Level Crossing Equipment.

4.4.5 Interlocking Panel/Frame

Interlocking systems ensure that trains are not able to pass into sections of track which are already occupied by another vehicle. This is critical to the safety of passengers and freight which are travelling on the rail network. Interlocking equipment ensures that the combinations of signals that are able to be in action at any given time do not have conflicts which would endanger the safe passage of trains through the network and were developed to remove the risk of human error. Historically, mechanical interlocking equipment would have been between the levers which controlled signals in the lineside signal boxes. As the railway has developed technologically the levers were replaced with buttons and switches on panels which indicated train locations with lights. At present these have mostly been replaced as signalling control operations are managed at regional command centres which digitally represent the locations of trains and distribute control actions to signalling equipment. Therefore, most mechanical interlocking equipment has been replaced with logic and decision algorithms as part of a digital control system. However, as with many aspects of the railways in GB there is still legacy infrastructure in operation as has been captured in this asset group which relates to faults with lever frames and older control panels.

4.4.5.1 Temperature and Interlocking Panel/Frame

The relationship profiles for Interlocking Panel/Frame assets and temperature can be seen in Table 4.16 where there is no consistency across variables or routes. Further investigation highlighted that there is no relationship between the fault rate of Interlocking Panel/Frames and diurnal temperature ranges.

Table 4.16: Relationship Profiles for Asset Category Interlocking Panel/Frame for Key Temperature Variables across all three routes.

Interlocking Panel/Frame		Temperature			
Route	Fault Counts	Max	Min	Diurnal Range	Asset Category percentage faults
LNW North	6967	1	2	0	5.10%
LNW South	3810	1	0	1	3.60%
Wessex	2260	0	1	-1	2.91%

Figure 4.42 indicates that Interlocking Panel/Frame assets could be sensitive to higher temperatures as the fault rate becomes significant from 31°C for LNW North and 33°C for LNW South. However, the fault rate for all of the routes does not pass the significance threshold until the extreme end of the temperature range and so no specific conclusion could be drawn for assets in any of the regions. There are few fault events caused by lower temperatures and these are only significant at particularly low

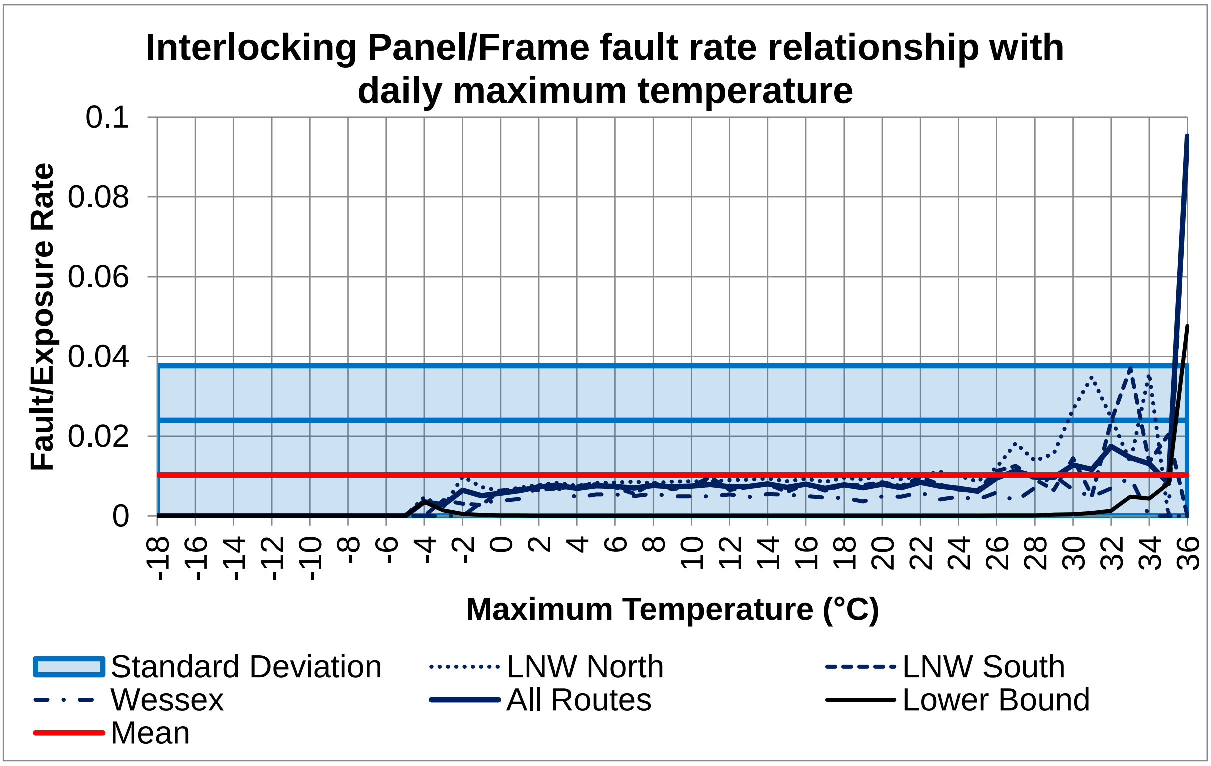

Figure 4.42: The relationship between the Daily Maximum Temperature and Fault Rate for Interlocking Panels, illustrating the relationships between each of the routes.

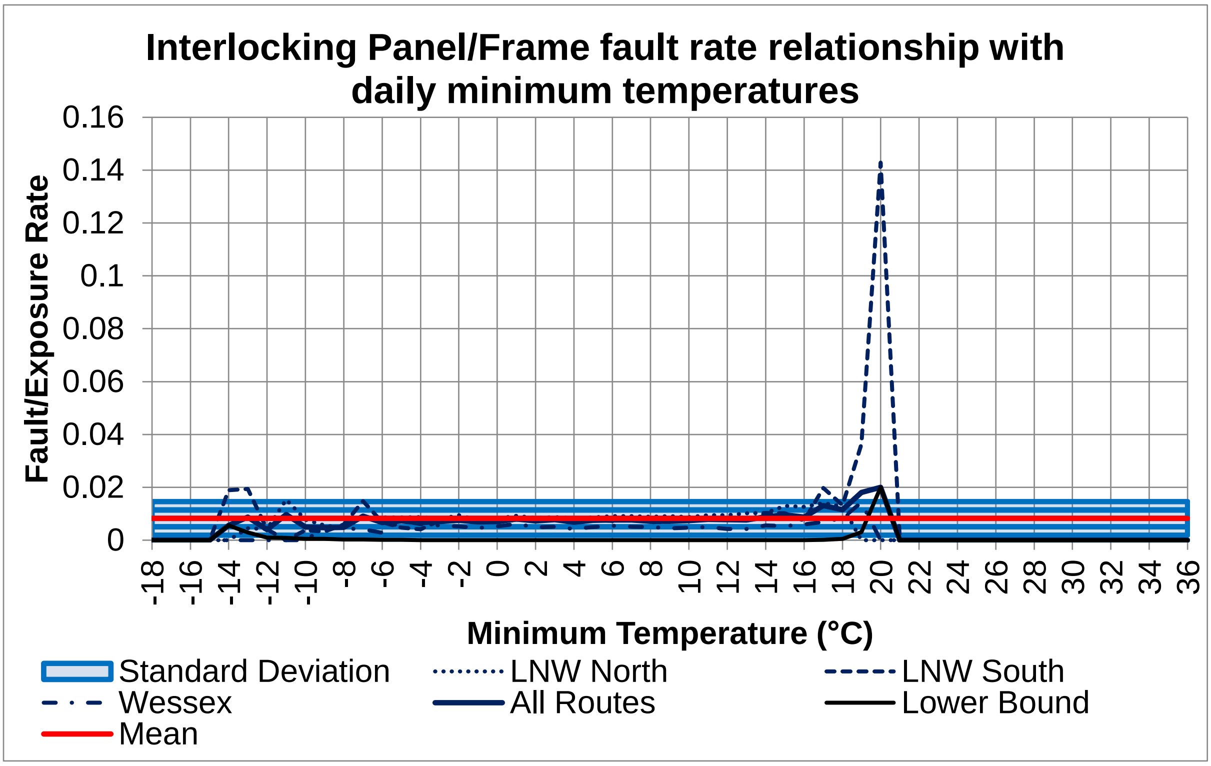

Figure 4.43: The relationship between the Daily Minimum Temperature and Fault Rate for Interlocking Panels, illustrating the relationships between each of the routes.

temperatures as shown in Figure 4.43, but there is no specific trend across the three routes. Consequently, it cannot be concluded whether there is a relationship between temperature and Interlocking Panel/Frame assets, although it is suspected that these assets are affected by higher temperatures, but further analysis would be needed to confirm this more precisely.

4.4.5.2 Precipitation and Interlocking Panel/Frame

There is no significant relationship for Interlocking Panel/Frame assets in Wessex and daily total precipitation as shown in Figure 4.44. However, LNW South experiences significant relationships with 22mm and 25mm of precipitation, whereas LNW North does not have any significant relationship with precipitation until the daily total is 36mm. However, across the three routes there is no consistent relationship.

Wessex also has no significant relationship with the week's accumulated precipitation as can be seen in Figure 4.45. LNW North has significant relationships for this asset category intermittently from 42mm of a week's accumulated precipitation total. Contrastingly, LNW South experiences more consistently significant fault rates between 52mm and 60mm and very significant fault rates beyond this. These relationships across the routes are reflected again in Figure 4.46 for precipitation accumulated over a month. This is with one exception, LNW South experiences a significant fault rate at 1mm accumulated precipitation, there are 19 individual fault events. However, no consistency in the cause of these faults could be found from investigation of the fault event records.

Overall there appears to be no consistent relationship between precipitation (over the course of a day, week or month) and the fault rate of Interlocking Panel/Frame assets. There does appear to be a relationship in one of the routes, but the cause for this may not be related solely to weather.

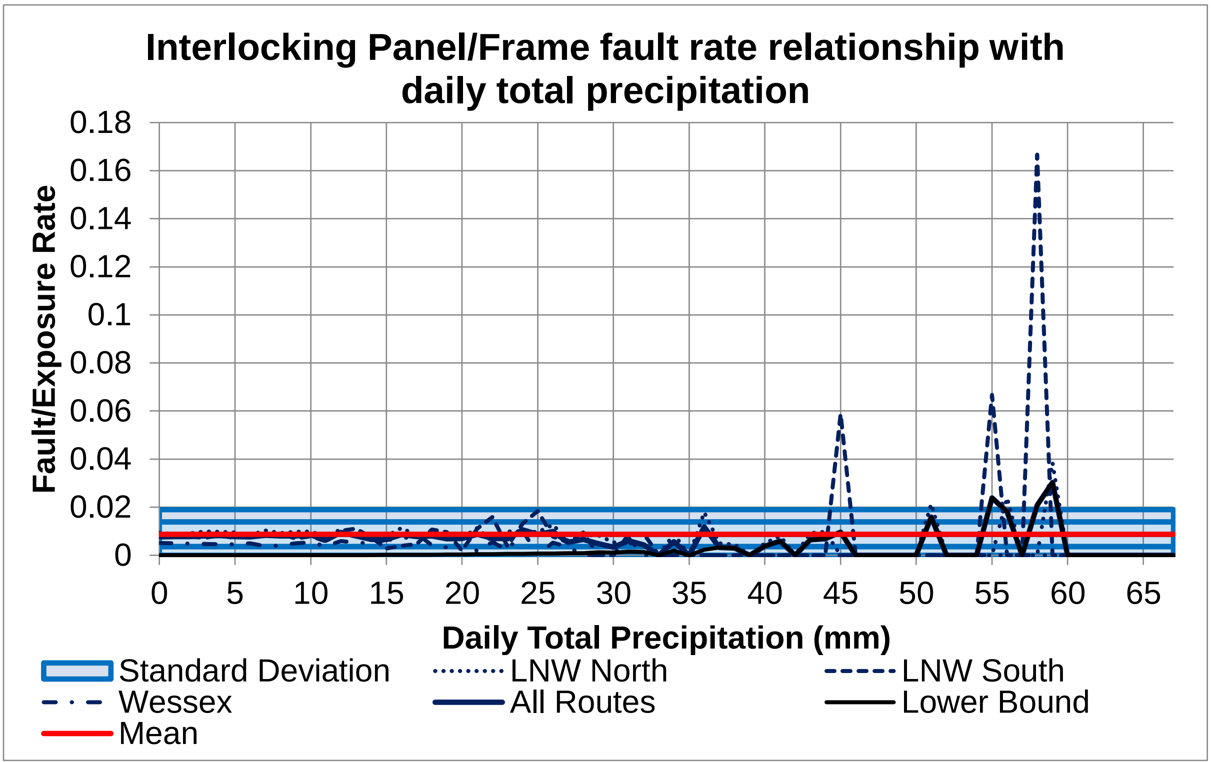

Figure 4.44: The relationship between daily precipitation totals and each route's fault rate for Interlocking Panel/Frame Assets.

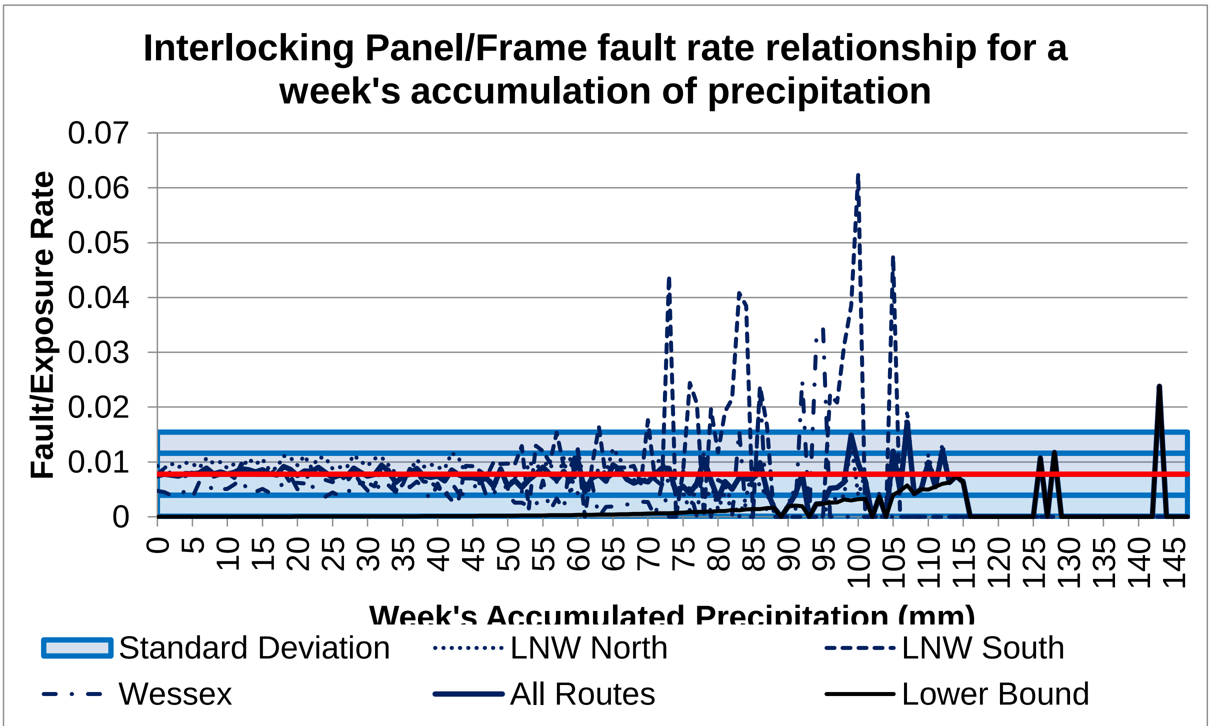

Figure 4.45: The relationship between the accumulation of precipitation for the Week prior to faults and each route's fault rate for Interlocking Panel/Frame assets.

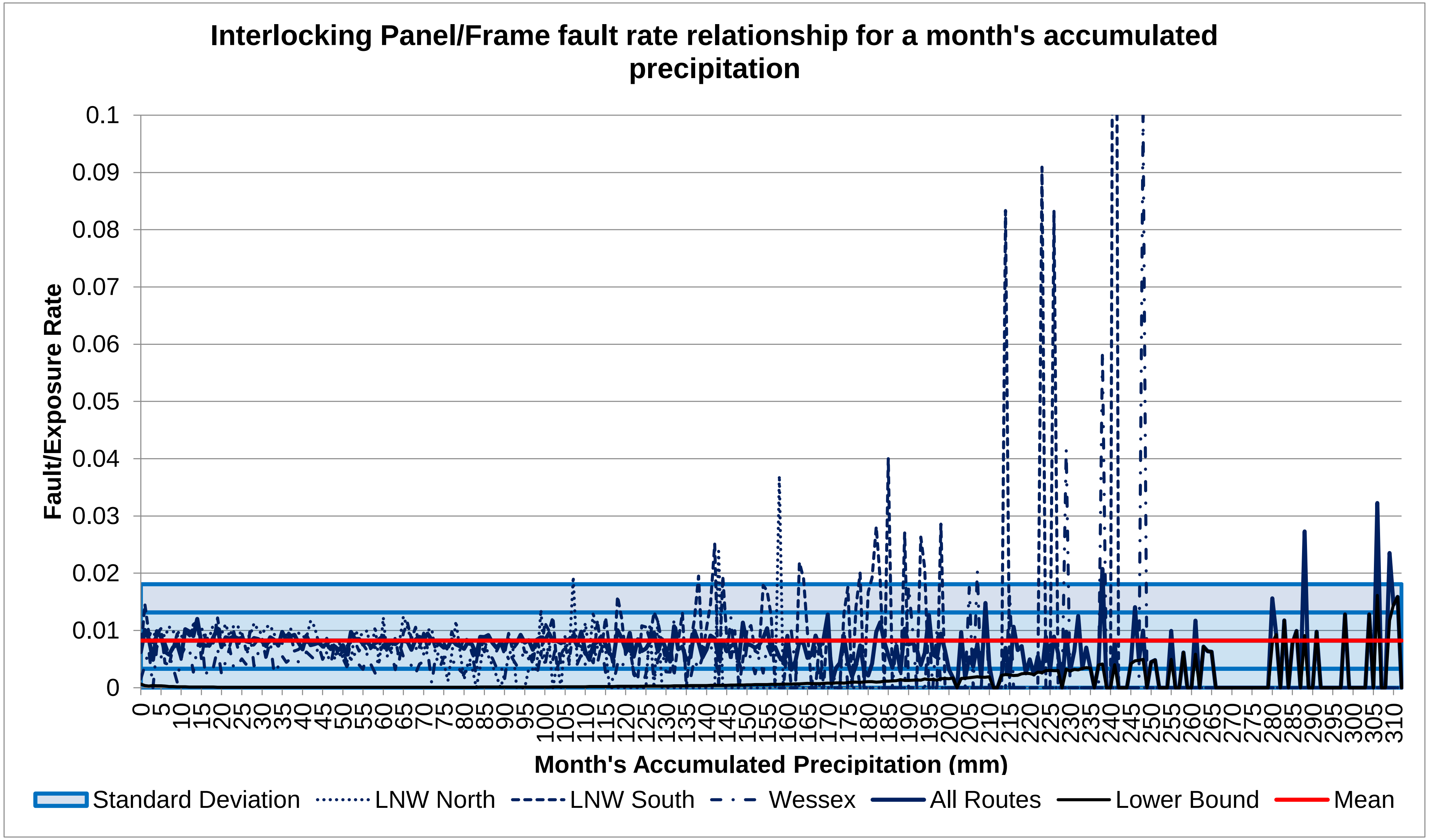

Figure 4.46: The relationship between the accumulation of precipitation for the Month prior to faults and each route's fault rate for Interlocking Panel/Frame assets.

4.4.6 Train Protection and Warning System

The Train Protection and Warning System (TPWS) prevents trains from passing signals at danger or going over the speed limit by automatically applying a train's brakes top reduce their speed when they pass this lineside equipment (RSSB, 2018). TPWS assets are a safety critical asset within the railway network which prevent signals being passed at danger (SPADs) and prevent speeding trains from derailing.

4.4.6.1 Temperature and TPWS

The relationship profiles for TPWS and temperature can be seen in Table 4.17, however there is no consistency across the three routes. Figure 4.47 and Figure 4.48 show there is no relationship with lower temperatures and higher temperatures are the main cause of TPWS faults. Assets in the Wessex route experience a significant fault rate beyond 27°C and those in LNW South experience significant fault rates beyond 32°C, however LNW North has no significant relationship. It is difficult to determine relationships between diurnal range and the fault rate for TPWS from Figure 4.49, suggesting that diurnal temperature ranges are not related to the failure mechanism and this asset fails with higher absolute temperatures. Although there are differences between each of the routes and the relationship of TPWS assets with temperature, these relationships are not based on an adequate sample of fault events and so no conclusion can be confidently drawn.

Table 4.17: Relationship Profiles for TPWS for Key Temperature Variables across all three routes.

Interlocking Panel/Frame		Temperature			
Route	Fault Counts	Max	Min	Diurnal Range	Asset Category percentage faults
LNW North	1709	0	1	1	1.25%
LNW South	2088	1	2	2	1.97%
Wessex	2362	1	1	-1	3.04%

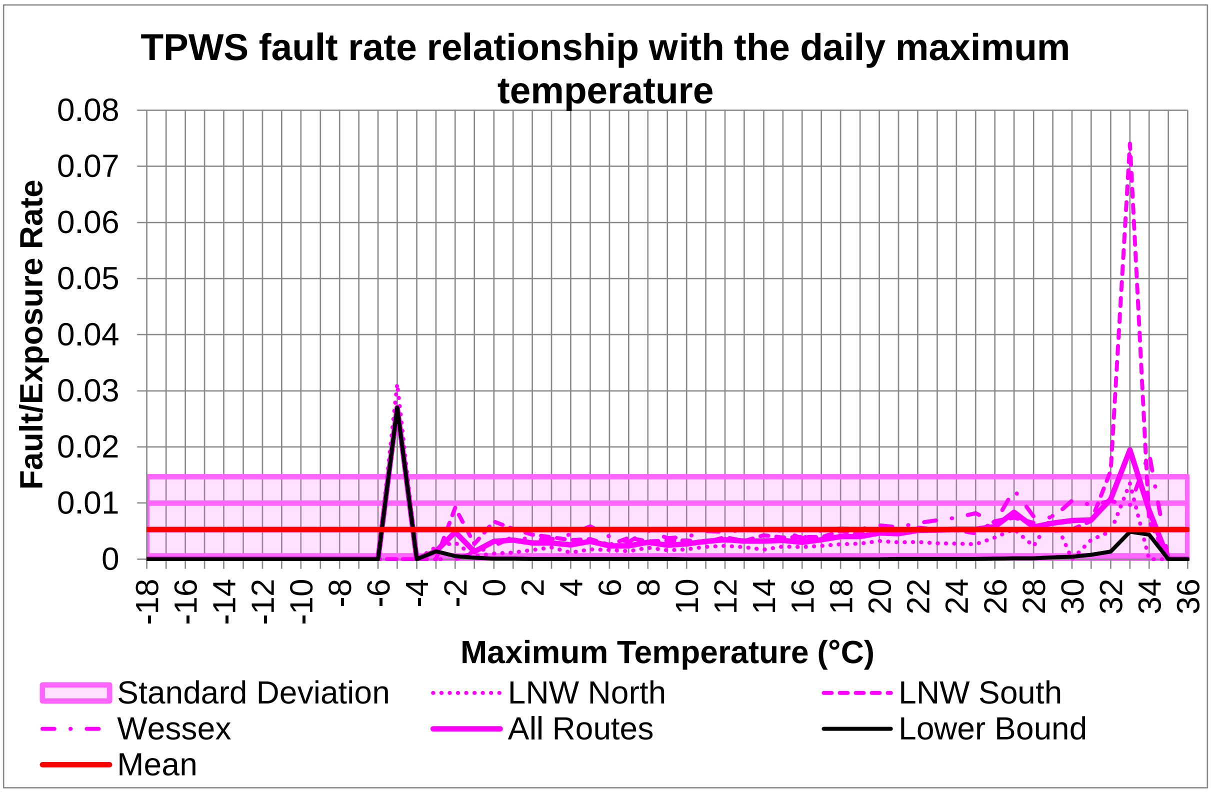

Figure 4.47: The relationship between the Daily Maximum Temperature and Fault Rate for TPWS Assets, illustrating the relationships between each of the routes and their significance relative to all three routes.

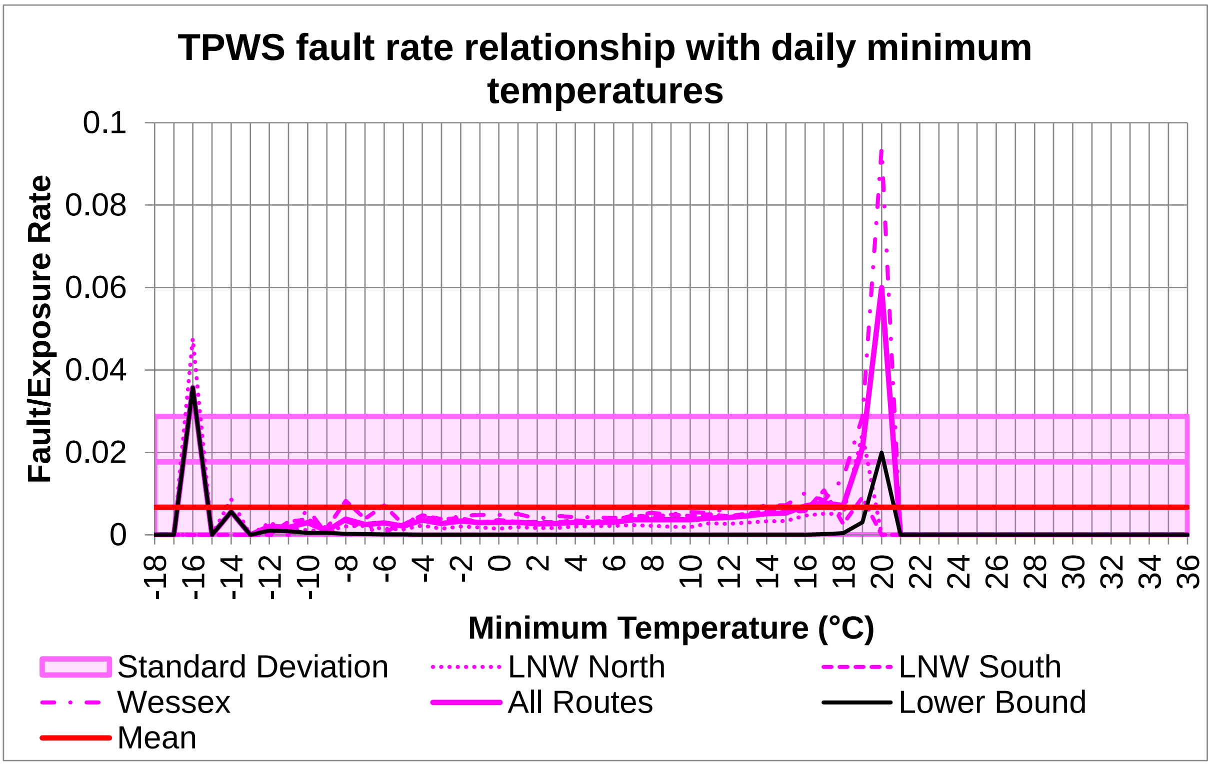

Figure 4.48: The relationship between the Daily Minimum Temperature and Fault Rate for TPWS Assets, illustrating the relationships between the routes.

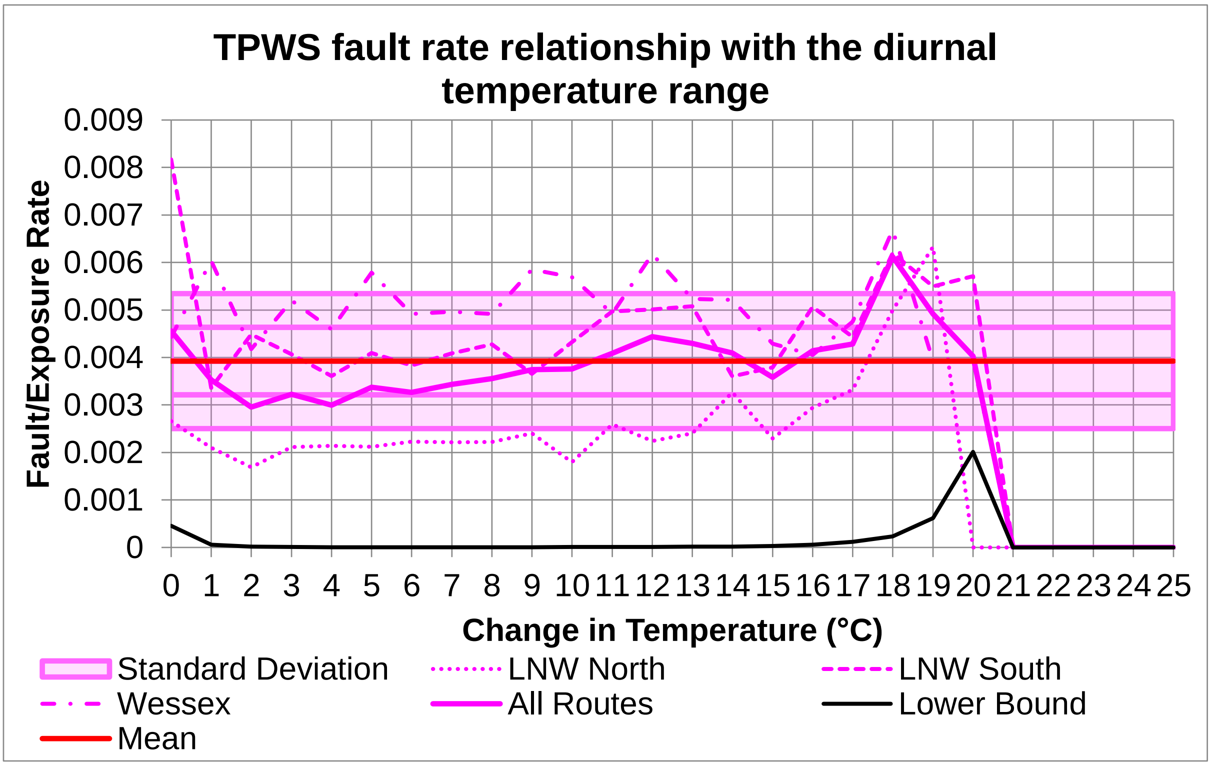

Figure 4.49: The relationship between the Diurnal Range of Temperature and Fault Rate for TPWS assets, illustrating the relationships between the routes.

4.4.6.2 Precipitation and TPWS

The relationships for daily total precipitation across the routes for TPWS are only significant at 36mm of total daily precipitation with 5 fault events. Therefore, it can be concluded that total daily precipitation is not a cause of TPWS faults. There are further relationships between TPWS assets and a week's accumulated precipitation as shown in Figure 4.50, however these vary greatly across the three routes. LNW North does not experience any significant fault rate unlike LNW South and Wessex which both experience significant and very significant fault rates across the whole range shown. A similar situation is shown in Figure 4.51 for the fault rate relationship with TPWS for a month's accumulation of precipitation. It can be seen that lower accumulation of precipitation for TPWS assets in the Wessex route for both a week and a month precipitation accumulation increases the fault rate. Conversely, TPWS assets in LNW South experience a greater fault rate with higher amounts of accumulated precipitation. However, the overall fault rate across the three routes is not significant, and the relationships for some of the individual routes suggests further analysis of all routes is needed to understand these relationships and their importance.

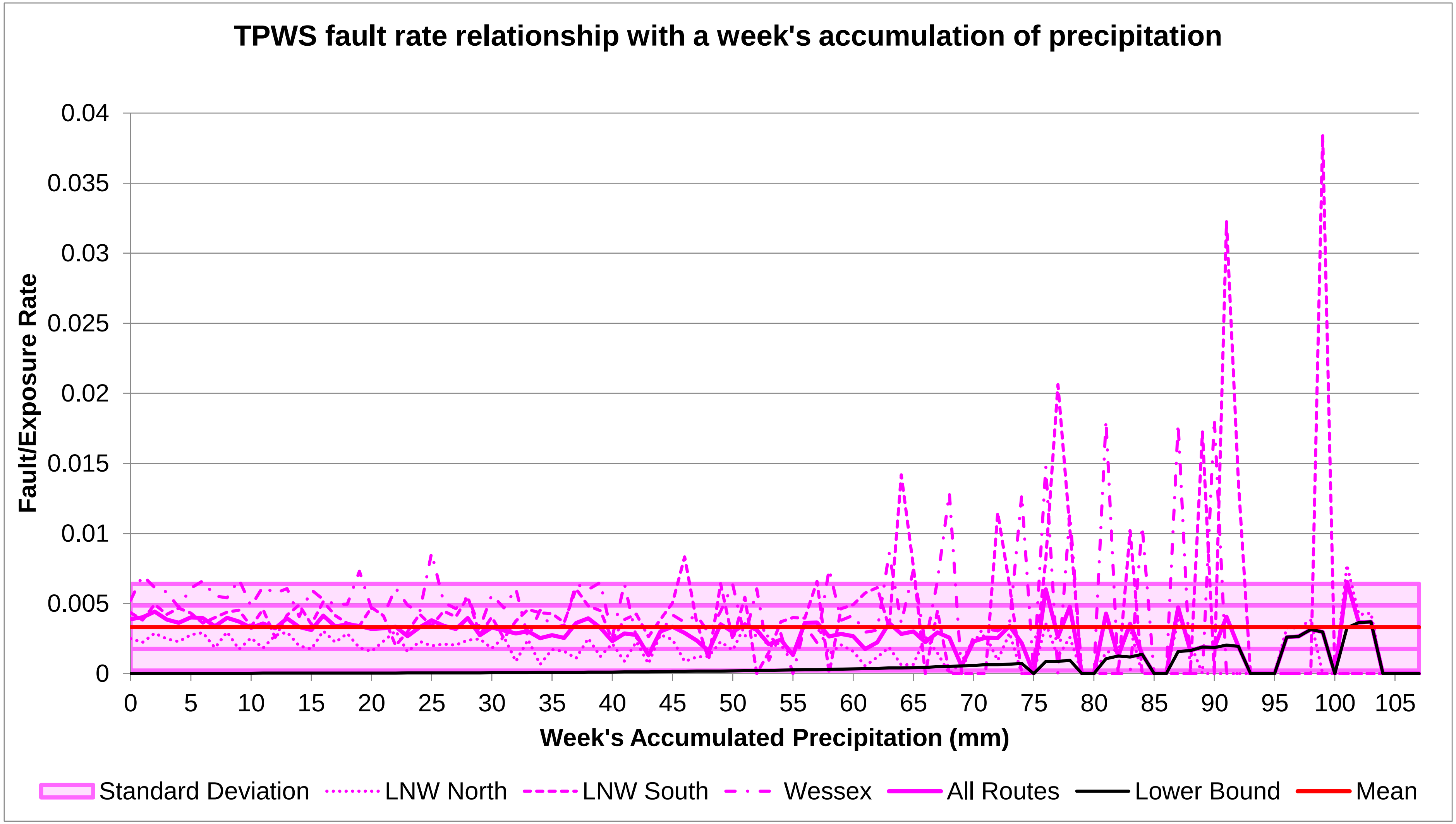

Figure 4.50: The relationship between the accumulation of precipitation for the Week prior to faults and each route's fault rate for TPWS assets.

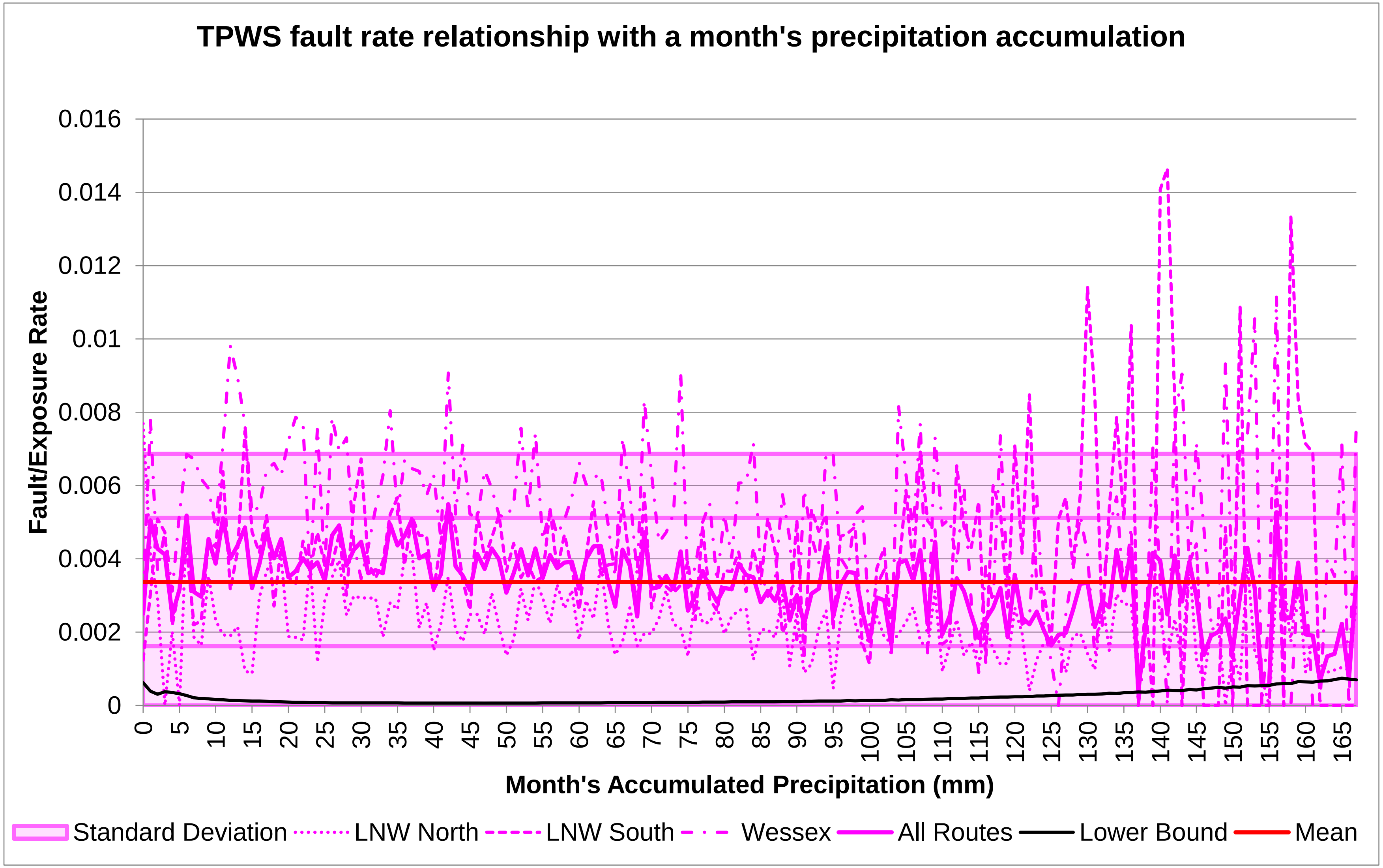

Figure 4.51: The relationship between the accumulation of precipitation for the Month prior to faults and each route's fault rate for TPWS assets.

4.5 Other Significant Asset Categories

Of the eleven significant asset categories the majority fall into either the Track or Signalling parent asset group, however there are two categories that do not fit into these and are therefore presented here separately. Table 4.18 shows the list of the significant asset categories again. It can be seen that the asset category with the FMS Suffix “No Equipment” ranks in fourth position for the average percentage of fault events that are attributed to this category across the three routes. The other asset category discussed in this section is Circuit Breakers at the bottom of the table which is the last asset category to have over 1% of the fault event counts across all three routes and still has an average fault percentage of over 2% the threshold established at the start of this chapter. The results for each of these asset categories are presented in the following sections.

Table 4.18: Asset categories with average percentage of faults across all three Routes over 2%.

	Short & Number	FMS Suffix Label	Asset Category percentage of total route faults			Average % of Faults
			LNW North	LNW South	Wessex	
1	Track Track 3	Track (P.W)	16.44%	10.94%	19.23%	15.54%
2	Sig Sig 4	Signal	12.81%	12.00%	11.24%	12.02%
3	Sig POE 2	Point Operating Equipment	6.87%	9.18%	6.37%	7.47%
4	UU 39	No Equipment	8.69%	7.75%	4.94%	7.28%
5	Sig TC 2	Track Circuit	6.39%	5.46%	6.48%	6.11%
6	Sig LC 1	Level Crossing Equipment	4.02%	2.18%	7.68%	4.63%
7	Track S&C 1	Points (P.W.)	4.45%	5.56%	3.28%	4.43%
8	Sig I 3	Panel/Frame	5.10%	3.60%	2.91%	3.87%
9	Track U 2	Boundary Measure	3.11%	1.94%	2.06%	2.37%
10	Sig TPWS 1	Train Warning System	1.25%	1.97%	3.04%	2.09%
11	E&P TP 1	Circuit Breakers	1.79%	3.00%	1.42%	2.07%

4.5.1 No Equipment

Of the seven parent asset groups that are presented in the fault event data used in this research, the parent asset group with the most FMS Suffixes and least asset subgroups is the parent asset group named “Unknown”. This parent asset group has only one asset subgroup also called “Unknown” while having a wide array of FMS suffixes with a total of 123, as shown in Table 4.19. This parent asset category therefore has 123 asset categories, of these there is a total of six asset categories that have greater than a 1% share of fault events on at least one of the three routes and the five years investigated. The significant unknown asset categories can be seen in Table 4.20 and even amongst this selection, the variety of equipment is evident. Only one of these asset categories ranks as one of the eleven most significant asset categories: Unknown: No Equipment. This asset category will be referred to by its FMS suffix label from this point forward, “No Equipment”.

Table 4.19: Asset Category breakdown listing the asset parent groups and the number of asset subgroups and FMS suffixes.

Parent Asset Group	***Number of Asset Sub-groups***	***Number of FMS Suffixes/ Asset Categories***
Building	2	6
E&P	4	28
S/E&P/T	2	3
Signalling	15	30
Telecoms	11	28
Track	4	8
Unknown	1	123
Total Counts	39	226

Table 4.20: Unknown categories with greater than 1% of at least one routes fault events. The significant (as shown in Table 4.18) Unknown asset categories are highlighted.

Parent Asset Group	Asset Sub-Group	FMS Suffix Labels	Short & Number	Full Asset Category Name
Unknown	Unknown	Bridge	UU 8	UU: Bridge
		Concentrator Voice	UU 16	UU: Concentrator Voice
		No Equipment	**UU 39**	**UU: No Equipment**
		Radio – Cab Secure	UU 59	UU: Radio – Cab Secure
		Telephone - Other	UU 83	UU: Telephone - Other
		Telephone - SPT	UU 84	UU: Telephone - SPT

4.5.1.1 Temperature and No Equipment

The relationship profiles for No Equipment assets and temperature can be seen in Table 4.21. Across the three routes it is indicated that higher temperatures and a greater diurnal range (except for Wessex) are experienced when there is a greater fault rate. Figure 4.52 and Figure 4.53 indicate that there is a greater fault rate with increasing temperatures across all routes as well as for greater diurnal ranges, as shown in Figure 4.54.

Table 4.21: Relationship Profiles for No Equipment for Key Temperature Variables across all three routes.

No Equipment		Temperature			
Route	**Fault Counts**	**Max**	**Min**	**Diurnal Range**	**Asset Category percentage faults**
LNW North	11863	1	1	1	8.69%
LNW South	8207	1	1	1	7.75%
Wessex	3843	1	1	-1	4.94%

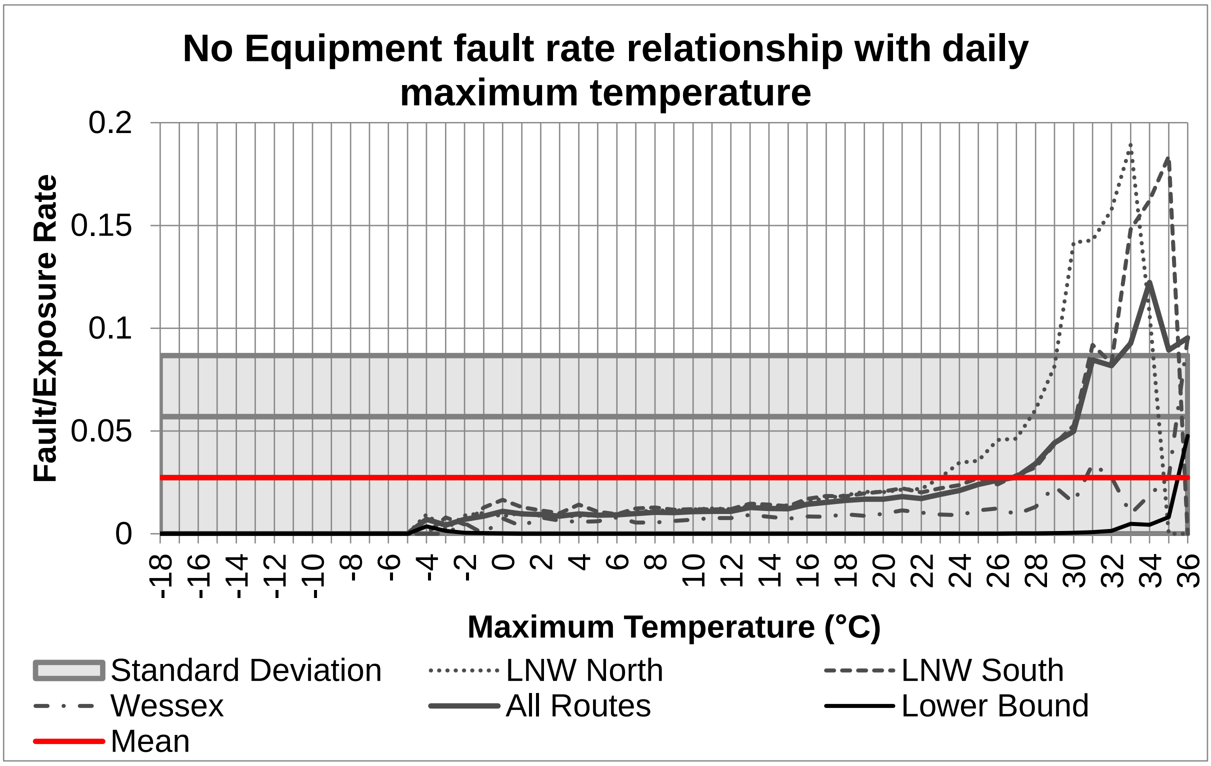

Figure 4.52: The relationship between the Daily Maximum Temperature and Fault Rate for No Equipment, illustrating the relationships between the routes.

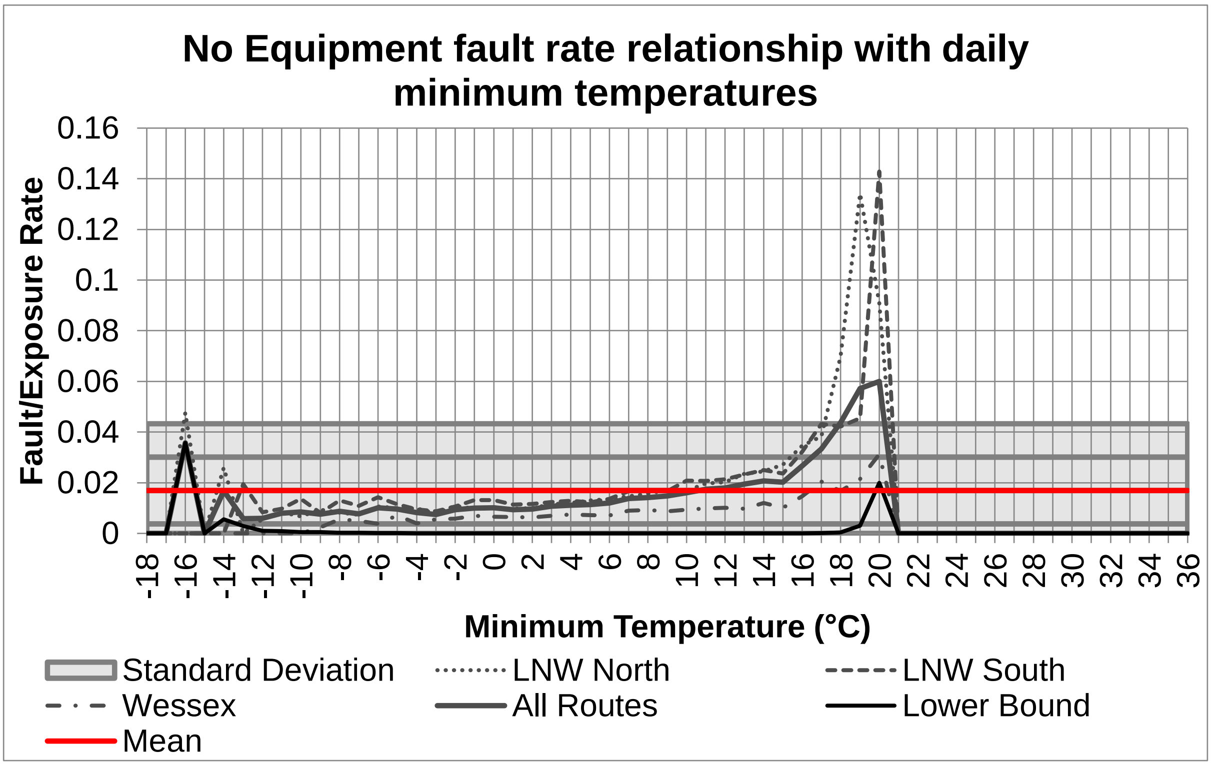

Figure 4.53: The relationship between the Daily Minimum Temperature and Fault Rate for No Equipment, illustrating the relationships between each of the routes.

In Wessex the fault rate for No Equipment assets isn't significant until a daily maximum temperature of 36°C, which is the highest maximum daily temperature recorded across all of the regions over the 5 years. This can therefore be considered as an extreme value which has only been recorded 21 times in this time period and has only been experienced in this region. This threshold is greater than those for the other two routes, significant fault rates occur from 28°C for LNW North and from 31°C for LNW South.

There are more faults recorded for LNW North and LNW South than for Wessex as shown in Table 4.21, which may explain the differences between each routes' fault rate. However, Wessex experiences higher temperatures at a similar frequency to LNW South and certainly more often than LNW North, suggesting the differences in the number of fault events recorded for No Equipment are not related to weather.

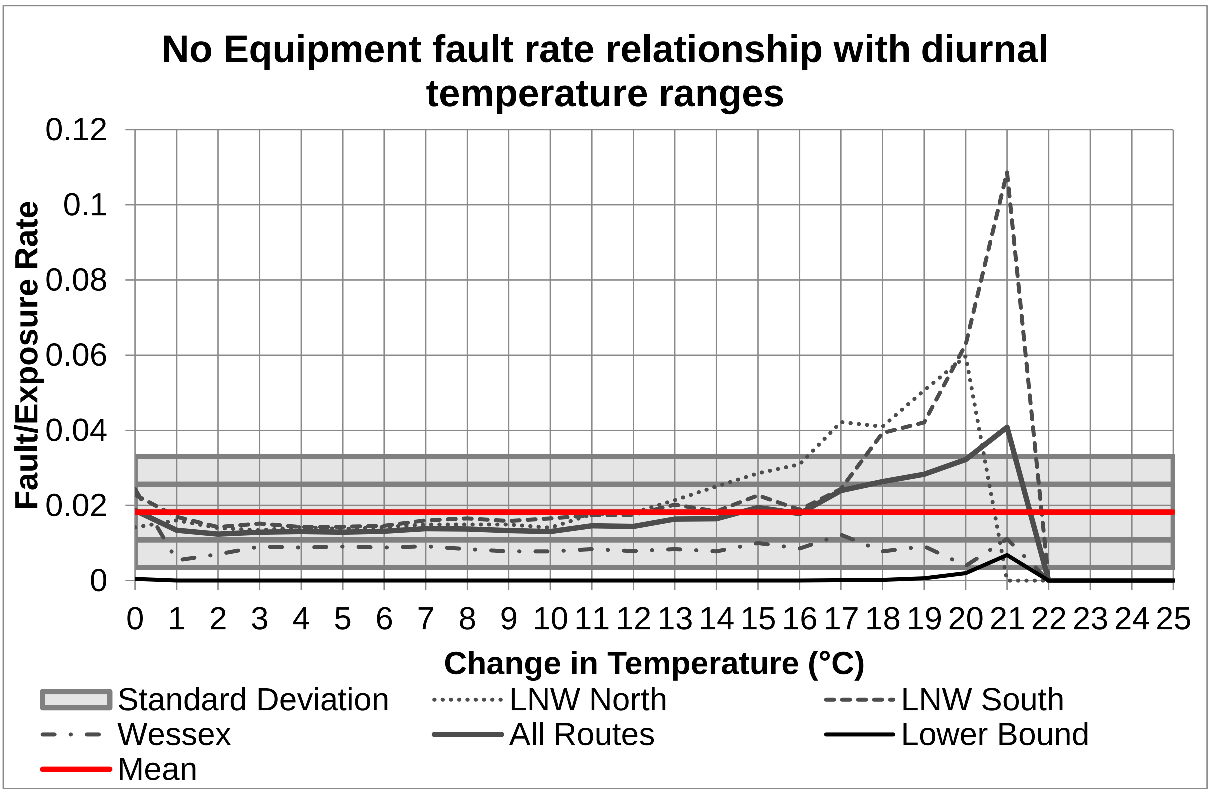

Figure 4.54: The relationship between the Diurnal Range of Temperature and Fault Rate for the No Equipment asset category, illustrating the relationships between each of the routes and their significance relative to all three routes.

These patterns are also echoed in Figure 4.54 between the fault rate and diurnal ranges. The No Equipment category has a strong correlation between the fault rate and temperature, across the three routes the fault rate becomes significant at temperatures of 31°C and very significant at 33°C. These peaks for the three routes' fault rate are contributed to by 109 and 19 fault events respectively. With the consistency of the relationship across the three routes these thresholds can be stated with confidence. Furthermore, diurnal ranges of 18°C are linked to significant fault rates which become very significant when the diurnal range is greater than 20°C with 112 and 16 contributing fault events respectively.

For an asset category with an unclear purpose this is surprising, however analysis of the fault event records for one route suggests that there is a common fault cause which is recorded for faults listed in this category. The fault events which contribute to the significant fault rate for LNW North experienced for daily maximum temperatures of 28°C or greater were categorised based on the information provided in the final column in the dataset and their frequency of occurrence is shown in Table 4.22. There is a large portion of the fault event records which have no FCAD attribute listed, however the largest category is that of fault events related to heat. Further investigation of the FCAD attribute reveals quite consistent reporting where the majority of the heat related fault event records have one of the following entries in the FCAD attributes:

- Heat
- Heat Speed
- Heat ESR
- Critical Rail Temperature

Table 4.22: Causation Categories for Faults events in LNW North occurring with a daily maximum temperature of 28°C or greater.

Causation Category	***Fault Event Count***
Animal Incursion	14
Blank	90
Error	5
Extreme Weather	1
Heat	155
Other	13
Unknown	12
Vegetation	10

4.5.1.2 Precipitation and No Equipment

A detailed analysis of the individual relationships across the three routes show that there are no significant fault rates which have been contributed to by greater than two fault events, it can therefore be said with certainty that none of the key precipitation variables have a relationship with the fault rate for the No Equipment asset category.

4.5.2 Circuit Breakers

The final parent asset group with significant asset categories is Electrical and Power (E&P) which has one significant asset category as shown in Table 4.23. The table shows the final significant category Traction Power Circuit Breakers, which enable the control of power supplies which power trains on electrified lines. Circuit breakers can either be located on rolling stock to protect the electrical systems of the train from overload and other risks, or they are located within the power distribution system of the railway network.

Table 4.23: E&P asset categories with greater than 1% of at least one route's fault events. The significant (as shown in Table 4.18) E&P asset categories are highlighted.

Parent Asset Group	Asset Sub-Group	FMS Suffix Labels	Short & Number	Full Asset Category Name
E&P	3rd Rail	Traction Supply (Third Rail)	E&P 3rd 2	E&P 3rd: Traction Supply (Third Rail)
	OHL	OLE Electrical Section	E&P OHL 2	E&P OHL: OLE Electrical Section
		OLE Structure	E&P OHL 6	E&P OHL: OLE Structure
	Signalling Power Supply	Electrical Supply Point	E&P SPS 2	E&P SPS: Electrical Supply Point
	Traction Power	**Circuit Breakers**	**E&P TP 1**	**E&P TP: Circuit Breakers**

4.5.2.1 Temperature and Circuit Breakers

The relationship profiles for Circuit Breakers and temperature can be seen in Table 4.24. Higher daily maximum temperatures consistently have a relationship with increased fault rates across all three routes, however there is no consistency between routes for the other weather variable relationship profiles. The relationships between the fault rates for Circuit Breakers and temperature can be seen in Figure 4.55, Figure 4.56 and Figure 4.57.

Table 4.24: Relationship Profiles for Circuit Breakers for Key Temperature Variables across all three routes.

Circuit Breakers		Temperature			
Route	Fault Counts	Max	Min	Diurnal Range	Asset Category percentage faults
LNW North	2450	1	2	0	1.79%
LNW South	3181	1	1	-2	3.00%
Wessex	1107	1	2	-1	1.42%

Over all three routes, Circuit Breakers have a significant fault rate from 29°C which becomes very significant beyond 34°C as shown in Figure 4.55. However, upon closer inspection it is evident that Circuit Breakers in Wessex do not have a significant relationship with high temperatures at all, but this may be due to there being fewer faults in this route for circuit breakers. In LNW South there is a significant relationship from 26°C which becomes very significant at 29°C, similarly the circuit breakers in LNW North have a significant fault rate from 28°C which becomes very significant from 31°C. Further investigation of all GB routes would provide more confidence in these results, however across the three routes considered in this research a significant thresholds for maximum temperatures a 29°C and very significant beyond 34°C can be stated with confidence with 43 and 5 fault events respectively.

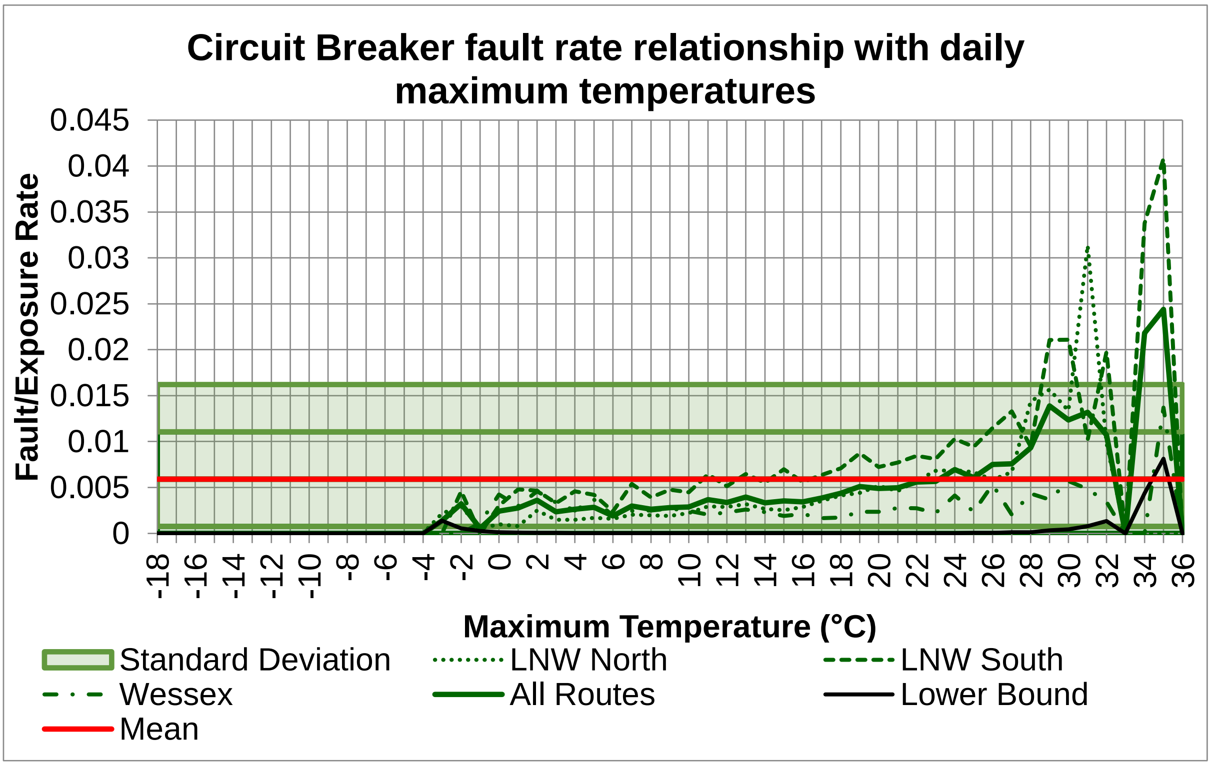

Figure 4.55: The relationship between the Daily Maximum Temperature and the Fault Rate for Circuit Breakers, illustrating the relationships for each of the routes.

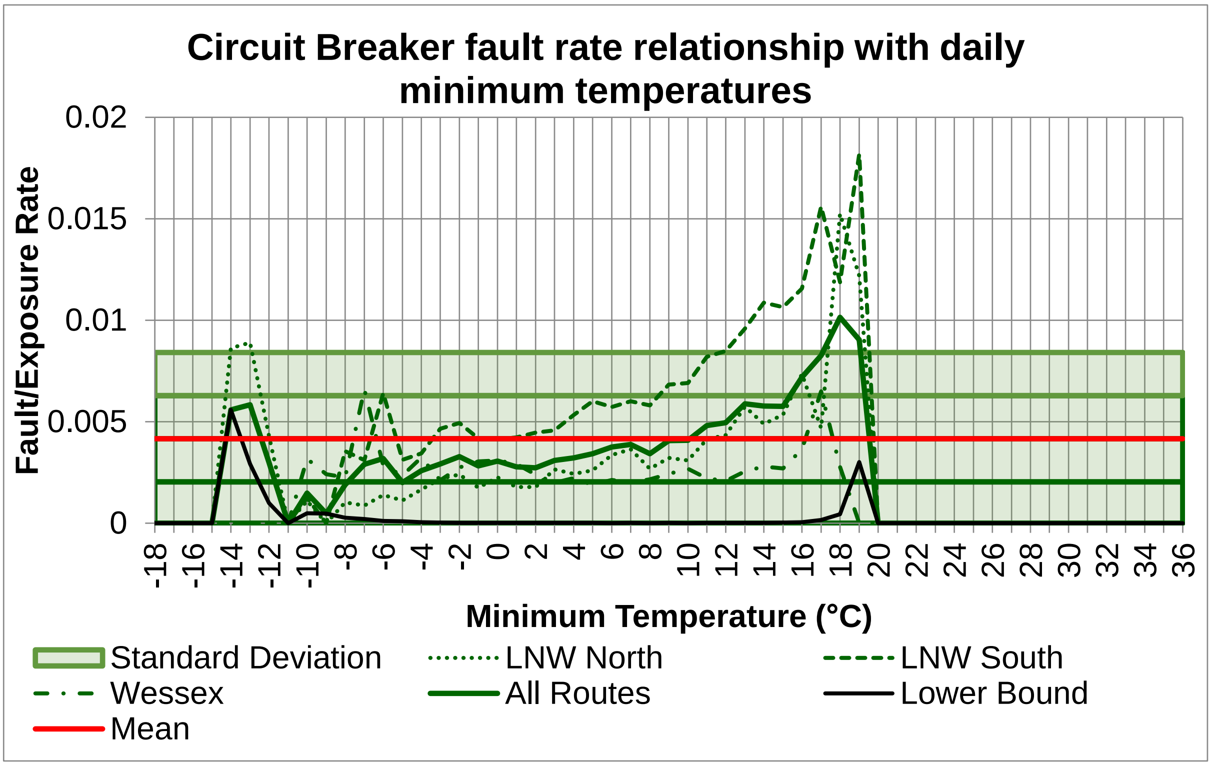

Figure 4.56: The relationship between the Daily Minimum Temperature and the Fault Rate for Circuit Breakers, illustrating the relationships for each of the routes.

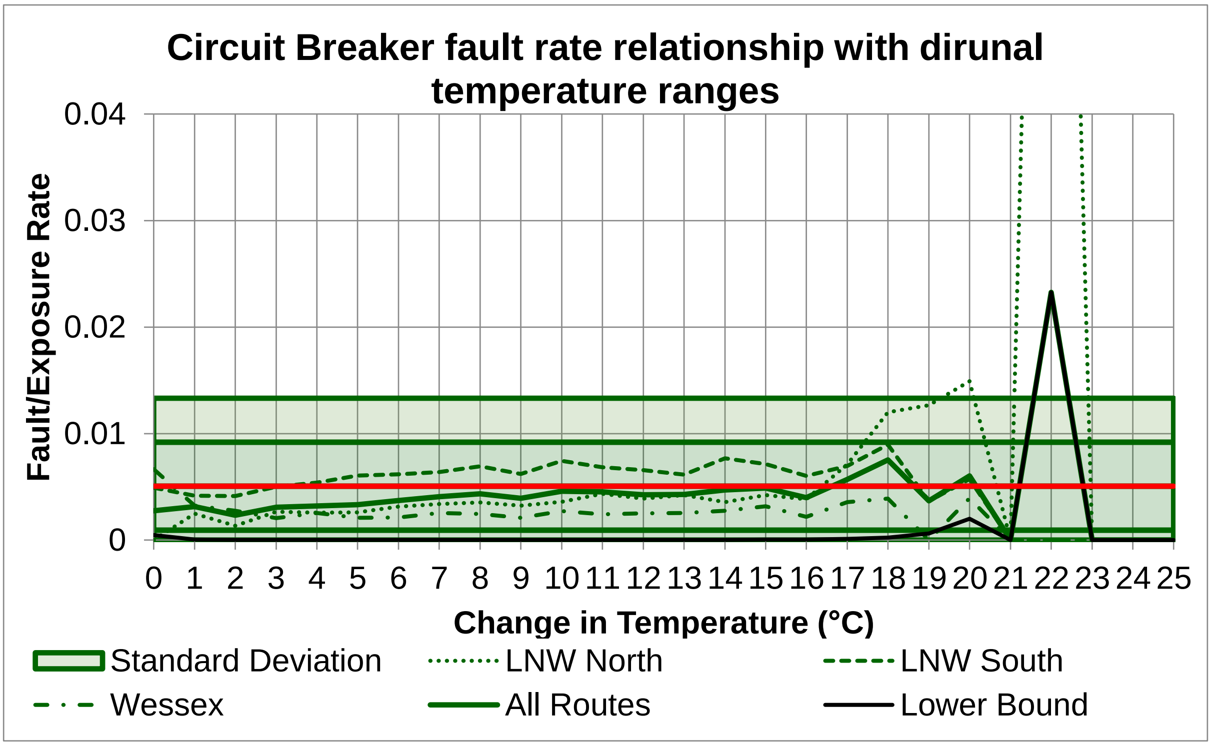

Figure 4.57: The relationship between the Diurnal Range of Temperature and Fault Rate for Circuit Breakers, illustrating the relationships between the routes.

Although there is no overall relationship between the fault rate for circuit breakers and the daily minimum temperature shown in Figure 4.56 there is a significant relationship for LNW South and Wessex when the daily minimum temperature is below -6°C and -7°C respectively. However, there is no significant relationship for circuit breakers in LNW North.

Figure 4.57 shows that there is no relationship overall between the diurnal temperature range and circuit breakers, however LNW North does experience a significant fault rate for circuit breakers when the diurnal range is greater than 18°C. This may be because these events are linked with another weather variable rather than faults being caused by the change in temperature.

4.5.2.2 Precipitation and Circuit Breakers

A cross the three routes there is a threshold for daily precipitation and a significant fault rate for circuit breakers at 22mm/day as can be seen in Figure 4.58, where this peak comprises of 86 fault events. However, both Wessex and LNW North do not have any significant fault rate across the range of daily total precipitation whereas LNW South experiences significant and often very significant fault rates across nearly the entire range. Very few of these faults are caused by weather as shown in Table 4.25. However, there is a noticeable number of faults caused by bird strikes to the OLE. Some of these strikes refer to bridges, engine sheds or other structures. It may be that the precipitation causes birds to seek shelter and in turn cause issues with the circuit breakers. The largest categories by far are No fault found, other, blank and unknown, and so it is difficult to draw conclusions regarding the cause of circuit breaker fault events in relation to precipitation.

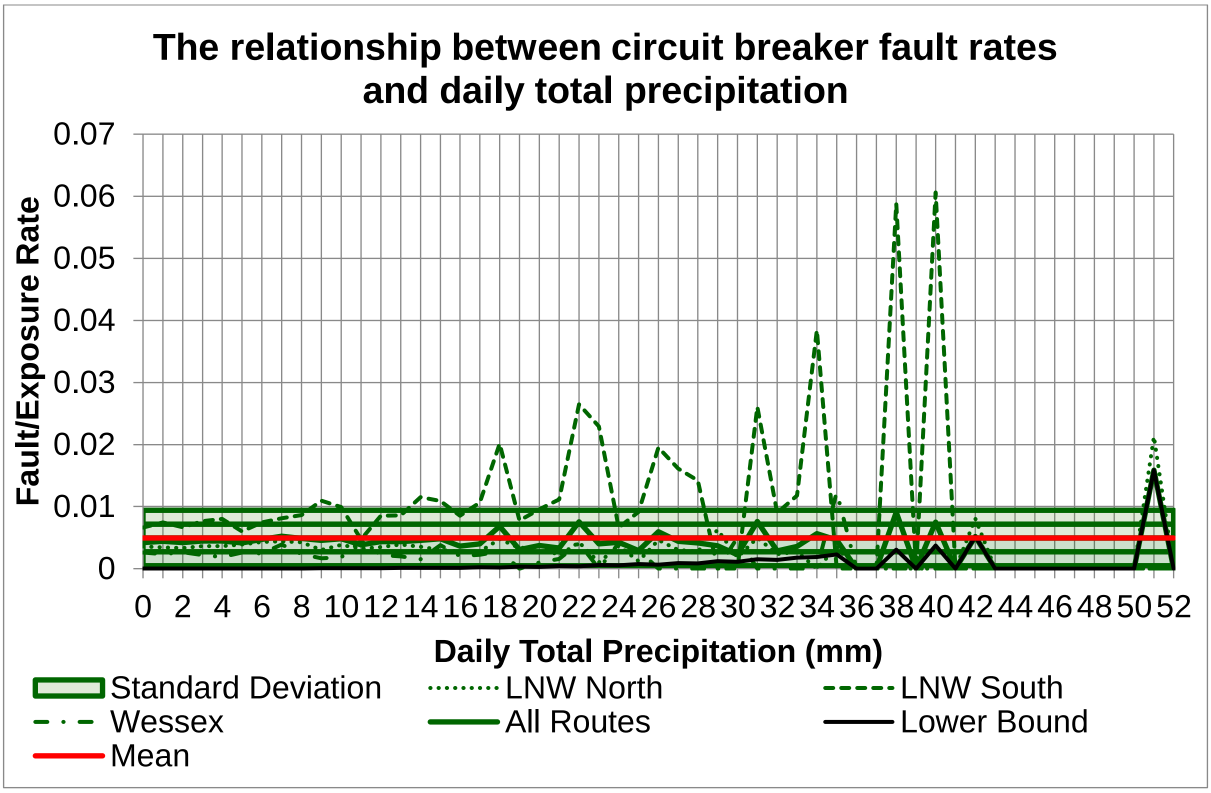

Figure 4.58: The relationship between the Daily total precipitation and the Fault Rate for Circuit Breakers, illustrating the individual and overall relationships for the routes.

Table 4.25: Causation Categories for Circuit Breaker Fault events in LNW South.

Causation Category	***Fault Event Count***
Animal	2
Bird	186
Blank	307
Burn Marks	32
Debris	11
Fuse	14
NFF	284
Other	107
Pan	14
Overload	10
Power	7
Trespass	3
Tripped	130
Unknown	249
Vegetation	27
Weather	18
Total	1401

Across the three routes there is no relationship with the accumulation of precipitation over the course of a week or month, this is also the case for Circuit Breakers in LNW North and Wessex. There are a few significant fault rates for LNW South, as these are not caused by substantial numbers of faults (i.e. no greater than 4) these figures have been omitted. It can be concluded that there is no clear relationship between precipitation accumulation and circuit breaker faults despite the relationship with the daily total precipitation.

4.6 Existing Failure Thresholds Comparison with Fault Rate Thresholds

As established in the literature review in Chapter Two, the railway industry uses operational thresholds as a point of reference. Exceedance of these thresholds assists NR with understanding asset performance, resilience, and to prompt an operational response to reduce the impact of known weather hazards and prevent them from becoming safety incidents (Network Rail, 2014b). Therefore, the fault rate thresholds that have been found during this analysis and presented throughout this chapter have been compared to the existing failure thresholds, identified by the TRaCCA project, that were previously presented in Chapter Two.

The fault rate thresholds were found for each of the significant asset categories where the relationship between the fault rate and the weather variable magnitude becomes significant or very significant. These have been identified in the presentation of the results for each of the significant asset categories in the previous sections. The fault rate thresholds for each weather category (higher temperatures, lower temperatures, diurnal ranges and precipitation), for the significant asset categories analysed in this research are concisely presented in the following sections alongside existing failure thresholds and can be seen in Table 4.26, Table 4.27, Table 4.28 and Table 4.29. This clearly summarises the thresholds found in this research whilst highlighting those asset categories that have not been found to have a significant fault rate relating to the weather variables explored in this research. Those assets where No Relationship was Found (NRF) have been highlighted, along with those categories with No Clear Relationship Found (NCRF). The thresholds found are broadly in line with existing thresholds considering the slight differences between the two measures as discussed in greater detail in the next chapter.

Table 4.26: Summary of results for combined route thresholds for significant asset categories for higher temperatures compared with those found in TRaCCA (RSSB, 2014). NRF = 'No Relationship Found' NCRF = 'No Clear Relationship Found'

Higher Temperatures Asset Category	Fault Rate Thresholds Significant	 Very Significant	Existing Failure Thresholds Significant	 Very Significant
Track (P.W)	>30°C	>31°C	>24°C	>30°C
Signal	>29°C	NRF	>20°C	>26°C
POE	>31°C	>32°C		
No Equipment	>30°C	>33°C		
Track Circuit	NCRF	NRF		
Level Crossing Equipment	>33°C	NRF		
Points (P.W)	NRF	NRF		
Panel/Frame	NRF	NRF		
Boundary Measure	NCRF	NRF		
TPWS	NCRF	NCRF		
Circuit Breakers	>29°C	>34°C	>22°C	>23°C

Table 4.27: Summary of results for combined route thresholds for significant asset categories for lower temperatures compared with those found in TRaCCA (RSSB, 2014). NRF = 'No Relationship Found' NCRF = 'No Clear Relationship Found'

Lower Temperatures Asset Category	Fault Rate Thresholds Significant	 Very Significant	Existing Failure Thresholds Significant	 Very Significant
Track (P.W)	NRF	NRF		
Signal	<-5°C	NRF		
POE	NCRF	NRF	<-4°C	<-7°C
No Equipment	NRF	NRF		
Track Circuit	NRF	NRF		
Level Crossing Equipment	NRF	NRF		
Points (P.W)	<-4°C	<-5°C	<0°C	<-4°C
Panel/Frame	NRF	NRF		
Boundary Measure	NRF	NRF		
TPWS	NRF	NRF		
Circuit Breakers	NRF	NRF		

Table 4.28: Summary of results for combined route thresholds for significant asset categories for diurnal temperatures compared with those found in TRaCCA (RSSB, 2014). NRF = ‘No Relationship Found’ NCRF = ‘No Clear Relationship Found’

Diurnal Temperatures	Fault Rate Thresholds		Existing Failure Thresholds	
Asset Category	Significant	Very Significant	Significant	Very Significant
Track (P.W)	NRF	NRF		
Signal	NRF	NRF		
POE	Δ>17°C	Δ>18°C	Δ>13°C	
No Equipment	Δ>18°C	Δ>20°C		
Track Circuit	Δ>21°C	Δ>21°C	Δ>13°C	
Level Crossing Equipment	Δ>21°C	Δ>21°C		
Points (P.W)	Δ<2°C	Δ<1°C		
Panel/Frame	NRF	NRF		
Boundary Measure	Δ 0°C	NRF		
TPWS	NCRF	NRF	Δ>17°C	
Circuit Breakers	NRF	NRF		

Table 4.29: Summary of results for combined route thresholds for significant asset categories for Precipitation compared with those found in TRaCCA (RSSB, 2014). NRF = ‘No Relationship Found’ NCRF = ‘No Clear Relationship Found’

Precipitation	Fault Rate Thresholds		Existing Failure Thresholds	
Asset Category	Significant	Very Significant	Significant	V.Significant
Track (P.W)	NRF	NRF	>25mm/day	
Signal	NCRF	NRF		
POE	NRF	NRF		
No Equipment	NRF	NRF		
Track Circuit	NRF	NRF		
Level Crossing Equipment	NRF	NRF		
Points (P.W)	NRF	NRF		
Panel/Frame	NRF	NRF		
Boundary Measure	<20mm/week, <35mm/Month	<20mm/week, <35mm/Month		
TPWS	NCRF	NCRF		
Circuit Breakers	>22mm/day	NRF	>15mm/3hr	

4.7 Summary of Results

Significant asset categories and weather variables were identified for analysis using the methodology developed and detailed in the previous chapter. By applying the methodology developed to these significant asset categories it was possible to observe significant relationships between asset categories and weather variables. The resulting fault rates for each asset category under different weather conditions have been presented and investigated in depth where appropriate.

Chapter Three outlined the methodological approach developed during the research the results of the application of this methodology have been presented in throughout this chapter. The initial results found that it would be beneficial in this research to concentrate on temperature and precipitation; specifically maximum, minimum and diurnal temperatures, and daily total precipitation alongside weekly and monthly accumulated precipitation as discussed in Section 3.2.1. In addition, the original specification of significant asset categories were too broad and could be refined further. For the purpose of illustrating the application of the methodology developed, eleven categories were identified as explained in Section 4.2.1.

This chapter continued by presenting the significant relationships found, whether they have previously been discussed in existing literature or addressed or not. Where possible these relationships were then explored in depth to identify failure mechanisms. An overview of the thresholds found have been presented alongside the thresholds in Section 4.6. The relevance of these relationships and the failure mechanisms identified are discussed in the next chapter. In addition, the methodology developed is evaluated to identify opportunities for further development of this methodology.

CHAPTER FIVE: DISCUSSION OF RESULTS

5.1 Overview of the Discussion

The previous chapter presented the results for the individual relationships between the significant asset categories and the key weather variables. In addition, the significant thresholds for these relationships were identified and presented alongside existing operational thresholds utilised by NR. This chapter builds upon these results to further explore the identified relationships, illustrate the benefits of applying this methodology in an asset management context, to establish how these findings can be validated against existing research and critically evaluate the findings and methodology developed. Throughout the chapter recommendations are presented alongside the discussion, they address various stakeholders of the railway industry presented in Table 5.1, where NR are addressed this may refer to any of the NR internal stakeholders whether in the route or elsewhere in the business. This chapter is then summarised with the Author's impression of the key goals for NR to create a resilient railway network for future mobility.

Table 5.1: WRCCA Stakeholder Groups (Source: (Network Rail, 2017b))

Government and Regulators	Internal Network Rail Stakeholders	External Stakeholder Groups
• Department for Transport (DfT) • Transport Scotland • Transport for Wales • Department for Environment, Food and Rural Affairs (Defra) • Office of Road and Rail (ORR) • Environment Agency (EA) • Scottish Environmental Protection Agency (SEPA) • Natural Resources Wales (NRW)	***Routes*** • Route Asset Management • Seasonal Delivery Specialists • Maintenance and Delivery Units • Project Sponsor and managers ***Project Developers (IP/WD)*** • Project Sponsors • Design Engineers ***STE/NOC*** • Weather Resilience Group • Safety Technical and Engineering (WRCCA team, analysts, risk managers, R&D etc.) • Chief Engineers Group (Heads of Asset Functions and Strategy) • National Weather Client • NR Weather Forecast Service • Business Continuity and Emergency Preparedness	• National Task Force • Rail Delivery Group • Infrastructure Operators Adaptation Forum • RSSB – Rail Safety Standards Board • TRaCCA[3] Implementation Group • National Flood Resilience Forum • Transport for London • CIRIA - Construction Industry Research and Information Association • CIWEM, IEMA and other professional groups • NERC – National Environment Research Council • Various academic and research groups

5.2 Implications for Vulnerable Asset Categories

The results presented in the previous chapter have illustrated asset specific relationships with a range of climatic conditions highlighting their susceptibilities to weather hazards. This has provided further insight into the resilience of a range of asset categories to the effects of weather. These specific implications for the significant asset categories identified during this analysis are discussed in the following sections, consequently recommendations for future research, development of new railway infrastructure technologies and improvement of current asset management practices are also presented.

5.2.1 Track (P.W.)

The results presented in the previous chapter echo findings in current research, higher temperatures are related to a significant number of faults for Track (P.W.) assets. This has been described in great detail in existing research and has also been reflected in the results of this analysis, validating the use of the methodology that has been developed. When investigated in detail in the TRaCCA project, the Track P.W. threshold for high numbers of failures are slightly lower than found in this analysis. A significant number failures occur at temperatures greater than 24°C, temperatures greater than 30°C exacerbate this and cause very significant numbers of failures (RSSB, 2014). The differences between these values and those found during this analysis that result from the methodology are discussed later in this chapter whilst critiquing the methodology in Section 0. Despite these, the similarities between existing thresholds and those outlined here indicate that the approach developed is able to not only identify the relationships between weather hazards and asset faults but also quantify them.

5.2.1.1 The role of track condition

It has been established that the probability of track buckling is largely dependent on the condition of the track with ambient air temperatures around 39°C required to cause a risk of a track in good condition buckling, but a much lower temperature of 25°C for a track in poor condition to be at risk of buckling. Existing literature suggests that when the temperature exceeds 27°C the frequency of buckles and the severity of the incidents increases drastically, suggesting maintaining good track conditions across the network is a significant challenge (Dobney et al., 2009). The variation between the significant thresholds found in this analysis could be attributed to changes in overall track condition over time. It is possible that the track condition in GB was improved between 2006 and 2011 and so this research returned values of 30°C and 31°C for significant and very significant fault rates for Track (P.W.) assets it is also possible that other factors are involved. For example, this research did not specifically investigate track buckling faults, but all faults recorded as affecting Track (P.W.) and the research would need to be focussed to analyse the impact of seasons and the effect of temperature on track buckling and buckle harvesting specifically.

When ambient air temperatures rise to 36°C blanket speed restrictions are put in place over large sections of the network, reducing the possibility of a rail exposed to high temperatures buckling, by reducing any additional loading it may be subject to ordinarily. An inevitable consequence of these speed restrictions is delays to trains on the network, but this is necessary in order to avoid train derailment and ensure passenger safety, however more recently the efficacy of this has been called into question (Ferranti et al., 2016a). Therefore, there may be scope to conduct further heat hazard mapping coupled with information regarding the condition of track to better target speed restrictions and preventative maintenance. Hazard mapping is discussed later in Section 5.5.1 as a practical step that can be taken by NR to move towards creating a more resilient railway network.

Recommendation 1: NR should explore how current maintenance and installation practices regarding track can be improved to ensure better overall track condition across the network.

Recommendation 2: NR and researchers should conduct heat hazard mapping to better inform preventative maintenance regimes and dynamic ESR zoning.

5.2.1.2 Stress Free Temperatures

Track buckling during summer months has been attributed as the cause of an annual average of over 25k delay minutes to train services in GB (RSSB, 2014). The mean annual costs for heat-related delays in the UK in the 2020s has been estimated to be £10.1m or £10.4m, for high and low emissions future climate scenarios respectively. Extreme weather during the summer months in the 2080s under a high emissions scenario could cost up to £23m based on current prices (Dobney et al., 2010). These figures reflect a scenario where no additional mitigation actions are taken but clearly reflects that improvements to maintenance regimes and asset design need to be considered now to prevent these escalating costs in the future. In addition, previous research has concluded that the SFT of track laid in GB needs to be reconsidered under future climates. The SFT at which track is usually laid is 27°C in the UK but in reality due to factors such as the "rolling out" effect where tension is lost due to changes in the track substructure after installation the SFT range is more likely to be 22°C to 24°C. However, routine maintenance practices increase this and so the general SFT range across the network in GB is between 21°C and 27°C. To be resilient in the 2080s the SFT needs to be concentrated at the upper end of this range. However, there is no evidence found by existing research to support raising the SFT above 27°C, instead it has been recommended in existing literature that improving track condition will protect track assets from the effects of both cold and heat related faults (Dobney, 2010). The results of this research support these conclusions as well as providing a potential approach for identifying failure mechanisms and preventative measures.

Recommendation 3: NR and researchers should further investigate the adaptation of Track assets to future climate change, particularly more frequent high temperatures, and how adjustment of the SFT can support this.

5.2.2 Points (P.W.)

Points (P.W.) are an asset under the Track parent asset group however they have a very different relationship with temperature compared to Track (P.W.). It was found in the previous chapter that Points (P.W.) are contrastingly most significantly affected by lower temperatures as has been established in existing literature and NR's current failure thresholds. The results presented in Section 4.3.2 identified an increase in points failures for sub-zero temperatures, becoming significant at -4°C and very significant at temperatures of -5°C and lower. This is broadly in line with existing research which suggests high failure rates at temperatures less than 0°C which then becomes very high for temperatures of -4°C and lower.

5.2.2.1 Switch Rail Obstructions of Ice and Snow

Analysis of the fault event records identified that for LNW North 86% of the fault events which occurred when the daily maximum temperature was 0°C or lower were defined as Switch Rail Obstructions. The switch rail is the moving rail which enables a train to change from one set of tracks to another at a junction or point, therefore obstructing the movement of this mechanical element impairs the function of the asset. Further investigation highlighted that the cause of more than 80% of these switch rail obstructions had been recorded as cold weather, including references to ice and snow. The compaction of ice and snow in mechanised elements of railway infrastructure is a known vulnerability of this particular asset type (Champion, 1947) causing these assets to be grit salted or more recently contain heating elements to prevent the build-up of ice or snow. The results of the analysis conducted in this research suggests that these measures are not adequate to mitigate the effects of low temperatures on points and specifically switch rail mechanisms. Consequently it is important that the impact of low temperatures and the build-up of snow and ice are considered in any future redesign of moving asset elements, in particular in relation to points (S-Code, 2020).

Recommendation 4: NR and Researchers to ensure the consideration of weather impacts on asset elements when designing next generation infrastructure.

5.2.2.2 (A Tale of) Two Severe Winters

The UK experienced two severe cold and snowy periods over the winters of 2008/09 and 2010/11 which were both identified during the analysis. These winters are both well known to have caused significant disruption to transport networks including railways. The development of the weather patterns for both events were reported in detail in the aftermath (Prior and Kendon, 2011a, 2011b; Met Office, 2009, 2013). However, these types of analysis do not go into sufficient detail to provide information for the failure mechanisms of specific transport infrastructure assets, regardless this level of meteorological assessment does inform understanding of failure mechanisms. The results presented in 4.3.2 highlight that there is a strong relationship between a small diurnal range and the fault rate for Points. If the diurnal temperature range is low there has been little or no change in temperature over the course of the day. This is specific to high pressure areas which experience high radiative cooling, meaning that any heat from the sun during the day is not retained. In addition to this, if there has been snow fall this will reflect sunlight and heat, this scenario of high albedo results in constant low temperatures. The impact of this for railway infrastructure is that ice and snow do not dissipate without the application of heating elements, gritting or other de-icing methods.

It was recognised that both of these events had significant impacts on the UK's transport networks and the operational responses were evaluated by the DfT (Department for Transport, 2010). Supporting this, the regulatory bodies for the railway network determined that considering the severity of the weather events, the railway network maintained a good level of service and overall had improved their asset reliability (ORR, 2010). It is possible that the reflection within the industry has improved asset reliability in winter as well as winter preparation practices since the fault events analysed in this research were reported. This supports the need for this type of methodological approach to be applied cyclically in order to provide ongoing feedback to inform operational procedure. In addition, the results of the application of this methodology have shown that analysis of these extreme events can play an important role in developing understanding in this area. Specifically, it was found that once these extreme events were identified they provided insight into the failure mechanisms associated with the weather hazards experienced. Ensuring that this type of approach is enforced and reflected in NR's processes and standards would enable more immediate, indiscriminatory information relating to failure mechanisms and weather hazards, further developing existing knowledge. Application of these findings would then provide the basis to inform renewals and associated decision making processes.

In addition, it has been shown that analysis of such weather events can help inform the estimation of the risk associated with forecast winter weather events informing preparations (Palin et al., 2016). However, this research highlighted that it is necessary to have a good understanding of failure mechanisms in order to provide detailed impact predictions. Therefore, improving the understanding of failure mechanisms through application of this type of methodological approach can support the development of fault forecasting techniques as explained in Section 5.5.2.

Recommendation 5: The DfT should encourage evaluation of the impacts of extreme weather events on transport infrastructure assets and network operation and serviceability. Lessons learnt should be appropriately distributed to improve current practice for network infrastructure managers and operators.

Recommendation 6: NR and researchers should analyse extreme weather events which have impacted rail infrastructure to expand existing knowledge of the effects of weather on infrastructure assets to inform adaptation of infrastructure to be resilient against future climates.

Recommendation 7: Researchers should work towards developing strategies to adequately investigate the impact of combined weather variables on transport infrastructure.

5.2.2.3 Future frequency of low temperatures

Existing literature has noted the absence of research investigating the future frequency of low temperatures and associated impacts (RSSB, 2014). Under future climates it is predicted that extreme low temperatures will be experienced less frequently in GB (Institution of Civil Engineers, 2018). Therefore, experiencing lower temperatures may become increasingly problematic as warmer winters become the norm, decreasing preparedness for dealing with issues such as frozen points or cracked rails. It is therefore necessary for NR to review their practices for winter weather preparations in light of future changing climates (Transport Committee, 2014a). It may be beneficial for climate impact assessments regarding this asset to include weather analogue analyses to understand how extreme cold temperatures are planned for in countries which experience the type of climate GB is likely to have in the future. This type of analysis should encompass assessment of the economic impact of various levels of operational preparedness for infrequent lower temperatures under future climate scenarios. Therefore, the resource expended on preventative measures can be suitably justified.

Recommendation 8: NR and researchers to conduct analysis of the future frequency of lower temperature weather events in order to estimate the likely future impacts of cold weather and adjust winter weather preparation guidance accordingly.

Recommendation 9: NR and researchers to conduct weather analogue analysis to determine the way future climates may effect railway infrastructure and what measures can be taken to mitigate these affects.

5.2.2.4 Precipitation and lubrication routines

Across all three routes assessed to develop this methodology, there is no clear relationship between the significance of the fault rate and the exposure of the network to precipitation. The results presented in 4.3.2 do highlight significant differences between the impact of weather on assets and the consequent fault rate. As the data was normalised to mitigate the effect of climate variation between geographic areas across the country, these differences must be for other reasons.

One influencing factor that has been identified during this analysis is the differences in maintenance regimes. LNW South had many more faults recorded for points often citing the fault to be related to a lack of lubrication for moving parts and suggesting in some records that the cause of this was the effect of intense precipitation. However, this does not seem to have been a significant issue for LNW North which experiences a similar number of fault events recorded over the period considered. Consequently, the only possible reasons for this difference between routes would be the efficacy of maintenance conducted for Points (P.W.) in LNW South or the quality of the lubricant used over the time period investigated.

Recommendation 10: Future research regarding the impact of weather on transport infrastructure should capture the effects of the intensity and duration of precipitation as well as the magnitude.

Recommendation 11: NR should prioritise preventative maintenance practices to ensure their assets are resilient to the effects of weather. Development of mechanisms to inform maintenance based on weather forecasts would support this action.

Recommendation 12: NR should work towards developing point assets which are low maintenance, needing limited lubrication or using lubrication products which are resistant to being washed off by intense rainfall.

Recommendation 13: NR should ensure that existing processes for evaluating the efficacy of maintenance and the performance of specific infrastructure assets adequately informs future maintenance planning and practices.

5.2.3 Boundary Measures

Boundary measures are a critical asset for NR as they protect the railway line from incursion from pedestrians, vehicles and animals. This is important to protect assets from damage or theft and to prevent the injury or death of humans and livestock (Network Rail, 2019f). This asset group has not previously been identified as a significant asset group or as having any relationship with weather that needs to be addressed. However, the results of this analysis found that there is a relationship between the fault rate of boundary measure assets and low accumulation of precipitation, or droughts. The precise reason for this was not successfully identified as there was a large number of fault events in this category and the data quality prevented any detailed analysis.

5.2.3.1 Seasonal effects on Boundary Measures

There is potentially a wide range of different hazards affecting boundary measures as they are not of uniform design or environment unlike other asset types. In addition, the inspection routines which follow seasonal patterns may influence the recording of boundary measure faults. It can be seen in Figure 5.1 that more faults with boundary measure assets are recorded in the spring as weather and visibility begins to improve and vegetation is not yet overgrown. However, this is also when livestock are returned to fields after spending the winter mainly inside. Similar numbers of boundary measure faults are experienced in the autumn, this may be as a result of winter weather

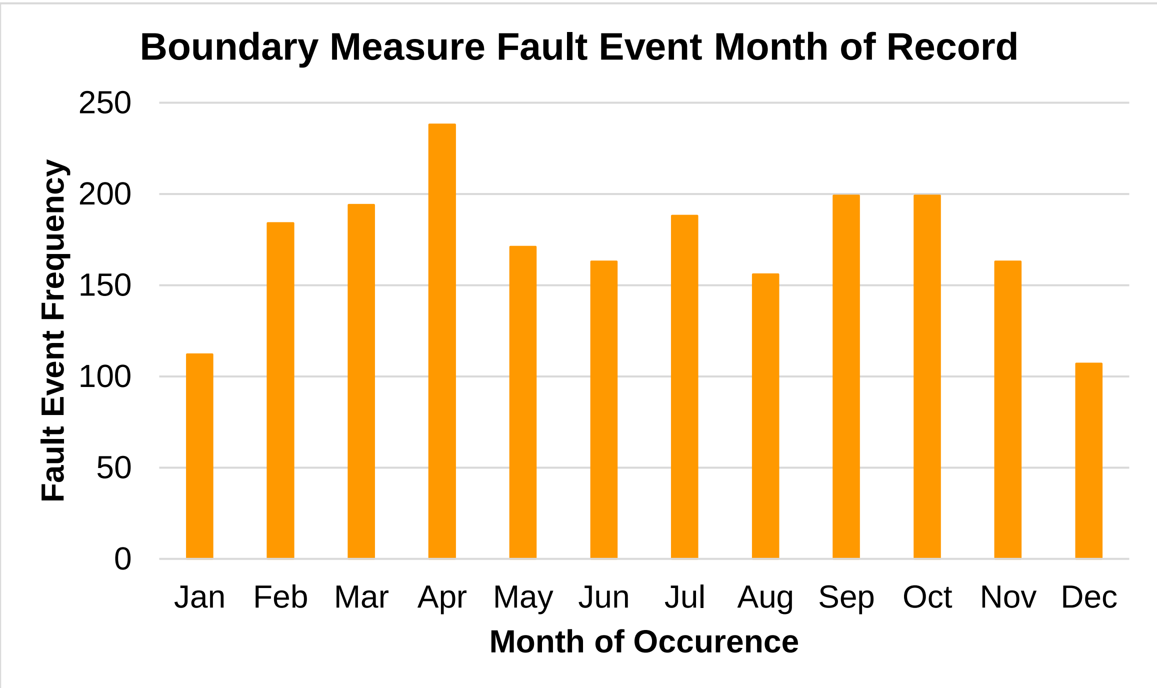

Figure 5.1: Frequency by month of boundary measure fault records, highlighting the possibility of seasonal variations.

returning. Further understanding of these possible fault causes is needed for any analysis of weather impact can be undertaken again however. This action would be supported by improvements in the quality of fault event records and the clarity of causes of fault events. Improvements and further work regarding fault event records, reporting and data quality are discussed in Section 0.

Recommendation 14: NR and researchers to conduct further analysis of the causes of boundary measure asset faults and investigate, develop and employ prevention methods.

Recommendation 15: NR to review inspection processes and the suitability of boundary measure structures with reference to localised weather hazard locations across the network.

5.2.4 Signals

The results presented in Section 4.4.1 show that Signals have significant relationships with both higher and lower temperatures as well as with total daily precipitation. However, Signals have not been found to be affected by diurnal temperature changes and the relationship between this asset group and precipitation accumulation needs further investigation to be confirmed. The relationships with higher temperatures have been previously identified however, there is little literature on the specific causes of these heat related failures, therefore this is an area for further investigation. The roles of low temperatures in signal faults have not previously been identified and will certainly need further investigation to develop adequate protection methods.

Recommendation 16: NR and researchers to conduct further analysis to determine the relationships between precipitation accumulation and faults for signal assets and explore fault causation.

Recommendation 17: NR and researchers to develop a better understanding of the causes of weather related signals faults, develop protection strategies and improve current practice.

5.2.4.1 Signals and Future Technologies

Currently all railway infrastructure is being overhauled as part of the Digital Railways Programme, in particular this scheme of modernisation aims to integrate digital signalling systems with rolling stock, physical infrastructure and telecommunications (Telecoms) assets. This will result in the signals on the network being managed from one of twelve operations centres across the country. Upgrading legacy infrastructure is an ongoing challenge for the railways in GB, this includes signalling infrastructure, 63% of which will need to be upgraded before 2035. This scheme is only economically viable if it results in lowering whole life costs of asset operation and management which it aims to do by improving the efficiency of railway operations. The Digital Railways Programme aims to be completed by 2025, this includes retrofitting all existing rolling stock with the European Train Control System in addition to the necessary upgrades to physical infrastructure and operations centres (Network Rail, 2018a).

As signalling infrastructure is set to radically change in GB over the next decade it is crucial to remember this when assessing the impact of the results presented in this research. The Digital Railway Programme will move most lineside signalling equipment into the Train Driver's cabin therefore removing most of the weather hazards associated with this asset category. This will also mean further development and implementation of additional communications equipment which may be situated lineside and therefore be exposed to the hazards of weather unless suitably protected. As part of this upgrade scheme it would be necessary to conduct appropriate risk assessments to ensure that the upgraded infrastructure is no less resilient and hopefully more resilient to the impacts of weather. This is particularly crucial if the railway network is to remain reliable and operational even under future adverse climates.

Recommendation 18: Ensure that the Digital Railway Programme conducts appropriate climate change impact assessments for future asset arrangements and that the effects of weather and climate change are considered during infrastructure design stages.

5.2.4.2 Resilience of Telecoms

No telecoms assets were determined to be significant during this research as the number of faults attributed to these asset categories were less than 1% of the total count across each of the routes included. However, the TRaCCA project identified that NR's operational thresholds do include telecoms assets, which have a significant number of fault incidents when temperatures are greater than 20°C. The number of fault incidents for telecoms becomes very significant when the temperature is greater than 26°C (RSSB, 2014). As this does not indicate which specific elements of telecoms assets are susceptible to higher temperatures, it is difficult to draw detailed conclusions about the resilience of future signalling infrastructure. However, based on current understanding it is clear that for the upgraded signalling systems to return similar or greater levels of resilience they will need to be protected from the effects of higher temperatures. This will become particularly crucial as GB's weather begins to warm as the climate changes.

Telecoms based signalling infrastructure must be appropriately resilient to the impacts of future climates. If adequate provisions have not been made whilst upgrading GB's signalling infrastructure it is possible that the whole life cost will not be reduced as expected. Instead, delays previously attributed to the failure of lineside signals may in the future be attributed to the failure of telecoms assets or rolling stock. This is all dependent on the specific type of infrastructure to be put in place, however existing research suggests that fixed line telecommunications infrastructure which is typical in the UK, experiences greater fault rates during the winter (Brayshaw et al., 2020).

Recommendation 19: NR should assess the risk of future climate change to future telecoms infrastructure to inform design development and adaptation measures.

5.2.4.3 Resilience of Power Supplies

Even if the Digital Railway Programme implements predominantly wireless technologies, the power supply network in GB is also vulnerable to the effects of weather, leading to power outage for consumers. This was the case in August 2019, where a lightning strike to an overhead transmission line disrupted the power supply from the National Grid and affected the railway network as a result. The reduced power supply to railway infrastructure directly and indirectly impacted railway operations in a range of ways causing widespread disruption and the loss of signalling power supplies at eight rural locations (ORR, 2020). Unfortunately, lightning strikes were not considered within the scope of this research because they are challenging to investigate. Regardless, this event is illustrative of how weather can cause widespread disruption to the railway network when it affects power supplies.

Power outages are likely when adverse weather is experienced and can be over extended periods when power transmission infrastructure is subject to extreme weather conditions (Ward, 2013; Panteli and Mancarella, 2015). Additionally, it is known that not only will future climates affect the ability for power infrastructure networks to supply electricity but it will also affect the consumer demand for power in the future (Staffell and Pfenninger, 2018).

This highlights the interdependencies between different infrastructure networks in GB. In addition, this shows that interdependencies between infrastructure networks will become more critical with the increase in electricity demand for the operation of the railway network while both networks are subject to more frequent adverse weather and extreme weather events. The criticality of railway assets and the interdependencies between national infrastructure networks, particularly power, need further investigation to inform appropriate resilience strategies (Hodgkinson, 2018).

Recommendation 20: National Grid and power distributors need to adequately account for the impact of climate change on existing infrastructure and consider this risk in the design of new infrastructure.

Recommendation 21: Infrastructure managers and researchers need to analyse the criticality of assets and the interdependencies between national infrastructure networks to inform resilience strategies.

5.2.4.4 Future GB Rail Power Demands

This leads to a wider question regarding the future power requirements of the railway network and the ability for the national grid to supply that demand. Although the use of hydrogen trains is a subject of current innovation and research (Gallucci, 2019), it is expected that electricity as a more traditional power source will be in greater demand in the future. This is for a number of reasons such as the expected increase in rail travel, due in part, because of the EU's strategy to move over 50% of passengers and freight by more sustainable modes such as rail by 2050 (European Commission, 2011). This compliments the UK's aim for carbon emissions to be net zero by 2050 (Committee on Climate Change, 2019) and development within the transport sector is necessary as the transport sector accounts for 40% of the UK's final energy usage (National Statistics, 2019). Although the UK is moving towards increasing the proportion of final energy usage to greener alternatives such as wind or solar power generation, the railway sector must also do the same. In response to this, diesel only passenger trains will no longer operate on the rail network by 2040 and greener electric vehicles and even hydrogen fuelled rolling stock will replace these. However, this further increases the electricity demand of the railways with further electrification of the network over the next few decades (Rail Safety & Standards Board, 2019) and increasing the power demand of rolling stock and assets. Ultimately this puts further strain on the interdependencies between vulnerable infrastructure networks such as rail and power.

Recommendation 22: The Department for Business Energy and Industrial Strategy should encourage further research into the effects of climate change on power demand and variability and the effects this may have on other infrastructure networks, including transport.

Recommendation 23: The DfT should work with transport infrastructure managers and operators to determine the impacts of future climate change on their power demand and supply.

5.2.5 Point Operating Equipment

NR are aware of the relationships between larger (Δ>13°C) diurnal temperature ranges. However, the results of the analysis conducted here concluded that the higher fault rates associated with higher diurnal temperatures also occur when higher daily maximum temperatures are also experienced. Further analysis of these relationships would be too complex and outside the scope of this research and so the specific cause is not clear. However, this does highlight the intricacies of the relationships of some asset categories with weather hazards which make analysis complicated and identification of the root causes difficult.

Recommendation 24: NR and research should further investigate the relationships between POE and temperatures to expand understanding of failure mechanisms to inform preventative measures.

POE assets were not found to be uniformly impacted by precipitation across the three routes. As previously discussed, these differences are not due to the different weather experienced in different locations as the methodology applied ensured the data was normalised to mitigate this, therefore these differences are as a result of the assets or some other factor.

Recommendation 25: NR should apply the methodology developed, dynamically to all routes to identify specific issues affecting assets on individual routes.

Recommendation 26: NR and researchers should further investigate the fault causation of total daily precipitation and the impacts on POE assets.

5.2.6 Track Circuits

As discussed in earlier chapters, the effects of weather on track circuits is known to infrastructure managers and has been the subject of some research. Although condition monitoring units for track circuits have successfully been developed the specific role of weather in fault causation has been more difficult to assess (Chen et al., 2008; Huang et al., 2017). The TRaCCA project identified that NR's operational thresholds for this asset type only relate to diurnal temperature ranges, stating that ranges greater than 13°C result in a significant number of fault incidents (RSSB, 2014). This research has identified a significant operational threshold of 21°C however it can be seen in Figure 5.2 that the fault rate steadily increases from approximately 13°C.

This difference may be as a result of the differences in the definition of significance between this method and those utilised by NR. However, it can be concluded that these findings are approximately in line with NR's existing operational threshold. Previous research has been unable to quantify the effect of absolute temperature on track circuit assets (Huang et al., 2017) however this methodology has concluded that there is a significant fault rate threshold for temperatures of 31°C and greater for one of the routes investigated. Although even in the South East, 31°C is considered at the extreme end of the temperature ranges expected currently, the impact of climate change will increase the frequency of exposure to temperatures of this magnitude. It is therefore possible that routes further north may also begin to experience significant fault rates for track circuit assets in the future as a result of the impact of climate

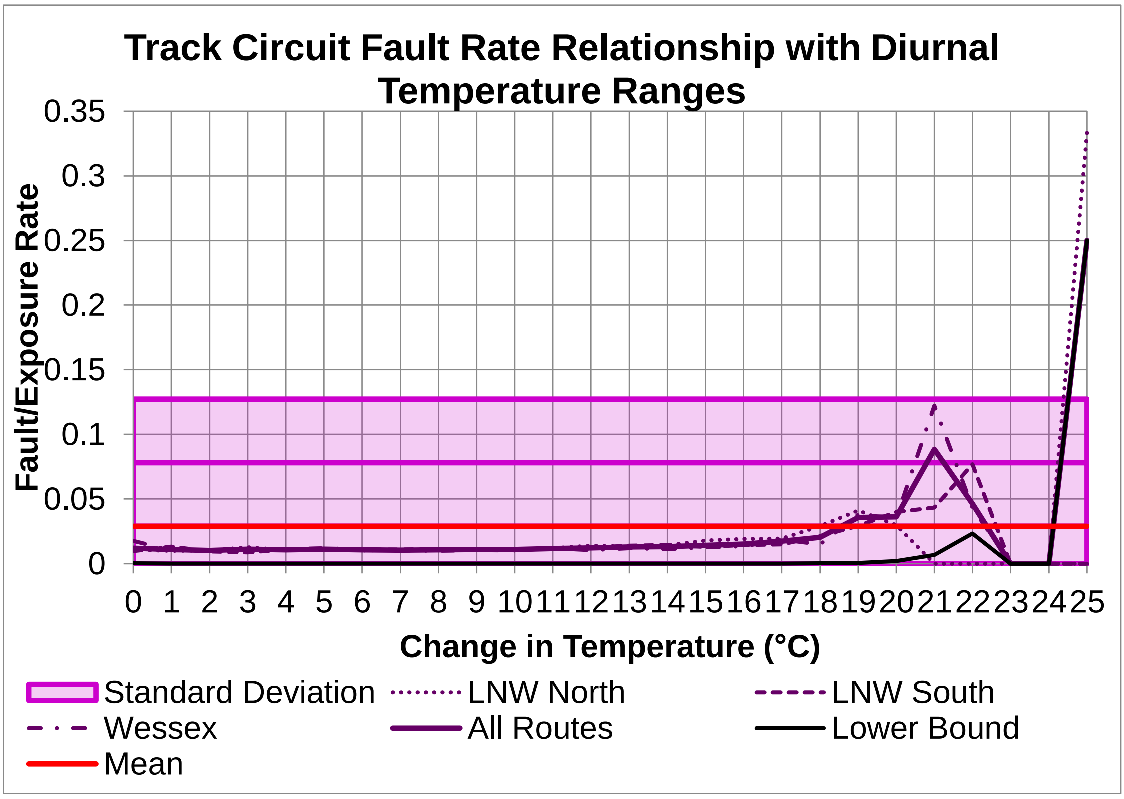

Figure 5.2: The relationship between the Diurnal Range of Temperature and Fault Rate for Track Circuits, illustrating the relationships between each of the routes and their significance relative to all three routes.

change. However, it is necessary to confirm this with further research. Analysis of the future probabilities of failure of track circuit assets under warmer future climates could easily be undertaken using a Monte Carlo Weather Cell analysis (Baker et al., 2010).

Recommendation 27: NR and researchers should further exploit the potential of Monte Carlo and stochastic analyses to better understand the probability of asset failure given certain weather conditions.

5.2.6.1 Track Circuit Condition Monitoring

No NR operational threshold was identified for track circuits and precipitation in previous research, this may be because condition monitoring measures are in place (RSSB, 2014). The impact of precipitation on track circuit faults has not been explicitly considered in previous literature despite track circuit performance being linked to environmental factors. One of these factors that relates to precipitation is the impact of the ballast degradation on the track circuit performance (de Bruin et al., 2017). This mechanism is linked to the presence of moisture which is dictated by the weather and condition of drainage in the vicinity of the asset. If the track ballast substructure is not free draining, then the amount of current that will leak from the track circuit is increased. However, this analysis found that precipitation variables did not have a significant impact on the fault rate of track circuit assets across the three routes.

5.2.6.2 Track Circuits and Future Technologies

The vulnerabilities of track circuits to weather are common knowledge to railway infrastructure mangers. This has resulted in NR deploying other technologies to determine the locations of trains on the network. On critical sections of the network track circuits have largely been replaced with Axle Counters. It is therefore interesting to note that Axle Counters fall just outside the criteria for significant assets (as defined in 4.2.1 and shown in Table 4.1) with an average of 1.88% of fault events across the three routes considered. However, Axle Counters are still less vulnerable to the effects of weather than track circuits which experience an average of 6.11% of fault events.

In addition, it has been found that automatic signalling systems are another reliable alternative which the DfT have encouraged NR to deploy more widely to support the continued upgrade of train position technologies (Department for Transport, 2014). Knowing the location of all trains on the network at any given time is crucial to continued safe and effective railway network operations. In fact, it also plays a vital role in traffic management and improving capacity on overcrowded railway networks. As a result this is an area of ongoing research and development to support the implementation of other future technologies for signalling systems more broadly (Durazo-Cardenas et al., 2014).

Recommendation 28: NR to continue to work towards improved digitally monitored and controlled signalling systems across the railway network.

5.2.7 Level Crossing Equipment

The challenge regarding LCs is that they are an interface between the railway network and road or pedestrian crossings and as a safety critical part of the railway network infrastructure their correct operation is crucial to protecting the public (ORR, 2016). LCs have not been found to have any conclusive relationships with any of the significant weather variables in the results presented in the previous chapter. Over the time period scrutinised it was found that LCs were a significant asset category because of the large number of fault events attributed to them. However, existing research has concluded that 90% of accidents at LCs have behavioural causes rather than being the result of asset or equipment failure. There is some reference to adverse weather affecting human responses at LCs in existing literature however this was not within the scope of the analysis conducted here. The impact of future climate change on human responses at LCs may however, be an avenue for future research considering the role of poor visibility that has been identified as a factor in many accidents at LCs (Khoudour et al., 2009). This is critical as it has already been established that weather related incidents on the railways can be a precursor for safety incidents (Bläsche et al., 2010).

Recommendation 29: The DfT should ensure that climate change research and preparations consider the impact on behaviour when using or interacting with transport networks. In particular, the effects on safety incidents and accidents as a result of adverse weather conditions and how these can be mitigated should be a topic of investigation.

Recommendation 30: NR to continue to identify the risks where the railway interfaces with the public to ensure that operations remain safe and this is not affected by climate change.

5.2.8 Interlocking Panel/Frame

As discussed in Section 4.4.5, Interlocking Panel/Frame fault records relate to legacy infrastructure that is still in operation. Their inefficacy is clear as they have featured in the selection of significant asset categories with more than 2% of the overall fault count. As this equipment is gradually being removed from the railway network the relationships found in this research are somewhat redundant. However, their unpredictability and maintenance requirements highlighted in this research support the business case for further replacement with modern digital systems.

It must be highlighted that the period analysed in this research is between 2006 and 2011, between then and the publication of this research, two CPs have passed. Therefore, for results from the type of analysis presented here to be of practical use it needs to be undertaken dynamically and relating to the current set of assets on the network, as discussed in Section 5.5.2. This will provide useful feedback on network asset performance and the efficacy of maintenance. In addition, this action would be supported with better collaboration with researchers and improved frameworks for the sharing of data for the purpose of conducting research to improve current practices and guidance.

Recommendation 31: NR and other data owners should improve the channels through which they share data for research with universities and other consultants.

5.2.9 Train Protection Warning System

TPWS assets are crucial to ensuring the safe operation of the railways by preventing trains from passing into sections of track that are already occupied by another train by forcing the train to reduce its speed. It has been observed in the previous chapter that no relationship with precipitation or temperature can be stated with confidence due to a small sample of fault events contributing to the significant fault rate. TPWS assets still have a significant number of fault events over the period analysed however, this research has not been able to confidently link these to weather.

Recommendation 32: NR and researchers should consider further investigation of the role of weather hazards in TPWS fault causation.

5.2.10 No Equipment

In the previous chapter the results of the analysis conducted in this research found that there was no relationship between this asset category and precipitation however there is a strong relationship between the No Equipment asset category and higher temperatures and diurnal ranges. This asset category has not been previously investigated, however this systematic methodological approach has highlighted this as a significant asset group with a strong relationship with higher temperatures. In addition, further interrogation of LNW North route faults under higher temperatures has identified that excluding fault event records that have no FCAD attribute the majority of those remaining are related to heat. The implementation of ESRs does not affect a particular asset or equipment however should this be classified as a fault? The results of this analysis may have only picked up on a practice for one route, further investigation and input from NR would be needed. However, even if recorded as a fault across all routes, there is a sufficient quantity of records that these types of faults should be recorded more explicitly as ESR incidents, the reporting practices of fault events is discussed in more detail in Section 5.5.2.1.

5.2.11 Circuit Breakers

The analysis conducted found that Circuit Breakers had a significant relationship with both higher temperatures and higher daily total precipitation. Although there was a significant relationship identified, investigation of the fault event records indicated that weather may not have been the direct cause of many of the faults. LNW South had the most faults recorded for circuit breakers and analysis of the FCAD attribute data, enabled a categorisation of suspected causes of the faults. The categories ranked by frequency can be seen in Table 5.2 which shows that weather is not a significant cause listed in the fault records. Excluding those categories which have no useful information in them, the largest category is “Bird”, where a bird has been listed as the cause of the fault to the circuit breaker asset. Some examples of the text in the FCAD attribute are:

- At Bridge 66 burn marks on catenary (suspect bird strike).
- Bird in contact with pulley wheel at structure G98/09.
- Bird strike at north end of carriage shed.

Table 5.2: Causation Categories for Circuit Breaker Fault events in LNW South.

Causation Category	***Fault Event Count***
Blank	307
NFF	284
Unknown	249
Bird	186
Tripped	130
Other	107
Burn Marks	32
Vegetation	27
Weather	18
Fuse	14
Pan	14
Debris	11
Overload	10
Power	7
Trespass	3
Animal	2
Total	1401

Many of the more descriptive free text inputs include the mention or reference to a structure, as indicated here. It is possible that many of these bird strikes occur when birds are seeking shelter from the rain. Although this is not a direct link to weather hazards it is an indirect relationship whereby weather hazards affect animal behaviour. It may be possible that protection of these assets from birds and other animals may be necessary to prevent this type of fault event.

Recommendation 33: NR to investigate the number of bird strikes causing circuit breaker faults and investigate possible protection methods.

5.3 Failure Thresholds

Whilst developing this methodology a review of NR's current practice highlighted the importance of thresholds as a tool to support decision making processes. Therefore, following the individual detailed results for each of the significant asset categories a review of the fault rate thresholds found is presented in this section alongside existing failure thresholds which have previously been presented in Section 2.5.1. Some of the asset categories with existing failure thresholds have not been investigated in this research as they were determined to be ‘Not Significant Asset’ (NSA) categories as they accounted for less than 1% of the total fault event counts on average across all routes as described in Section 4.2.1.

5.3.1 Higher Temperatures

It has been reiterated in this document that research into the effects and impact of higher temperatures on railway infrastructure is the most well understood relationship at present. This is predominantly due to the fact that higher temperatures affect the most congested sections of the railway network, as London and the South East experience the highest temperatures across the network. Therefore, higher temperatures have the greatest impact in terms of incident numbers, delay minutes and also cost, of any weather variable. Despite this, it can be seen in Figure 5.3 that this research has provided further insights into the effects of higher temperatures on railway infrastructure assets.

Not only has this highlighted the significance of track asset failures and the validation of this methodology through the similarities between the approach taken here and the existing thresholds already used in practice. Many of the failure thresholds previously presented for Command, Control and Signalling (CCS) asset categories are no longer in this figure as the thresholds relating to diurnal ranges have been transferred into a separate table and shown later in Section 5.3.3. However, this research has found that many of these asset categories which fall into CCS have a significant fault rate threshold and relationship with higher temperatures. These are relationships which have not previously been identified. These assets are managed through generic guidance for seasonal management of asset and there is no specific guidance for assets in this grouping. The quality of the guidance document has not been reviewed as part of this research however, NR should have a review process in place to update these as understanding of relationships, development of operational responses and prevention measures are improved.

Recommendation 34: The DfT, ORR and RSSB should support NR in developing asset specific guidance for maintenance and operational processes which considers weather hazards including seasonal management.

Recommendation 35: NR and researchers should conduct threshold exceedance frequency analysis to determine the probability that assets will fail under future climate scenarios, particularly where there are gaps in existing knowledge.

Relating to higher temperatures there is only one asset category that has a suspected impact without any NR standard or other research associated, this group is S&C or Points (P.W.). It was not found that this asset category has a relationship with higher temperatures, therefore this is a specific asset group that will need further exploration of the role of higher temperatures in its failure. However, the relationships between S&C and lower temperatures has been confirmed in this research as discussed in the next section.

High Temperature Thresholds

TSI	Railway System	Failure Threshold High	Failure Threshold V.High	Fault Rate Threshold High	Fault Rate Threshold V.High	NR Standards	Other Research	Impact
CCS	Signalling ATP	>18°C	>20°C	NSA		General Documentation 365 Weather Management - Summer	None	Suspected Impact
	Signalling	>20°C	>26°C	>29°C	NRF			
	Telecoms	>20°C	>26°C	NSA				
	POE			>31°C	>32°C			
	Remote Control			NSA				
	Signalling Control			NSA				
	Track Circuit			NCRF	NRF			
	PETs			NSA				
	TPWS			NCRF	NCRF			
Energy	3rd Rail	>26°C		NSA		General	None	Suspected Low Impact
	Signalling Power	>26°C		NSA				Unknown
	OLE	>22°C	>26°C	NSA		Specific		Av. 550mins per year
	Traction Power	>22°C	>23°C	>29°C	>34°C	General		Unknown
Infrastructure	Track	>24°C	>30°C	>30°C	>31°C	Specific	SFT increase from 21C	Av. 26758mins per year
	S&C			NRF	NRF	Unknown	None	Suspected Impact
	Earthworks			NSA		General		Unknown

Figure 5.3: High Temperature failure threshold found in the TRaCCA project compared to the Fault Rate thresholds resulting from this research.

NSA = Not a Significant Asset NRF = No Relationship Found NCRF = No Clear/Consistent Relationship Found

Low Temperature Thresholds

TSI	Railway System	Failure Threshold High	Failure Threshold V.High	Fault Rate Threshold High	Fault Rate Threshold V.High	NR Standards	Other Research	Impact
CCS	Signalling ATP			NSA		General Guidance GE GN 8628 - Guidance on preparation and operating during winter	None	Suspected Impact
	Signalling			<-5°C	NRF			
	Telecoms			NSA				
	POE	<-4°C	<-7°C	NCRF	NRF			
	Remote Control			NSA				
	Signalling Control			NSA				
	Track Circuit			NRF				
	PETs			NSA				
	TPWS			NRF				
Energy	3rd Rail			NSA		Specific Guidance NR/WI/ELP/3091 DC electrified lines work instructions GE GN 8628 - Guidance on preparation and operating during winter	None	Suspected High Impact
	Signalling Power			NSA				Unknown
	OLE	<-7°C		NSA			< -14C train pantographs have problems raising.	Suspected Impact
	Traction Power			NRF				Suspected Impact
Infrastructure	Track			NRF		Specific	None	Av. 150 Broken Rails per year.
	S&C	<0°C	<-4°C	<-4°C	<-5°C			Suspected Impact
	Earthworks			NSA				Suspected Impact

Figure 5.4: Low Temperature failure threshold found in the TRaCCA project compared to the Fault Rate thresholds resulting from this research.

NSA = Not a Significant Asset NRF = No Relationship Found NCRF = No Clear/Consistent Relationship Found

5.3.2 Lower Temperatures

It has previously been discussed that there is limited understanding of the impacts of lower temperatures on railway assets. This research has provided further understanding of the effects of lower temperatures on railway infrastructure assets as shown in Figure 5.4. Previously TRaCCA identified that only three asset categories of the physical infrastructure groups have known thresholds relating to low temperatures. OLE was not considered to be a significant asset category during this research but the other categories both relate to points, S&C and POE. No conclusive threshold for POE assets was found in this research due to the low number of fault events experienced at these temperatures. However, the findings from this research support those thresholds previously established for S&C considering the differences between the approaches which have been highlighted throughout this chapter but are discussed in Section 0. However, this finding reiterates the need for further work to be conducted to understand how we can better protect S&C assets from low temperatures.

A previously unidentified relationship has been established in this research, between signals assets and low temperatures. Although signals are covered in the general guidance for winter preparedness there is a suspected but unquantified impact of signal failures at low temperatures. As discussed in Section 5.2.4 signals are particularly sensitive to extremes in temperature compared to other assets but are unaffected by changes in temperature. The reasons for this needs to be further investigated to establish the causation of cold temperature signal faults.

No evidence was found to support the idea of 3rd Rail asset failures as a result of low temperatures despite these faults being suspected to cause a high impact on operations. Both the omission from this research and the reason for the magnitude of the suspected impact are related. 3rd rail assets are predominantly present in the south east and have therefore mostly been missed in this research but would be captured if this methodological approach were expanded.

Recommendation 36: NR and researchers should conduct impact assessments where assets failure is suspected to have a high impact on railway network operations (e.g. 3rd rail and low temperatures).

5.3.3 Diurnal Ranges

The failure thresholds collated in the TRaCCA project, the thresholds for diurnal ranges were presented in combination with the table for higher temperatures. It was found that a number of the significant asset groups analysed were susceptible to the effects of diurnal ranges, so these results have been presented separately in Figure 5.5. Those CCS assets that have been found to be significant in this research have had their relationships confirmed with the fault rate results presented here. Except for TPWS faults, which could not be confirmed. In addition to supporting existing relationships, this research has found that S&C have a relationship with small diurnal temperature changes. This links with S&C's associated failure mechanisms in low temperatures as previously discussed in Section 5.2.2. However, the TRaCCA project found no evidence of the impact of these faults. Now that this relationship has provided a threshold, an exceedance frequency analysis can be undertaken to determine the impact of consistently low daily temperatures.

Recommendation 37: NR or researchers should undertake threshold exceedance frequency analysis to determine the impact of small diurnal ranges and S&C faults and extrapolate these results to consider future climate change.

Recommendation 38: NR and researchers to ensure that diurnal temperature ranges are considered when planning maintenance or forecasting faults.

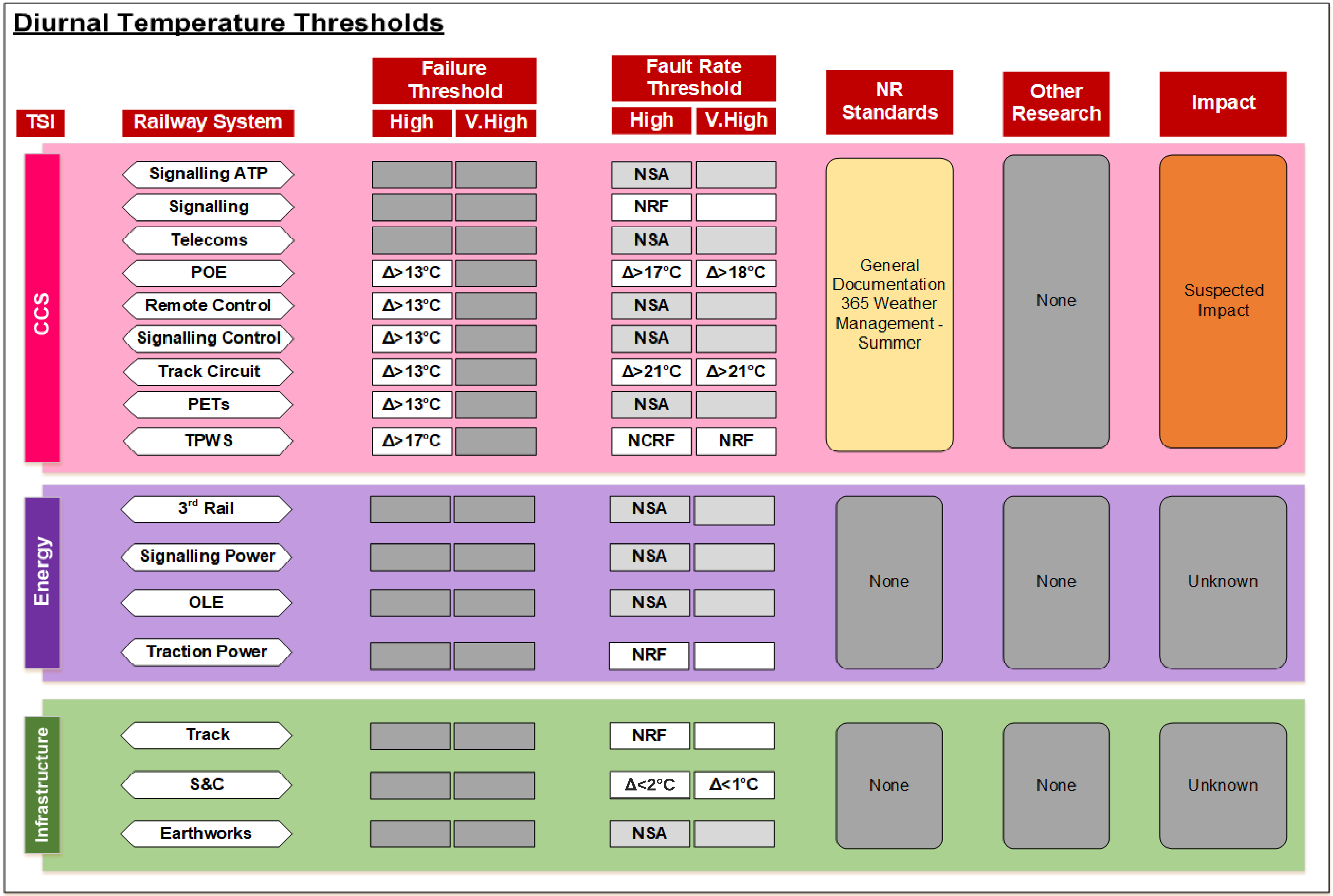

Figure 5.5: Diurnal Temperature change failure threshold found in the TRaCCA project compared to the Fault Rate thresholds resulting from this research.

NSA = Not a Significant Asset NRF = No Relationship Found NCRF = No Clear/Consistent Relationship Found

Precipitation Thresholds

TSI	Railway System	Failure Threshold High	Failure Threshold V.High	Fault Rate Threshold High	Fault Rate Threshold V.High	NR Standards	Other Research	Impact
CCS	Signalling ATP			NSA		General Guidance GE RT8000-M3 - Managing incidents, floods and snow	None	Suspected Impact
	Signalling			NCRF	NRF			
	Telecoms			NSA				
	POE			NRF				
	Remote Control			NSA				
	Signalling Control			NSA				
	Track Circuit			NRF				
	PETs			NSA				
	TPWS			NCRF	NCRF			
	Cable Route	>10mm/hr		NSA				
Energy	3rd Rail			NSA		Specific Guidance NR/WI/ELP/ 3091 DC electrified lines work instructions	None	Suspected High Impact
	Signalling Power			NSA				Suspected Impact
	OLE							
	Traction Power	>15mm/hr		>22mm/ day				
Infrastructure	Track	>25mm/ day		NCRF		Specific Guidance NR/L3/TRK/ 1010 - Management of responses to extreme weather conditions at structures, earthworks and other key locations	None	Suspected Impact
	S&C			NRF				Suspected Impact
	Embankments, Cuttings And Rock Cuttings	>5mm/ 3hr, >15mm/ day, >50mm/ 15days	>20mm/ day, >100mm/ 15days >20mm/ day	NSA				In 2010/11 there were 61894 delay minutes due to civil engineering, structures, earthworks and building failures

Figure 5.6: Precipitation failure threshold found in the TRaCCA project compared to the Fault Rate thresholds resulting from this research.

NSA = Not a Significant Asset

NRF = No Relationship

Found NCRF = No

Clear/Consistent Relationship

Found

5.3.4 Precipitation

As previously discussed, there is little consideration for the effects of precipitation on railway infrastructure assets beyond geotechnical failures or flooding. Therefore, there are very few thresholds relating to this weather hazard. Thresholds for Earthworks infrastructure feature heavily in existing guidance as shown in Figure 5.6. These asset types were not specifically included in the data utilised in this research. This is because detailed faults relating to earthworks assets are stored and managed in a separate management system.

Cable routes feature under precipitation thresholds as shown in Figure 5.6 however, these were not found to be a significant asset in this research. The remaining two assets with precipitation thresholds identified by TRaCCA were both found to be significant asset categories in this research However, no clear relationship was found between the fault rate of track (P.W.) assets and precipitation. Therefore, the only asset category with a previously identified failure threshold relating to precipitation which was also found to have a significant relationship with the fault rate is circuit breakers, labelled as traction power in these figures. The thresholds have different time basis' where previous thresholds relate to the magnitude of precipitation in the space of an hour and this research was only able to investigate daily precipitation totals. Although this asset category has specific guidance relating to the management of weather hazards relating to precipitation, the impact of faults of Traction Power assets is unknown.

Recommendation 39: NR and researchers to understand the role of precipitation intensity and Traction Power faults and quantify the impact of these faults.

There are two asset categories which were identified as significant where their relationship with precipitation could not be clearly defined with a threshold. These two asset categories fall into CCS and are Signals and TPWS and have a suspected impact on the railway network's operations. However further analysis of these, beyond the scope of this research, would be needed to confirm these relationships and associated failure mechanisms. In addition, further analysis would be needed to quantify the suspected impact reported in the TRaCCA results.

Recommendation 40: NR and researchers to further investigate the relationships between precipitation and CCS assets particularly TPWS and Signals and quantify the impact of failures caused by precipitation.

5.4 Critique of Methodology

So far, this chapter has discussed the direct results and findings from the analysis conducted in this research. While the implications for the infrastructure manager and facilitation of future work are discussed later in this chapter. The methodology has been developed with consideration of NR's current practices, approaches in current research as well as the data available at the time of analysis. The systematic approach developed has made few assumptions and has therefore been able to indiscriminately explore the relationships between railway assets and weather hazards. In doing so the results of the analysis conducted in this research look beyond the established areas of investigation to identify those lesser known relationships and strengthen the existing base of knowledge. By utilising observed gridded weather datasets and systematically considering all asset types the method developed is also robust and of a suitable granularity considering the data available. Furthermore, the results from the analysis conducted have been validated through comparison with existing thresholds proving its capabilities. Despite this success the methodology has areas which could be improved if it were to be repeated or applied in industry, these areas are explored in the following sections.

5.4.1 Relationship Profiles

Part of this research attempted to develop a simple and effective way of identifying relationships between asset faults and weather hazards. Therefore, the Relationship Profiles were developed for all weather variables and asset categories. However, only those for relationships between key temperature variables and significant asset categories were presented in the previous chapter alongside the detailed results. The relationship profiles for the key precipitation variables were omitted as the approach was oversimplified and returned inaccurate results. The large ranges of total precipitation (whether daily, weekly or monthly) and the decreasing frequencies of measurements over the range meant that using a static precipitation range and fixed quartiles created misleading results. Consequently, nearly all of the relationship profiles returned, were either -1 or 0, incorrectly representing the relationships. In order to utilise this simplified approach, the ranges used for precipitation would need to be specific to the locations analysed. For example, rather than using the maximum precipitation measurements across all routes, the maximum recorded precipitation for the route should be applied. In addition, it may be beneficial to limit the range temporally as well, to a year or a season. Furthermore, to provide accurate results outlying values should be removed to reduce the skewedness of the resulting relationships.

The placement of quartiles in order to identify the relationship or trend of the relationships provides a simple but rather crude attempt to observe trends. In order to apply this simple method whilst also ensuring the accuracy of the results the size of the range of precipitation measurements and the interquartile ranges utilised should be calculated with greater care. The method provided reliable results for the key temperature variables however, which successfully provide a simple overview of the relationship profiles for each asset category. Therefore, with the improvements discussed in this section, this approach can be used to give a simple overview of relationships from which more detailed investigation can be directed.

5.4.2 Comparison Across Routes

This analysis sought to capture relationships between asset faults and key weather variables irrespective of a route's regional climate, which were suitably eliminated as a factor in the causation of faults through the normalisation of the data explained in the methodology. Individual analysis of each route was conducted successfully and reliably when the lower bound excluded fault events that had occurred just once for the route in question. However, when this analysis was broadened for the comparison of routes and the identification of observable thresholds the lower bound used to exclude single data points at route level was no longer appropriate. If this methodology was applied in the future this could be adjusted with ease to ensure that data points with only one event for any of the routes were excluded from the analysis.

This methodology has successfully taken into account the differences in the weather experienced in each region. However, there are a number of aspects this methodology has not captured or excluded, including; regional geology, urban or rural factors, maintenance routines and the number or specification of each asset within a route. Where there have been great differences between routes one or more of these factors may be the reason. For example, the weather data applied excluded Urban Heat Island

(UHI) effects however the analysis did not account for this. Therefore, differences between fault rates across the routes investigated may have been impacted by the proportion of each route within UHIs. This is just one example, however it is still reasonable to conclude that the results of this analysis highlight assets that are more susceptible to the effects of weather hazards. To confirm this, the methodology would need to be expanded to encompass all national routes as would be the case if this analysis were to be applied in an operational context. The relevant managing parties would be able to better understand the outputs with the additional context of each route, which would need to be considered if these results were used to inform asset design. However, the method developed took reasonable measures to eliminate the impacts of variations across routes, and providing that the results presented here are viewed within this context they are still adequate to inform operational and decision making processes.

5.4.3 Threshold Comparison

The thresholds compiled by the TRaCCA Project are the most comprehensive and concise presentation of railway asset thresholds to date. As a project aiming to make their findings accessible to the wider European railway infrastructure network managers the assets were categorised in accordance with the TSIs. From the data that was available for this analysis the asset categories were formed systematically from the asset attributes recorded (parent group/subgroup/FMS Suffix) however these categories did not directly match with those outlined by TRaCCA. This has not been deemed to have a significant impact on the outputs of this research as the asset categories were overlaid as closely as possible and any differences highlighted in the presentation of the results in Section 5.3.

The threshold comparison presented in Section 5.3 does not compare like for like thresholds. The thresholds used by NR relate to the number of daily failures as a percentage of the average number of failures on a “normal” day. The high threshold refers to weather magnitudes which correspond with between 200% and 300% of daily failures and the very high failure threshold refers to greater than 300% of average daily failures. These thresholds use the current railway operability as a point of reference which limits the ability to extrapolate these findings to conduct future frequency analysis (RSSB, 2014). Considering that the main measure of performance for NR and other rail industry stakeholders is operability and punctuality this seems to be the most obvious measure to use. However, this approach is limiting when investigating the fundamental causes of asset failures to improve railway network resilience.

By comparison, the thresholds established in this research to the weather variable magnitude when the fault rate for an asset is significant, where the fault rate refers to the number of faults under certain climatic conditions relative to the frequency of exposure to these. This approach does not make reference to the operations of the railway but only to the probability of failure of an asset when exposed to certain climatic conditions. Despite the differences between the defined thresholds, they are broadly in line with one another thus validating the results of this analysis and the methodological approach developed. In addition, the thresholds developed in this methodology still enable analysis of future frequencies of climate parameters unlike thresholds relating to operational performance.

5.4.4 Threshold Analysis

The results of this methodology require some interpretation to understand in part due to the use of a basis of one day which does not allow for the precise point of failure to be considered in this analysis. Although threshold analysis approaches are not exact or detailed they provide an average beyond which the fault rate of a particular asset becomes significant. Some individual assets may fail before this threshold and even if the cause is hazardous weather this is likely due to the condition of the asset as well (Dobney et al., 2009). However, it was found in Chapter Two that thresholds are often used in existing NR practices as well as in academic research as they provide a useful indication of when operational responses or asset maintenance are likely to be required. Furthermore, increasing the temporal resolution of the weather data utilised in the analysis would also improve the attribution for the dominant weather variables at the root cause of fault events however this further complicates analysis and the fault event records do not accurately record the precise time of the fault occurring but instead the time the fault was reported, which could be several hours after the incident as many faults are reported by train drivers.

To further address this issue the development of a more advanced methodology which employs the concepts of machine learning or artificial intelligence would provide a truly data-driven approach with little, subjective human input. However, even the interpretation of results from these methods and their creation are subject to the influence of human error. Regardless, this type of approach would improve the accuracy of the results obtained however employing this type of methodology would require significant improvements in the fault event data, asset condition data or other infrastructure data reported by NR before this approach could be employed. The use of more advanced statistical, data-driven or even automated methods is certainly an improvement to consider in the future.

5.5 Further Methodological Development and Application

The limitations of this methodological approach have been outlined as well as sufficient validation to suggest this approach can be utilised to inform actions to improve the resilience of railway infrastructure assets. Some of the steps to improve this methodology have been discussed throughout this chapter and the previous chapter. However, the methodology developed is scalable and tractable and this section illustrates improvements that can be made to direct future operational applications and research.

5.5.1 Towards Weather Hazard Mapping

This research has applied gridded weather observation data to railway fault events at a greater resolution than is currently used for weather and resilience analysis within NR. Despite the improved resolution of weather variables utilised in this methodology it is possible that this is still not adequate to enable the observation of some relationships between certain weather variables and railway infrastructure assets. The methodology has been developed in such a way that the range of weather variables could easily be expanded and the resolution of weather data could be improved. This section details the future possibilities when utilising this methodology with the intention of creating weather hazard mapping capability to inform pre-emptive maintenance and renewals to improve the resilience of assets.

5.5.1.1 Expanded Weather Variables

The utilisation of this methodology can be expanded to include other weather types, such as wind, lightning or coastal events. This of course is dependent upon the quality of weather data that can be applied but could be possible if sufficiently accurate weather data is acquired. In addition, it would be possible to conduct a seasonal analysis if the weather data were handled appropriately. This may expand the current understanding of the asset relationships with this wider selection of weather variables as well as inform understanding of failure mechanisms.

Recommendation 41: NR and researchers to expand analysis of weather impacts on railway infrastructure to include all meteorological aspects.

In addition, this methodology could be further developed to consider the impact of combinations of weather variables and the hazards they cause when these adverse conditions are combined. The complexity of the hazards and their impacts is largely to be blame where little research has been conducted to quantify their effects on GB's railways. A line side fire for example, may not explicitly be the consequence of high temperatures; other causes include arson and accidental causes, where the latter is more likely when prolonged high temperatures have led to vegetation desiccation along the railway line. This demonstrates that it is not just the role of temperature that creates a greater risk of lineside fires, it is also the role of precipitation, or indeed the lack of. It is the intricacies of these processes that result in weather variables impacting the railway network that complicates analysis, but through their identification it has been highlighted that the railways are affected by hazards that are a result of the actions of a combination of weather variables.

Recommendation 42: Meteorologists and researchers to develop metrics which can be applied to consider the combined effects of weather variables, allowing for the analysis of storms etc. on national infrastructure.

5.5.1.2 Extreme Weather Events

This research investigated the relationships between asset faults and weather over a period of five years. Despite the reasonable temporal range of the data utilised independent weather events stood out in the results. For example, the cold and snowy winter of 2010/11 and the wet July day in the south of England in 2007. Investigating the events over the course of a particular weather event has been a methodology that has previously been used in research (Ferranti et al., 2018; Jaroszweski et al., 2015). Although this method was discounted for this particular research which sought to identify trends and thresholds, it is valuable to investigate independent, extreme weather events. This approach enables a better understanding of the development of events leading to faults or failures of railway infrastructure, giving a detailed impression of what happened. This method is particularly helpful for supporting the identification of failure mechanisms however it is often limited to smaller geographic areas than analysed in this methodological approach. In addition, extreme weather events provide an opportunity to evaluate the operational response of NR's EWAT and recovery from the adverse impacts on the railway network. This is only beneficial if reflection leads to lessons learnt and these are incorporated into standards and processes (Nolte and Rupp, 2011).

Recommendation 43: Meteorologists and researchers to continue analysis of individual extreme weather events to further develop understanding of extreme weather events on national infrastructure networks as well as failure mechanisms of infrastructure asset categories.

Recommendation 44: The DfT should work with national transport infrastructure managers and support the development of a multimodal Extreme Weather Event database. Each transport infrastructure manager should be encouraged to have a robust extreme weather event and impact recording process to retain and understand the development of network disruption.

Recommendation 45: The DfT, ORR and RSSB to ensure NR have a robust procedure to review the operational response to extreme weather events to ensure that lessons are learned, and improvements made where necessary.

This analysis highlighted the significance of a number of extreme weather events which are known to have occurred throughout the period analysed e.g. Points and winter weather. Therefore, this suggests that there is value in conducting assessments based only on extreme events, providing there is enough data. This could be facilitated through the application of extreme weather indices (Zhang et al., 2011). The 27 core extremes indices previously developed can be seen in Table 5.3. The extremes indices are determined by assessing probability of occurrence of given quantities or on absolute or relative threshold exceedances (relative to a fixed climatological period). In addition, some of the extremes indices also capture duration and intensity of extreme events (Stocker et al., 2013). However, these are global extreme indices, but these will vary from region to region. For example, there are many parts of the world which experience above 25°C nearly all year, however the summer in other regions is only considered to be for 6 months. Other indices do use percentiles of the weather experienced in a region, therefore making the measurement relative to the weather usually experienced in the region.

As this research has investigated weather variables broadly and extreme events are usually infrequent, this level of detail is not highlighted in the current research, however the methodology could be very easily adapted to undertake this type of analysis. The Core Extreme Temperature and Precipitation Indices that have previously been developed as global guidelines could be applied to this methodology to identify extreme weather events. These extreme indices could be adapted for analysis of a specific country/region and used to conduct a threshold exceedance analysis similar to previous work discussed in Section 2.6.1.2 (Palin et al., 2013). The fault rate for each asset category could then be calculated for where these extreme index thresholds are surpassed. This would provide a measure to extrapolate future fault rate projections for different asset groups. By undertaking this focused analysis this would inform NR's WRCCA strategy as extreme weather events are expected to become more frequent under future climates.

Recommendation 46: Meteorologists and researchers should develop national and possibly regional extreme index values to facilitate future research for climate impact analysis.

Recommendation 47: NR and Researchers to conduct threshold exceedance analysis using extreme indices to identify fault rates for different asset categories during extreme weather events and extend this to project the probabilities of future faults.

Table 5.3: The Core Extreme Temperature and Precipitation Indices (Zhang et al., 2011; Stocker et al., 2013).

ID	Indicator Name	Indicator Definitions	Units
TXx	Max Tmax	Monthly maximum value of daily max temp	$^{\circ}$C
TNx	Max Tmin	Monthly maximum value of daily min temp	$^{\circ}$C
TXn	Min Tmax	Monthly minimum value of daily max temp	$^{\circ}$C
TNn	Min Tmin	Monthly minimum value of daily min temp	$^{\circ}$C
TN10p	Cool nights	Percentage of time when daily min temp <10th percentile	%
TX10p	Cool days	Percentage of time when daily max temp <10th percentile	%
TN90p	Warm nights	Percentage of time when daily min temp >90th percentile	%
TX90p	Warm days	Percentage of time when daily max temp >90th percentile	%
DTR	Diurnal temp range	Monthly mean difference between daily max and min temp	$^{\circ}$C
GSL	Growing season length	Annual (1st Jan to 31st Dec in NH, 1st July to 30th June in SH) count between first span of at least 6 days with TG>5 $^{\circ}$C and first span after July 1 (January 1 in SH) of 6 days with TG <5 $^{\circ}$C	days
FD0	Frost days	Annual count when daily minimum temp <0 $^{\circ}$C	days
SU25	Summer days	Annual count when daily max temp >25 $^{\circ}$C	days
TR20	Tropical nights	Annual count when daily min temp >20 $^{\circ}$C	days

Table 5.1: The Core Extreme Temperature and Precipitation Indices (Zhang et al., 2011; Stocker et al., 2013).

ID	Indicator Name	Indicator Definitions	Units
WSDI	Warm spell duration indicator	Annual count when at least six consecutive days of max temp > 90th percentile	days
CSDI	Cold spell duration indicator	Annual count when at least six consecutive days of min temp <10th percentile	days
RX1 day	Max 1-day precip amount	Monthly maximum 1-day precip	mm
RX5 day	Max 5-day precip amount	Monthly maximum consecutive 5-day precip	mm
SDII	Simple daily intensity index	The ratio of annual total precip to the number of wet days (≥1mm)	mm/day
R10	No. of heavy precip days	Annual count when precip ≥10mm	days
R20	No. of very heavy precip days	Annual count when precip ≥20mm	days
CDD	Consecutive dry days	Maximum number of consecutive days when precip <1mm	days
CWD	Consecutive wet days	Maximum number of consecutive days when precip ≥1mm	days
R95p	Very wet days	Annual total precip from days >95th percentile	mm
R99p	Extremely wet days	Annual total precip from days >99th percentile	mm
PRCP TOT	Annual total wet-day precip	Annual total precip from days ≥1mm	mm

5.5.1.3 Greater Resolution of Weather Data

As each asset or even each individual component experiences slightly different conditions the resolution of the weather variables used in this research may not be adequate to observe the detail of these relationships. This is partly because of the spatial resolution of the data but also because the temperatures used are daily ambient air temperatures rather than equipment temperatures. This is particularly influential when establishing relationships for electrical equipment which may generate its own local heat. By conducting experimental analysis of different railway infrastructure assets and their various components, it is possible to establish the specific relationship each asset type has with any given weather variable. Improving understanding of these individual relationships can help inform design of protective measures or the assets themselves to make them more resilient to the effects of weather in the future. This has previously been done for track temperatures (Hunt, 1994), however other studies have concluded this relationship is more complicated than previously understood (Chapman et al., 2008).

Recommendation 48: NR and researchers should conduct experiments on equipment to identify each asset category's relationship with weather variables.

The temporal resolution of the weather data applied in this methodology could also be improved. The smallest temporal basis applied in this research was that of one day which was chosen in order to develop the methodology which could then be expanded further in the future for both temperature and precipitation. Although the results returned from the analysis conducted here has built upon current understanding it is possible to further develop this by including hourly weather readings. This would enable analysis of the impact of precipitation intensity on railway infrastructure faults

(Jaroszweski et al., 2015), providing a more reliable significance threshold for both precipitation and temperature. This would also expand the existing methodology to be able to investigate the effects of heating rates of elements of the railway and mitigate the effect of localised shading on results (Chapman et al., 2008; Chapman and Bell, 2018).

Recommendation 49: NR and researchers to conduct analysis of the impact of precipitation intensity on railway infrastructure considering future changes to intensity of precipitation.

5.5.1.4 Weather Hazard Mapping

In order to identify all of the locations on the GB rail network that experience regular or extreme failures as a result of weather, hazard mapping can be used to bring together existing knowledge of all vulnerable locations on the network. For example, utilising flood maps or hydrological models will provide insight when used alongside a spatial analysis of historic fault events. This type of spatial analysis would also inform a criticality analysis identifying those locations of greatest priority for the implementation of adaptation measures. The development of spatial hazard models would improve the identification and understanding of failure mechanisms associated with railway asset faults as well as providing scope to conduct useful climate change impact assessments. It is therefore necessary for NR to integrate their different reporting, modelling and analysis tools so that all relevant information is available in order to inform hazard mapping and modelling and appropriate renewals, enhancements or adaptation methods are taken.

Once NR have collected several years' (to allow adequate quantification of seasonal effects) of route weather monitor observations, this data could be utilised in the methodology developed here to provide a further level of spatio-temporal resolution to the results. To facilitate this, the route weather monitor observations would need to undergo interpolation to produce gridded observations specifically for the railways. Utilising gridded railway weather observations and national gridded observations in conjunction would highlight localised micro-meteorological weather features, further downscaling the level of analysis possible. This would enable a high resolution of weather hazard identification relating to the impacts of weather on railway infrastructure assets. Previous research has also recommended that railway infrastructure managers utilised weather hazard mapping for the ultimate purpose of informing adaption and improving network resilience (Network Rail, 2017b).

Recommendation 50: NR should engage with meteorologists and researchers conduct a trial study of the weather data collected from the Scotland route weather monitors and develop gridded railway observations to identify specific localised hazards.

Recommendation 51: NR should develop weather hazard mapping tools and embed these within their decision support systems alongside other relevant information sources (e.g. hydrological models).

5.5.2 Towards Fault Forecasting and Predictive Maintenance

The previous section explained how this methodology can be further developed to move towards a system whereby NR could forecast weather hazard locations. In order to develop this further to predict where assets may fail in the near and distant future, NR need to improve their fault reporting practices. One of the challenges in this research was the interpretation of fault event records considering the inconsistent recording practices. In some instances, it was possible to further interrogate the fault event records to confirm if the cause of the fault was related to weather and also to indicate possible failure mechanisms. Overall, it has been identified that improvements to fault recording classification can improve the output of analysis as well as improving the depth of understanding that can be gained. In addition, these improvements could enable NR to adopt a truly pre-emptive strategy through operational fault forecasting and future fault projections.

5.5.2.1 Fault Reporting

One of the main challenges during this research was regarding the data handling of fault event records which required extensive cleaning and careful consideration in order to develop the methodology. In addition, this research sought to highlight the value of the big datasets that Infrastructure Managers like NR create and own, in addition to illustrating how value can be add to these data assets. It would be practicable, of value to the railway industry and improve the quality of the analysis conducted here if the recording of fault events was more consistent and complete.

Whilst identifying the significant asset categories it became apparent that there was a lot of overlap between the different categories particularly those attributed to the Unknown parent asset group. The FMS Suffixes of these asset categories often repeat those for assets attributed to other parent assets. For example, the track boundary measure asset category, which was identified as significant, has an additional asset category attributed to the Unknown Parent Asset Group. Further investigation would need to be undertaken to confirm that these are indeed used to record the same type of fault. It would be beneficial if this was supported with confirmation from NR of their fault reporting practices.

As well as duplicate asset categories there are also inconsistencies within the attribution of fault events to the correct asset category. For example, faults relating to

Boundary Measures have been identified within the significant asset category Track (P.W.) despite having a dedicated asset category track unknown: boundary measures which was also found to be significant. The extent of the impact of these errors in recording fault events has not been explicitly identified within this research, however improving fault event recording practices moving forwards would only improve the results found utilising this methodology.

Reporting errors for the attribution of fault events is enabled by the inclusion of similar component categories within more than one asset category (Parent/Sub/FMS Suffix/Component). It would be recommended that NR streamline their reporting processes to ensure that there is clarity and consistency not only for the purposes of data analysis, but also for operational and reporting efficiency. Although the Component 1 & 2 attributes for the fault events were not used to define asset categories, they were used to identify failure mechanisms or susceptible components of an asset group. Therefore, this information could be very valuable if this methodology were to be developed further once the quality of this reporting has been improved. In some instances, even the use of the component attributes did not make it clear what the fault or failure mechanism had been at the time of reporting. In addition, it was sometimes possible to identify further information from the final FCAD attribute for the fault event records. Often there was not sufficient clarity for this to form a useful aspect of the interpretation of the results, in part because this free text column was often left blank or referred to other notes that were not available for this analysis. The information in this FCAD attribute may be more useful for analyses such as this if it were divided into four individual attributes that remained free text input. By providing a greater opportunity to freely record one or all of these components there could be a better understanding of the causation of and failure mechanisms which could inform further analysis. The implementation of digital technologies for efficient and accurate reporting could support the implementation of streamlined asset categories or fault attributes whilst retaining the ability to capture detailed reports. NR's "My Work App" would be the appropriate interface for this level of detailed reporting which enables efficient working whilst retaining the accuracy of data.

Recommendation 52: NR should ensure that their user interfaces with the FMS platform enable greater capture of detail relating to fault events, with the aim to provide an intuitive and effective recording practice.

Recommendation 53: NR to review current reporting practices to ensure that fault attribution is streamlined for clarity of data at the point of recording and review the roles of the component 1, component 2 and FCAD information too.

Not all faults that occurred during the timeframe analysed would have been recorded in NR's FMS and may have instead been captured through NR's inspection and maintenance activities. In addition, it was shown in Section 5.3.4 that issues regarding earthworks are currently managed through a separate system and are not captured in FMS and therefore were not considered during this research. However, due to the interdependencies between different asset types for example, drainage faults can lead to track geometry faults, it is necessary for all of these systems to be joined up. In part, this would aid the identification of failure mechanisms and ensure actions taken will prevent further issues. However, integrated management systems would also give the infrastructure manager a better picture of the overall health of their infrastructure and inform decision making processes to benefit whole systems within national infrastructure networks.

Recommendation 54: NR to review the integration of asset management systems across their business to ensure a consistent and effective approach.

In order to improve current understanding of the impact of weather on railway infrastructure it has been recommended that infrastructure managers improve how they record and document the effects of weather on their assets (Nolte and Rupp, 2011). The application of the methodology developed in this research would return a far clearer picture of the role of weather in the causation of fault events and the specific failure mechanisms if this was enacted by NR. In addition to classifying faults in a systematic and comprehensive manner it is necessary for infrastructure managers to unify practice across their business particularly with regards to data integration. The data quality issues regarding NR's FMS is representative of a broader data management challenge for NR, however robust data gathering and integration should inform vulnerability assessments and wider adaptation strategies, enabling informed decisions to be made across the business (Quinn et al., 2017).

5.5.2.2 Fault Classification

In addition to improvements to fault reporting, this research has also found that it would be valuable to include reporting categories for frequent fault incidents that do not currently have a specified category. A particular example of this is fault incidents pertaining to line incursion by animals which is an area of particular concern for NR (Network Rail, 2019f). At present these fault incidents are spread out between several different asset categories mainly Track (P.W.), Track Boundary Measures and Unknown No Equipment. By attributing these faults to a specific category, the relationships within the other asset categories will become clearer enabling more effective further analysis on the relationships between these categories and the effects of weather.

Faults that are recorded within TRUST are done so for the purpose of distributing responsibility for delays on GB's rail network and therefore identifying which party is due compensation for the disruption of service. Not all fault events stored in NR's FMS are recorded under TRUST as not all fault events cause delays. However, the occurrence of "exceptional" extreme weather events is recorded in TRUST and these events are attributed to NR even if the weather experienced is outside of the design limits of their infrastructure (Delay Attribution Board, 2017). This is done for regulatory reasons, however as the climate begins to change exceptional weather events may will occur with greater frequency. By implementing a classification system across both TRUST and FMS the effects of these events and their frequency will be easy to explore in order to inform solutions or identify which assets need to be redesigned in order to have greater tolerances to certain types of weather hazard.

Recommendation 55: NR should engage with researchers to evaluate their current fault reporting categorisation to ensure a more consistent approach.

Recommendation 56: NR and supply chain stakeholders to explore the design standards of railway equipment to evaluate how the tolerances of assets can be improved to cope with future climates.

Improving the quality of fault data recorded by NR would enable a greater capability to identify failure mechanisms, the analysis of which could then be incorporated into this methodology. There have been some attempts to date to develop strategies to achieve this however these have been limited to specific asset groups or weather variables (Usman et al., 2015; Ferranti et al., 2016a). Incorporating the identification of failure mechanisms into this methodology would enable the identification of those mechanisms that are previously unidentified or poorly understood.

In particular it would be beneficial if there was greater and more consistent detail recorded for faults regarding the likely cause of the fault. This would need to be achieved in a consistent and systematic way with appropriate guidance provided to those recording faults or managing records within the FMS. However, this could be achieved by applying a system of codifying the cause of faults more effectively than at present. A greater understanding of failure mechanisms is crucial to determining precisely how asset faults occur and therefore are necessary to inform the implementation of appropriate protections. Such protections would reduce the susceptibility of assets to weather hazards and therefore reduce the vulnerability of individual assets. In doing so the physical resilience of individual assets would be improved and consequently the operational resilience of the railway network would also be increased.

Recommendation 57: NR should work with researchers to investigate the role of infrastructure ontologies to inform FMS recording structures.

5.5.2.3 Thresholds

It has been shown in this research that temperature can have a detrimental impact on some railways assets including track, signalling and POE as shown in the previous chapter. Although there is a relatively good understanding of the relationship between ambient air temperature and track temperatures (Dobney et al., 2009; Chapman and Bell, 2018) there is a limited understanding of the relationships between ambient air temperatures and many other types of equipment (Ferranti et al., 2016a). This research has gone some way to filling the gaps within the operational thresholds through a systematic analysis of the relationships between historic fault events and the temperatures experienced at the time. However, there is a need for further investigation of these relationships to accurately inform operational thresholds. This should be conducted through experimental and numerical modelling, taking observations of temperatures using remote sensing equipment as the technology for this already exists (Chapman and Bell, 2018). This will improve on the current tacit knowledge base (Palin et al., 2013) and facilitate targeted asset research and development to improve their resilience against present weather conditions and those that will be experienced in the future.

Increasing the physical resilience of the infrastructure reduces the need for an operational response, to mitigate the impact of disruptive events on train services. However, the range of weather events experienced today, potential changes in the future, and the prohibitive scale of investments required to mitigate all weather risks, means that the operational responses will always be a critical process for asset managers to mitigate safety risks (Network Rail, 2014b). Operational thresholds are crucial to the safe and efficient operation of the railways in GB and are informed by failure thresholds supported by other information such as material properties and design standards. Therefore, the methodology developed here can support the development of operational thresholds however, this approach would be more beneficial when used to evaluate performance and inform decisions.

5.5.2.4 Fault Forecasting and Predictive Maintenance

Improving asset management is a key objective for NR across all asset types for many reasons, to improve the life span of existing assets, prevent failure of assets interrupting train services and to reduce the costs of maintaining the railway network's infrastructure assets. To this end, NR are currently undertaking their Intelligent Infrastructure Programme which aims to improve asset management through the implementation of remote technologies and improved data management. Remote technologies or the use of train-borne condition monitoring devices are being used to provide a better picture of asset conditions so that pre-emptive proactive maintenance or renewals can be undertaken in a timely fashion (Network Rail, 2018b). The most well established example of these in NR's arsenal is the plain line pattern recognition system which optically assesses the track condition, for example by identifying missing clips which secure the track to the sleepers. This technology is mounted on NR's New Measurement Train which is also equipped with track geometry and OHL inspection systems (Network Rail, 2020a). Smart Sensing is being explored and developed as part of NR's Intelligent Infrastructure Programme with research currently being undertaken in a variety of fields the outputs of which will revolutionise the way the railway network is maintained and operated in GB.

The condition data captured through the use of NR's Intelligent Infrastructure technologies could be coupled with weather observations in order to conduct a vulnerability assessment of assets based on their condition degradation. The methodology developed in this research could be effectively adapted to undertake this analysis. The results would return a detailed insight into the effects of weather on railway infrastructure assets and their weather related failure thresholds. This information could be applied to their current spatial analysis tools or incorporated into future hazard mapping visualisation to support the information recorded and collected to inform asset management decision making. This would support the generation of predictive and preventative maintenance regimes through the integration of condition scores and weather forecasts, overcoming a key challenge for NR (Network Rail, 2019c).

Recommendation 58: NR should ensure that their Intelligent Infrastructure data architecture incorporates both weather data and remote condition monitoring data streams to provide real time identification of weather hazards and fault forecasts.

If the methodology developed here were further developed to harness railway gridded observations this would facilitate a dynamic analysis of the relationships between a wide variety of weather variables (i.e. including wind etc.) and all asset types. By performing a dynamic analysis of these relationships this would provide a real-time assessment of the operational thresholds for each of these relationships with greater accuracy than has previously been achieved. This would ensure operational thresholds are route specific and still allow network wide performance analysis. This would better inform route managers enabling them to improve the performance of assets within their route by targeting pre-emptive action to combat the effects of adverse weather reducing the need for a reactive operational response. These actions may include improved maintenance regimes and enhancement or renewal of assets (Network Rail, 2014a).

With some further development discussed in the previous section, this methodological approach can be practically applied by NR, returning a dynamic vulnerability analyses for asset categories across all of their routes. The systematic nature of this analysis will return results that will enable Route Asset Managers (RAMs) to target their maintenance work based upon forecast weather, moving towards a predict and prevent approach to the delivery of maintenance. By developing a preventative maintenance strategy supported by comprehensive risk forecasting and holistic decision making this can also inform efficient allocation of resources. Additionally, asset categories will be identified for future enhancement and renewal supporting RAM decision making with greater information regarding the effect of weather currently with a greater insight into how climate change may affect their assets. This is particularly useful where certain asset types are identified as needing to be replaced with assets which have a greater physical resilience to the effects of weather as is the case with track circuits and Axle Counters (Department for Transport, 2014). Findings such as these and subsequent work to improve the physical resilience of vulnerable assets support more efficient railway network operation by reducing the need for an operational response, however this will always be necessary to some degree to mitigate immediate safety risks (Network Rail, 2014b).

Recommendation 59: NR should develop route specific thresholds to evaluate performance across different routes and identify route based challenges.

Recommendation 60: NR should engage with researchers to develop a preventative maintenance strategy alongside comprehensive risk forecasting and holistic decision support tools to inform efficient allocation of resources.

5.6 Next Steps Towards a Resilient Railway Network for NR

NR's key mechanism to creating a railway network that is more resilient to the effects of weather hazards is through their WRCCA Strategy, Framework and Route Plans. The Route plans reviewed in this research were published in 2014 and NR have recently published a few updated route plans which evaluate their progress and continue to identify specific impacts since the last assessments were undertaken. Unfortunately, these were published too recently to properly review them. However, NR's most recent Annual Return indicates that there is going to be a great change from the WRCCA plans of 2014. In particular, there will be improvements in the level of integration of consideration of WRCCA measures in NR's policies, standards and guidance (Network Rail, 2019a, 2019i). This is welcome progress as existing documentation is standalone and is not integrated into many of the processes conducted by the infrastructure manager and instead appears to be an optional addition rather than business as usual.

To support this, NR need to radically overhaul how they manage, utilise and integrate the datasets they collect and own. In addition, developing a greater level of understanding regarding the vulnerability of NR's assets to the effects of weather will help asset managers at all levels make better informed decisions. This could be more effectively communicated across the business if the WRCCA strategies and the route level WRCCA plans are updated at least twice per control period in order to review their progress. In addition, it may be helpful to require the routes' updated WRCCA plans are due by a specific time so that the performance and progress across routes may be more readily compared.

The methodology presented here provides the foundation for improved data driven analysis of the relationships between weather and railway assets which can be harnessed in many ways as discussed in the previous sections. The application of the approaches developed here would support NR or any transport infrastructure manager to identify those areas where weather hazards frequently cause faults and to create thresholds which enable fault forecasting in the short term. In addition, these thresholds can be developed further to support climate change impact assessments through threshold exceedance analysis, which could include economic quantification.

5.7 Summary of Recommended Actions

Throughout this chapter recommendations have been made, it is the Author's opinion that these target three main areas: asset specific recommendations, NR's current challenges and the main focus in order to create a resilient railway from the perspective of the infrastructure manager. With this in mind, the key goals for NR to improve the resilience of railway assets and the operation of the railway network, should be:

1. To develop better scientific understanding of the effects of weather variables on railway assets through experimentation, modelling and field tests. This will inform asset specific fault knowledge which should be retained and inform new asset design practice and renewals.
2. To consolidate existing data, practices and guidance in a meaningful way in order to implement changes to the operation and management of GB's rail network.
3. To reduce the need for operational resilience and response as much as is practicable by improving the physical resilience of railway assets across the network. This can be achieved through better informed maintenance practices predominantly better utilisation of data, predictive maintenance practices and fault forecasting mechanisms.

CHAPTER SIX: CONCLUSIONS

6.1 Overview of Conclusion

The discussion of the results and the context surrounding these outputs in the previous chapter has drawn the investigation of these topics to a close. Therefore, this chapter illustrates explicitly that the aim of this research and its constituent objectives have been completed. The conclusion chapter begins with a summary of how each of the objectives were met and consequently the aim achieved.

6.2 The Achievement of the Research Aim and Objectives

The aim of this research was to develop a systematic, methodological approach to assess the vulnerability of railway infrastructure assets susceptible to the effects of hazardous weather. This has been achieved as detailed in previous chapters by fulfilling a number of research objectives. This section concisely illustrates that each of these objectives was achieved during the process of this research.

6.2.1 Developing a Novel, Systematic Methodological Approach

Objective One: Review existing methodologies and industry practice used to investigate the relationships between weather and railway infrastructure assets to inform the development of a novel and systematic methodological approach.

Chapter Two of this thesis investigated a wide range of approaches to assessing the vulnerability of railway infrastructure assets to the effects of hazardous weather. These existing methodologies were evaluated based on the weather hazards they encompassed, their consideration of railway infrastructure assets and how they inform operational thresholds and processes. Through this systematic review of current procedure within NR and existing literature it was possible to identify the needs of current NR operations and combine elements of existing methodologies to create a methodological approach that addressed NR's objective of basing decisions on the results of data-driven analysis. This methodological approach successfully meets this objective as it is fundamentally lead by statistical analysis of the data provided in order to focus on significant relationships returning results for these from the reliable data that has been identified. It is because of this that this methodology is both Novel and effective meeting both NR's objectives as well as Objective One set out for this research.

6.2.2 Identification of Significant Relationships

Objective Two: Identify significant relationships between weather variables and railway assets and interrogate further, utilising the methodological approach developed.

The methodological approach developed to meet Objective One was utilised to meet the second objective of this research. Both significant assets and significant weather variables were identified and presented at the beginning of Chapter Three and the significance of their relationships was observed in the resulting analysis utilising the methodological approach developed. The results of which were presented in Chapter Three and were then interrogated in more detail to get a better understanding of any interesting or novel relationships identified.

The application of this systematic methodological approach has enabled the identification of previously unknown (in current literature) significant asset categories, in particular Boundary Measures and the No Equipment asset categories. Additionally, both of these were found to have significant relationships with weather which had again previously been overlooked in existing research. This shows the importance of applying an objective systematic approach when conducting vulnerability assessments, ensuring that all asset categories that are susceptible to the impacts of weather have been identified.

6.2.3 Evaluating Current Thresholds

Objective Three: Establish known weather thresholds and produce improved thresholds, outlining how they address current knowledge gaps and validate the analysis.

Previously the TRaCCA project had collated all of NR's operational thresholds and reviewed them alongside existing research to identify knowledge gaps. The findings in this report were condensed into tables and can be seen in Chapter Two. The concise presentation of the existing operational thresholds highlighted where there were both suspected impacts of weather variables on railway infrastructure assets and a lack of operational threshold, operational guidance or wider research. The identified knowledge gaps were highlighted and compared with the results of this research in Chapter Five. The comparison validated the approach developed whilst also illustrating the necessity of developing such an approach as the results were able to build upon current understanding.

6.2.4 Areas for Further Development and Future Research Needs

Objective Four: Critically evaluate the methodological approach developed and the results found, outlining areas for further development and future research needs.

Following a discussion of the results and their implications, the methodology developed, and the resulting findings were critically evaluated in Chapter Five. Those areas where the methodology required improvement were highlighted and suggestions for remedying these were put forward. Regardless, it was concluded that largely the methodology was fit for purpose because the systematic method employed is aligned with the NR current objective of ensuring their decisions are made based on the results of data-driven approaches (Network Rail, 2017b). In addition, the results of this research were derived from data that is of the best resolution and quality available and until fault records improve or a greater resolution of reanalysis data is available, this is the best that can be utilised as established in Chapter Two. Fortunately, progress is being made to implement remote condition monitoring more widely across the network as just one example of how NR are improving their approaches to data collection regarding assets. The next challenge however, will be to ensure the quality data collected is harnessed correctly to inform predictive maintenance strategies. In addition, the development of NR's own weather observations for weather experienced across the railway network will provide a more reliable and scalable weather data solution. These datasets will be beneficial for many applications across their business as well as for use in methodologies such as the approach developed in this research.

Whilst discussing the results in Chapter Five a number of areas for further development have been identified regarding improved data quality, facilitating the practical application of this methodology for infrastructure managers as well as how this can be built upon to progress towards creating a resilient railway network. To further improve the application of this methodology a number of areas have been identified for further research including experimental development of individual asset thresholds, undertaking criticality and interdependency assessments of railway infrastructure as well as developing an improved climate impact assessment based on the results and methodology developed in this research. The results of this further research would further inform the progression and actions required to create a resilient railway network.

6.2.5 Practical Application of the Developed Methodology

Objective Five: Illustrate how the developed methodology can be practically applied to inform operations, asset management and associated decision making processes in addition to further recommendations for associated stakeholders.

The methodology developed in this research can be practically applied by railway infrastructure managers such as NR, to conduct a dynamic weather hazard assessment of their assets to support fault forecasting to inform predictive asset maintenance strategies as described in Chapter Five. To support this, a number of recommendations were made in Chapter Five alongside the discussion of the results of the analysis conducted here. These recommended actions provide rail industry stakeholders with direction to address the existing challenges and those identified in this research more specifically to enable progression towards a resilient railway network.

6.3 Concluding Remarks

The previous sections have illustrated how this research has successfully achieved its aim, expanding existing knowledge of the relationships between weather variables and railway infrastructure assets and informing asset management strategies. Existing thresholds have been reviewed and improved, applying these to further research will enable a better understanding of how future climate changes may affect the operation of GB's railway network. Although this methodology is practical for application by infrastructure managers it needs further development to continue progression to creating a resilient railway network.

Ultimately there is a need to draw together the individual threads of knowledge and understanding of the relationships between both weather hazards and railway assets in order to begin to understand the behaviour of the woven fabric of the railway network as a national infrastructure.

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APPENDIX A: Significant asset groups and labels

Asset Parent Group	Asset Subgroup	Short	FMS Suffix	Short & Number
E&P	3rd Rail	E&P 3rd	TRACTION SUPPLY (THIRD RAIL)	E&P 3rd 2
	OHL	E&P OHL	OLE ELECTRICAL SECTION	E&P OHL 2
			OLE STRUCTURE	E&P OHL 6
	Signalling Power Supply	E&P SPS	ELECTRICAL SUPPLY POINT	E&P SPS 2
	Traction Power	E&P TP	CIRCUIT BREAKERS	E&P TP 1
Signalling	AWS	Sig AWS	TRAIN WARNING SYSTEM	Sig AWS 2
	Axle Counter	Sig AC	AXLE COUNTER	Sig AC 1
	HABD	Sig HABD	HOT BOX DETECTOR	Sig HABD 1
	Interlocking	Sig I	INTERLOCKING	Sig I 1
			PANEL / FRAME	Sig I 3
			SOLID STATE INTERLOCKING	Sig I 4
			TRAIN DESCRIBER	Sig I 5
	Level Crossing	Sig LC	LEVEL CROSSING EQUIPMENT	Sig LC 1
	Point Operating Equipment	Sig POE	POINT OPERATING EQUIPMENT	Sig POE 2
	Signal	Sig Sig	SIGNAL	Sig Sig 4
	TPWS	Sig TPWS	TRAIN WARNING SYSTEM	Sig TPWS 1
	Track Circuit	Sig TC	TRACK CIRCUIT	Sig TC 2
Telecoms	Telephone	Tel Tel	TELEPHONE - OTHER	Tel Tel 5
			TELEPHONE - SPT	Tel Tel 6
Track	S&C	Track S&C	POINTS (P.W)	Track S&C 1
	Track	Track	TRACK (P.W)	Track Track 3
	Unknown	Track Unknown	ACCESS POINT	Track Unknown 1
			BOUNDARY MEASURE	Track Unknown 2
UNKNOWN	UNKNOWN	UU	BRIDGE	UU 8
			CONCENTRATOR - VOICE	UU 16
			NO EQUIPMENT	UU 39
			RADIO - CAB SECURE	UU 59
			TELEPHONE - OTHER	UU 83
			TELEPHONE - SPT	UU 84

APPENDIX B: Locating Weather Variable Data VBA Macro Script

```
Option Explicit
Sub copylocationdailyweathervariablevaluestoatable()
'This macro will read a list of cell coordinates and copy the values in each of these cell locations from each dated text file to the worksheet to (at a later date) be counted
''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
'Workbook and worksheet location dims
Dim WVWKB As Workbook
Dim WVWKS As Worksheet

'Inputs
Dim Route As String
Dim TP As String
Dim WeatherVariable As String

'file location and file name Dims
Dim Myfilepath As String
Dim Myfile As String
Dim MyExtension As String
Dim CurrentFileName As String
Dim CurrentFile As String

'Row and Col Dims
Dim StartRow As Long
Dim EndRow As Long
Dim CurrentRow As Long
Dim StartCol As Long
Dim EndCol As Long
Dim CurrentCol As Long
Dim gridxcol As String
Dim gridycol As String

'Date Dims
Dim day As String
Dim month As String
Dim year As String
Dim dayno As Long
Dim monthno As Long

'Cell Coordinate Dims
Dim gridx As Long
Dim gridy As Long

'Copy and Paste Ranges
Dim tempval As Range
Dim tempcell As Range

'Timer Dims
Dim StartTime As Double
Dim SecondsElapsed As Double

''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''

'Optimize Macro Speed
Application.ScreenUpdating = False
Application.EnableEvents = False
Application.Calculation = xlCalculationManual

'Remember time when macro starts
StartTime = Timer
''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
'Inputs
Route = InputBox("LNW North, LNW South, Wessex")
TP = InputBox("T/P")
```

```
WeatherVariable = InputBox("Max, Min, Mean, DailyRain & Etc.")


'Set Workbook and Worksheet locations
Set WVWKB = Application.Workbooks(Route + " Weather Variables.xlsm")
Set WVWKS = WVWKB.Sheets(Route + " " & TP + WeatherVariable)

'Set Row and Col locations
StartRow = 2                EndCol = 2103               gridxcol = "A"
EndRow = 404                CurrentRow = StartRow       gridycol = "B"
StartCol = 3                CurrentCol = StartCol

'Set Start Date
day = "01"                  year = 2006                 monthno = 4
month = "04"                dayno = 1

If TP = "T" Then

'set folder to be searched
Myfilepath = ("C:\Users\rxf000\My PhD\Working PhD\Data Analysis\Raw Data\Weather\Temp\Temp Unzipped\Daily " & WeatherVariable + " Temp")

End If

If TP = "P" Then

'set folder to be searched
Myfilepath = ("C:\Users\rxf000\My PhD\Working PhD\Data Analysis\Raw Data\Weather\Precip\Precip Unzipped\Daily Rainfall")

End If

'Set the file Extension
 MyExtension = ".txt"

'While the date is one that has a column heading set up
Do While CurrentCol >= StartCol And CurrentCol <= EndCol

  'Set a status bar value
```

```
Application.StatusBar = (day + "-" & month + "-" & year)

'Start building the file name for each date
day = dayno
month = monthno

If dayno <= 9 Then

day = "0" & dayno

End If

If monthno <= 9 Then

month = "0" & monthno

End If

If TP = "T" Then
  CurrentFileName = WeatherVariable + "Temp_" & year + "-" & month + "-" & day + "_Actual"

  If year > 2006 Then

  CurrentFileName = WeatherVariable + "Temp_" & year + "-" & month + "-" & day + "_ACTUAL"

  End If
End If

If TP = "P" Then
  CurrentFileName = "daily_rainfall_" & year + "-" & month + "-" & day + "_actual"
End If

'Compile the file name
CurrentFile = Myfilepath + "\" & CurrentFileName + MyExtension

'Open the file
Workbooks.OpenText Filename:=CurrentFile, StartRow:=1, DataType:=xlDelimited, ConsecutiveDelimiter:=False, Tab:=True, Semicolon:=False, Comma:=False, Space:=True
```

```
    'Work through each row reading each location for which the daily weather variable needs to be found
    Do While CurrentRow >= StartRow And CurrentRow <= EndRow

    'activate the workbook
    WVWKB.Activate

    'read the coordinates
    gridx = WVWKS.Cells(CurrentRow, gridxcol).Value
    gridy = WVWKS.Cells(CurrentRow, gridycol).Value + 6

    'Activate the days weather variable file
    Workbooks(CurrentFileName + ".txt").Activate

    'Select and copy the weather variable value for the current location
    ActiveWorkbook.ActiveSheet.Cells(gridy, gridx).Select
    Selection.Copy

    'Activate the location list and daily weather variable table
    WVWKB.Activate

    'Copy weather variable value to the table cell
    WVWKS.Cells(CurrentRow, CurrentCol).Select


    Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=False

    'Make values integers
    WVWKS.Cells(CurrentRow, CurrentCol).Value = Round(WVWKS.Cells(CurrentRow, CurrentCol).Value, 0)

    'move onto the next location
    CurrentRow = CurrentRow + 1
    Loop

  'Close days weather variable file
  Workbooks(CurrentFileName + ".txt").Close

  'application status bar value
```

```
  Application.StatusBar = (day + "-" & month + "-" & year)

  'Move onto the next day
  CurrentCol = CurrentCol + 1

  'Move back to the first location
  CurrentRow = StartRow

   'set the next day
   dayno = dayno + 1
   If dayno >= 28 Then

    If month = 1 Or monthno = 3 Or monthno = 5 Or monthno = 7 Or monthno = 8 Or monthno = 10 Or
monthno = 12 Then

     If dayno > 31 Then
     dayno = 1
      If monthno <> 12 Then
      monthno = monthno + 1

      End If

      If monthno = 12 Then
      monthno = 1
      year = year + 1
      WVWKB.Save
      End If
     End If
    End If

    If monthno = 4 Or monthno = 6 Or monthno = 9 Or monthno = 11 Then

     If dayno > 30 Then
     dayno = 1
     monthno = monthno + 1

     End If
        End If
    If monthno = 2 Then
```

```
        If year = 2008 Then

          If dayno > 29 Then
            dayno = 1
            monthno = monthno + 1

          End If
        End If

        If year <> 2008 Then

          If dayno > 28 Then

          dayno = 1
          monthno = monthno + 1

          End If
        End If
      End If
    End If
  Loop

WVWKB.Save

'Determine how many seconds code took to run
 SecondsElapsed = Round(Timer - StartTime, 2)

'Notify user in seconds
 MsgBox "This code ran successfully in " & SecondsElapsed & " seconds", vbInformation

 'Reset Macro Optimization Settings
  Application.EnableEvents = True
  Application.Calculation = xlCalculationAutomatic
  Application.ScreenUpdating = True

End Sub
```

APPENDIX C: Frequency Analysis VBA Macro Script

```
Option Explicit

Sub CompileFrequencyTables()

'Counts variables from ranges given in variable boundary sheet for each of the variables_
'and filled out frequencies for locations for each variable value and add sub totals.

'Dims
'WKB & WKS
Dim WVFWKB As Workbook
Dim VBoundariesWKB As Workbook
Dim WVVWKB As Workbook

Dim VBoundariesWKS As Worksheet
Dim WVFWKS As Worksheet
Dim WVVWKS As Worksheet
Dim BlankWKS As Worksheet
Dim NewWKS As Worksheet

'Cols and Rows
Dim WVVStartCOL As Long
Dim WVVEndCOL As Long
Dim WVFStartCOL As Long
Dim VBoundariesMinCOL As Long
Dim VBoundariesMaxCOL As Long
Dim WVFHeaderROW As Long
Dim WVFStartROW As Long
Dim WVFEndROW As Long
Dim WVFSubTotalROW As Long
Dim WVVEndROW As Long
Dim WVVROW As Long
Dim WVVStartROW As Long
Dim VBoundariesStartROW As Long
Dim VBoundariesEndRROW As Long
Dim VBoundariesCurrentROW As Long
Dim VBoundariesVCOL As Long

'Cells
Dim WVFStartHeader As Range
Dim VariableRange As Long
Dim WVFEndHeader As Range
Dim WVVRowStartCell As Range
Dim WVFRowEndCell As Range
Dim WVVRowRange As Range
Dim WVVRowEndCell As Range

Dim VBoundariesVariable As Range
Dim VBoundariesMinVariable As Range
Dim VBoundariesMaxVariable As Range

Dim VBoundariesVariableName As String

Dim WeatherVariableValue As String

Dim Cell As Range

Dim Subtotal As Long
Dim SubtotalCell As Range

Dim i As Long
Dim r As Long
Dim v As Long

Dim Count As Long
```

```
'Timer Dims
Dim StartTime As Double
Dim SecondsElapsed As Double

'Route
Dim Route As String

''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''

'Optimize Macro Speed
Application.ScreenUpdating = False
Application.EnableEvents = False
Application.Calculation = xlCalculationManual

'Remember time when macro starts
StartTime = Timer
''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
'Inputs
Route = InputBox("LNW North, LNW South, Wessex")
i = 28
r = 2

'Set WKBs and WKSs
Set WVVWKB = Application.Workbooks(Route + " Weather Variables.xlsm")
Set WVFWKB = Application.Workbooks(Route + " Weather Variable Frequencies.xlsm")
Set VBoundariesWKB = Application.Workbooks("Variable Boundaries")

Set WVFWKS = WVFWKB.Sheets(i)
Set WVVWKS = WVVWKB.Sheets(i)
Set VBoundariesWKS = VBoundariesWKB.Sheets("Variable Boundaries")
Set BlankWKS = WVFWKB.Sheets(Route & " Blank Grids")

'Set COls
WVVStartCOL = 3
WVVEndCOL = 2103
WVFStartCOL = 3

VBoundariesMinCOL = 16
VBoundariesMaxCOL = 17

'Set Rows
```

```
WVFHeaderROW = 1
WVFStartROW = 2
WVFEndROW = WVVEndROW
WVFSubTotalROW = WVVROW + 1

WVVStartROW = 2
WVVEndROW = WVVWKS.Range("A1", WVVWKS.Range("A1").End(xlDown)).Rows.Count
WVFEndROW = WVVEndROW

VBoundariesStartROW = 2
VBoundariesEndRROW = 47
VBoundariesCurrentROW = i
VBoundariesVCOL = 1

'Loop through each variable
For i = 2 To 47

  Set VBoundariesVariable = VBoundariesWKS.Cells(i, VBoundariesVCOL)
  Set VBoundariesMinVariable = VBoundariesWKS.Cells(i, VBoundariesMinCOL)
  Set VBoundariesMaxVariable = VBoundariesWKS.Cells(i, VBoundariesMaxCOL)

  'Most will go through this process except those with string values
  'If its got a max and minimum variable values then these will not equal N/A
  If VBoundariesMaxVariable.Value <> "N/A" Then

    'Blank Sheet as Template
    BlankWKS.Select
    Application.CutCopyMode = False
    Sheets("LNW North Blank Grids").Copy After:=WVFWKB.Sheets(i - 1)

    'Variable ranges and values
    Set WVFWKS = WVFWKB.Sheets(i)
    Set WVVWKS = WVVWKB.Sheets(i)

    Set VBoundariesVariable = VBoundariesWKS.Cells(i, VBoundariesVCOL)
    Set VBoundariesMinVariable = VBoundariesWKS.Cells(i, VBoundariesMinCOL)
    Set VBoundariesMaxVariable = VBoundariesWKS.Cells(i, VBoundariesMaxCOL)
```

```
  'Create a sheet with the name of the variable
  VBoundariesVariableName = VBoundariesVariable.Value
  WVFWKS.Name = (Route & " " & VBoundariesVariableName)

  'Add header with variable ranges
  Set WVFStartHeader = WVFWKS.Cells(WVFHeaderROW, 3)
  VariableRange = VBoundariesMaxVariable.Value - VBoundariesMinVariable.Value
  Set WVFEndHeader = WVFWKS.Cells(WVFHeaderROW, VariableRange + 3)

  VBoundariesWKS.Activate
  VBoundariesMinVariable.Copy
  WVFWKS.Activate
  WVFWKS.Cells(WVFHeaderROW, 3).PasteSpecial Paste:=xlPasteValues
  WVFWKS.Cells(WVFHeaderROW, 3).DataSeries Rowcol:=xlRows, Type:=xlLinear, Date:=xlDay, _
  Step:=1, Stop:=VBoundariesMaxVariable, Trend:=False

  WVFWKS.Cells(1, 1).Copy
  WVFWKS.Range(WVFStartHeader, WVFEndHeader).PasteSpecial Paste:=xlPasteFormats

End If

'Different for NEW MAX
If i = 30 Then

  'Blank Sheet as Template
  BlankWKS.Select
  Application.CutCopyMode = False
  Sheets("LNW North Blank Grids").Copy After:=WVFWKB.Sheets(i - 1)

  'Variable ranges and values
  Set WVFWKS = WVFWKB.Sheets(i)
  Set WVVWKS = WVVWKB.Sheets(i)

  'Create a sheet with the name of the variable
  VBoundariesVariableName = VBoundariesVariable.Value
  WVFWKS.Name = (Route & " " & VBoundariesVariableName)

  'Add header with variable ranges
```

```
  Set WVFStartHeader = WVFWKS.Cells(WVFHeaderROW, 3)
  Set WVFEndHeader = WVFWKS.Cells(WVFHeaderROW, 4)
  WVFStartHeader.Value = "Y"
  WVFEndHeader.Value = "N"

  WVFWKS.Cells(1, 1).Copy
  WVFWKS.Range(WVFStartHeader, WVFEndHeader).PasteSpecial Paste:=xlPasteFormats

  'Set the variable range
  VariableRange = 1
End If

'Different for Wet Dry
If i = 42 Then

  'Blank Sheet as Template
  BlankWKS.Select
  Application.CutCopyMode = False
  Sheets("LNW North Blank Grids").Copy After:=WVFWKB.Sheets(i - 1)

  'Variable ranges and values
  Set WVFWKS = WVFWKB.Sheets(i)
  Set WVVWKS = WVVWKB.Sheets(i)

  'Create a sheet with the name of the variable
  VBoundariesVariableName = VBoundariesVariable.Value
  WVFWKS.Name = (Route & " " & VBoundariesVariableName)

  'Add header with variable ranges
  Set WVFStartHeader = WVFWKS.Cells(WVFHeaderROW, 3)
  Set WVFEndHeader = WVFWKS.Cells(WVFHeaderROW, 5)
  WVFStartHeader.Value = "Wet"
  WVFEndHeader.Value = "Dry"
  WVFWKS.Cells(WVFHeaderROW, 4).Value = "Wet/Dry"

  WVFWKS.Cells(1, 1).Copy
  WVFWKS.Range(WVFStartHeader, WVFEndHeader).PasteSpecial Paste:=xlPasteFormats
```

```
  'Set the variable range
  VariableRange = 2
End If

If i = 43 Then

  'Blank Sheet as Template
  BlankWKS.Select
  Application.CutCopyMode = False
  Sheets("LNW North Blank Grids").Copy After:=WVFWKB.Sheets(i - 1)

  'Variable ranges and values
  Set WVFWKS = WVFWKB.Sheets(i)
  Set WVVWKS = WVVWKB.Sheets(i)

  'Create a sheet with the name of the variable
  VBoundariesVariableName = VBoundariesVariable.Value
  WVFWKS.Name = (Route & " " & VBoundariesVariableName)

  'Add header with variable ranges
  Set WVFStartHeader = WVFWKS.Cells(WVFHeaderROW, 3)
  Set WVFEndHeader = WVFWKS.Cells(WVFHeaderROW, 5)
  WVFStartHeader.Value = "Wet"
  WVFEndHeader.Value = "Dry"
  WVFWKS.Cells(WVFHeaderROW, 4).Value = "Wet/Dry"

  WVFWKS.Cells(1, 1).Copy
  WVFWKS.Range(WVFStartHeader, WVFEndHeader).PasteSpecial Paste:=xlPasteFormats

  'Set the variable range
  VariableRange = 2
End If

'Different fo same antecedent variable
If i = 44 Then

  'Blank Sheet as Template
  BlankWKS.Select
```

```
  Application.CutCopyMode = False
  Sheets("LNW North Blank Grids").Copy After:=WVFWKB.Sheets(i - 1)

  'Variable ranges and values
  Set WVFWKS = WVFWKB.Sheets(i)
  Set WVVWKS = WVVWKB.Sheets(i)

  'Create a sheet with the name of the variable
  VBoundariesVariableName = VBoundariesVariable.Value
  WVFWKS.Name = (Route & " " & VBoundariesVariableName)

  'Add header with variable ranges
  Set WVFStartHeader = WVFWKS.Cells(WVFHeaderROW, 3)
  Set WVFEndHeader = WVFWKS.Cells(WVFHeaderROW, 4)
  WVFStartHeader.Value = "Same"
  WVFEndHeader.Value = "Diff"

  WVFWKS.Cells(1, 1).Copy
  WVFWKS.Range(WVFStartHeader, WVFEndHeader).PasteSpecial Paste:=xlPasteFormats

  'Set the variable range
  VariableRange = 1
End If


'loop through each location/row
For r = 2 To WVVEndROW

'Find row range
Set WVVRowStartCell = WVVWKS.Cells(r, 3)
Set WVVRowEndCell = WVVWKS.Cells(r, WVVEndCOL + 3)
Set WVVRowRange = WVVWKS.Range(WVVRowStartCell, WVVRowEndCell)

  'loop through variable values or columns
  For v = 3 To (VariableRange + 3)

    WeatherVariableValue = WVFWKS.Cells(WVFHeaderROW, v).Value
```

```
      'Zero Count
      Count = 0

      'Count values the same as that variable value
      For Each Cell In WVVRowRange
        If (Cell.Value = WeatherVariableValue) Then Count = Count + 1
      Next

      'Add count to frequency table
      WVFWKS.Cells(r, v).Value = Count

    Next

  Next

  Next
  WVFWKB.Save
'Determine how many seconds code took to run
 SecondsElapsed = Round(Timer - StartTime, 2)

'Notify user in seconds
 MsgBox "This code ran successfully in " & SecondsElapsed & " seconds", vbInformation

 'Reset Macro Optimization Settings
  Application.EnableEvents = True
  Application.Calculation = xlCalculationAutomatic
  Application.ScreenUpdating = True
End Sub
```

APPENDIX D: Significant Asset Category Fault Counts

Table of fault frequencies for the 11 Asset Categories with the greatest percentage of faults across all three routes.

Top 10 Rank	Short & Number	Short & Suffix	Asset Category fault frequencies for each route LNW North	LNW South	Wessex	Fault Total	Range
1	Track Track 3	Track Track: TRACK (P.W)	22439	11587	14955	48981	10852
2	Sig Sig 4	Sig Sig: SIGNAL	17490	12708	8742	38940	8748
3	Sig POE 2	Sig POE: POINT OPERATING EQUIPMENT	9375	9723	4949	24047	4774
4	UU 39	UU: NO EQUIPMENT	3843	8207	11863	23913	8020
5	Sig TC 2	Sig TC: TRACK CIRCUIT	8718	5776	5042	19536	3676
6	Sig LC 1	Sig LC: LEVEL CROSSING EQUIPMENT	5491	2303	5971	13765	3668
7	Track S&C 1	Track S&C: POINTS (P.W)	6079	5885	2552	14516	3527
8	Sig I 3	Sig I: PANEL / FRAME	6967	3810	2260	13037	4707
9	Track Unknown 2	Track Unknown: BOUNDARY MEASURE	4242	2053	1598	7893	2644
10	Sig TPWS 1	Sig TPWS: TRAIN WARNING SYSTEM	1709	2088	2362	6159	653
11	E&P TP 1	E&P TP: CIRCUIT BREAKERS	2450	3181	1107	6738	2074

APPENDIX E: Fault Incidence and Weather Event frequency for Asset Category Track (P.W.) for Maximum Temperatures Greater than 19°C across all three routes.

	All Routes			LNW North			LNW South			Wessex		
	Mean Fault Rate		0.031	Mean Fault Rate		0.029	Mean Fault Rate		0.027	Mean Fault Rate		0.040
	1 Standard Deviation		0.050	1 Standard Deviation		0.044	1 Standard Deviation		0.045	1 Standard Deviation		0.068
	2 Standard Deviations		0.070	2 Standard Deviations		0.060	2 Standard Deviations		0.063	2 Standard Deviations		0.096
T Max °C	**TMax Counts**	**Fault Counts**	**Fault Rate**	**TMax Counts**	**Fault Counts**	**Fault Rate**	**TMax Counts**	**Fault Counts**	**Fault Rate**	**TMax Counts**	**Fault Counts**	**Fault Rate**
20	**100685**	3108	0.031	**35948**	1288	0.036	**31583**	720	0.023	**33154**	1100	0.033
21	**63512**	2100	0.033	**19957**	638	0.032	**20749**	542	0.026	**22806**	920	0.040
22	**56558**	1924	0.034	**16790**	527	0.031	**19669**	590	0.030	**20099**	807	0.040
23	**33723**	1191	0.035	**9554**	358	0.037	**12348**	359	0.029	**11821**	474	0.040
24	**28334**	948	0.033	**7999**	280	0.035	**9420**	247	0.026	**10915**	421	0.039
25	**17642**	603	0.034	**5236**	193	0.037	**6045**	174	0.029	**6361**	236	0.037
26	**14086**	521	0.037	**4120**	156	0.038	**4711**	142	0.030	**5255**	223	0.042
27	**7386**	249	0.034	**2248**	76	0.034	**2708**	67	0.025	**2430**	106	0.044
28	**6969**	240	0.034	**1740**	59	0.034	**3387**	91	0.027	**1842**	90	0.049
29	**3100**	116	0.037	**639**	16	0.025	**1378**	58	0.042	**1083**	42	0.039
30	**2187**	138	0.063	**374**	14	0.037	**759**	24	0.032	**1054**	100	0.095
31	**1288**	99	0.077	**287**	17	0.059	**588**	31	0.053	**413**	51	0.123
32	**746**	49	0.066	**203**	4	0.020	**253**	18	0.071	**290**	27	0.093
33	**205**	23	0.112	**74**	6	0.081	**27**	3	0.111	**104**	14	0.135
34	**229**	6	0.026	**28**	2	0.071	**148**	4	0.027	**53**	0	
35	**123**	5	0.041	**1**	0		**49**	0		**73**	5	0.068
36	**21**	0		**0**	0		**0**	0		**21**	0	