EVALUATING NETWORK CRITICALITY OF INTERDEPENDENT INFRASTRUCTURE SYSTEMS: APPLICATIONS FOR ELECTRICAL POWER DISTRIBUTION AND RAIL TRANSPORT

by

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ABSTRACT

Critical infrastructure provides essential services of economic and social value. However, the pressures of demand growth, congestion, capacity constraints and hazards such as extreme weather increase the need for infrastructure resilience. The increasingly interdependent nature of infrastructure also heightens the risk of cascading failure between connected systems. Infrastructure companies must meet the twin-challenge of day-to-day operations and long-term planning with increasingly constrained budgets and resources. With a need for an effective process of resource allocation, this thesis presents a network criticality assessment methodology for prioritising locations across interdependent infrastructure systems, using metrics of the expected consequence of an asset failure for operational service performance.

Existing literature is focused mainly upon simulating the vulnerability of national-scale infrastructure, with assumptions of both system dynamics and dependencies for simplicity. This thesis takes a data-driven and evidence-based approach, using historical performance databases to inherently capture system behaviour, whilst network diagrams are used to directly identify asset dependencies. Network criticality assessments are produced for three applications of increasing complexity from (i) electricity distribution, to (ii) railway transport, to (iii) electrified railway dependencies on external power supplies, using case studies of contrasting infrastructure management regions.

This thesis demonstrates how network criticality assessments can add value to subjective tacit knowledge and high-level priorities both within and between infrastructure systems. The spatial distribution of criticality is highlighted, whilst the key contribution of the research is the identification of high-resolution single points of failure and their spatial correlation across systems, particularly within urban areas. Service-level metrics also have a broad applicability for a range of functions, including incident response, maintenance and long-term investment. The role of network criticality within a holistic and systemic decision-making process is explored, for risk assessment and resilience interventions. The limitations of the research, regarding sample-size caveats and the definition of system boundaries within performance databases, lead to recommendations on cross-system fault reporting and the improvement of information systems.

Keywords: criticality, risk, resilience, infrastructure, interdependencies, networks, systems, rail, electricity.

This thesis is dedicated to the memory of Joan Elizabeth Davies.

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LIST OF ABBREVIATIONS AND ACRONYMS

BSP	Bulk Supply Point
CA	Customers Affected
CI	Customer Interruptions
CML	Customer Minutes Lost
CNAIM	Common Network Asset Indices Methodology
DM	Delay Minutes
DNO	Distribution Network Operator
EMU	Electrical Multiple Unit
FOC	Freight Operating Company
GB	Great Britain
GIS	Geographic Information Systems
GSP	Grid Supply Point
HV	High Voltage
ICT	Information and Communication Technology
IIS	Interruptions Incentive Scheme
IoT	Internet of Things
IPEMU	Independently Powered Electrical Multiple Unit
ISO	International Organisation for Standardisation
Km	Kilometres
kV	Kilovolts
LNW	London North Western
LV	Low Voltage
NaFIRS	National Fault and Interruption Reporting Scheme

NG	National Grid
NR	Network Rail
OFGEM	Office Of Gas and Electricity Markets
OLE	Overhead Line Electrification
ORR	Office of Rail and Road
SML	Supply Minutes Lost
SRS	Strategic Route Section
STANOX	Station Number
TOC	Train Operating Company
TRUST	Train Running System on TOPS
UHI	Urban Heat Island
UK	United Kingdom
UKCP09	UK Climate Projections 2009
UoB	University of Birmingham
WCML	West Coast Mainline
WPD	Western Power Distribution
WRCC	Weather Resilience and Climate Change

CHAPTER ONE: **INTRODUCTION AND BACKGROUND**

1.1 Critical Infrastructure

1.1.1 Value of Infrastructure

Critical infrastructure is essential to support modern life, providing services crucial for the prosperity of a nation in terms of maintaining both economic growth (Solomon, 2013; NIC, 2017; Li et al, 2018) and social wellbeing (Haughwout, 2001; MHCLG, 2018; Sapkota, 2018). For example, the rail industry and its supply chain generate upwards of £10 billion in GVA for the UK each year (Oxera, 2015), whilst key business and leisure functions rely upon on a continuous electricity supply, with supplies to services and utilities, such as hospitals and sanitation, vital for the health and safety of a population.

For the United Kingdom, the Centre for the Protection of National Infrastructure defines Critical National Infrastructure (CNI) as “facilities, systems, sites, information, people, networks and processes, necessary for a country to function and upon which daily life depends” covering thirteen national infrastructure sectors (CPNI, 2018). However, the majority of infrastructure planning and investment converges around a more focused group of sectors, typically involving energy, transport, digital communications/IT, water supply, waste water, flood protection and solid waste (Tran et al, 2014; Hall et al, 2017). The Infrastructure Transitions Research Consortium (ITRC) advocates a strategic and systematic approach to investment and decision making for national infrastructure, both in the UK and globally, involving analysis of the performance of infrastructure and a direction for adaptable yet clear pathways for investment over long-term planning horizons (Hall et al, 2017). Such a systematic approach is being adopted in the UK, following the establishment of the National Infrastructure Commission (NIC) in 2015 to develop a framework for planning major infrastructure investment.

To inform the work of the NIC, a National Needs Assessment was developed which provides an independent and long-term vision for UK infrastructure where "'the UK will invest efficiently, affordably and sustainably in infrastructure assets and services that will drive the economic growth necessary to enhance the UK's position in the global economy, support a high quality of life and realise a low carbon future" (Armitt et al, 2016). This assessment involved a detailed analysis of future infrastructure service needs and provided the foundation for a National Infrastructure Assessment (NIA). The recently published NIA outlines a long-term and cross-sectoral infrastructure strategy and vision for the period 2020-2050, involving a significant programme of upgrades centred around fibre broadband, renewable energy and urban transport (NIC, 2018). In terms of capital investment, the National Infrastructure and Construction Pipeline includes projected public and private investment plans of over £600 billion in UK economic and social infrastructure between 2017-2027 which can be sustained long-term with the NIC having been given a fiscal remit of 1 to 1.2% of GDP (IPA, 2017).

1.1.2 Risk and Resilience

Infrastructure provides services and utilities which are distributed through spatial networks of connected assets from source to sink. For example, electricity is transported from generation sites to homes and businesses, and railways transport passengers from boarding to alighting stations and freight between terminals. Infrastructure owners and operators face a variety of challenges and in the management and maintenance of a portfolio of assets, in order to sustain their functionality and continuity of service. At a high-level, Hall et al (2017) state that the two major challenges for national infrastructure management are complexity and uncertainty. Infrastructure networks can vary significantly in their design and operation, whereas the number of 'moving parts' increases, the complexity of understanding and managing infrastructure increases. Uncertainty relates to the number of unknown factors that determine infrastructure supply and demand, with a vulnerability to potentially unexpected future changes, such as population, economic growth and technology. The ability to break down the complexity of infrastructure networks is therefore crucial to effective planning and management, as are efforts to obtain information on network dynamics and projections of future trends.

The continued operation of infrastructure networks is of paramount concern, with significant capital investment required in the face of challenges from the 'three Cs' of congestion, lack of capacity and carbon (NIC, 2017) for infrastructure to keep pace with population growth and modern life. With capacity constraints, infrastructure demand is a major global challenge, particularly with increasing and ageing populations in cities putting urban infrastructure under stress (Tran et al, 2014; Heathcote, 2017). For example, all infrastructure relies upon a continuous supply of electricity, and with an increasing demand for and dependence on electrical power driven in part by communication technologies, whilst on the railway there is an increasing demand for both passenger and freight services (ORR, 2016; 2017). However, such an intensive utilisation of infrastructure networks adds to an already complicated management challenge, with inherent capacity and design limitations presented by ageing networks with limited redundancy. Ageing infrastructure assets are a particular issue across multiple sectors, which incur repair costs for public and private sectors whilst increasing the threat of business and supply chain interruptions (Zurich, 2017) leading to insecurity of supply. In addition, infrastructure management is influenced by a broad range of factors including the financial climate, regulation, network effects, multi-stakeholder perspectives, siloed thinking (Parlikad & Jafari, 2016) and a general desire to maintain and improve environmental standards, including cross-sector decarbonisation (Tran et al, 2014).

Alongside the capacity and design pressures on infrastructure, owners and operators that are already under stress must also manage specific risks to their asset portfolios. The concept of risk is a broad one and can be thought of as the probability of events or situations occurring that pose a threat to the normal functionality of infrastructure and the subsequent provision of services. According to the Engineering Council (2011), risk can be considered as the potential for an adverse outcome, and is a multifaceted idea including elements relating to the expected consequence and likelihood of harmful events. The determinants of risk have interchangeable terms, with different envelopes of meaning dependent on the discipline in which they are applied. A review of risk terminology by Thywissen (2006) identifies risk as the probability of damage, comprising the key concepts of hazards (events with the potential to cause adverse effects), vulnerability (the potential for damage) and exposure (the number of elements at risk). Cardona et al (2012) define the determinants of weather and climate risk as vulnerability and exposure, alongside the major drivers of risk and the impacts when risk is realised. Particularly for natural phenomenon, risk is highly dynamic and spatiotemporally variable. In the context of this thesis, risks to infrastructure can be defined as the combination of: a hazard, such as extreme weather; the vulnerability or susceptibility of assets to this hazard; and, the consequence of these assets failing for infrastructure service operations and performance.

As part of the UK's National Security Strategy (HM Government, 2015b) one of Government's key priorities is to the need to improve the security of Critical National Infrastructure against attack, damage or destruction. Risks can be in the form of internal and external shocks, ranging from mechanical breakdown of equipment to more serious threats such as climate change, terrorism and systemic failure (ICE, 2009) alongside the emergent threat of cyber-attacks (DfT, 2016; POST, 2017). Unplanned events present a significant threat to network management, as well as having major socioeconomic impacts. For example, despite the rail network being considered a robust mode of transport (Eddowes, 2003) the intense storms of 28th June 2012 resulted in 10,000 delay minutes to train services across GB and severed key rail links between England and Scotland (Jaroszweski et al, 2015). Furthermore, any significant electricity supply interruption could potentially have significant economic consequences for the UK (Royal Academy of Engineering, 2011; 2014). In April 2018 a city-wide power cut in Birmingham, UK resulted in the loss of supply to 9600 customers causing shops to close and disruption to departure boards and lighting at Birmingham New Street railway station (ITV, 2018).

Of particular concern, and most readily observed, are the risks posed by climate change and extreme weather. Baker et al (2010) outline how infrastructure has a two-way relationship with weather and climate, through carbon emissions from operations and the need to mitigate the effects, along with the impact of extreme weather on infrastructure assets and the need to adapt to changing conditions. It is the latter that is of most interest for maintaining network functionality. It is the ‘extreme’ weather events, such as flooding, heatwaves and storms that present the greatest risks to infrastructure (Thornes et al, 2012). Climate change is increasing the likelihood of experiencing more frequent extreme weather events (IPCC, 2012) which in turn increases the risk of infrastructure failure. Thornes & Davis (2002) estimate that up to 20% of unplanned delays to railway services may be as a result of adverse weather conditions, whilst Dawson et al (2016) highlighted how projections of increasing sea levels are likely to increase days with line restrictions by up to 1170% and lead to repair costs in the £10s of millions. For energy, McColl et al (2012) reported that weather-related faults on the UK electricity distribution network in 2008/2009 caused approximately 1.9 million customer interruptions. Focusing on urban infrastructure, Chapman et al (2013) outlined how urban heat can place great stress on critical infrastructure networks in cities, through a greater demand for services and increasing vulnerabilities. For example, the Urban Heat Island (UHI) effect can cause heat to be retained by buildings and infrastructure in cities, elevating urban temperatures and increasing energy consumption for cooling (Azevedo et al, 2016). Public health issues are also of interest, with Thornes et al (2017) and Hickman et al (2018) exploring air quality in enclosed facilities, such as Birmingham New Street railway station. Health and social care systems can be impacted by extreme weather, through increased demand for services alongside the direct impact on supporting systems and networks (Curtis et al, 2017).

Given the variety of risks, the provision of resilient and effective infrastructure is a global policy priority, with the African Development Bank and Asian Development Bank both making the case in recent reports for increased infrastructure investment to promote national development (ADB, 2017; AfDB, 2018). The building of resilient infrastructure also forms part of the United Nation's Sustainable Development Goals (UN, 2015). Resilience is another broad concept, with no commonly accepted definition. Different actors, organisations, regulators and stakeholders will have a different viewpoint on resilience dependent on their functions and interests, so it is important that the complete spectrum of resilience be accounted for when considering interventions. The definition of resilience from the UN (2016, p22) describes the "ability of a system, community or society exposed to hazards to resist, absorb, accommodate, adapt to, transform and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions through risk management".

Resilience is multi-faceted and involves multiple timescales, with the World Economic Forum (2013) defining five core components of resilience as robustness, redundancy, resourcefulness, response and recovery. According to Howell (2013), robustness relates to protection elements such as fail-safes and firewalls, redundancy is the creation of excess capacity and alternative options for service provision, resourcefulness is building networks of resources and organisations to react efficiently to events, response involves feedback mechanisms for early recognition and response to issues, whilst recovery is the capacity to adapt and rebound from disruption. Wang (2015) also introduces concepts of reliability and sustainability, taking a more holistic and long-term view of infrastructure by using failure as an opportunity for improvements and building back better. Thywissen (2006) explains how the concept of resilience also incorporates the idea of coping capacity, relating to the level of damage a infrastructure can cope with whilst still providing a service. In the context of this thesis, resilience can be considered as the ability of infrastructure to provide a service before, during and after a hazardous event, with elements of improving robustness; the ability to resist disruption, redundancy; the ability to use backup assets and pathways to provide a service during disruption, and recovery; the ability to rapidly return to normal service following disruption.

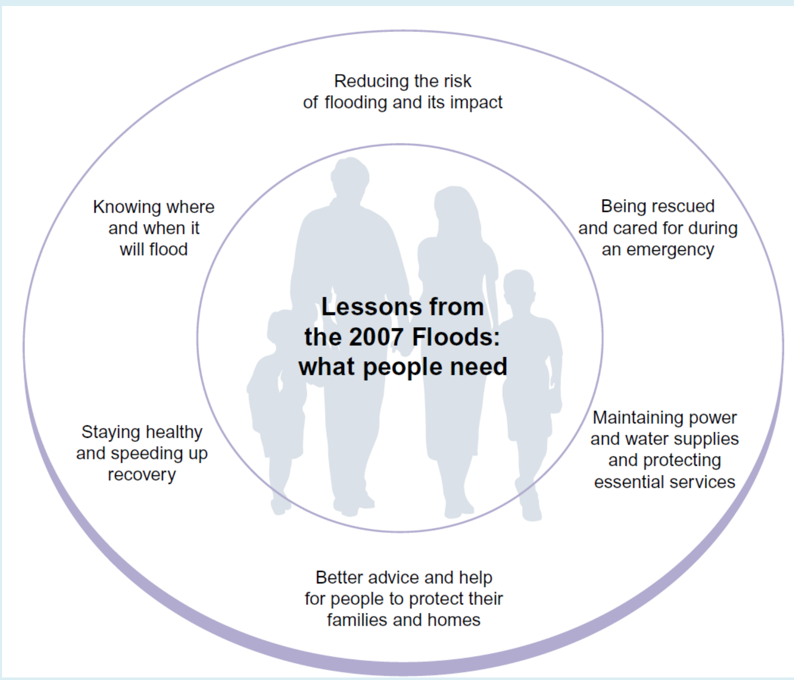
1.1.3 Infrastructure Interdependencies

The vulnerabilities of infrastructure networks extend beyond the directly managed asset portfolio, with disruption to key supporting elements such as electricity and ICT (Information and Communication Technology) resulting in a loss of service. The management of critical infrastructure, and the resilience to major challenges and hazards, is complicated by the increasingly interconnected and interdependent nature of infrastructure. Interconnected and tightly coupled infrastructure can lead to social and service disruption that is greatly out of proportion to physical damage caused, as a result of cascading failure from localised damage (Vespignani, 2010). In the context of this thesis, infrastructure interdependency relates to the reciprocity between physical assets, in that interdependent assets influence each other's functionality due to physical proximity of operational interaction (O'Rourke, 2007). There is also an element of directionality, in that interdependent assets place demands upon each other, whilst dependent assets have a one-way dependency upon external assets.

CASE STUDY – SUMMER 2007 FLOODING IN THE UK

Source: Pitt Review of flooding in the UK during the Summer of 2007 (Pitt, 2008).

The experience of extreme weather events highlights the potential for national-scale impacts across a number of infrastructure sectors. Extensive flooding in the UK during the Summer of 2007, extensive floods presented a major civil emergency, with 55,000 properties being inundated with water, tens of thousands of people made homeless, 7000 people rescued from by the emergency services and 13 fatalities. Many essential infrastructure services were lost, with almost half a million people without mains water or electricity, transport networks failed, a dam breach was narrowly averted, and emergency facilities were inaccessible. Specifically, Gloucestershire was severely affected with the loss of a water treatment works leaving 350,000 people without mains water supply for up to 17 days, the shutdown of a major electricity substation leaving 42,000 people without power in Gloucester for up to 24 hours, 10,000 people left trapped on the M5 motorway and commuters left stranded on the rail network. Overall, insurance costs were estimated at over £3 billion, with further substantial costs faced by central government, local public bodies, businesses and private individuals.



Lessons from the 2007 floods

CASE STUDY – EXTREME WEATHER DURING WINTER 2013/14 IN THE UK

Source: Brown review of extreme weather in the UK during the winter of 2013/14 (DfT, 2014a)

The experience of extreme weather in the UK during the winter of 2013/14 paints a similar picture for transportation, where a combination of storm activity, extreme rainfall, flooding, wind and coastal damage, and storm surges resulted in prolonged disruption to road and rail. Most evident was the impact on rail, with coastal storm damage severing the only rail line to South West England at Dawlish, leading to rail services west of Exeter being suspended for two months. Elsewhere, trees blown over in the storms caused severe disruption and damage to number of lines on multiple occasions, particularly after the St Jude's storm on 28th October, whilst intense rainfall caused flooding and triggered embankment slips resulting in several lines being closed or disrupted for many days. Key roads in the region were on high alert, whilst others were closed for varying periods due to flooding as well as trees or power lines temporarily blocking the carriageway. Gatwick Airport also suffered severe disruption on 23rd and 24th December, with the partial closure of the North Terminal because of basement flooding disrupting key power and IT systems. The Port of Immingham was also closed for a number of days in December 2013 with the east coast tidal surge overtopping the main dock gates, causing extensive flooding of the port area and also disrupting key power and IT systems.

Railway lines at Dawlish were severely damaged by wind and high tides

The conceptual basis of infrastructure interdependencies is explored by Rinaldi et al (2001), who outline how infrastructure networks are mutually dependent because the continued functionality of one network may depend upon the functionality of another external network. Two key types of interdependency defined by Rinaldi et al (2001) are *geographic* – where assets are co-located in the same geographic area and therefore exposed to the same hazards, and *physical* – where one asset depends upon a flow of resources from another external asset. Zimmerman (2001; 2004) defines similar concepts as spatial and functional interdependencies. There is widespread evidence that the interdependence of infrastructure can be the source of emergent opportunities and risks, and therefore there is value in the identification and management of interdependencies (Frontier Economics, 2012). Operational efficiency through the use of ICT management systems, and economic efficiency through increased return on investment from cross-sector projects present benefits from interdependence, whilst an increasing reliance on technology and external resource supplies mean that the implications of asset failure may be widespread. As defined by Rinaldi et al (2001) interdependencies present the potential for common cause failure (Zuo et al, 2018), where multiple infrastructure assets are exposed to the same hazard and fail at the same time either because assets are located in the same physical corridor or the hazard is widespread, and cascading failure (Lu et al, 2018), where disruption can propagate through infrastructure due to a loss in functionality of an asset in one network to which an asset in another network is directly connected and directly dependent for its functionality.

UK infrastructure comprises a highly complex and interdependent collection of networks and assets that depend upon each other to work successfully (HM Treasury, 2013). There is widespread evidence that interdependencies are important for the planning, design and operation of critical infrastructure and this only set to increase with greater reliance on technology, digital connectivity and power supply (The Resilience Shift, 2018). The difficulty in integrating interdependencies into the planning, design and operation of infrastructure is that, historically, policy and decision making has been made in isolation for individual infrastructure sectors and projects, with little regard for other interconnected infrastructure (Tran et al, 2014). It is crucial that long-term infrastructure planning involves strategic thinking, overcoming the challenges of a complex governance landscape, the existence of regulation at multiple geographical scales, and the need to implement policies to facilitate low-carbon transitions and innovation.

Exploring key cross-sector interdependencies, Tran et al (2014) identifies water-energy and energy-transport interactions as key interdependencies that may influence the future performance of these sectors. Looking at interactions between the water and energy, energy supply has interdependencies with water availability as thermal power plants use water for cooling, in addition to the existing hydro and pumped storage capacity, therefore hydrological variability poses a risk to water-dependent electricity generation. Murrant et al (2017a; 2017b) explored the resilience of the water-energy nexus, finding that a lack of available freshwater resource may compromise the UK government's policy of increasing thermal generation capacity, but seawater resources may reduce generation costs during low freshwater flows. For interactions between energy and transport, electricity demand is likely to increase through an increase in the adoption of electric vehicles and the electrification of heat and transportation, which would increase both electricity consumption and peak loads. This would require large investment in additional generating capacity, national transmission networks and local distribution networks (Baruah et al, 2014).

The electrification of transport networks increases the dependency of transport on energy, meaning that a significant failure on the electricity network has the potential to cascade onto the transport network with far reaching consequences (Chapman et al, 2013). In 2003, the failure of three electricity transmission substations in South London resulted in the loss of supply to London Underground for over 30 minutes, and almost 40 minutes to Network Rail causing significant disruption to services (NG, 2003). In 2015, Euro Tunnel rail services between England and France were disrupted for over six days due to power supply issues with just a single line operating, resulting in delays of up to an hour (Kitching, 2015). There were also further knock-on impacts for the transport sector, with congestion on the coastbound M20 motorway in Kent due to Operation Stack (which involves parking HGVs on the carriageway to ease congestion to the Port of Dover) causing 20 miles of tailbacks.

Exploring the concept of interdependencies between infrastructure assets involves an understanding of the infrastructure systems in which they reside. A broad definition of a system from INCOSE (2018) is a collection of different elements that together produce results not obtainable by the elements alone, with whole system-level value added by the relationships and interconnections among the parts. Therefore, a system is more than the sum of its parts, exhibiting behaviour that cannot be fully understood by examining the parts in isolation.

Dawson et al (2018) considered a systems view of infrastructure, with a system comprising of physical components; the resources moved by, or used in the construction of the infrastructure; the service provided; the users that depend on them, including supply and demand dynamics; and the governing processes, including various actors and protocols. Within these various components, infrastructure can depend upon other infrastructure to function, by means of technical, social and economic interdependencies. The distribution of different risks throughout a system is also highlighted by Dawson et al (2018) with specific risks to physical assets, network scale risks, interdependent risks produced by the relationships between assets of different types, and systemic risks at the level of the whole infrastructure system, such as supply chain disruption. For example, the railway system has a physical infrastructure sub-system which both relies upon and influences other sub-systems such as the supply chain, funding and socio-political factors (RSSB, 2016b). A systems-of-systems approach to analysing infrastructure is advocated by Hall et al (2013), moving beyond traditional siloed-thinking around isolated systems and viewing national infrastructure as a series of interconnected systems, such as transport and energy, which place demands on each other.

In the context of this thesis, the principal focus is on risks presented by connected physical assets either at the network scale, or the level of interdependent assets that present a connection between different systems. Therefore, the scope of direct interest in an infrastructure system is thus limited to technical interdependencies between the physical sub-systems and networks contained within them, and their interactions, whilst recognising that assets have social and economic interdependencies with other sub-systems.

Thacker et al (2017b) presents a multi-scale system-of-systems characterisation of physical infrastructure to facilitate such an approach, shown in Figure 1.1, with infrastructure represented as a collection of nodes and edges operating at different systemic levels. Interdependencies exist both internally (within individual sectors) and externally (between connected sectors). The lowest layer of this structure is customers, who consume, and place demands upon infrastructure services. Infrastructure consists of assets, which are physical components that provide a function, which collectively form a network of interconnected elements. Networked assets that fulfil a similar function, such as railway signalling, can be grouped into sub-systems and subsequently those sub-systems form part of a system for that sector.

A system-of-systems is thus a collection of systems from different infrastructure sectors, each with their own moving parts, that comprise a national infrastructure system. These systemic interactions mean that if one part of the systems fails, whole system failure can occur (Beckford, 2014).

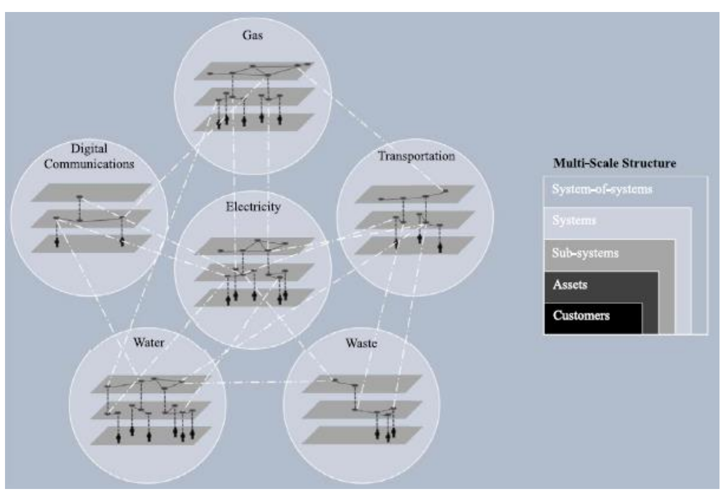


Figure 1.1 System-of-Systems Representation of Multi-Scale Critical National Infrastructure. Adapted from (Thacker et al, 2017b).

CASE STUDY - DECEMBER 2015 FLOODING IN LANCASTER, UK

Source: Ferranti et al (2017).

Intense rainfall during 4-5 December 2015 had a major impact on Lancaster's critical infrastructure. A two-day rainfall total of 82mm through persistent heavy rainfall, resulted in common-cause failure through localised flooding. Business and residential properties were flooded whilst road transport was severely disrupted, leading to the closure of the key route around the city centre along with key bridges and part of the M6 motorway. A significant power outage caused by flooding of a major electricity substation led to approximately 61,000 homes in Lancaster and the surrounding areas being without power for over two days until emergency generators were brought in. A major issue here was the flood water in excess of one metre in height at the substation site presenting difficulties for maintenance access. Another power outage cut off supplies to 45,000 homes overnight before the power supply was maintained via generators until reconnection to the mains supply later in the week. There was a clear case of cascading infrastructure failure, with widespread disruption across Lancaster and the surrounding area due to the unavailability of a power supply. With no residential or public broadband connection, and mobile base stations out of operation providing no mobile phone signal, there was a reliance on radio for information. There was no power for street or traffic lights on the roads, and no fuel available from electric pumps, whilst trains could only stop at Lancaster station during daylight as there was no lighting. Hospitals cancelled routine appointments and non-critical surgery, whilst care services, schools and the University were also suspended. Overall, every critical infrastructure network, across road, railway, electricity, digital communications, emergency services, and water were impacted either directly by flooding, demonstrating common-cause failure, or indirectly by the failure of the substation, demonstrating cascading infrastructure failure.

1.2 Context of Thesis

From the above, it is clear that (i) infrastructure is important socially and economically (ii) infrastructure has a variety of challenges to face and risks to manage (iii) infrastructure networks are interdependent which increases efficiency but also amplifies single sector risks. There is therefore a need to improve the resilience of infrastructure to both sectorial and interdependent risks, in order to maintain the value of an infrastructure system.

Resilience of critical infrastructure is a key priority for the UK government. As part of the National Security Strategy (HM Government, 2015b) annual Sector Security and Resilience Plans are produced (Cabinet Office, 2017) which set out the current resilience of critical infrastructure to hazards, risks and other threats alongside proposed measures to improve resilience. These plans involve a range of potential resilience interventions. For example, for the energy sector, measures include ensuring an acceptable and affordable level of Black Start service, an assessment of cyber-attack risk, fuel delivery contingencies and flood protection, whilst for the transport sector, measures focus on multi-agency planning, technological solutions, incident response, cyber-attacks, flood protection, industrial action and space weather. Internal resilience plans exist within infrastructure owners and operators, who need to respond to dynamic risks such as climate change to maintain service provision and prevent escalating costs. Climate change adaptation reports have been produced by multiple infrastructure sectors including rail (NR, 2015a), electricity distribution (WPD, 2011) and water (Severn Trent, 2015). It is however crucial that interdependent network properties are considered in any resilience interventions to prevent cascading failure (Buldyrev et al, 2010).

Infrastructure resilience involves a range of types of intervention across multiple divisions and activities of multiple organisations. There are also multiple spatial scales to consider. The Pitt Review (Pitt, 2008) of the summer 2007 flooding in the UK presented a case of a national-scale civil emergency. However, Ferranti et al (2017) demonstrated very localised impacts of an extreme weather event for Lancaster, at the city-scale. For the railway network, Network Rail have produced specific route-based weather resilience and climate change (WRCC) adaptation plans, e.g. (NR, 2016c), highlighting targeted and local-level resilience interventions. Urban climate resilience is becoming increasingly important, with growing urban populations exposed to extremes such as urban heat (Tyler & Moench, 2012) requiring interdisciplinary action, high resolution monitoring and modelling of weather impacts on infrastructure systems (Chapman et al, 2013). The centralised nature, density and interdependencies of urban infrastructure lead to interconnectedness between services, meaning that disruption at one point in the system can have significant knock-on effects (Guthrie & Konaris, 2012).

1.2.1 Problem Description: Resource Allocation

Despite the heightened need for infrastructure resilience, owners and operators must manage a broad portfolio of activities, at multiple organisational and spatial levels, within the constraints of a limited management budget and finite resources. These activities can include day-to-day maintenance programmes, network operations, incident response, fault resolution as well as implementing long-term asset renewal and upgrade programmes (WPD, 2014; NAO, 2015). With such a range of undertakings and the high number of assets involved within an infrastructure network, it is not feasible or possible to enhance the resilience of every location. A major network management challenge is the allocation of resources for such undertakings, in order to make the most cost-effective use of the funding, personnel and equipment that are available (Durango-Cohen and Madanat, 2008). There is therefore a need for prioritisation in resource allocation, where resilience interventions are targeted to assets or locations within a network where they will have the greatest potential benefit. The optimal allocation of resources and budgets for specific projects can be based upon cost-effectiveness and the valuation of an asset within an infrastructure system (Bier et al, 2008) and can be used to prioritise which projects to pursue and in what order (Carbno, 1999). A targeted prioritisation scheme can promote efficiency in decision making for operational and financial benefits. However, optimising investment and expenditure for infrastructure projects requires novel approaches to strategic and tactical asset management decisions (Parlikad & Jafari, 2016). They propose a quantitative and interdependent approach to decision making, moving from ad-hoc and qualitative prioritisations for single networks to value-based priorities across systems.

1.2.2 Proposed Solution: Network Criticality

An effective quantitative approach to prioritising resilience interventions for infrastructure networks is through risk-based resource allocation, where projects are prioritised according to the perceived degree of system risk they are designed to mitigate. Farrell et al (2013) outline how risk-based processes can be used to allocate scarce resources across multiple systems, which have common traits in that they are all focused on protecting assets, have many potential locations for disruption and have many sources of risk to monitor and oversee. A key function of strategic asset management is the risk-based evaluation and prioritisation of options, prioritising projects principally based upon the potential location of application (IEC, 2015; Montesinos-Valera et al, 2017).

Verner et al (2017) suggest that the protection of critical infrastructure should focus on the identification and prioritisation of such locations based on the potential network consequence of asset failure, using objective measures to avoid reliance on expert or tacit knowledge which may have personal judgement bias and lack appreciation of system-level resilience. Such a prioritisation would assess risk from network effects, recognising that whilst assets only provide value when combined with other assets within networks and systems, individual assets can have a different influence on the overall value dependent on their criticality to service operations (Parlikad & Jafari, 2016). Therefore, if the response of the network to asset failure is dependent upon the locational characteristics of an asset, the spatial distribution of operational risk through a network is unlikely to be uniform and suggests that an assessment of network criticality would be of value for identifying more and less 'critical' locations. Network criticality assessment is common in both academic research (Jonsson et al, 2008; Dunn & Wilkinson, 2013; Faramondi et al, 2018) and internally within infrastructure owners and operators (NR, 2016d; Ofgem, 2017a) with a focus on identifying critical nodes, edges or components in infrastructure networks based upon various metrics and measures of performance-based risk.

Central to a location-based prioritisation scheme for resource allocation is the identification of localised *single points of failure* which are strategically important locations that, should they be disrupted, have the potential to cause large scale consequences for service performance and potentially sever key social and economic links (DfT, 2014a). For the railway network, critical locations are often referred to as *Golden Assets* which are defined as “equipment and facilities situated at locations where any failure of this equipment would have a severe detrimental impact on the operation of the railway” (Ellis, 2010, p177). The criticality of a location within an infrastructure network is a measure of its strategic importance for maintaining service performance, which can be defined by the potential consequence of failure. For the railway network, criticality would be mainly influenced by the number and frequency of trains passing or calling at that location (RSSB, 2016a). Therefore, as the topological characteristics and service patterns within a network have significant spatial variability, incidents or faults occurring at different locations on a network can have vastly different consequences for service performance, and thus a very different measure of network criticality. Jaroszweski et al (2015) demonstrated how weather-related incidents at key locations can cut off access to large parts of a transport network, not only through disruption to train services at the point of failure but also through knock-on disruption that propagates widely throughout the network resulting in costs and delays significantly greater than just the local impact. In an electricity distribution network, there is also a clear hierarchy of assets as one higher voltage substation can supply several lower voltage substations. Therefore, faults occurring at different substations on the network can have vastly different consequences for service performance and the continuity of electricity supply.

Network criticality can help to understand the distribution of risk throughout a network and prioritise interventions at locations where the greatest service performance improvement would be yielded from the investment. Introducing externalities to a system adds greater complexity to network management activities and thus resource allocation. In order to appreciate a more holistic view of risks to a network and avoid siloed thinking, it is necessary to look beyond the traditional boundaries of that particular system at external assets that may influence the functionality of that system.

1.2.3 Research Gap

Based upon the above, there is clear need for an efficient and cost-effective prioritisation scheme for resource allocation, that targets activities towards critical network locations where the use of finite resources is likely to have the greatest benefit for service performance and resilience of the whole infrastructure system. This thesis aims to develop a network criticality assessment methodology for the identification of localised single points of failure, demonstrated for both individual infrastructure networks and between dependent infrastructure systems to produce a risk assessment that transcends system boundaries.

The originality of the network criticality assessment methodology presented in this thesis, and thus the contribution to research, is primarily through the spatial scale and resolution of assessment, and the resultant benefits for reliability, certainty and application of the single points of failure identified. To quantify network criticality, the principal direction of existing literature is towards national-scale mathematical modelling and simulation of infrastructure vulnerability often across multiple interdependent systems (Thacker et al, 2014; Cats et al, 2016; Pant et al, 2016; Thacker et al, 2017b). Whilst such simulations may have a broad scope, and the ability to explore a range of infrastructure and failure scenarios, the scale of the models requires a series of assumptions on the behaviour of infrastructure systems for simplicity and to reduce computational expense which constrain the reliability of the results i.e. Thacker et al (2014). Vulnerability models are also limited by their uncertainty surrounding asset dependencies, often inferring dependencies from spatial proximity with assumptions that an asset in one network is dependent upon the geographically closest asset in the connected network i.e. Pant et al (2016). National-scale simulations have applications for informing the high-level direction of infrastructure investment and provision, but the application of the output for local-level decision making within infrastructure owners and operators, particularly at the level of prioritising specific assets, is not viable due to the reliability and uncertainty challenges as well as the definition of properties relative to national demand profiles (Pant et al, 2014; Thacker et al, 2014).

There is therefore a research gap in developing a network criticality assessment methodology that better represents real-world infrastructure systems, with applications for localised resource allocation. In this thesis, the challenge of representing reliability in system behaviour is approached through a data-driven methodology. Historical fault databases can be used in the risk-based evaluation and prioritisation of options to identify fault trends for specific assets (IEC, 2015). Metrics of service performance can be used to quantify the consequence of asset failures and thus identify critical locations that have the greatest propensity to generate a high magnitude of disruption should a fault occur. Historical disruption records facilitate a criticality assessment that incorporates real world network behaviour and allow a very focused prioritisation scheme for a broad range of network management activities. For the challenge of certainty in system dependencies, an evidence-based approach is used in this thesis. Utilising information sources from infrastructure owners and operators to accurately trace dependent pathways between cross-system assets increases the certainty in system connectivity. When identifying and integrating asset and system dependencies into a network criticality assessment, a high degree of certainty is required for local-scale applications.

As well as better representing real-world system behaviour and dependencies, there is a need for a more localised focus and spatial resolution with assessments of network criticality based upon historical performance data. For example, the internal prioritisation scheme from Network Rail (2016d) applies a financial metric of network criticality to broad sections of railway track as long as 100km, in terms of the typical cost of disruption from an asset failure relative to the national average. However, whilst this metric is useful for allocating budgets for infrastructure projects at a high-level, a higher resolution of network criticality is required for localised management, for example, at the level of railway links, stations and junctions, and electricity substations, whilst a metric relative to the regional distribution would be more informative. The quantification of regional and high-resolution service performance priorities, within and between connected networks has applications for informing decision making and improving targeted resource allocation for a range of localised asset management and resilience interventions. Through more cost-effective use of the constrained management budget and resources available, robust asset management and network resilience can be promoted whilst identifying opportunities for cross-sector mutual benefit in resilience solutions and enhancements, a priority of the National Needs Assessment for UK infrastructure (Armitt et al, 2016).

The development and interpretation of the network criticality assessments also benefit from stakeholder engagement, including a series of interviews with key personnel at the national and route levels within Network Rail, and discussions with a variety of management personnel at several WPD stakeholder workshops.

1.2.4 Literature Scope

The literature employed in the development of the research presented in this thesis, and that which has been excluded, is influenced by the nature of the resource allocation problem and the application of the proposed solution of network criticality assessment. The originality of the research principally lies in the formalised prioritisation of physical infrastructure for improving resource allocation at the local scale. To define and quantify the criticality of infrastructure at an appropriate level of spatial granularity for localised management (individual assets and their connections i.e. electrical substations and cables) it was necessary to consult literature which represented infrastructure as a network of connected assets. For this reason, the main body of literature employed in the research is that of infrastructure network modelling and simulation. Such work presents technical and quantitative methodologies for understanding the criticality of assets, determined by network topology and flows, such as Panteli et al (2017) who developed fragility curves for networked electricity assets and Pant et al (2014) who modelled passenger flows between networked railway assets. The limitations to the existing literature were then identified and the methodological approach of this thesis, in using industry performance data and metrics to represent real-world infrastructure network flows and behaviour, was developed.

For a single infrastructure network, such as a railway or electricity grid, the identification of the most appropriate literature for informing the research was quite clear. However, when considering an infrastructure network as part of a 'system' and the interdependencies between these systems, there is a wider spectrum of literature available. At a high level, systems thinking literature provides a long-established conceptual basis for considering any technical or social entity as a system comprised of multiple dynamic, interconnections and hierarchical components, where the behaviour of the entity can only be fully understood by analysing interactions at the level of the 'whole system' rather than static and individual elements (Senge, 1990: APM, 2018). There are multiple systems thinking philosophies and methodologies, such as Checkland's Soft Systems Methodology (Checkland, 2000) and Ackoff's Interactive Planning (Ackoff, 2001) which provide frameworks for understanding complex problems and the dynamic behaviour of processes or entities within a system. Evolving from this broader theoretical literature, the systems engineering discipline applies systems thinking to project management, such as the construction or renewal of infrastructure, through an interdisciplinary approach that ensures customer and stakeholder needs are satisfied throughout the lifecycle of the system (INCOSE, 2018). Systems engineering combines multiple branches of engineering to understand the problem in its entirety, with Blockley & Godfrey (2017) outlining how rethinking the construction of infrastructure and collaborative learning can overcome deep and complex issues, echoed in the recommendations of iBuild (2018) in developing an integrated and holistic approach to infrastructure business models.

Understanding infrastructure as a 'whole system', and the application of systems thinking and engineering methodologies, involves the consideration of elements beyond physical asset interdependencies, such as governance and economics. Therefore, the literature employed in the interdependent infrastructure research element of this thesis is dependent on the parts or sub-systems of a system that are directly of interest. This thesis is concerned with defining the criticality of networked physical assets, that may depend on a flow of resources from other physical assets external to that system. The interdependencies directly assessed are thus between networked infrastructure assets from physical sub-systems (i.e. overhead rail electrification and electricity distribution) that are part of broader 'whole systems' (i.e. rail and energy) that are influenced by other interacting sub-systems (i.e. rail franchising and electricity generation). For this reason, the primary body of literature employed to inform the interdependent infrastructure network criticality assessment was that of network systems modelling and simulation. Such work models the interactions between networks of assets across system boundaries, via actual or derived pathways (physical connections or geographic proximity), such as Thacker et al (2017b) who developed a system-of-systems model for disruption propagation between electricity and flight networks, and Thacker et al (2017a) who modelled geographic risk hotspots based on the spatial density of dependent customers on cross-system assets. The limitations to this literature were then identified to inform the methodological approach, in using multiple system performance metrics and network diagrams to represent real-world infrastructure interdependencies.

It is important to acknowledge that interdependent physical infrastructure networks are part of 'whole systems' with multiple interacting elements, and the foundation that systems thinking and systems engineering disciplines have provided for recent network modelling methodologies. Infrastructure interdependencies both influence and are influenced by other sub-systems, therefore there is the potential to scale-up the research with the application of systems methodologies or tools and thus the direct modelling of all system elements, but this is beyond the scope of this thesis. As a result, systems thinking and engineering literature was excluded in the development of the research. Nevertheless, some systemic concepts are helpful for the context of the application of network criticality, such as the work of Beckford (2016) on information management and organisational structure, and are included in the latter chapters of the thesis to aid the interpretation of the research.

1.3 Scales of Complexity

Network criticality is influenced by different scales of complexity in both infrastructure systems and geography. All infrastructure management involves complex tasks, yet different networks have different relative levels of complexity, and thus different degrees of management difficulty, dependent upon the topology, service patterns or flows, and operational processes involved. Therefore, the spatial distribution of risk and thus single points of failure is likely to differ between infrastructure networks, as are the requirements for resilience interventions. Within infrastructure networks, the management of both day-to-day tasks and long-term planning is typically devolved into a series of geographic management regions. Alongside differences in complexity between infrastructure networks, there are also differences in operational characteristics of areas within them. Therefore, this thesis aims to develop a scalable methodology for assessing infrastructure network criticality, demonstrated for three applications of increasing scales of complexity through a case-study approach. The level of complexity is scaled up in each stage, conducting a network criticality assessment firstly for a relatively less complex network in electricity distribution, then a comparatively more complex railway transport network, with both assessments applied to two different regional-scale management areas of varying operational characteristics within each network. The final stage involves scaling up complexity further by bringing the two network criticality assessments together in order to assess the dependencies of an electrified railway on external electricity distribution for traction power supplies at the local-scale.

1.3.1 Less Complex Network - Electricity Distribution

The UK's electricity network delivers power to industrial, commercial and domestic consumers and is divided into two parts. National-scale circuits operating at high voltages (HV) up to 400kV comprise the transmission network, transporting power from generation sites to large substations, which is owned and maintained by a single infrastructure company in National Grid (NG). Regional-scale circuits operating at and below 132kV are the responsibility of Distribution Network Operators (DNOs). The distribution network transforms power from HV via a series of stages down to 11kV and below for residential supplies. DNOs undertake a variety of activities. Alongside design and development, and logistics, the core function within a DNO is network services, involving the management of safety, physical delivery and delivery costs, along with the day-to-day requirements of depots (WPD, 2014). Key tasks are local project planning and delivery such as asset replacement, inspection and maintenance such as tree cutting, customer services, and 'trouble calls' which involve the resolution of faults causing interruptions to customer supplies.

The network is operated by different DNOs, which are separate infrastructure companies, covering different geographic areas of the UK. Within a DNO, network management is further divided into a series of regions known as licence areas, with responsibility for regional distribution services. There are currently fourteen licence areas in GB, managed by six DNOs (Figure 1.2). This thesis focuses on two licence areas of contrasting topology and operations, in the South West and West Midlands, both of which are managed by Western Power Distribution (WPD).

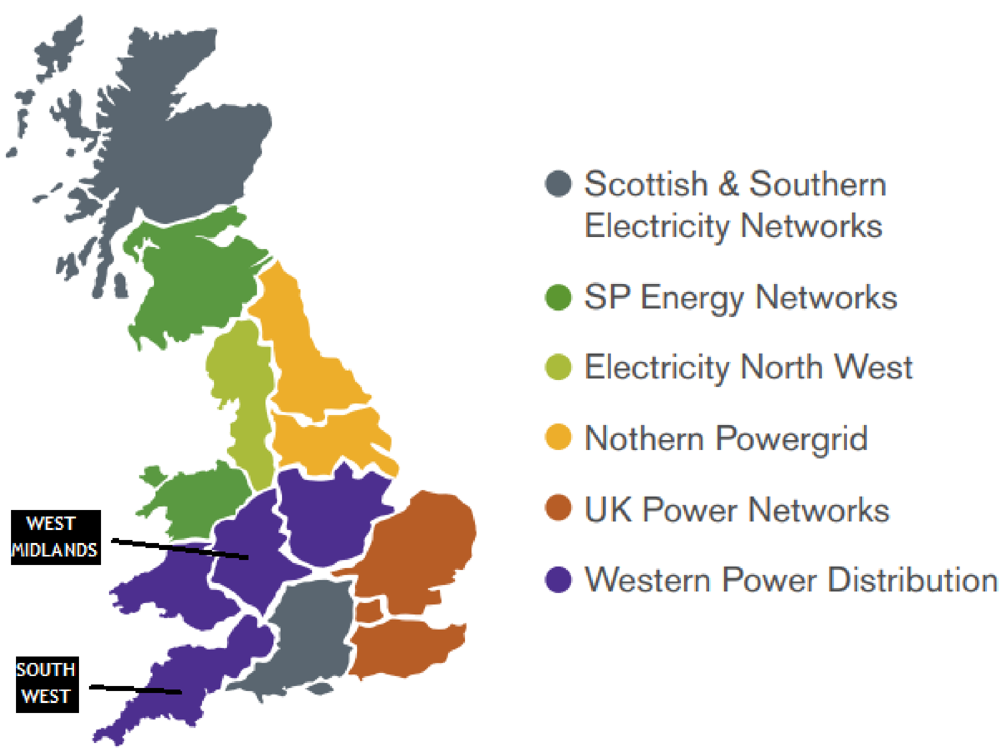


Figure 1.2. Map of electricity distribution network DNOs and Licence Areas. Adapted from Ofgem (2018).

Electricity networks have quite a simplistic and hierarchical topology, where power flows from source to sink (transmission/generation to consumer) and from a small number of HV substations to a greater number of lower voltage substations. Power flows are downstream and unidirectional, with the exception of distributed generation and smart grid technologies, therefore the pathways between substations, and thus the footprint of assets is clearly defined. A substation failure will typically only impact the substations and customers to which it supplies electricity. There is potential for cascades of failure between substations, but this is likely to be within an operating voltage level and with limited spatial propagation. Electricity distribution networks are typically comprised of substation sites connected by underground cables or overhead lines. The distinction between the locational characteristics of substations comes from the operating voltage and the demand/load profiles. Infrastructure management and service operations are also combined, falling under the jurisdiction of the DNO.

1.3.2 More Complex Network - Railway Transportation

The UK's railway network transports both passengers and freight between stations and terminals using rolling stock/trains moving on steel rails. The majority of rail infrastructure is owned and maintained by a single infrastructure company in Network Rail (NR). The operation of train services is the responsibility of separate and privately-owned Train Operating Companies (TOCs) and Freight Operating Companies (FOCs) for passenger and freight trains respectively. For NR, managing the railway network involves three main business activities (NAO, 2015). These are (i) Network Operations – including nearly 75% of the workforce but less than a third of spend, covering in-house maintenance and operations including signalling, day-to-day running and activities, along with small renewal projects (ii) Infrastructure Projects – including 12% of the workforce but two-thirds of spend, involves strategic planning and delivery of large projects, renewals (modernising infrastructure) and all upgrades (performance and capacity) (iii) Long-term planning – includes elements such as plans for meeting future capacity and demand projections, group and corporate strategies, and the digital railway programme within the horizons of five-year Control Periods.

NR devolve the day-to-day responsibility for railway management into nine strategic geographical routes (Figure 1.3), including Freight and National Passenger Operations (FNPO). These routes are semi-autonomous business units and can make operational and financial decisions within the national-level framework and oversight from the National Operations Centre (NOC) in Milton Keynes. This thesis focuses on two routes of contrasting topology and operations, in Wessex and the southern half of London North Western (LNW).

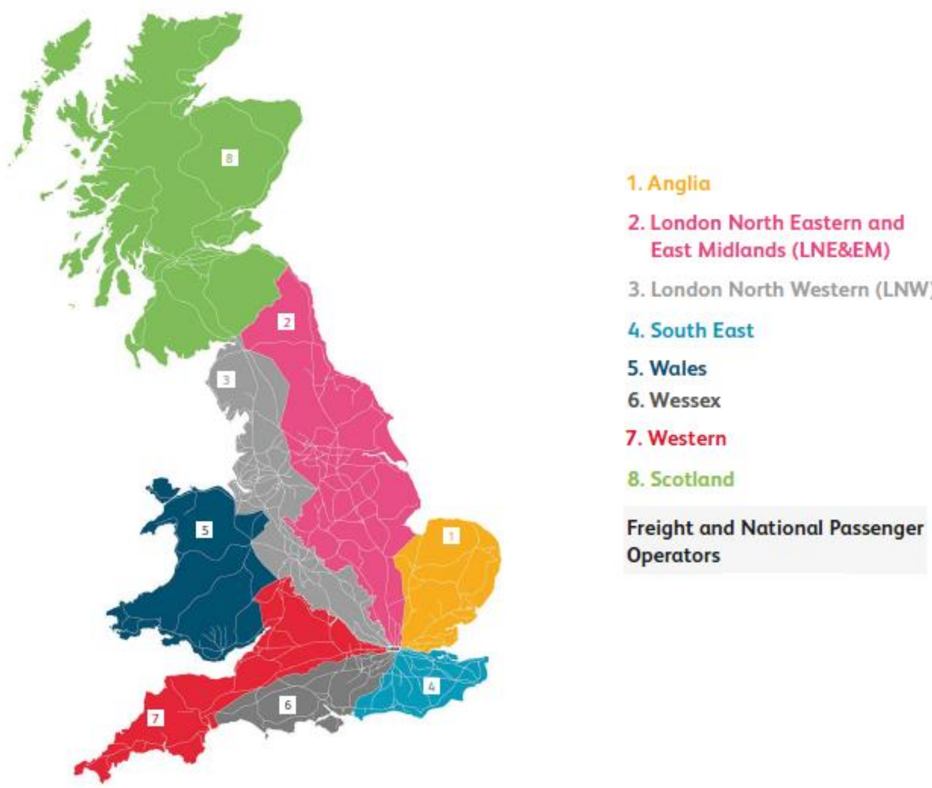


Figure 1.3. Map of strategic routes within NR. Adapted from NR (2017b).

Railway networks have a quite complex topology, as locations are highly interconnected. In theory, it is possible to travel between any two points on the railway network, with any location having the potential to act as both a source and sink for train services. Therefore, service flows are multi-directional, with trains able to operate upstream and downstream along a section of track, dependent upon the number of up/down lines available. There are often multiple possible pathways between locations, and thus the footprint of assets is variable and dependent on train service patterns. There is high potential for spatial propagation of disruption, as an asset failure can have widespread consequences for network performance. It is demonstrated by Jaroszweski et al (2015) how an incident at a relatively minor location on the railway network, such as Barnt Green, has the potential to disrupt services in Scotland and South West England due to reactionary delays to long-distance services.

There is a high variability in the characteristics of locations on the railway network, such as stations, junctions, depots and freight terminals, with demand/load profiles variable dependent on service patterns and different categories of line, such as main lines and branch lines. The management of infrastructure and the operation of services are also separated, although Route Control within NR maintains responsibility for the regulation of services but does not operate rolling stock. The railway network is highly complex, with many ‘moving parts’ and sub-systems such as signalling and communications, many different types of assets and the added complication of human-factors with regulating services, passenger behaviour and train drivers. Multiple competing T/FOCs and train services in the same railway corridor effective and efficient operational and infrastructure management.

1.3.3 Dependent Networks – Railway Electric Traction

An exemplar of the dependence of the transport system on the energy system, and the potential for cascading infrastructure failure, is the clear one-way dependency of rail transport systems upon external power distribution systems for a supply of electrical power for various rail sub-systems including traction current, signalling, stations and control centres (RDG, 2017). The energy sector is critical to all other sectors, as all infrastructure relies upon a constant electricity supply, therefore, a significant electricity supply interruption could potentially have major economic consequences (Royal Academy of Engineering, 2011; 2014). Furthermore, the success of rail transport is highly reliant on physical infrastructure, including well maintained rail track, power supply and train fleet (Leviakangas & Saarikivi, 2012). The most direct dependency is the supply of traction power for electrified rail to move rolling stock. Approximately 40% of the British railway network is currently electrified, with UK railway traction electricity demand at 3.4 TW/h in 2015-16, making the rail network one of the largest single consumers of electricity in the UK (NR, 2017c).

Combining network criticality for two networks of contrasting topologies, service operations and management structures presents a challenge, with complexity scaled up further when attempting to identify and understand the dependencies between the two systems overall. For this specific application, dependent network criticality is assessed for a local-scale example of an electrified railway dependent on external electricity distribution infrastructure supplying power for the traction feeder system. This is treated as a one-way dependency, although it is recognised that the electricity demands of a railway will influence the design of both electricity distribution and transmission networks.

The operation of a traction feeder system is influenced by the activities of two infrastructure companies from different infrastructure sectors, in this case NR and WPD. In order to assess cross-sector risk, there must be a consideration of multiple factors which introduce complexity such as (i) different types of assets – from electricity distribution and traction feeder substations, to railway electrification infrastructure (ii) different types of service flows – unidirectional power flows and multi-directional train services (iii) different network topologies – hierarchical and interconnected (iv) different management regions – licence areas and routes (v) different approaches to service and infrastructure management – integrated for electricity, separated for the railway (vi) different organisational targets and priorities. Assessing system externalities increases the envelope of risks and vulnerabilities to a system, and thus the scope of resilience interventions required. It also increases the opportunity for cross-sector collaboration and integration of infrastructure planning and operation, for mutual benefits.

There is also a difference in geographic complexity, moving from single-sector and regional-scale network criticality assessment to cross-sector and local-scale risks. For specific dependencies between assets, a greater detail of information is required to determine individual dependent pathways and resource flows. A case-study of the electrified suburban Cross City railway line, in the West Midlands, UK, was chosen to allow a focus on locally specific risks and dependencies (Figure 1.4).

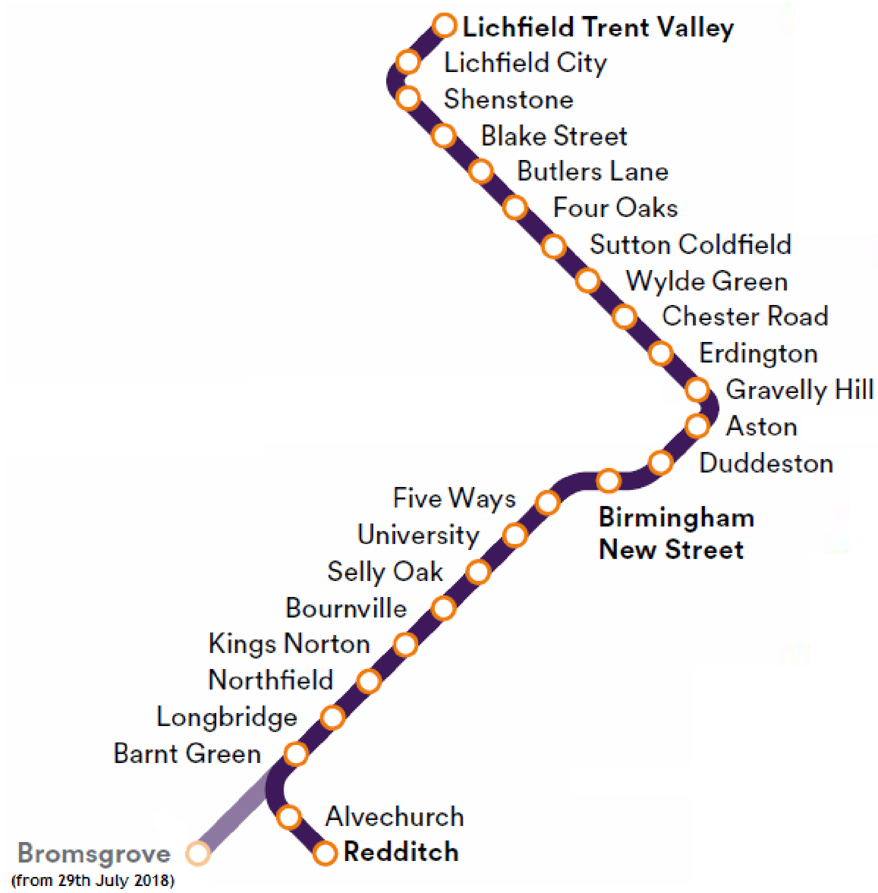


Figure 1.4. Map of Cross City railway line. Adapted from WMR (2018a).

The Brown review of transport resilience to extreme weather, based on the experience of winter 2013/14 (DfT, 2014a) highlighted the resilience of the electricity supply as a specific threat to the continued operation of the rail system. In particular, the failure of key substations can be an unforeseen source of vulnerability during a disruptive event and it is recommended that rail and electricity network managers liaise to trace critical substations and cables through which traction power is supplied and identify single points of failure where resilience improvements can be targeted. To contribute towards this recommendation, this thesis undertakes a network criticality assessment of dependent power distribution and electrified railway systems.

1.4 Aim and Objectives

The overall aim of this thesis is ***to develop and demonstrate a local-scale and high-resolution network criticality assessment methodology for the evidence-based identification of single points of failure within infrastructure systems of different scales of complexity and dependency***. A series of specific objectives are designed to facilitate the achievement of this aim.

Objective One: ***To evaluate network criticality for a relatively less complex infrastructure system – electricity distribution.***

Objective Two: ***To evaluate network criticality for a relatively more complex infrastructure system – railway transportation.***

Objective Three: ***To evaluate network criticality for two dependent infrastructure systems – traction feeder supplies to an electrified railway.***

Objective Four: ***To explore the practical implications of the presented network criticality assessments for infrastructure system management.***

Objective Five: ***To evaluate the contribution of the developed network criticality assessment methodology and explore future directions for the quantification of infrastructure network criticality.***

1.5 Thesis Structure

This chapter has provided a background the thesis, including the importance of infrastructure, the challenges and risks faced, and the interdependencies between systems, along with an overview of the context of the thesis and the research gap, including an outline of the problem, the proposed solution and the approach of the thesis to network criticality assessment. Each of the specific objectives detailed above is covered by a dedicated chapter in this thesis.

As a result of the range of data and information sources used in the thesis, and the differences in application, there is no overall literature review or methodology chapter, to aid interpretation of the material Chapters 2-4 contain a review of the relevant research background and the development of the specific network criticality assessment methodology used. Chapter 5 explores how the results of the criticality assessments can be applied for infrastructure management, with Chapter 6 providing a critique of the methodology and suggestions for future improvements. Finally, the overall conclusions of the thesis are presented in Chapter 7 alongside considerations of potential future changes that may influence network criticality and opportunities for future research. Figure 1.5 provides an overview of the thesis structure.

It should be stated that the material in Chapter 3 is based upon a paper from Hodgkinson et al. submitted to the international journal '*Transportation Research Part A: Policy and Practice*', the manuscript of which is included in *Appendix A*. To outline the various author contributions, Simon Hodgkinson analysed the data and prepared the manuscript, whilst David Jaroszweski, Andrew

Quinn and Lee Chapman contributed with suggestions and comments prior to the manuscript submission.

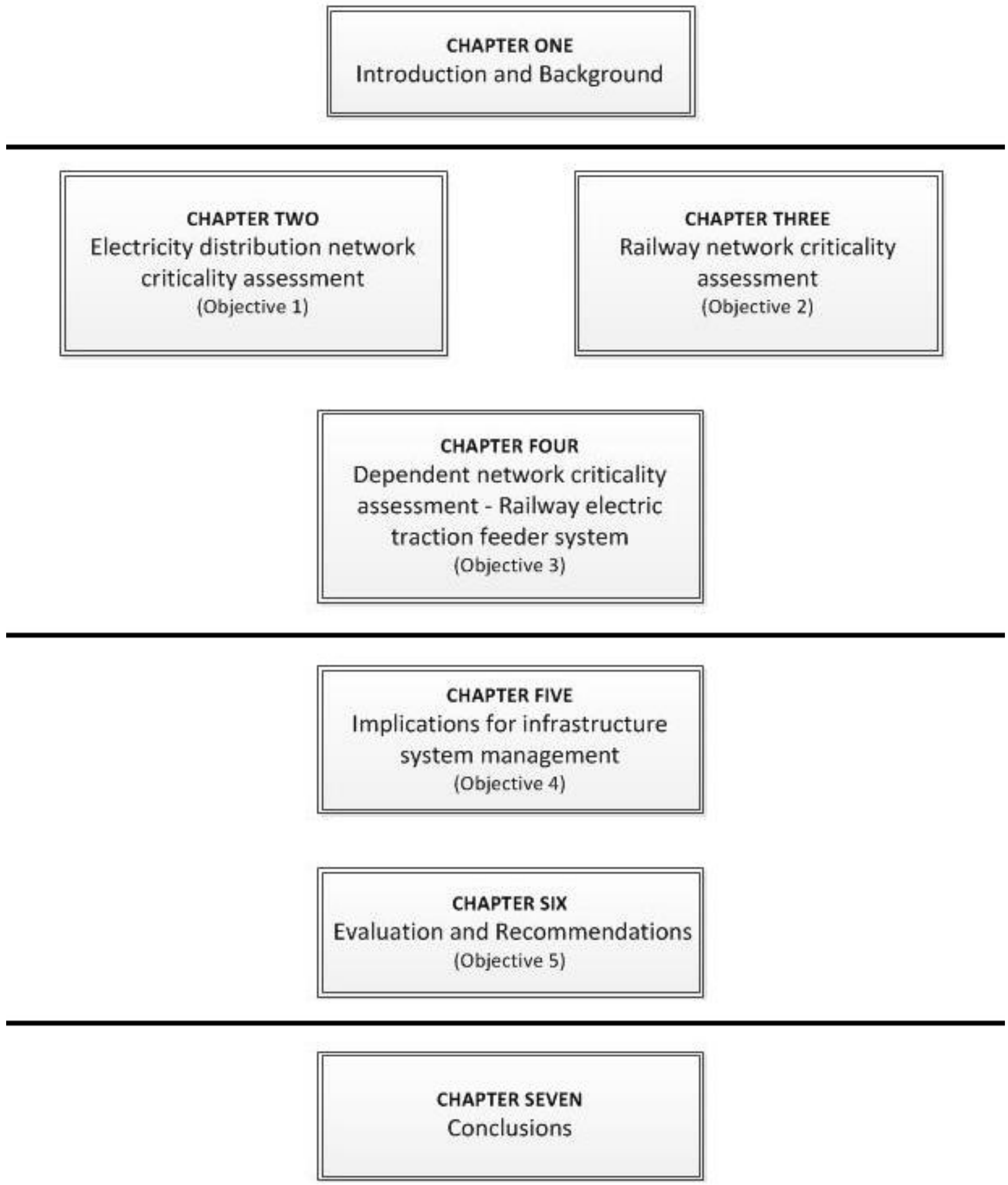


Figure 1.5. Structure of Thesis (including Chapters and Objectives).

CHAPTER TWO: **ELECTRICITY DISTRIBUTION NETWORK CRITICALITY ASSESSMENT**

2.1 Introduction

This chapter provides an assessment of electricity distribution network criticality, a relatively less complex system compared to railway transport, with a clearly defined hierarchical topology and unidirectional power flows. The UK's electricity network is divided into two parts. Circuits operating at HV up to 400kV comprise the transmission network, transporting power from generation sites to large substations, which is owned and maintained by a single infrastructure company in NG. Circuits operating at and below 132kV are the responsibility of DNOs. The distribution network transforms power from HV via a series of stages down to 11kV and below for residential supplies. The network is divided into a series of geographic regions known as licence areas, which are operated by different DNOs. There are currently fourteen licence areas in GB, managed by six DNOs. This chapter is concerned with the management of electricity distribution network substations at the local-level, which operate at a lower voltage than the transmission system but are greater in number. The security and generation of electricity are beyond the scope of this chapter.

DNOs must manage a broad portfolio of activities within the constraints of a limited management budget and finite resources, including day-to-day maintenance programmes and operational incident response as well as implementing long-term asset renewal and upgrade programmes. A major network management challenge is the cost-effective allocation of resources for such undertakings, in order to make the most cost-effective use of the funding, personnel and equipment that are available (Durango-Cohen and Madanat, 2008). A key function of strategic asset management for electricity networks is the risk-based evaluation and prioritisation of options, which can be based upon historical fault databases to identify fault trends for specific assets (IEC, 2015). Decision making can be informed by a targeted prioritisation scheme where resources are allocated to elements of the distribution network where they will have the greatest benefit for service performance.

A location-based prioritisation scheme for electricity distribution undertakings can be achieved through an assessment of network criticality, which aims to identify localised critical locations through single points of failure which are strategically important substations that, should they fail, have the potential to cause large scale consequences for service performance. The criticality of a substation within an electricity distribution network is a measure of its strategic importance for maintaining service performance, which can be defined by the potential consequence of failure and is influenced by a range of factors including network topology and power flows. Therefore, as the topological characteristics and power flows within an electricity distribution network have significant spatial variability, faults occurring at different locations in the network can have vastly different consequences for service performance, and thus a very different measure of network criticality. As power flows from source to sink (transmission/generation to consumer, except for distributed generation and smart grid technologies, flows are unidirectional. There is also a clear hierarchy of assets as one higher voltage substation can supply several lower voltage substations. Therefore, faults occurring at different substations on the network can have different consequences for the continuity of electricity supply.

Metrics of service performance can be used to quantify network criticality by measuring the consequence of asset failures at a high level of granularity across the electricity distribution network and thus identifying single points of failure that have the greatest propensity to generate a high magnitude of disruption to the electricity supply should a fault occur. Historical disruption records for electricity distribution network faults facilitate a criticality assessment that incorporates real world network behaviour with benefits for the reliability of single points of failure identified, whilst the spatial and temporal resolution also facilitates a localised and focused prioritisation scheme for a broad range of network management activities.

This chapter presents and demonstrates a local-scale and high-resolution network criticality assessment methodology for electricity distribution infrastructure, using an evidence-base of operational data on service performance between 2009 and 2014. The study area encompasses the South West and West Midlands licence areas of the GB electricity distribution network, assessing localised criticality within two contrasting areas managed a single DNO in WPD. Applying the output from such an assessment informs decision making and can improve targeted resource allocation. Through more cost-effective use of the constrained management budget and resources available, robust asset management and network resilience can be promoted.

2.2 Research Background

Essentially, there are two broad approaches to defining criticality within electricity infrastructure management. At a high level, economic benchmarking is part of the price review process for networks and can be used to compare the efficiency of similar functions between businesses, identifying areas where efficiency improvements can be targeted through the cost reduction of interventions (Pollitt, 2005). However, for the purpose of this chapter in defining location-based criticality within the GB electricity distribution network through identifying single points of failure, network-based approaches are the most pertinent as they focus on prioritising interventions at specific locations rather than departments or business units, allowing an assessment of network criticality. Pagani and Aiello (2013) undertook a review of Complex Network Analysis (CNA) approaches to analysing the reliability of electricity distribution systems, where infrastructure is modelled as a connected graph of nodes and edges, which in this case would typically consist of substations, overhead lines and underground cables. Pagani and Aiello (2013) found that most studies focus on purely topological properties, with reliability parameters relating to the structure of the network and the position of nodes within a graph, i.e. node degree distribution and in some cases betweenness distribution for centrality. Such approaches are rooted in graph theory and apply an attack strategy to an indirected graph, assessing the connectivity between elements should nodes and edges be removed. Examples include the work of Rosato et al (2007) who used spectral analysis to estimate damage to three European transmission networks; Dey et al (2016) who examined how changes in topology influence cascading failure propagation in electrical grids using a branching process metric applied to IEEE (Institute of Electrical and Electronics Engineers) test networks; and Koc et al (2016) who assessed structural vulnerability and robustness in electricity distribution networks using a metric of Upstream Robustness with applications for defining asset criticality in real-world topologies.

Topological studies are useful for understanding how nodes and edges may be critical to maintaining network connectivity but are abstract mathematical approaches with limited information on the physical properties and functions of a system. Pagani and Aiello (2013) suggest that purely topological measures of network reliability may be inappropriate and produce inaccurate results due to the omission of physical laws and power flows, highlighting a recent move towards weighted networks considering physical and electrical parameters including electrical engineering detail such as AC/DC power flow models and impedance of lines. Such approaches involve more reliable simplifications due to the physical and electrical dynamics involved, making enhanced CNA models more akin to real networks (Pagani and Aiello, 2013). Hines et al (2010) also conclude that evaluating vulnerability in electricity networks using purely topological metrics can be misleading, which could result in erroneous allocation of resources for risk reduction, instead advocating the use of metrics that account for network behaviour which provide more realistic risk assessments.

More of the real-world system operations and behaviour can be captured through the use of supply and demand modelling, using information on network flows. At a broad level, Augutis et al (2016) assessed component criticality within a simulated mixed energy system, involving input-output models of district heating and electricity generation. Supply and demand of energy branches (electricity, heat and fuel) were derived using an optimisation model. More specifically, Bollinger and Dijkema (2016) assessed the resilience of the transmission network in the Netherlands to extreme weather, evaluating a series of adaptation options. The unified electricity network model accounted for the structure and properties of electricity infrastructure, including a power flow model based on known peak and mean consumption values, alongside generator capacities. Panteli et al (2017) examined the resilience of a test version of the GB power system to extreme weather, developing analytical fragility curves for individual towers and lines which were included in a network level model. Failure probabilities were combined with modelled optimal power flows in a sequential Monte Carlo simulation, with the aim of prioritising critical sections using both infrastructure and operational metrics. However, perhaps the most comprehensive model is that of Thacker et al (2014) who assessed the vulnerability of present and future configurations of the GB electricity network to climate hazards using a spatial hierarchical model of national-scale integrated transmission and distribution. Capacity and demand values were assigned to nodes and edges using a capacity constrained shortest-path resource allocation model to map pathways of flows between sources (generators) and sinks (customers), based on demographic data for demand estimates and known capacity values.

Information on power system characteristics, such as generation capacities, end user demand and flow pathways provide a greater appreciation of the likely consequence of link or node removal for system operations. When combined with predicted or observed hazards, such as extreme weather, more comprehensive models can have additional applications for electricity distribution network management problems, such as evaluating resilience interventions. However, any model by its nature is a simplification of reality, therefore there remains the limitation of the necessity for assumptions on network behaviour. For example, Thacker et al (2014) assume that electricity follows the shortest path between two points, but the actual regulation of power flows may be more complex in real networks. Such assumptions are quite justifiable given the spatial scale of the simulations and the number of failure modes or disruption scenarios involved but are still sources of uncertainty. Risk assessment can involve elements of hazard occurrence and likelihood, asset vulnerability and susceptibility, and the consequence of asset failure for system performance. Assumptions on any or all of these elements introduces uncertainty in simulations.

There remains a gap in understanding electricity network behaviour and response to asset failure using historical evidence of interruptions. The benefit of using historical evidence is that it can provide a more complete picture of historical risk, inherently capturing the complex operational and behavioural mechanisms that may be omitted or simplified in more theoretical network modelling and simulation approaches. In order for a consequence to have been observed and recorded in the data, an asset must have been vulnerable to a hazard resulting in asset failure and performance degradation. Therefore, a data-driven risk assessment is more likely to represent the complexity of real world network management challenges. Using historical data overcomes the need for assumptions and simplifications of system behaviour, increasing the reliability of critical locations identified, whilst also providing the spatial and temporal granularity to facilitate a more localised and focused assessment of network criticality with direct applications for a range of electricity distribution infrastructure management activities, such as maintenance and electrical switching. The utility of the national-scale approaches is limited for local asset management, for example, Thacker et al (2014) defines priorities relative to the entire GB electricity distribution network which will highlight national priorities, but those demand or load centres which are important within a local area but less prominent at the national-level are unlikely to be explored. Local priorities can be determined using historical data to a high spatial resolution.

To obtain a complete picture of risk, an observed measure of consequence is required. Pagani and Aiello (2013) highlight the need for network risk assessments that cross-check their results with the experience of DNOs, improving the applicability of results for real power systems, and the difficulties of such analysis given the confidentiality of information on network topology and properties. There is currently an absence of published academic literature that uses a metric of historical electricity distribution network service performance to produce a network criticality assessment for GB electricity distribution infrastructure. There are studies that describe statistical relationships between hazards and electricity asset failure using historical data, such as McColl et al (2012) who assessed the potential impact of climate change on UK electricity networks using data on weather-related faults and climate change projections. The relationships identified can provide great insight into the vulnerability of types of asset, but do not normally account for the structure or function of assets within a network either due to the absence of information or the need to anonymise individual assets.

However, Ofgem, the regulator of gas and electricity networks in GB, in conjunction with DNOs, have developed a Common Network Asset Indices Methodology (CNAIM) for assessing the health and criticality of network assets internally within DNOs (Ofgem, 2017a) with a similar process for transmission networks (Wright et al, 2016). The purpose of CNAIM is to facilitate regulatory reporting and benchmarking of condition-based asset risk deliverables under the RIIO-ED1 price control, and to ensure DNOs target their internal asset management plans, including upgrades and renewals, towards high risk assets. Under CNAIM, monetised indices are calculated for each individual asset on health and failure probability, relating to asset condition and remaining lifetime, along with indices on consequence of failure and criticality. These indices are then combined to calculate an overall risk index per asset. The methodology for criticality indices is of most interest in this case. A Consequence of Failure (CoF) metric is calculated per asset, for four categories of consequence: financial, safety, environmental, and network performance. CoF is a monetised value in GBP of the likely cost incurred from a loss of supply to that asset, relative to the average cost for the consequence category and asset type. Each asset is allocated a criticality band based on the calculated CoF, ranging from C1 ('low' <75% of average cost) to C4 ('very high' criticality ≥ 200% of average cost).

CNAIM (Ofgem, 2017a) is an evidence-based assessment as reference costs are 'typical' failures from DNO experience, established from historical reported number of customers interrupted and duration of interruption values as part of the Interruptions Incentive Scheme (IIS). To ensure that the topological and operational situation for each asset is considered, the derived reference cost is modified using specific local factors, such as number of customer connections and volume of load carried for network performance indices. Basing a risk assessment on historical performance inherently incorporates elements of network behaviour, as supply and demand for electricity, along with operational and control mechanisms will influence the consequence of an asset failure, captured in the metrics or indices used.

The utility of a criticality assessment depends upon its intended application, including the geographic scale and type of intervention. CNAIM (Ofgem, 2017a) calculates metrics at the asset level, defining the consequence of a supply loss to specific pieces of equipment. However, the potential financial cost of asset failures is calculated relative to the average for all DNOs in GB. To facilitate a cost-benefit analysis in the development of a long-term investment plan, a criticality assessment based on national-scale financial metrics is suitable. CNAIM has been used by Northern Ireland Electricity Networks to rank assets by monetised risk and provide an objective cost benefit assessment of interventions (Hutchen et al, 2016). However, there remains the need to translate national-scale financial allocations into projects of importance for local service levels. Furthermore, managing and responding to supply interruptions locally requires a more spatial prioritisation scheme, that moves beyond pure economic assessment of assets to understand direct risks to service level performance. An improved understanding of operational service risk at the local-level will allow more informed decisions to be made regarding the allocation of resources to critical locations for regular maintenance, interruption management and long-term asset renewals whilst also formalising and challenging priorities that may currently exist as tacit knowledge within a DNO. As such, this chapter presents and applies a high-resolution and data-driven methodology for defining critical locations within regions of the GB electricity distribution system.

2.3 Methodology

Historical asset fault data from WPD is used to classify critical substations across the electricity distribution network in terms of the expected magnitude of performance degradation should an interruption occur at that location. Understanding the distribution and drivers of criticality from the infrastructure management perspective promotes a criticality assessment that can be applied to both operational and strategic decision making. The approach of this chapter adds to the existing literature by assessing electricity distribution network criticality using a pure service performance metric to define and map licence area level single points of failure. In doing so, it provides the means to prioritise resource allocation to a high spatial resolution, for a variety of local applications including operations and maintenance. The details of the data and method used to conduct the network criticality assessment are outlined below.

2.3.1 Study Area

This chapter focuses on two licence areas, both managed by WPD but varying in terms of topology and supply patterns: namely the South West and West Midlands (Figure 2.1). Applying the proposed methodology to two contrasting licence areas demonstrates the transferability and robustness of a network criticality assessment, responding to different types of supply patterns and thus interruption dynamics.

The South West licence area covers the southwestern peninsula of England, an area of approximately 14,400 km^2 (WPD, 2016) delivering electricity to around 1.4 million customers. Stretching from Bristol and Bath in the north east to Land’s End in the south west, the licence area is quite isolated having limited interaction with other DNO networks. Electricity distribution is supported by a 400kV transmission ring around the peninsula, connected at eight GSPs, between which the 132kV network operates in parallel along the coast. 33kV lines branch out along the coasts and also connect the east and west of the licence area. The South West is largely rural, particularly the central areas including the National Parks of Dartmoor and Exmoor and is dominated by resorts along the coastline. The centre of the region is more rural and thus electricity distribution is sparser. The principal demand centres around the cities of Bristol, Plymouth, Exeter and Bath where there is a higher density of circuits.

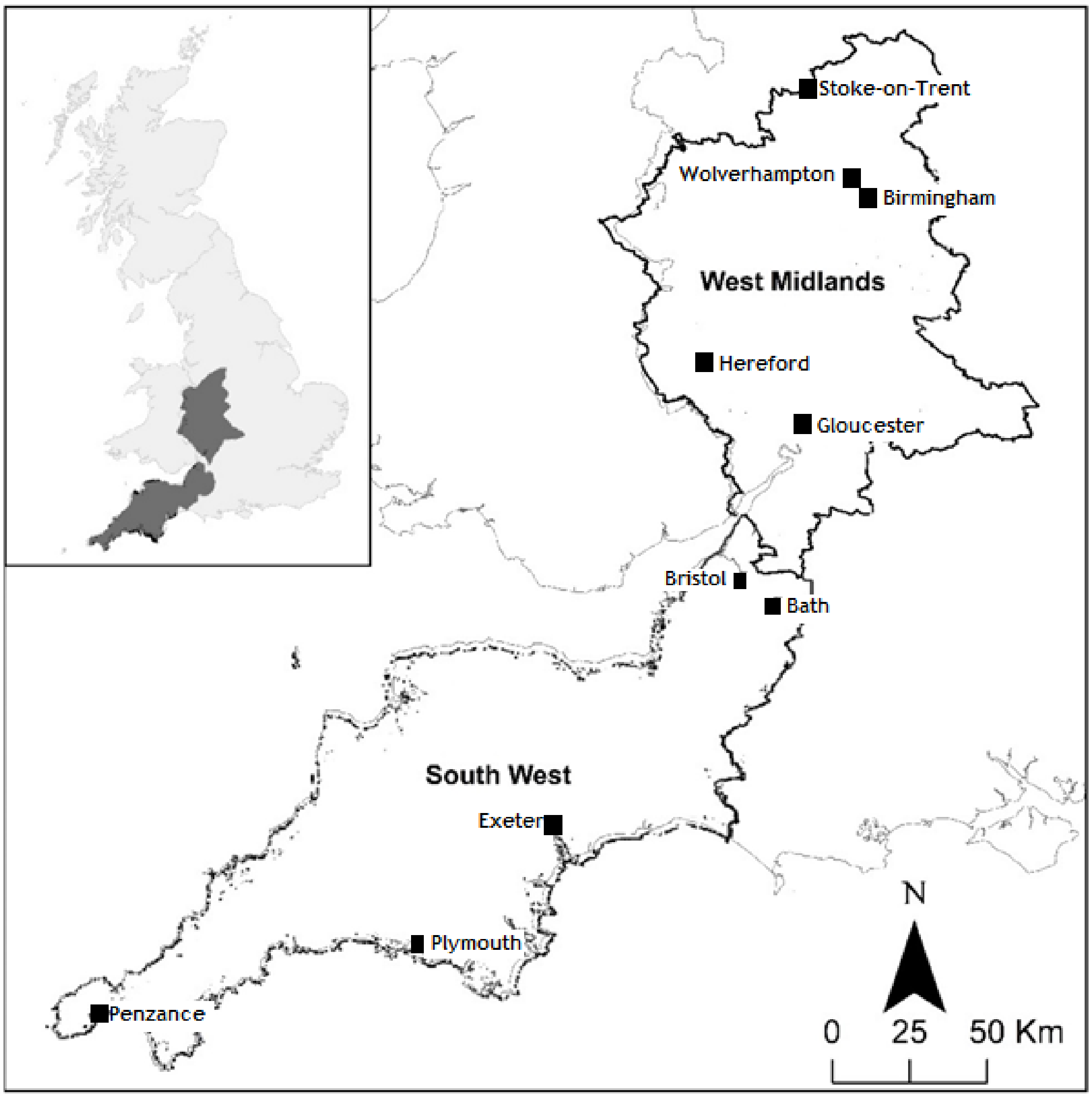


Figure 2.1. The main map shows the extent of the South West and West Midlands licence areas used. The inset map shows the location of the two licence areas within GB. Adapted from Ofgem (2018).

The West Midlands licence area is located centrally within England, covering an area of approximately 13,300 km^2 delivering electricity to around 2.4 million customers (WPD, 2018). Stretching from the Welsh border eastwards to Banbury (Oxfordshire), and from Congleton (Cheshire) in the north towards the outskirts of Bristol in the south, the licence area is quite open and potentially influenced by other DNOs at the boundaries. The interconnected 275/400kV transmission network supplies seventeen GSPs in the West Midlands. The main 132kV lines from these GSPs run north to south through the region, branching out to the major conurbations. 66kV lines branch out to cover the centre of the region, whilst 33kV lines cover the north and south. Key demand centres are concentrated in the north and east of the licence area, including the city of Birmingham, the Black Country region including Wolverhampton, and the Potteries region including Stoke-on-Trent. The south and west are more rural, including Gloucestershire and Herefordshire. There is also significant manufacturing and industrial activity, as well as logistics and agriculture which present more singular high demand centres (WPD, 2018).

2.3.2 Data and Metrics

Electricity distribution network performance metrics can be used to assess and quantify the degree of disruption to a substation during a specific time period. Electricity network operators globally use similar performance metrics, such as the *System Average Interruption Duration Index (SAIDI)* which is a measure of the average outage duration per customer served (IEC, 2015). Alongside operational metrics, there are economic based measures such as *Value of Lost Load (VoLL)* which represents the value attributed to security of supply (London Economics, 2013).

To ensure that DNOs meet minimum levels of performance, the regulator Ofgem has set out a price control framework known as RIIO-ED1 where the revenues that companies can earn relate to the level of performance output across six primary categories: safety, environment, customer satisfaction, connections, social obligations, and reliability and availability (Ofgem, 2017b). The latter category includes assessment of network performance, where the *IIS* exists as an incentive for DNOs to reduce the frequency and duration of interruptions through a scheme of rewards and penalties for performance above or below set targets. For unplanned interruptions, DNOs must report metrics of *Customer Interruptions (CI)*, defined as the number of customers interrupted per 100 customers per year where an interruption is three minutes or longer, and *Customer Minutes Lost (CML)*, defined as the average duration of interruptions to supply per customer per year, where an interruption is three minutes or longer (Ofgem, 2017b). Therefore, operational service performance is monitored for electricity distribution networks at the licence area level, through measures of temporal disruption and the scale of the asset footprint. The scheme applies only to incidents within the control of DNOs, excluding exceptional events, cut-out failures and short interruptions, ensuring that performance is assessed from the infrastructure management viewpoint.

To complement the primary outputs for RIIO-ED1, secondary deliverables are used as indicators of long-term delivery and value for money, in the form of health, criticality and load indices (Ofgem, 2017b). These deliverables are based on the CNAIM methodology (Ofgem, 2017a) which assesses asset criticality in terms of the potential economic cost of a supply loss to pieces of equipment. In terms of network performance, CNAIM applies cost values to calculated CML and

CI metrics, adjusted for individual assets, to produce a monetised *Consequence of Failure (CoF)* metric in GBP of the consequence of a supply loss relative to the to the average cost for the asset type. Therefore, financial service performance is monitored for electricity distribution networks at the asset level, through measures of the economic cost of disruption.

When selecting a metric for analysis of electricity distribution network criticality, it is important to consider whether the basis of the metric and the geographic scale are appropriate for the application involved. An operational metric in CML is beneficial as it provides a neutral performance measure, where one minute of supply lost has an equivalent weight at each substation. Financial metrics, such as CoF used under CNAIM, may not be representative of the degree of operational or management difficulty associated with an interruption, involving network reconfiguration and switching, which would be accounted for in CML. Furthermore, if the financial cost of disruption differs between locations, this can introduce a level of bias and pre-defined priorities into a criticality assessment. For the geographic scale, licence area reporting is too broad, asset level risk is of significantly greater utility for application to prioritisation local-scale asset management interventions.

Decision making using a measure of pure electricity distribution service performance will provide a different prioritisation of interventions than financial costs. In order to focus the criticality assessment in this chapter on operational service performance priorities of local-level significance, an adaptation of the CML metric was used at the substation level. Network criticality is derived from WPD's fault reporting database which records causation, consequence and locational information regarding asset failures that result in CI occurring in their licence areas. To record such data, most DNOs use the *National Fault and Interruption Reporting Scheme (NaFIRS)* or an equivalent system (Ofgem, 2015). NaFIRS is administered by the Energy Networks Association (ENA) and is an electronic system for reporting, checking and correction of data on supply performance including the cause and effects of component failure (ENA, 2012). Therefore, similar metrics and information should be reported across all DNOs in GB and the reliability of the data is likely to be improved through the verification and checking process.

To provide a representative sample and distribution of interruptions, fault records were extracted from WPD's database for the South West and West Midlands licence areas between April 2009 to March 2014. Historical records of electricity supply disruption are not widely used in network vulnerability and resilience studies, mainly due to access and confidentiality issues, but can provide a valuable platform for detailed analysis, with a high degree of spatial and temporal disaggregation. For every individual asset failure that results in an interruption of supply, WPD report information regarding the time/date, the location and attributes of the substation from which supply was lost, the cause of the interruption and two disruption metrics: *Customers Affected (CA)* and *CML.* Whilst the metrics reported to Ofgem under the IIS are averages for the licence area, in this case the values reported describe the actual impact of individual interruptions. CA is defined as the total number of customers interrupted due to the reported asset failure, whilst CML is the aggregate number of electricity supply minutes lost across all connected customers (actual interruption duration * number of connected customers). Using the reported values of CML as a measure of criticality would produce single points of failure weighted by customer numbers. Therefore, in order to prevent the resultant prioritisation being directly forced towards a small number of substations with the highest loads or demands, a metric of *Supply Minutes Lost (SML)* was calculated for each interruption, as CML/CA, defined as the actual supply outage duration. This metric allows for a comparison of the criticality of substations as single points of failure in a network, controlling for the different voltage levels and thus differences in the number of connected customers and substations, known as the asset footprint. The influence of supply and demand dynamics for substations is also inherently accounted for in the CML metric, as network reconfiguration and switching procedures would influence the outage duration and impact on customers from a substation. The railway network criticality assessment in Chapter 3 is also unweighted, with the influence of passenger loadings inherent within the metrics used but not applied to force the assessment towards major train service paths.

Asset faults can occur either at substation sites (i.e. transformers) or within the circuits they supply (i.e. cables). Each record in WPD's fault reporting database specifies both the substation site and outgoing circuit to which supply was lost, along with the voltage level of the assets. In this chapter, a criticality metric is applied at the level of substation sites (a site can have multiple substations at different voltages i.e. 11kV/33kV) both in order to identify single points of failure and aid interpretation of the output, as each substation can have multiple outgoing circuits. The database contains records for all voltage levels within the electricity distribution network: 132kV, 33/66kV, 11kV and LV(230V). However, only faults at 11kV or above were taken forward for analysis, meaning that LV (Low Voltage) faults were omitted. This filter was applied as there are LV faults attributed to over 43,000 different distribution substations, transforming incoming 11kV to 230V outgoing, across the West Midlands and South West licence areas, whereas there are only 761 primary substations, Bulk Supply Points (BSPs) and Grid Supply Points (GSPs) which collectively transform power from incoming 275/400kV to 132kV to 66/33kV down to 11kV outgoing, with reported faults. Calculating criticality at the LV level would present significant challenges in both the visualisation and interpretation of output. Furthermore, LV circuits are supplied from smaller distribution substations, typically at the street scale, and are the final connections to residential and business premises. Therefore, it is recognised that an LV failure would have a relatively minor impact and be unlikely to affect surrounding substations. Further filters are applied to the database prior to the calculation of the criticality metric, to enhance the reliability of the resultant prioritisation. Faults classified as "cause unknown" were removed, as were any records with null values for metrics of CML and CA. The criticality assessment in this chapter is interested only with verified asset failures that result in a consequence for service performance.

2.3.3 Criticality Assessment

To undertake a criticality assessment, it was first necessary to extract fault counts along with CML and CA metrics from WPD's fault reporting database for each primary substation, BSP or GSP site in the South West or West Midlands licence area with at least one recorded interruption. The aggregated values were initially used to calculate a *SML* metric for each substation site (CML/CA giving the actual supply outage duration) before criticality bands were applied using the process described in Figure 2.2. Essentially, a measure of SML per incident for each location is compared to the relative distribution for the licence area in question and allocated a criticality band. Band definitions similar to the CNAIM methodology (Ofgem, 2017a) were employed, but here bands are based on electricity distribution service performance relative to the mean for substations in the licence area, rather than financial costs across all DNOs. Allocating criticality bands as opposed to using the calculated values of SML per incident facilitates the classification of locations into different categories or priorities for action, aiding the interpretation and application of network criticality.

The final stage of the criticality assessment involved the visualisation of the calculated criticality bands in a GIS (Geographic Information System). A shapefile of electricity distribution assets in the South West and West Midlands licence areas was obtained from WPD's online Planning Data Portal. Such spatial data allows a representation of network topology and geographic substation locations, information which is typically difficult to obtain due to availability and confidentiality reasons. In this case, in order to maintain confidentiality of network locations, substations are anonymised as far as is reasonably practicable. In order to map criticality, the calculated criticality bands were imported into a GIS and manually allocated to each substation site based on the substation name, in the absence of an exact common identifier between the fault database and the spatial database (neither the substation codes or names matched exactly).

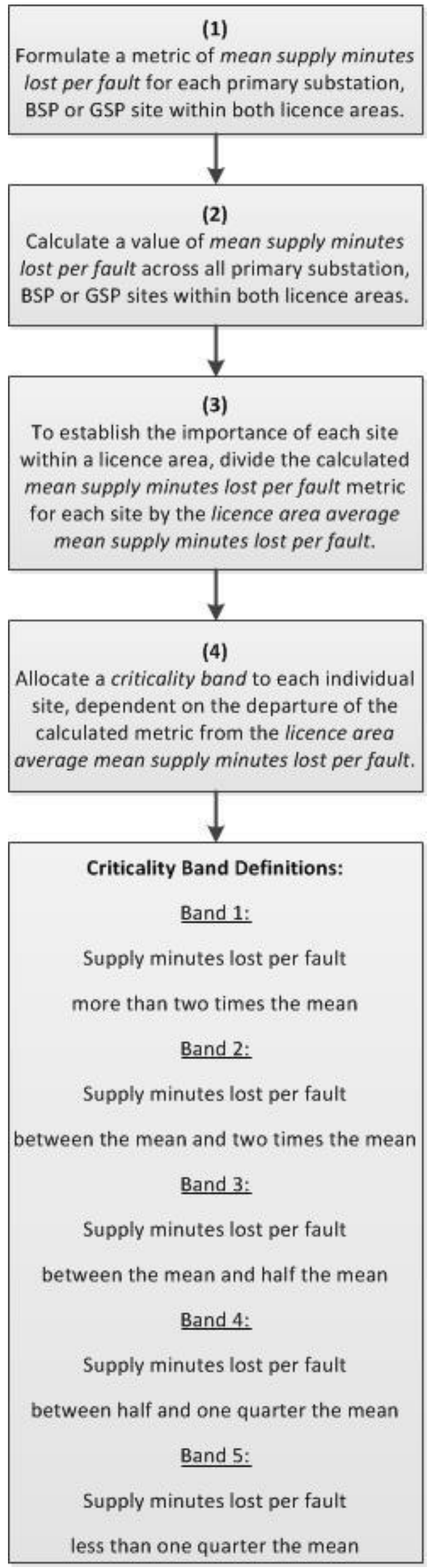


Figure 2.2. Flowchart of Methodology.

2.4 Results

In excess of 20,000 supply interruptions due to ≥11kV asset faults in the South West and West Midlands licence areas between 2009 and 2014 were included in the criticality assessment, with a combined impact of over 640 hours of outages to customers. Overall, the South West was found to have a mean SML per fault value of 11.77 minutes which is almost 50% greater than the value of 7.86 minutes for the West Midlands. Therefore, it should be noted that the average magnitude of disruption originating from a Band 1 critical substation site in the South West is likely to be significantly greater than from a Band 1 critical substation site in the West Midlands. However, this chapter focuses on the relative criticality of substation sites within a licence area and the overall spatial distribution, rather than drawing numerical comparisons of locations between licence areas. Owing to the confidentiality and security implications of locational information for electricity distribution networks, substation sites are mapped and described by their attributes, but the substation name is anonymised.

2.4.1 South West

Figure 2.3 shows mapped criticality bands for substation sites within the South West licence area. Key centres of criticality are distributed through the region, with several clusters of highly critical substations. The most critical substations are concentrated around major urban areas, such as larger towns and cities. The geography of South West England dictates that the larger population centres are located in coastal areas, particularly on the South Coast and to the north east of the region, around the Bristol Channel. Therefore, coastal regions have both more substations overall and more highly critical substations. The centre of the South West licence area is more rural, with fewer and smaller conurbations resulting in a reduced density of electricity distribution infrastructure, where substations are almost exclusively low criticality. It is evident that the greatest concentrations of critical substations are present in the two cities with the highest populations in the licence area; Bristol and Plymouth. There are also key clusters of criticality located around the south west of Cornwall, north Devon, and the Exeter/Exmouth area. Alongside these clusters, more isolated critical substations are present in the regions of Bath, Newton Abbott, Yeovil and south west Dorset. There is also a series of medium criticality substations to the east of the region between Weston-Super-Mare on the north coast, Taunton and Torquay on the south coast.

Table 2.1 details the most critical (Band 1) substation sites within the South West licence area. There are a high number of substations allocated to the highest criticality band, with 36 Band 1 sites. The Bristol district contains one third of all Band 1 substations in the licence area, highlighting the criticality of electricity distribution infrastructure in this major urban area.

However, the top three ranked critical substations in the South West are actually located in Cornwall, specifically in the Bodmin and Redruth districts. The high resolution of the criticality assessment allows the identification of more localised single points of failure alongside traditional criticality centres. Regarding the voltage levels of these substations, 26 of the 36 sites allocated to the highest criticality band are primary substations with a downstream voltage of 11kV, however, the top three ranked substations are BSPs with a downstream voltage of 33kV. Most Band 1 critical substations are located in significant residential areas or town/city centres. However, many of the substations are located in close proximity to either an industrial site, a key facility such as a dock or water treatment plant, or various renewable energy generation sites including a wind farm and multiple solar farms for photovoltaic (PV) energy. A complete list of the criticality bands allocated to all substation sites in the South West licence area is included in *Appendix B*.

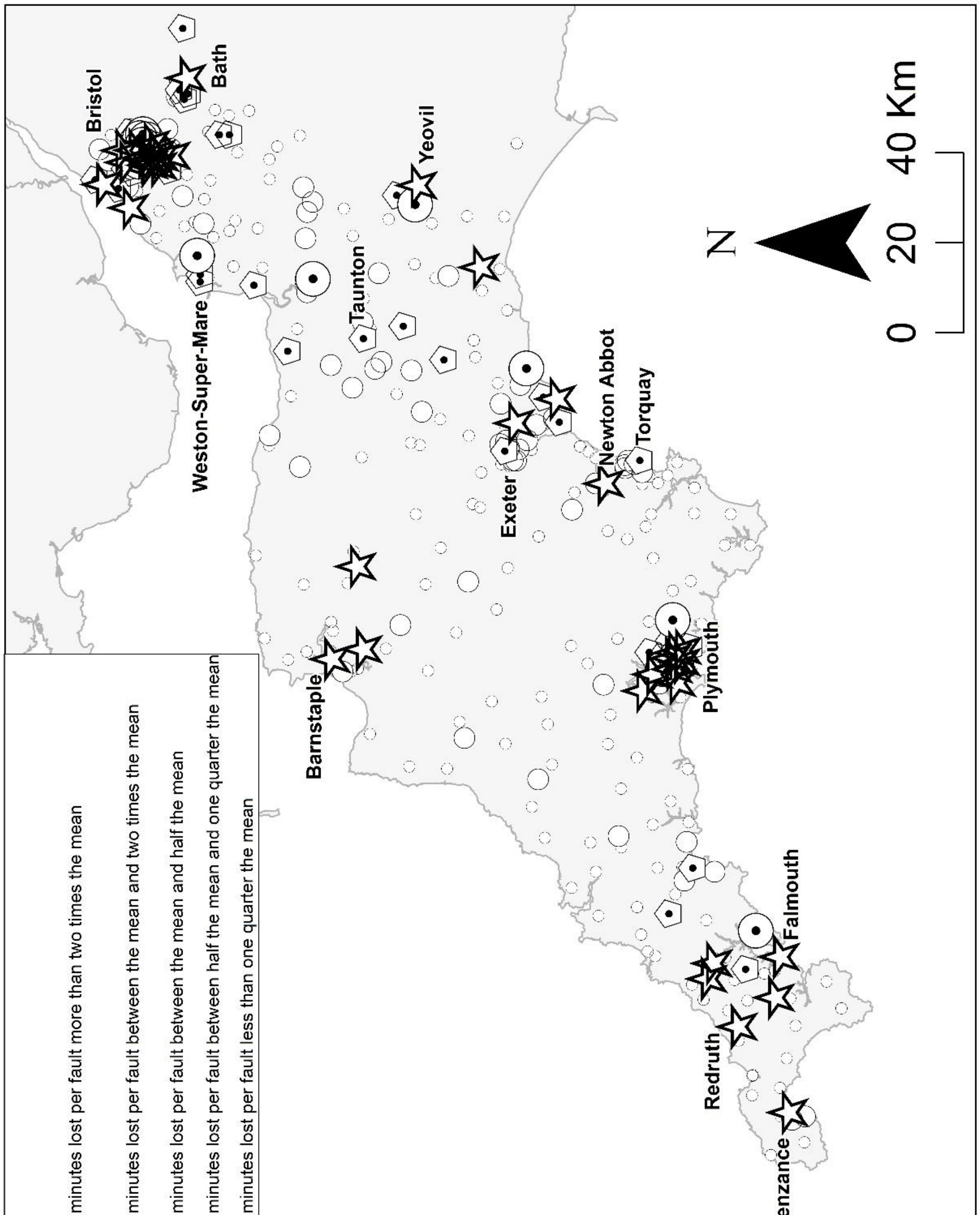


Figure 2.3. Mapped criticality bands for the South West licence area.

Table 2.1. Substations allocated Criticality Band 1 (highest) for the South West licence area, ranked in descending order of disruption magnitude.

Rank	District	Asset Type	Voltage (Up/Down)	Faults	SML	SML per fault
1	Bodmin	BSP	132/33	1	620.0	620.0
2	Redruth	BSP	132/33	2	674.0	337.0
3	Redruth	BSP	132/33	3	777.7	259.2
4	Exeter	Primary	33/11	2	324.1	162.1
5	Plymouth	Primary	33/11	1	117.8	117.8
6	Barnstaple	BSP	132/33	2	220.5	110.3
7	Barnstaple	BSP	132/33	2	186.0	93.0
8	Bristol	Primary	33/11	1	69.2	69.2
9	132 kV	GSP	400-275/132	1	65.0	65.0
10	Projects	BSP	132/33	1	63.0	63.0
11	Bristol	Primary	33/11	5	308.4	61.7
12	Bristol	Primary	33/11	1	60.0	60.0
13	132 kV	BSP	132/33	1	55.7	55.7
14	Bristol	Primary	33/11	1	55.2	55.2
15	Redruth	BSP	132/33	1	52.0	52.0
16	Plymouth	Primary	33/11	1	51.7	51.7
17	Plymouth	Primary	33/11	1	51.0	51.0
18	Bristol	Primary	33/11	1	48.0	48.0
19	Redruth	Primary	33/11	2	94.1	47.1
20	Redruth	Primary	33/11	1	46.8	46.8
21	Exeter	Primary	33/11	1	45.3	45.3
22	Plymouth	Primary	33/11	1	45.1	45.1
23	Bristol	Primary	33/11	1	44.0	44.0
24	Weston	Primary	33/11	1	40.0	40.0
25	Bristol	Primary	33/11	3	119.6	39.9
26	Bath	Primary	33/11	2	72.8	36.4
27	Bristol	Primary	33/11	1	34.7	34.7
28	Bristol	Primary	33/11	1	32.5	32.5
29	Bristol	Primary	33/11	1	32.1	32.1
30	Projects	BSP	132/33	1	31.5	31.5
31	Taunton	Primary	33/11	8	244.6	30.6
32	Plymouth	Primary	33/11	1	30.5	30.5
33	Bristol	Primary	33/11	1	28.5	28.5
34	Plymouth	Primary	33/11	3	80.7	26.9
35	Plymouth	Primary	33/11	1	25.4	25.4
36	Bristol	Primary	33/11	2	48.0	24.0

2.4.2 West Midlands

Figure 2.4 shows mapped criticality bands for substation sites within the West Midlands licence area. There is a limited distribution of key centres of criticality through the region, with the only clustering of highly critical substations being in the West Midlands conurbation to the east. More critical substations are concentrated in this urban area, including the cities of Wolverhampton and Birmingham. These larger population centres have a greater density of electricity distribution infrastructure and more highly critical substations. The rest of the licence area has comparatively smaller conurbations, however, there are the cities of Stoke-on-Trent, Lichfield, Worcester, Hereford and Gloucester which have surprisingly low criticality substations. Southern parts of the region are more rural, including Herefordshire and Gloucestershire, resulting in a reduced density of electricity distribution infrastructure, where substations are almost exclusively low criticality. The limited distribution of clusters of critical substations serves to highlight the criticality of the West Midlands conurbation within the licence area. However, whilst there may only be one cluster of highly critical substations, there are also more isolated highly critical substations that present single points of failure near to the north and south boundaries of the licence area. Several of the most critical locations are actually outside the West Midlands conurbation. Alongside these substations, there are medium criticality substations located in the regions of Shrewsbury, Ironbridge and Worcester.

Table 2.2 details the most critical (Band 1) substation sites within the West Midlands licence area. Compared to the South West, there are a low number of substations allocated to the highest criticality band, with just 11 Band 1 sites. The Birmingham district contains five of the Band 1 substations in the licence area, highlighting the criticality of electricity distribution infrastructure for major urban areas in the West Midlands. However, the second and third ranked critical substations are actually located outside the West Midlands conurbation, in the Stoke and Gloucester districts respectively. The identification of such localised single points of failure is achieved through the high resolution of the criticality assessment, alongside traditional criticality centres. Regarding the voltage levels of these substations, 6 of the 11 sites allocated to the highest criticality band are BSPs with a downstream voltage of 33kV, however, the top ranked substation is a GSP with a downstream voltage of 132kV. Most Band 1 critical substations are located in close proximity to heavy industrial sites, such as cement works, manufacturing plants or agriculture sites. All of the Band 1 substations outside of the West Midlands conurbation come into this category. The remaining substations are located in significant residential areas or town/city centres. A complete list of the criticality bands allocated to all substation sites in the West Midlands licence area is included in *Appendix B*.

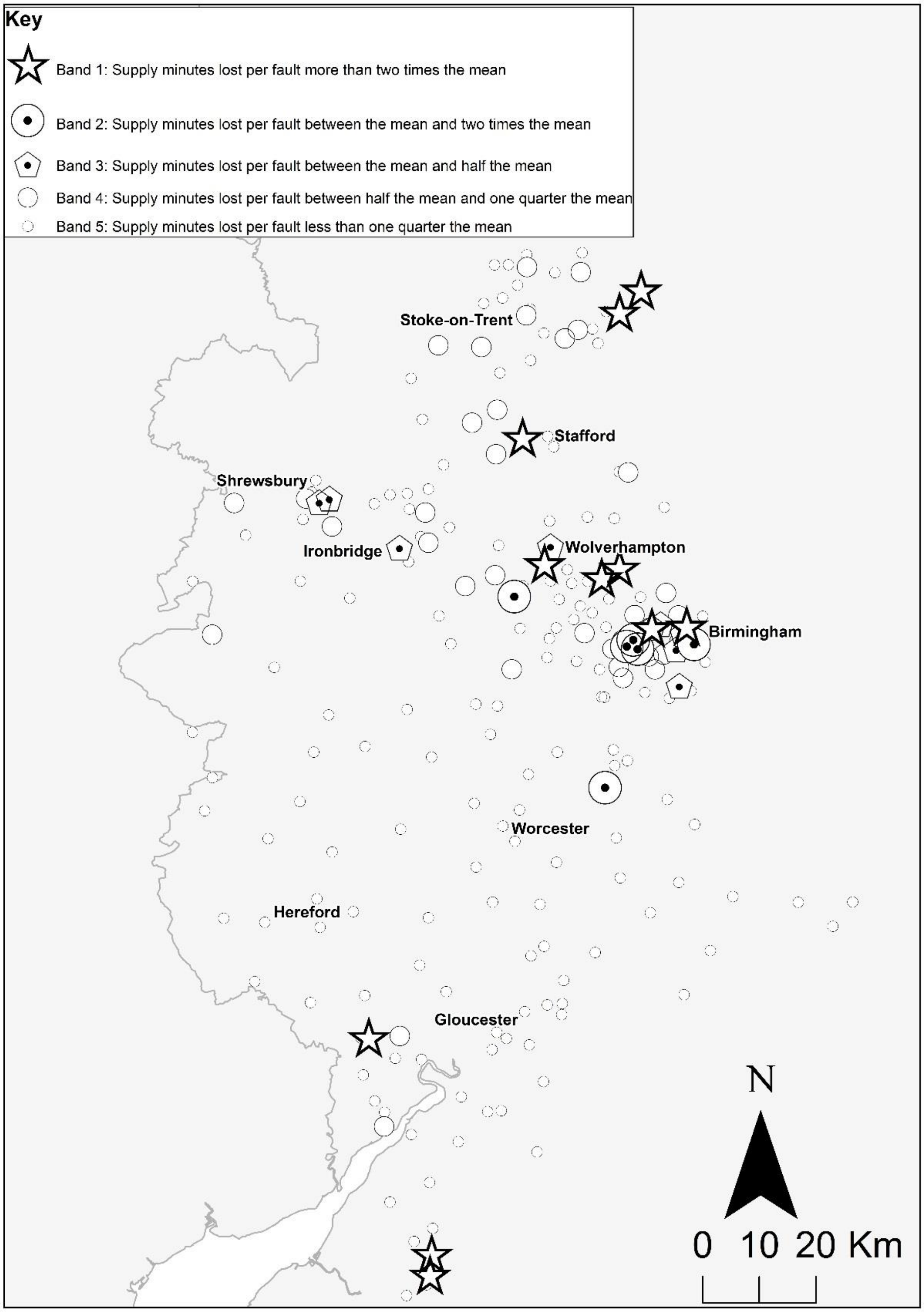


Figure 2.4. Mapped criticality bands for the West Midlands licence area.

Table 2.2. Substations allocated Criticality Band 1 (highest) for the West Midlands licence area, ranked in descending order of disruption magnitude.

Rank	District	Asset Type	Voltage (Up/Down)	Faults	SML	SML per fault
1	Birmingham	GSP	400-275/132	1	421.0	421.0
2	Stoke	BSP	132/33	1	263.0	263.0
3	Gloucester	Primary	33/11	1	197.0	197.0
4	Birmingham	Primary	33/11	1	118.0	118.0
5	Birmingham	BSP	132/33	1	97.0	97.0
6	Stoke	BSP	132/33	1	71.0	71.0
7	Birmingham	Primary	33/11	3	188.5	62.8
8	Stoke	Primary	33/11	1	54.0	54.0
9	Gloucester	BSP	132/33	5	210.0	42.0
10	Birmingham	BSP	132/33	1	25.0	25.0
11	Gloucester	BSP	132/33	1	21.3	21.3

2.5 Discussion

The results of the criticality assessment have highlighted the overall pattern of network criticality within the South West and West Midlands licence areas, alongside the presence of specific and localised single points of failure, both of which can be used to inform a prioritisation scheme for interventions. Comparing the two licence areas, the South West and West Midlands have contrasting criticality distributions. The distributions are predominantly a result of the geographies of the regions; the South West of England covers an area of approximately 14,400 km^2 in which load centres are quite spatially distributed, particularly for Bristol and along the south coast, whereas the West Midlands covers an area of approximately 13,300 km^2 in which load centres are concentrated more centrally within the West Midlands conurbation including Wolverhampton and Birmingham. It is therefore expected that as the South West licence area is slightly larger, containing more substations and more dispersed loads, there will be a greater number of critical substations identified. However, even though the West Midlands is slightly smaller it serves around one million more customers than the South West, therefore loads are expected to be more concentrated in key areas, making the smaller number of Band 1 critical substations identified even more critical due to their higher loadings. This also highlights the benefits of defining network criticality bands relative to the individual licence areas, as in this case combining the regions would likely highlight the West Midlands substations and dampen the influence of the South West. Despite the contrasts, there is clear commonality in the attributes of substations that are classified as highly critical, outlined in Table 2.3, demonstrating the transferability of the methodology.

Table 2.3. Critical substation attributes and characteristics.

Attributes	Characteristics	Examples
Major Load Centres	The majority of critical substations are located within or nearby major load centres, such as larger towns and cities. Substations may fail more often if the demand cannot be met, whilst the duration of a power outage can be extended by the increased management complexity. Load switching and network reconfiguration in the event of a failure is more difficult with greater loads and a high number of customers clustered in one area. There is also an increased risk of cascading failure, where a substation fails, and the alternative/nearby supplies cannot cope with the increased load, causing a chain reaction of failures.	Larger towns and cities.
City-Scale Networks	Within cities, an electricity distribution network branches out over multiple circuits in order to supply power to different areas of a city. Whereas a major load centre as a whole may be identified as critical, on dense and highly connected network any substation has the potential to generate a high magnitude of disruption. The relative criticality of substations within the boundaries of an urban area can provide a detailed layer of information for decision making.	Bristol and Birmingham.
Larger Consumers	Many critical substations can be attributed to large single consumers of electricity. Heavy industry, such as cement works, and key facilities, such as ports and water treatment plants have greater electricity demands than residential and business customers, and are often supplied at higher voltages, either 33kV or 11kV, from dedicated substations. Should these substations fail, there is again the issue of switching and network reconfiguration to restore such high loads. If these sites are located on the periphery of urban areas, or in rural areas, the density of the network may be reduced leaving fewer potential alterative supplies to switch to. Furthermore, as in most cases only a single customer/operation would be directly affected, as opposed to a large number of homes/businesses, the priority of response may be reduced with the exception of safety critical operations.	Heavy industry and key facilities.
Distributed Generation Sites	Applicable specifically to the South West licence area, some critical substations can be attributed to distributed generation sites. These area private enterprises for generating renewable energy, either from wind turbines or solar panels (PV). Here, electricity is either consumed on site, stored, or sold back to the electricity grid. However, feeding electricity upstream into the DNO network presents a number of challenges. The system must be designed to accept reverse power flows and have the necessary capacity to accept the generated load. Electricity networks are usually designed for transporting energy from source to sink and so bidirectional flows can cause a substation to fail.	Solar and wind farms.

The voltage level of critical substations is also a consideration. Considering Band 1 critical substations, there is only one GSP (132kV out) in each licence area, whilst there are half as many BSPs (33kV out) as primary substations (11kV out). This reflects the number of substations at each voltage level, where as the voltage increases the number of substations decreases. Failures at 132kV are comparatively rare, with greater protection and redundancy, but when such substations do fail the impact can be of a high magnitude. Failures at lower voltages are more common, and present locally important single points of failure. Assessing criticality across three voltage levels in this chapter allows a comparison of relative criticality, independent of the established hierarchy of electricity distribution infrastructure.

It is clear that traditional critical locations that are well understood, including cities and industrial sites, are worthy of prioritisation for interventions. There are no critical substations in remote locations where the reasoning for the high criticality band is unclear. This criticality assessment therefore acts as an objective evidence base to support the subjective priorities that may exist only as tacit knowledge within licence areas, formalising critical locations. However, local variations in supply and demand dynamics along with network topology also present very localised single points of failure, the identification of which adds further value to existing prioritisation schemes. Major cities such as Birmingham and Bristol have a consistently high criticality, whilst still encompassing more and less critical locations where a more localised layer of prioritisation would be of benefit. At the city or regional scale, a detailed and granular assessment of criticality facilitates the identification of hotspots where local asset management and incident response can be prioritised.

Such single points of failure are influenced by the regional scale assessment and selected performance metric. Defining criticality bands within single licence areas, rather than for all GB DNOs, allows the identification of locations that may not feature as prominently in a national assessment but are very important for regional level management. Also, using a performance metric relating to the service level output rather than pure financial costs treats all power outages of the same magnitude equally with no pre-weighted prioritisation scheme. Under a financial compensation metric, applying costs to outages based on CA, key load centres would likely be identified as critical but the distribution of criticality within those areas would be different. However, the influence of industry and distributed generation would likely be reduced as most of these sites involve a single customer where the fault reporting database is concerned.

The more localised single points of failure within urban areas require careful interpretation due to the nuances of using a historical data set. Analysing historical asset failures has the advantage of incorporating real world system dynamics and thus captures all inherent behavioural mechanisms. However, the main limitation is that the criticality bands of the majority of substations are based upon a small sample of incidents. This is a particular issue with power networks due to the number of substations involved presenting many potential failure points, and the general rarity of power cuts overall. A trade-off exists between sample size and granularity, whereby combining substations at the district or county level would increase the sample size and thus the reliability of the calculated criticality band but also reduce the localised focus of the methodology and reduce the applicability for city or regional scale asset management. In this case, the criticality bands of most substations are based on a single failure.

The criticality of a substation should therefore be taken as an indication that a fault occurring at such a location does indeed have the potential to cause a significant level of disruption, but the degree to which such a failure represents a typical disruption scenario is difficult to determine in such cases. However, for all Band 1 substations across both licence areas with more than one fault, only one observation at one substation had a Z-score ≥2. This would suggest that the calculated criticality bands are not unduly influenced by extreme values.

It is important to understand the caveats to the analysis, and the factors that contribute to a location being rated as highly critical for maintaining service performance, in order to ensure that the criticality assessment is interpreted and applied in the most useful manner to achieve the aim of improving the efficiency of resource allocation and promoting cost-effective decision making for interventions. The added value of the criticality assessment methodology is in the identification of localised and granular single points of failure within urban areas, enhancing the understanding of licence area level electricity distribution service performance priorities as well as confirming the importance of expected critical locations in key load centres and industrial sites.

The presented analysis demonstrates a criticality assessment of the South West and West Midlands licence areas of the GB electricity distribution network which can aid the identification of priority locations for maintaining service levels within a licence area. The insights gained can inform decision making for a broad range of interventions, such as long-term asset renewals and short-term maintenance, with the goal of promoting cost-effective resource allocation.

The criticality assessment provides a quantification of the relative importance of locations to maintaining service performance within a licence area. Understanding how much more or less critical a location is compared to the rest of the region is essential information for decision making on resource allocation.

2.6 Conclusion

This chapter has presented a network criticality assessment methodology for electricity distribution infrastructure, which facilitates a prioritisation scheme for a range of interventions for GB DNOs. It is demonstrated that the assessment can add value through integration with existing prioritisation schemes by objectively identifying localised single points of failure that are strategically important for maintaining service performance.

Using historical data on service performance to define network criticality to a high level of spatial granularity leads to the identification of single points of failure within well understood key load centres, such as the cities of Birmingham and Bristol. These locations can be used to refine high level financial allocations, translating funding into specific projects, whilst also objectively defining and challenging priorities that currently exist only as subjective tacit knowledge. The enhanced granularity provides a new layer of information for decision making and, whilst the specific application of criticality depends on the scale and timeframe of the decisions involved, all interventions are ultimately local therefore no matter what type of project is in focus, there is a role for localised single points of failure in risk assessments.

The operational and behavioural mechanisms of the GB electricity distribution network are inherently captured in the criticality assessment, yet there is a clear trade-off between the spatial scale of analysis and the sample size available. A district or county level analysis would provide a higher frequency of faults and thus a more reliable indication of criticality, but for licence area level management using such broad areas is not adequate for localised decision making. However, criticality bands for substations with more than one fault do not appear to be influenced by extreme events.

Although demonstrated for two specific licence areas of the GB electricity distribution network, the presented criticality assessment methodology is transferable and can be applied to the entirety all DNO licence areas to inform decisions across GB, as well as other international networks, dependent on the availability and quality of spatial and operational data. Overall, the key contribution of the chapter is the formalisation of localised critical locations at the licence area level, to inform decision making and promote cost-effective resource allocation. Chapter 3 scales up the complexity of analysis to provide a criticality assessment for the railway network, involving more complex elements of topology and system behaviour.

CHAPTER THREE: **RAILWAY NETWORK CRITICALITY ASSESSMENT**

3.1 Introduction

In the previous chapter, a network criticality assessment was produced for a comparatively less complex system in electricity distribution. This chapter scales up the complexity of analysis to assess railway network criticality, involving more complex elements of topology and system behaviour. The majority of rail infrastructure in GB is owned and maintained by a single infrastructure company (NR) with responsibility for managing the railway network devolved to a series of nine geographic regions known as routes. Within the constraints of a limited management budget and finite resources, these routes must manage a broad portfolio of rail undertakings, including day-to-day maintenance programmes and operational incident response as well as implementing long-term asset renewal and upgrade programmes. A major network management challenge is the cost-effective allocation of resources for such undertakings, in order to make the most cost-effective use of the funding, personnel and equipment that are available (Durango-Cohen & Madanat, 2008). Decision making can be informed by a targeted prioritisation scheme where resources are allocated to elements of the rail network where they will have the greatest benefit for train service performance.

Montesinos-Valera et al (2017) found that the principal factor in prioritising rail projects was the location of application, rather than the project characteristics or technical criteria. A location-based prioritisation scheme for rail undertakings can be achieved through an assessment of network criticality, which aims to identify localised critical locations through single points of failure which are strategically important locations that, should they be disrupted, have the potential to cause large scale impacts for train service performance and potentially sever key social and economic links (DfT, 2014a). The criticality of a location within a railway network is a measure of its strategic importance for maintaining service performance, which can be defined by the potential consequence of failure and is mainly influenced by the number and frequency of trains passing or calling at that location (RSSB, 2016a). Therefore, as the topological characteristics and train service paths within a rail network have significant spatial variability, incidents occurring at different locations in the network can have vastly different consequences for train service performance and mobility, and thus a very different measure of network criticality. Jaroszweski et al (2015) demonstrated how weather-related incidents at key locations can cut off access to large parts of a transport network, not only through cancellations or disruption to train services at the point of failure but also through knock-on disruption that propagates widely throughout the network resulting in costs and delays significantly greater than just the local impact.

Metrics of train service performance can be used to quantify network criticality by measuring the consequence of asset failures at a high level of granularity across the rail network and thus identifying single points of failure that have the greatest propensity to generate a high magnitude of disruption to train services should an incident occur. Historical disruption records for railway network incidents facilitate a criticality assessment that incorporates real world network behaviour with benefits for the reliability of single points of failure identified, whilst the spatial and temporal resolution also facilitates a localised and focused prioritisation scheme for a broad range of railway undertakings.

This chapter presents and demonstrates a local-scale and high-resolution network criticality assessment methodology for rail infrastructure, using an evidence-base of operational data on train service performance between 2011 and 2016. The study area encompasses the Wessex and LNW (South) routes of the GB rail network, assessing localised criticality within two contrasting routes. Applying the output from such an assessment informs decision making and can improve targeted resource allocation. Through more cost-effective use of the constrained management budget and resources available, robust asset management and network resilience can be promoted.

The material in this chapter is based upon a paper from Hodgkinson et al. submitted to the international journal '*Transportation Research Part A: Policy and Practice*', the manuscript of which is included in *Appendix A*. To outline the various author contributions, Simon Hodgkinson analysed the data and prepared the manuscript, whilst David Jaroszweski, Andrew Quinn and Lee Chapman contributed with suggestions and comments prior to the manuscript submission.

3.2 Research Background

Essentially, there are two broad approaches to defining criticality within railway infrastructure management. At a high level, economic benchmarking can be used to identify railway undertakings where financial efficiency gains can be made through improving the cost efficiency of interventions (RSSB, 2016a). However, for the purpose of this chapter in defining location-based criticality within the GB railway network through identifying single points of failure, network-based approaches to are most pertinent as they focus on prioritising interventions at specific locations rather than departments or business units, allowing an assessment of network criticality. Mattsson and Jenelius (2015) outline two principal modes for network-based analysis of the vulnerability and resilience of transport systems. The first category is topological vulnerability studies, which are rooted in graph theory and network science, representing a transport network as an abstract graph with a series of connected nodes and links, which may have directions and weightings applied. Examples include the work of Ukkusuri & Yushimito (2009) who assess the criticality of highway transport nodes with a heuristic procedure using a performance measure of travel time; Khaled et al (2015) who modelled train design and route optimisation for freight railways using an iterative heuristic algorithm designed to minimise delay during disruptive events; and von Ferber et al (2012) who analysed the vulnerabilities of the London and Paris transit networks to random failure or attack examining how the removal of stations or links impacts upon connectivity properties based on complex network theory.

Topological studies are useful for understanding how stations or links may be critical to maintaining network connectivity, and the structural robustness of a transport network, but they are abstract mathematical approaches with limited information on the physical properties and functions of a transport system. Mattsson and Jenelius (2015) highlight a second category of transport vulnerability models, which involve system-based approaches, representing more of the real-world system operations by using supply and demand models with node or link weights applied corresponding to actual costs, such as track length or travel time. Examples include the work of Voltes-Dorta et al (2017) who classified the criticality of European airports, simulating full day closures under a series of disruption scenarios using information from flight schedules and passenger itineraries to model aggregate passenger delay; Wei et al (2016) who performed an empirical analysis of airport network criticality in China, using a spectral clustering algorithm with data on flight schedules; and Rodriguez-Nunez & Garcia-Palomares (2014) who examined the criticality of the Madrid metro system using a full-scan approach in GIS with data on trip distributions. However, perhaps the most pertinent approach is that of Pant et al (2014) who assessed the criticality of the GB rail network using a national-scale model of passenger traffic. Passenger flows were estimated for stations, junctions and track sections using an origin-destination trip assignment model, based upon data for passenger entries and exits at stations and railway timetables. Daily passenger trips are mapped, providing an indication of criticality based on the relative travel pattern importance across links and nodes.

Information on railway system characteristics, such as link capacities, passenger demand and train pathways from timetables provides a greater appreciation of the likely consequence of link or node removal for system operations. When combined with predicted or observed hazards, such as extreme weather, more comprehensive models can have additional applications for railway network management problems, such as evaluating resilience interventions. However, any model by its nature is a simplification of reality, therefore there remains the limitation of the necessity for simplifications of network behaviour. For example, Pant et al (2014) use a railway trip assignment model that provides only estimations of passenger flows, given the absence of observed trip patterns, and also downscales annual passenger entries and exits at stations to obtain a daily number of passenger trips allocated to a daily number of trains between pairs of stations based upon a representative weekly timetable. Such assumptions are quite justifiable given the spatial scale of the models, and the number of failure modes or disruption scenarios involved but are still sources of uncertainty. Risk assessment can involve elements of hazard occurrence and likelihood, asset vulnerability and susceptibility, and the consequence of asset failure for system performance. Assumptions on any or all of these elements introduces uncertainty in simulations.

There remains a gap in understanding railway network behaviour and response to asset failure using historical evidence of disruption. The benefit of using historical datasets is that they can provide a more complete picture of historical risk, inherently capturing the complex operational and behavioural mechanisms that may be omitted or simplified in more theoretical network modelling and simulation approaches. In order for a consequence to have been observed and recorded in the data, an asset must have been vulnerable to a hazard resulting in asset failure and performance degradation. Therefore, a data-driven risk assessment is more likely to represent the complexity of real world railway network management challenges. Using historical data overcomes the need for assumptions and simplifications of system behaviour, increasing the reliability of critical locations identified, whilst also providing the spatial and temporal granularity to facilitate a more localised and focused assessment of network criticality with direct applications for a range of railway infrastructure management activities, such as maintenance and event response. The utility of the national-scale approaches is limited for local asset management, for example, Pant et al (2014) defines priorities relative to the entire GB rail network which will highlight national priorities, but those passenger flows which are important within a local area but less prominent at the national-level are unlikely to be explored. Local priorities can be determined using historical data to a high spatial resolution.

To obtain a complete and localised assessment of railway network criticality, an observed measure of consequence is required. There is currently an absence of published academic literature that uses a metric of historical train service performance to produce a network criticality assessment for GB rail infrastructure. There are studies that describe statistical relationships between hazards and railway asset failure using historical data, such as Dobney et al (2010) who assessed the potential impact of higher summer temperatures due to climate change on track buckles for the UK rail network using data on heat-related train delay incidents and a weather-generator. The relationships identified can provide great insight into the vulnerability of types of asset, but do not normally account for the structure or function of assets within a network either due to the scope of the study or the absence of information.

However, NR have an internal network criticality assessment (NR, 2016d) used to inform their asset management plans including maintenance programmes and track renewals or upgrades. The national rail network is disaggregated into a series of 305 Strategic Route Sections (SRS) and compensation costs based on train service delay records from NR's TRUST system were used to define critical track sections. Each section was allocated a criticality band relative to the mean historic financial cost of train delays per asset failure, ranging from one (highest – cost per incident more than two times the mean) and five (lowest – cost per incident less than one quarter the mean). By analysing historical train service performance, elements of rail network behaviour and delay propagation based on train service patterns and network topology will be inherently incorporated into the criticality assessment.

The utility of such a criticality assessment depends upon its intended application. NR (2016d) use broad sections of track, some of which exceed 100 track kilometres. The potential financial cost of asset failures on a track section are also calculated relative to the national average. To facilitate a cost-benefit analysis in the development of a long-term investment plan, a criticality assessment at a coarse granularity and national-scale is suitable. However, there remains the need to translate national-scale financial allocations into local-level projects and interventions. Furthermore, managing and responding to disruptive events locally requires a more granular and location specific prioritisation scheme, that moves beyond pure economic assessment to understand direct risks to train service performance. An improved understanding of operational service risk at the local-level will allow more informed decisions to be made regarding the allocation of resources to critical locations for regular maintenance, disruption management and long-term asset renewals whilst also formalising and challenging priorities that may currently exist as tacit knowledge within NR. As such, this chapter presents and applies a high-resolution and data-driven methodology for defining critical locations within regions of the GB railway system.

3.3 Methodology

Building upon the methodology of NR (2016d) historical train delay data from NR's TRUST system is used to classify critical locations across the railway network in terms of the expected magnitude of performance degradation should a disruptive incident occur at that location. Understanding the distribution and drivers of criticality from the infrastructure management perspective promotes a criticality assessment that can be applied to both operational and strategic decision making. The approach of this chapter adds to the existing literature by assessing railway network criticality using pure train service performance to define and map route level single points of failure. The details of the data and method used to conduct the network criticality assessment are outlined below.

3.3.1 Study Area

This chapter focuses on two contrasting routes, both in terms of topology and operations: namely Wessex and the southern section of LNW (Figure 3.1). Applying the proposed methodology to two contrasting routes demonstrates the transferability and robustness of a network criticality assessment, responding to different types of train service patterns and thus delay propagation dynamics.

Figure 3.1. The main map shows the extent of the Wessex and LNW (South) routes. The inset map shows the location of the two routes within the GB rail network.

The Wessex route is located in the south of England, including the Isle of Wight, and is one of the busiest and most congested routes on the GB rail network (NR, 2016b). Wessex has a mainly longitudinal boundary containing the South West mainline and is largely a contained, single TOC route with most traffic being operated by South Western Railway. Traffic consists of suburban and commuter services to and from London, local and long-distance services to the south coast as well as significant freight traffic. London Waterloo is the major hub, with regional centres at Southampton Central, Bournemouth and Portsmouth & Southsea.

LNW (South) is part of the biggest single mixed-use route on the GB rail network and covers a substantial breadth of England from the South East to the West Midlands. The route contains large sections of the West Coast and Chiltern mainlines (Figure 3.2), with the West Coast mainline (WCML) recognised as a strategic transport corridor linking GB to mainland Europe (NR, 2016c). LNW (South) is a very open multi TOC route with a large volume of mixed traffic including long-distance, regional urban, commuter, branch and freight. London Euston and Birmingham New Street are the major hubs, with regional centres at Wolverhampton, Coventry, Rugby, Northampton and Milton Keynes Central.

3.3.2 Data and Metrics

Train service performance metrics can be used to assess and quantify the degree of disruption to a route or line during a specific time period. In this chapter, passenger and freight rail performance are derived from NR's *TRUST (Train Running System on TOPs)* system which records detailed train timing information regarding asset failures or incidents occurring on the GB rail network that have an operational impact on train service performance. To monitor regulatory targets, passenger performance is predominantly assessed using the *Public Performance Measure (PPM),* whilst freight performance is assessed using the *Freight Delivery Metric (FDM)* (ORR, 2018). Such measures of punctuality and reliability relate to the percentage of scheduled trains arriving at their planned destination “on time” or “significantly delayed”. Punctuality and cancellations are common factors of performance metrics globally, with several international rail metrics performing a similar function to PPM (RSSB, 2016a).

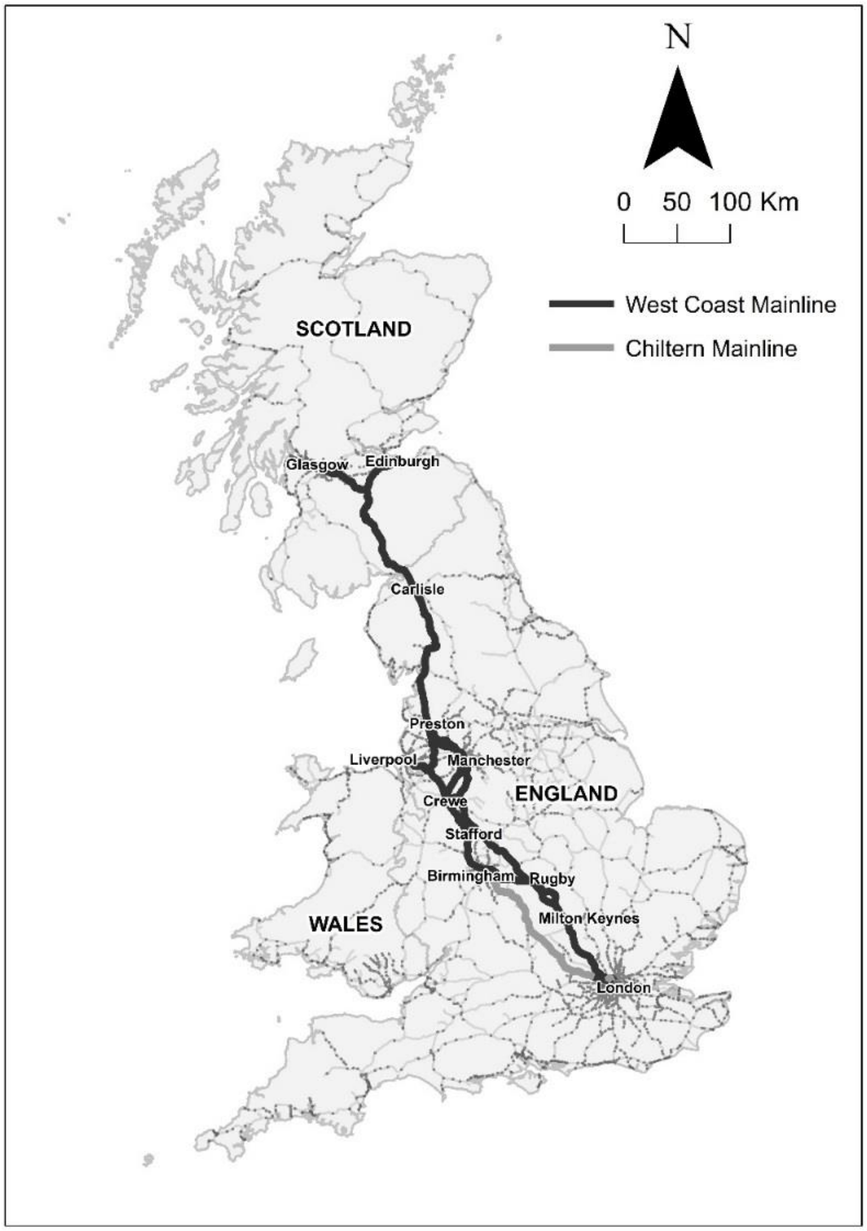


Figure 3.2. Map showing the WCML and Chiltern Mainline paths through the GB rail network.

Regulatory metrics are underpinned by a fundamental measure of punctuality known as *Delay Minutes* (DM) (ORR, 2018) which are recorded should a passenger or freight train arrive at a timing point behind the Working Timetable (WTT) (RSSB, 2016a). Records exist for individual delayed train services, for which a detailed attribution process is undertaken in order to determine the causative incident and thus the party responsible for the delay (DAB, 2018). Therefore, in order to assess train service performance from the infrastructure management viewpoint, only NR attributable delays count towards regulatory targets. Delay minutes or passenger weighted DM are common factors of railway performance metrics globally (RSSB, 2016a) and are also a commonly accepted form of assessment for the road network (DfT, 2014b; Pregnolato et al, 2016).

DM and the TRUST system underpinning them are seen as a useful tool for network management and supporting decision making (RSSB, 2016a). However, the principal commercial focus of DM and attribution is to facilitate the financial compensation regime agreed between NR and operators. This regime has elements which compensate operators for unplanned train service disruption caused by NR and other operators (ORR, 2015) whilst also covering planned unavailability of rail infrastructure (RSSB, 2016a). DM are a neutral measure of punctuality whereby a delay minute on a main line is equivalent to a delay minute on a branch line. However, for regulatory metrics, different operators or lines may have different targets to meet and thus manage towards, distorting the comparability between lines or routes. Compensation costs have pre-determined priorities with respect to operators and lines, for example, long-distance services on mainlines would likely have a greater cost of delay per minute than local services operating on branch lines. Therefore, using such costs as a measure of performance introduces a significant bias, where the impact of each delay minute is treated differently dependent on where it originates in the network.

Decision making using DM as a measure of pure train service performance will provide a different prioritisation of undertakings than financial costs or regulatory metrics. In order to focus the criticality assessment in this chapter on pure train service performance priorities of local-level significance, a metric of DM was used. Using DM therefore defines network criticality priorities based upon the service dynamics, train paths and topological design of the rail network, covering network effects and behaviour as opposed to simply mapping TOC or FOC priorities. The use of DM is an improvement upon existing research as they capture the real-world dynamics of the railway system, with the complexity of train operations, timetables, disruption mechanisms and the influence of human decisions, such as signalling and service amendments, captured in the metric of consequence recorded for an incident.

To provide a representative sample and distribution of disruptive incidents, delay records were extracted from NR's TRUST system for January 2011 to May 2016. Historical records of transport disruption are significantly underutilised sources of information for vulnerability and resilience studies (Jaroszweski et al, 2015) but can provide a valuable platform for detailed analysis, with a high degree of spatial and temporal disaggregation. Several previous studies have used NR's TRUST system to assess priorities for resilience and performance enhancement (Dobney et al, 2009; Dobney et al, 2010; Jaroszweski et al, 2015; Ferranti et al, 2016).

The complete TRUST database contains records for all NR attributable delays, where the cause of the initial incident was deemed to come under the remit of NR. However, only delays caused by asset failures (such as track, communications, power and signalling faults) are taken forward for analysis to ensure that the resulting criticality assessment is within the asset management domain. By restricting the assessment to asset failures, the criticality of a location will also include a more reliable indication of the exposure of that location to hazards as assets have a fixed location and can only fail in situ whereas other hazards, such as trespass and bovine incursions, can have a more random spatial distribution and do not necessarily involve the failure of or damage to an asset. Furthermore, as only train service affecting failures are of interest, any records with less than one delay minute were removed. In order to limit the influence of extreme values or outliers having a disproportionate influence on the criticality of a location, Z-scores of skewness were calculated for incidents at each individual location, with any incident having a Z-score greater than 2 removed from the analysis. Locations with only one incident were also omitted as Z-scores could not be calculated.

Incident locations in TRUST are recorded at timing points throughout the network which are used to monitor train movements, defined by NR as the STANOX (Station Number) level. The location of an incident can either be reported as an individual timing point location, such as stations, junctions and sidings, or the location can be a track section between two timing points. The reported location depends upon where the initial train to be directly delayed by an incident was located at the time of delay, either travelling between two points or idle at a station or junction. These track sections are on average a third of the length of a SRS used in the internal NR (2016d) criticality assessment. Whilst the initial incident is reported as occurring at a specific location, the reported metric of DM includes all delays to services attributed to that incident across the entire GB rail network, with both delay caused directly to trains on site as well as propagation and reactionary delays due to network effects. Therefore, TRUST data allows the identification of localised single points of failure that can have consequences for the wider network.

To ensure that only incidents within the Wessex and LNW (South) routes were included in the criticality assessment, the TRUST data were spatially filtered in a GIS using a complete list of timing locations within the route boundaries to create a subset of the national database. Only incidents at timing locations wholly within the route boundary were retained in order to ensure that the criticality assessment was as route specific as possible. Up and down lines were collated into single sections where necessary, to aid visualisation and interpretation of the network criticality assessment.

3.3.3 Criticality Assessment

To undertake a criticality assessment, it was first necessary to extract incident counts and delay magnitudes from TRUST for each incident location in Wessex or LNW (South) with at least one recorded incident. Therefore, any locations without a reported incident in the database were not included in the criticality assessment and are therefore will not appear on the mapped output, explaining any omissions or 'gaps' in the rail network. The aggregated incident and delay values were used to calculate criticality bands for each incident location within Wessex or LNW (South) by employing the process described in Figure 3.3. Essentially, a measure of DM per incident for each location is compared to the relative distribution for the route in question and allocated a criticality band. Band definitions similar to the methodology of NR (2016d) based on train service performance relative to the mean, were used in order to facilitate potential integration of both criticality assessments. Allocating criticality bands as opposed to using the calculated values of DM per incident facilitates the classification of locations into different categories or priorities for action, aiding the interpretation and application of network criticality.

The final stage of the criticality assessment involved the visualisation of the calculated criticality bands in a GIS. Jaroszweski et al (2015) demonstrated the benefits of using novel visualisations of transport disruption metrics to understand network response to disruptive events. In order to map criticality for Wessex and LNW (South) the individual track sections were manually digitised. Mapping was supported by open train timetable data from Real Time Trains http://www.realtimetrains.co.uk and base maps from Open Street Map https://www.openstreetmap.org. Finally, the calculated criticality bands were imported into GIS and mapped for each route. In some cases, there was a degree of overlap between track sections due to the manner in which incident locations are recorded. Where sections overlap, the highest criticality band was mapped to provide a visual indication of potential key disruption centres.

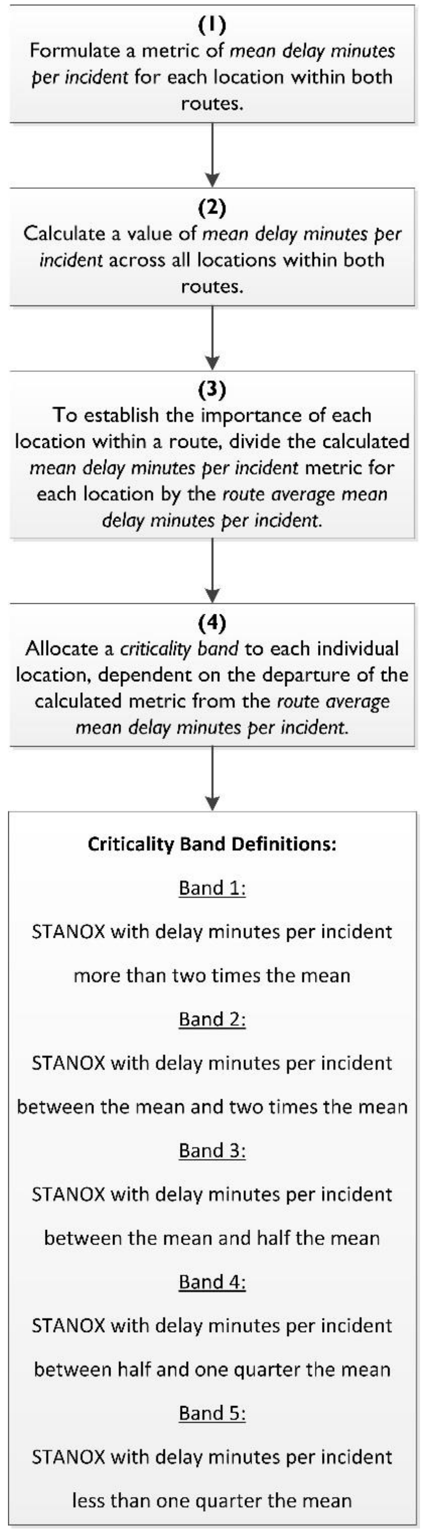


Figure 3.3. Flowchart of Methodology.

3.4 Results

In excess of 22,000 asset failure incidents originating in Wessex and LNW (South) between 2011 and 2016 were included in the criticality assessment, with a combined impact of over 2.5 million DM to train services. Overall, LNW (South) was found to have a mean delay minute per incident value of 124.28 which is 54% greater than the value of 80.69 for Wessex. Therefore, it should be noted that the average magnitude of disruption originating from a Band 1 critical location in LNW (South) is likely to be significantly greater than from a Band 1 critical location in Wessex. However, this chapter focuses on the relative criticality of locations within a route and the overall spatial distribution, rather than drawing numerical comparisons of locations between routes.

3.4.1 Wessex

Figure 3.4 shows mapped criticality bands for locations within the Wessex route, with Figure 3.5 focusing specifically on the London area. It is evident that a key centre of criticality is the London area, including the heavily utilised commuter line between the major hub London Waterloo and Woking. There is another area of high criticality towards the centre of the route, including the lines towards the regional hubs of Portsmouth & Southsea, Bournemouth and Southampton Central which serve as termini for several long-distance services including significant freight traffic. The western section of the route is mostly medium to low criticality, with the exception of the area around Yeovil Junction, with a relatively isolated and sparse rail network. Across the route, key locations of criticality are junctions; such as Clapham Junction, depots; such as Northam C.S.D, freight terminals; such as Fawley Esso, and major hubs; such as London Waterloo.

Wessex is a predominantly single TOC route, dominated by local South Western Railway services from London Waterloo to the west of the city, and thus there is a more lateral pattern of criticality emanating from the capital. In general, the route is rather isolated with the main inter-route services to London and the south coast, which contribute to these areas being classified as the most critical.

Table 3.1 details the most critical (Band 1) locations within the Wessex route. The locations of highest criticality are mostly concentrated within the eastern half of the route, with 11 of the 23 Band 1 locations situated within the London area, including the top four ranked locations. When examining the criticality of the London area in detail, the value of high resolution critical locations is apparent. There are several highly critical locations between London Waterloo and Woking, highlighting the importance of this line. However, the top two ranked critical locations are actually on branches off this line, and act as localised single points of failure. A similar situation is evident for the South Coast, with a cluster of highly critical locations around Southampton Central and Portsmouth & Southsea, combined with the two lines towards the South Coast being predominantly Band 1 criticality. In terms of granularity, 13 Band 1 locations are track sections whilst 10 are individual elements such as stations and junctions. The most critical Band 1 track section has the second shortest length at 1.54km. Whilst the longest section is 50.66km, most sections are less than 7km which highlights the increased spatial resolution of the network criticality assessment. A complete list of the criticality bands allocated to all locations within the Wessex route is included in *Appendix C*.

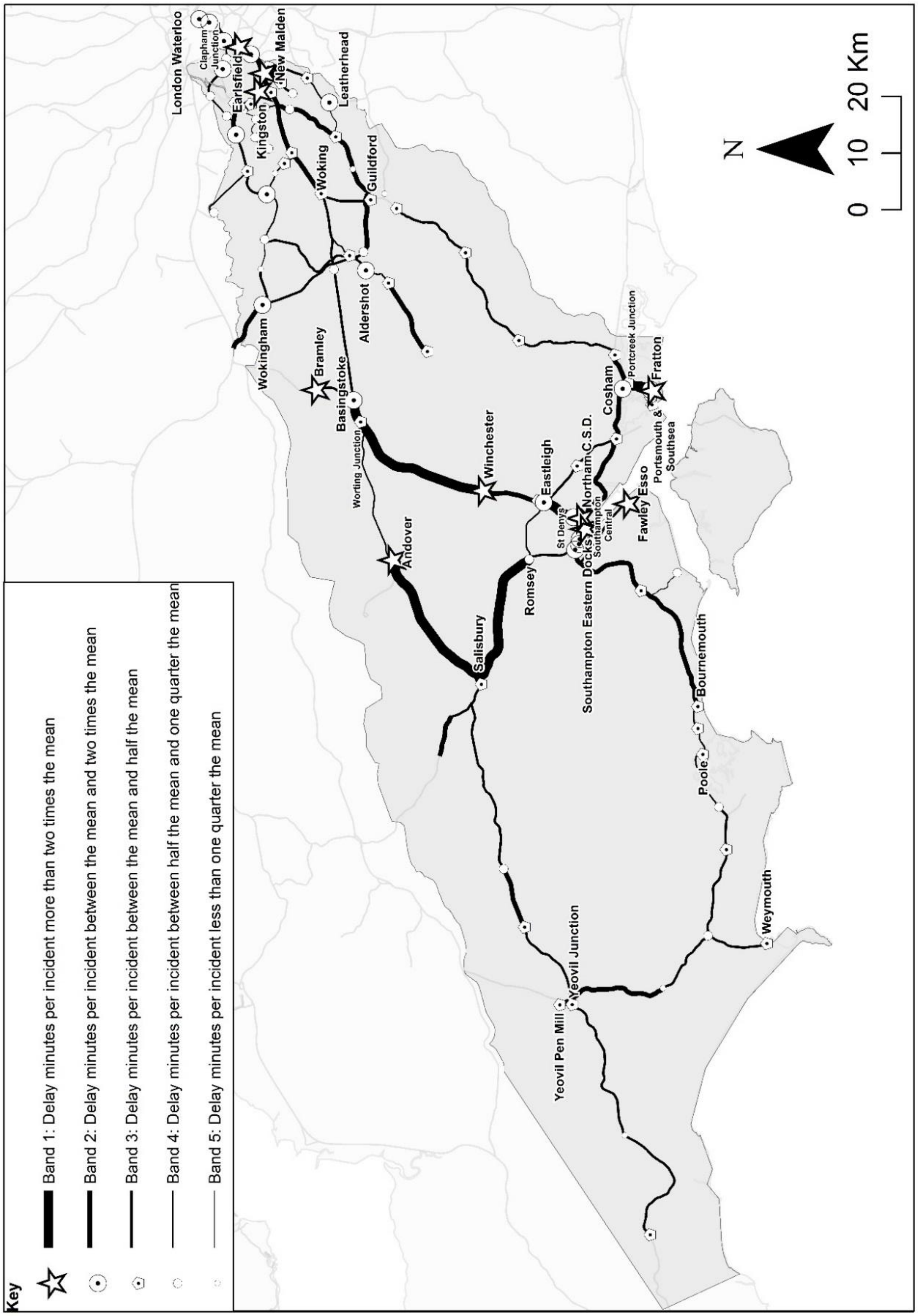


Figure 3.4. Mapped criticality bands for the Wessex route.

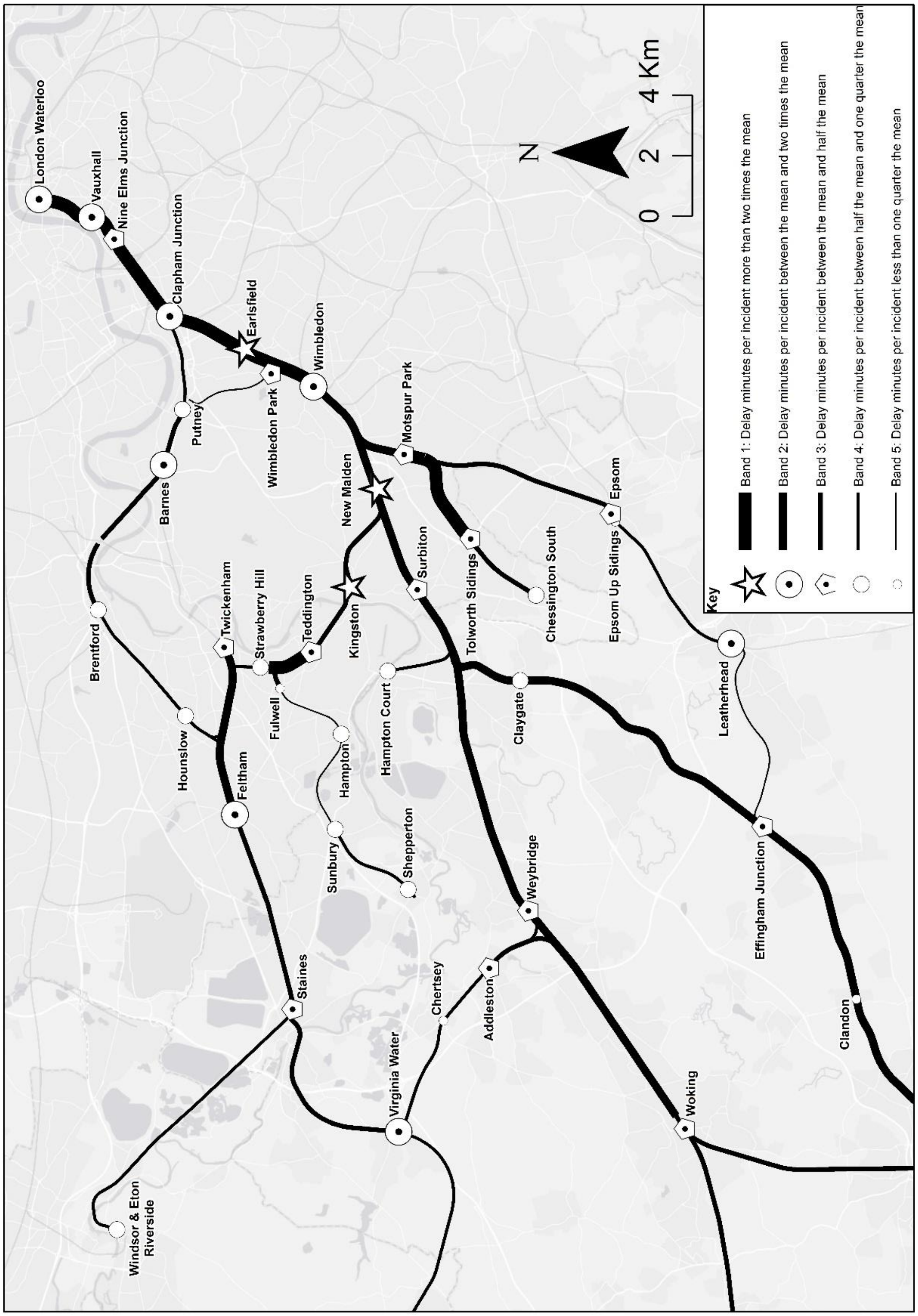


Figure 3.5. Mapped criticality bands for the London area within the Wessex route.

Table 3.1. Locations allocated Criticality Band 1 (highest) for the Wessex route, ranked in descending order of disruption magnitude.

Rank	Location	Length (Km)	Incidents	DM	DM per Incident
1	Strawberry Hill C.S.D. to Teddington	1.54	2	1504.6	752.3
2	Motspur Park to Tolworth SDGS	3.86	2	945.8	472.9
3	Nine Elms Jn to Vauxhall	1.07	5	1607.5	321.5
4	Clapham Junction to Vauxhall	3.99	36	10512.6	292.0
5	Fratton to Portcreek Jn	4.55	63	17983.9	285.5
6	Clapham Junction to Wimbledon	5.21	88	23787.4	270.3
7	New Malden	NA	31	8103.8	261.4
8	Andover to Romsey	50.66	4	1042.0	260.5
9	Northam C.S.D.	NA	6	1482.5	247.1
10	Earlsfield to Wimbledon	2.65	29	7128.2	245.8
11	Clapham Junction to London Waterloo	6.15	202	46136.7	228.4
12	Winchester	NA	44	9175.6	208.5
13	Andover	NA	2	416.0	208.0
14	Eastleigh to St Denys	6.00	127	26286.3	207.0
15	Earlsfield	NA	23	4753.1	206.7
16	Fawley Esso	NA	3	567.0	189.0
17	Winchester to Worting Jn	26.20	346	61683.8	178.3
18	London Waterloo to Nine Elms Jn	2.95	15	2646.2	176.4
19	Fratton	NA	47	8250.0	175.5
20	Basingstoke to Worting Jn	4.07	11	1861.9	169.3
21	Southampton Eastern Docks	NA	3	505.4	168.5
22	Kingston	NA	8	1341.4	167.7
23	Bramley (Hants)	NA	27	4483.6	166.1

3.4.2 LNW (South)

Figure 3.6 shows mapped criticality bands for locations within the LNW (South) route, with Figure 3.7 focusing specifically on the London area and Figure 3.8 on the Birmingham area. LNW (South) is a very open route, where significant long-distance and through traffic involving multiple TOCs provide potential for train service disruption to be both imported and exported. Therefore, the pattern of criticality is rather dispersed through the route. A clear area of high criticality is the line towards the major hub London Euston from Watford Junction, with a high frequency of local and long-distance services, as well as significant freight traffic. In the West Midlands there is another major centre of criticality, particularly for train services passing through the major hub Birmingham New Street, such as the line to Wolverhampton. Both the West Midlands and London areas have a high frequency of local services, as the WCML runs from north to south through the route it has a major influence on the criticality distribution. Delays to train services on the line itself can have a major impact, but long-distance services also have potential to spread reactionary delay through the route and beyond, as is the case with the Chiltern mainline to a lesser extent. Across the route, key locations of criticality are junctions; such as Aynho Junction, depots; such as Tyseley L.M.D, freight terminals; such as Willesden Euroterminal, and major hubs; such as London Euston. In general, there is a lateral pattern of criticality along the two mainlines and near London Euston, with a more radial pattern around the West Midlands region. The route topology is highly connected, with no particular isolated areas.

Table 3.2 details the most critical (Band 1) locations within the LNW (South) route. The locations of highest criticality are not confined to particular parts of the route, due to the degree of long-distance traffic along the two mainlines. The WCML is the dominant feature, with 10 out of 18 Band 1 critical locations. The Chiltern mainline has 2 locations of maximum criticality. At either end of the mainlines, there are two major metropolitan networks in the West Midlands and London which have more localised critical locations. The granularity of criticality is most apparent around the city of Birmingham where there are several highly critical locations on heavily utilised local lines, which act as single points of failure. The top two ranked critical locations are actually away from the WCML, located to the west of Birmingham and on the Chiltern mainline respectively. In terms of granularity, 10 Band 1 locations are track sections whilst 8 are individual elements such as stations and junctions. The most critical Band 1 track section has the shortest length at 3km. Whilst the longest section is 21.25km, most sections are less than 10km which highlights the increased spatial resolution of the network criticality assessment. A complete list of the criticality bands allocated to all locations within the LNW (South) route is included in *Appendix C*.

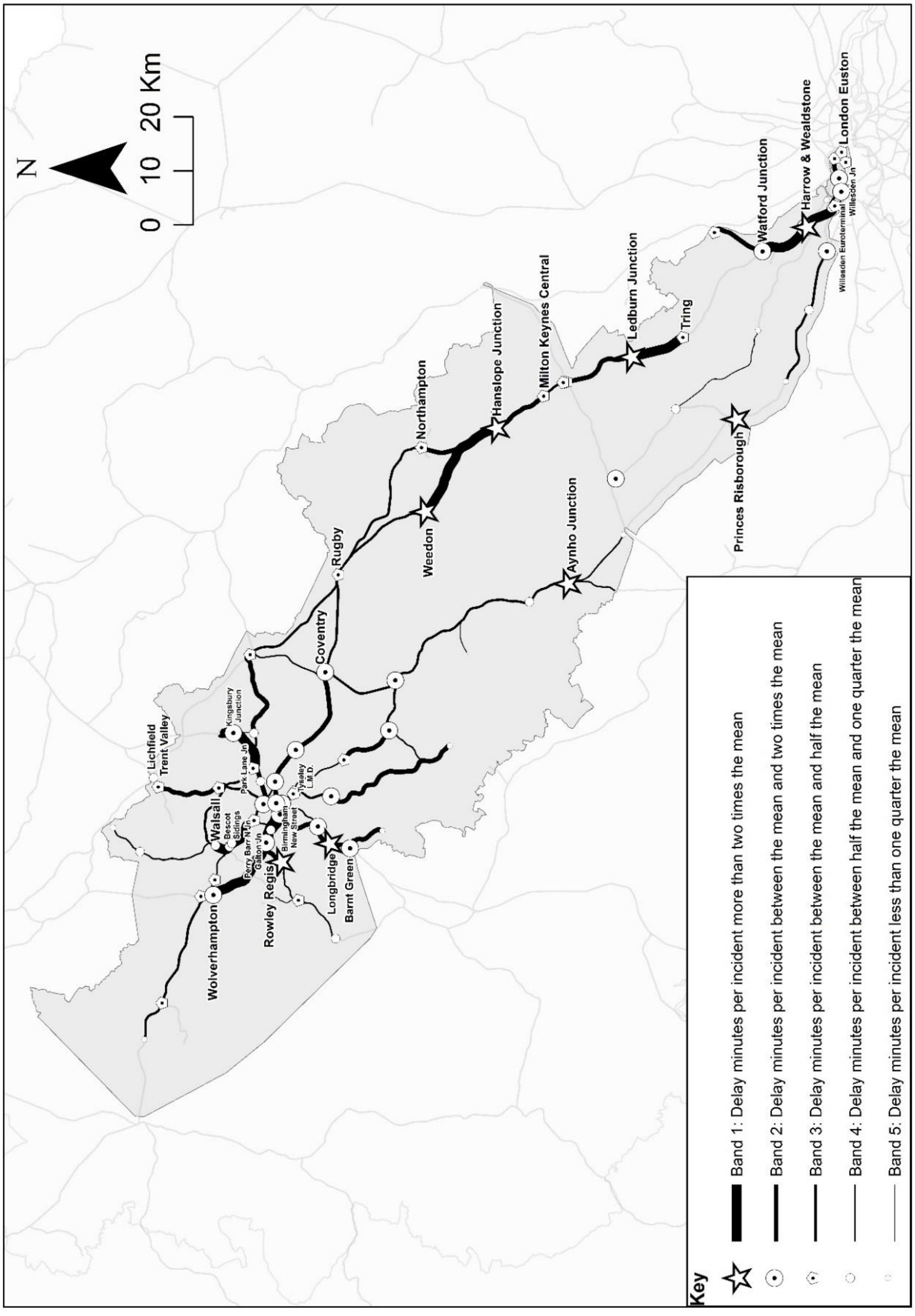


Figure 3.6. Mapped criticality bands for the LNW (South) route.

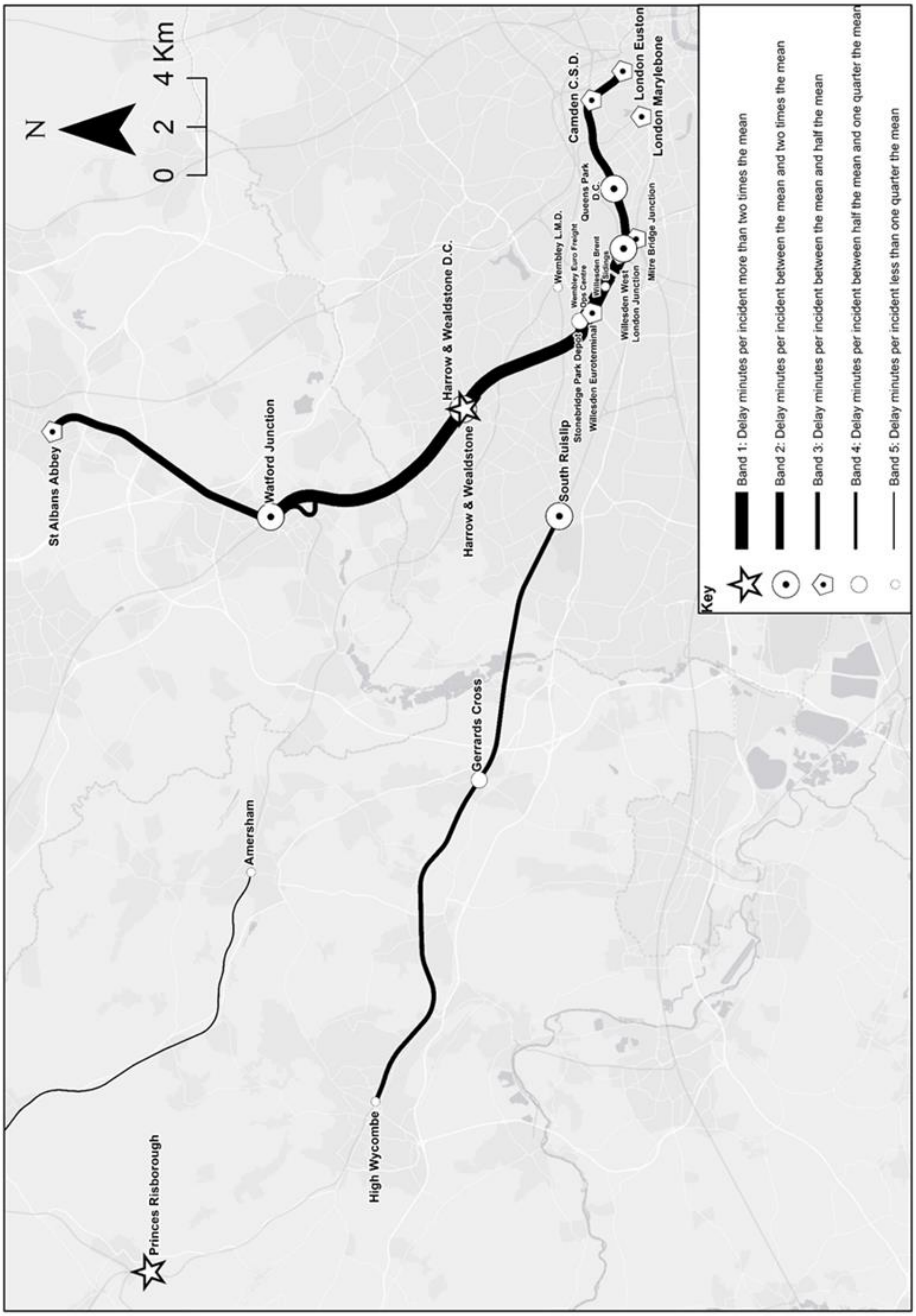


Figure 3.7. Mapped criticality bands for the London area within the LNW (South) route.

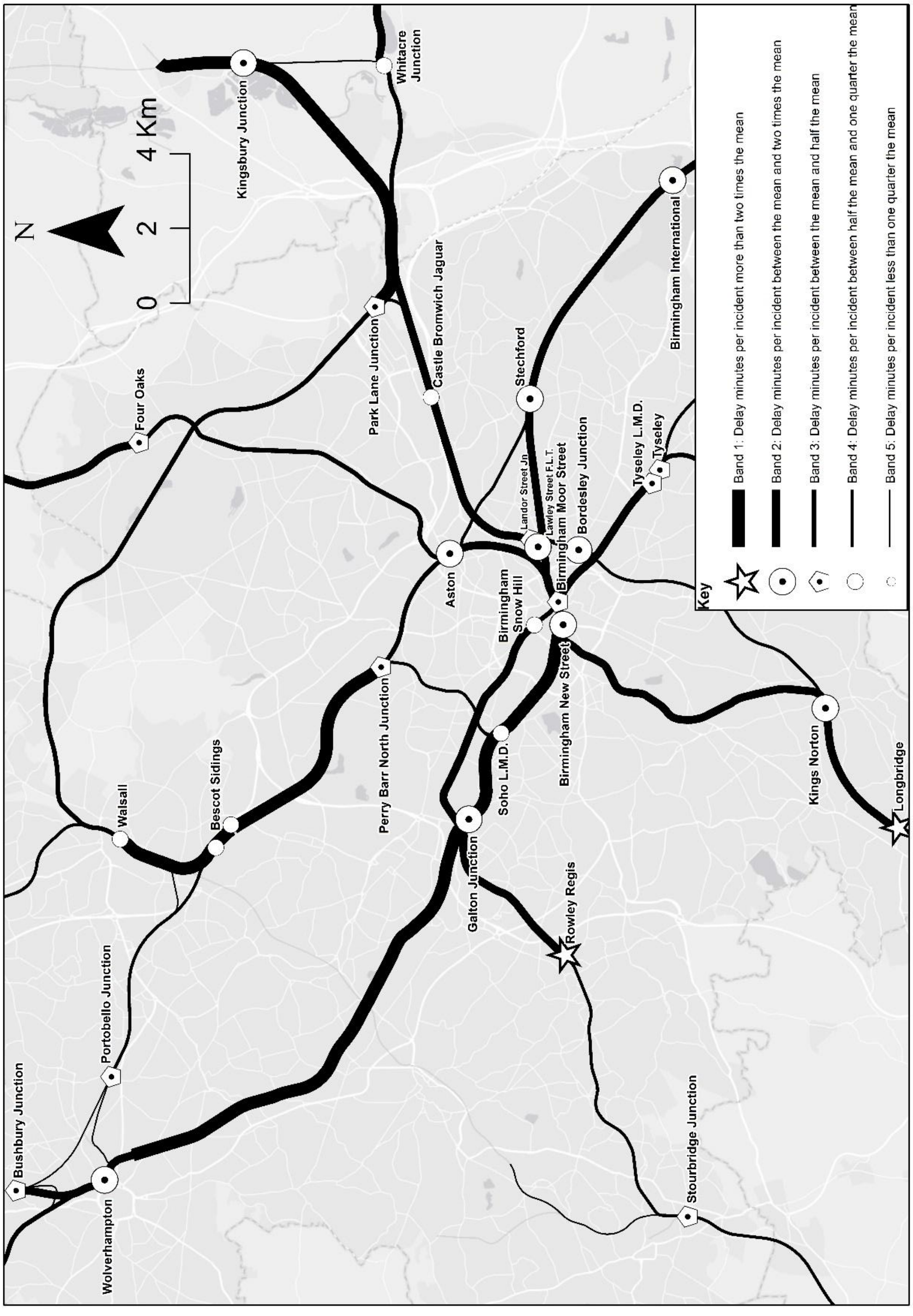


Figure 3.8. Mapped criticality bands for the Birmingham area within the LNW (South) route.

Table 3.2. Locations allocated Criticality Band 1 (highest) for the LNW (South) route, ranked in descending order of disruption magnitude.

Rank	Location	Length (Km)	Incidents	DM	DM per Incident
1	Rowley Regis	NA	4	4157	1039.3
2	Princes R'Boro Ace	NA	3	2446.3	815.4
3	Weedon	NA	5	3778	755.6
4	Kingsbury Jn to Kingsbury SDGS	3.00	2	1285	642.5
5	Bescot Up Engineers SDGS to Perry Barr North Jn	6.25	2	1218.5	609.3
6	Ledburn Jn	NA	64	27871.5	435.5
7	Harrow & Wealdstone	NA	24	10203.5	425.1
8	Longbridge	NA	28	11645.5	415.9
9	Hanslope Jn to Weedon	21.25	133	55278.1	415.6
10	Hanslope Jn	NA	59	22727.8	385.2
11	Kingsbury Jn to Park Lane Jn	8.54	6	2302	383.7
12	Galton Jn to Wolverhampton Steel Term	13.64	9	3251.5	361.3
13	Bescot Holding Sidings to Walsall	5.13	2	645	322.5
14	Harrow & Wealdstone to Watford Junction	9.75	224	63578.3	283.8
15	Ledburn Jn to Tring	10.58	76	21474.5	282.6
16	Harrow & Wealdstone D.C. to Willesden Jn Low Level	9.33	199	55682.3	279.8
17	Aynho Jn	NA	10	2701.6	270.2
18	Birmingham New Street to Galton Jn	9.35	169	43990.3	260.3

3.5 Discussion

The results of the criticality assessment have highlighted the overall pattern of network criticality within the Wessex and LNW (South) routes, alongside the presence of specific and localised single points of failure, both of which can be used to inform a prioritisation scheme for rail undertakings. Comparing the two routes, Wessex and LNW (South) have contrasting criticality distributions. Wessex has quite distinct criticality centres whereas LNW (South) has more dispersed criticality, dominated by the WCML. The two routes are on a very similar scale geographically but have markedly different network topologies and train service patterns. LNW (South) has a much denser and connected network than Wessex, presenting more single points of failure, along with more long-distance services that can propagate train service disruption. However, there is clear commonality in the types of locations that are classified as highly critical, outlined in Table 3.3, demonstrating the transferability of the methodology.

Table 3.3. Critical location types and characteristics.

Location Type	Characteristics	Examples
City-Scale Networks	Present in both routes, criticality is influenced by a combination of frequent local services and longer distance services through major hubs. There are clear priority lines, but on dense and highly connected networks any location has the potential to generate a high magnitude of disruption.	West London and Birmingham.
Long Distance Lines	The majority of long-distance lines are attributed to the top criticality bands. Multiple service groups travelling long distances, through multiple major hubs and across multiple routes have the potential to import and export disruption, propagating delays across the network. The number of up and down lines can influence the ability to regulate services. Disruption may also be exported to diversionary routes, should they be available.	WCML and the lines to the south coast of England.
Freight Lines	Freight paths cover significant distances, increasing the volume of traffic as well as the potential for reactionary delays to passenger services should they become blocked by a freight train. Limited looping places and loop lengths	Lines around freight terminals at Lawley Street (Birmingham) and

	restrict the ability to manage freight traffic. Consignments are usually time critical in a supply chain, thus they are difficult to divert and cannot be terminated early or amended. Incidents at or near freight terminals can also generate a high magnitude of disruption.	Southampton Docks.
Key Junctions	With a high volume and frequency of traffic, multiple train service paths can be disrupted which can then result in congestion and spread reactionary delays further across the network. Many of the key junctions in both routes create pinch points on the network and are thus allocated to the highest criticality bands. Regulating late running traffic at junctions is a key management problem, placing great emphasis on the decision making of the local Signalling Controller.	Clapham Junction and Barnt Green.
Major Hubs	Any incident at or near a major hub, such as point or signal failures, can block traffic in or out. This can cause major disruption through direct and reactionary delays. Congestion can occur should platforms be occupied for longer than scheduled. Train crew may also become displaced or delayed, disrupting subsequent services. Short turnaround times for services mean delays on inbound trains can cause delay on the outbound service as there is no recovery time.	London Waterloo and Birmingham New Street.
Depots	Incidents at or near depots can restrict access, affecting the ability to bring rolling stock onto the network to operate train services, or causing congestion with units backed up on the network and unable to return to depot. The train services comprised of the units involved may be delayed, along with reactionary delay from congestion.	Northam C.S.D (Southampton) and Tyseley L.M.D (Birmingham).

It is clear that traditional critical locations that are well understood, including main lines, key hubs and junctions are worthy of prioritisation for rail undertakings. This criticality assessment therefore acts as an objective evidence base to support the subjective priorities that may exist only as tacit knowledge within routes, formalising critical locations. However, local variations in train service patterns and network topology also present very localised single points of failure, the identification of which adds further value to existing prioritisation schemes. Mainlines have a consistently high criticality, whilst still encompassing more and less critical locations where a more localised layer of prioritisation would be of benefit. At the city or regional scale, a detailed and granular assessment of criticality facilitates the identification of hotspots where local asset management and incident response can be prioritised. In fact, some of the top ranked locations in both routes are on branch lines, such as Rowley Regis in LNW (South) and Strawberry Hill C.S.D. to Teddington in Wessex. The increased granularity is highlighted by the fact that of the 41 Band 1 critical locations across both routes, 23 are track sections, with 18 sections less than 10km in length. Using shorter track sections allows prioritisation of resource allocation to have a much more localised focus, targeting more specific locations and saving time and money.

In some cases, branch line incidents may generate a high number of DM as it can be easier to isolate the line and contain disruption, therefore maintaining a train service is less of a priority as the impact on the wider network should be minor. Such single points of failure are also a product of the regional scale assessment and selected performance metric. Defining criticality bands within a single route, rather than for the GB rail network, allows the identification of locations that may not feature prominently in a national assessment but are very important for route level management. Also, using a train service performance metric of DM treats all delays of the same magnitude equally with no pre-weighted prioritisation scheme, therefore some of the more remote branch line locations may have a high criticality band as incidents at that location have a significant impact on train service levels, but under a financial compensation metric such delays would have a low weighting and be regarded as a lower priority.

However, the more localised single points of failure require careful interpretation due to the nuances of using a historical data set such as TRUST. Analysing historical asset failures has the advantage of incorporating real world system dynamics and thus captures all inherent behavioural mechanisms. However, the main limitation is that the criticality bands of some locations are based upon a small sample of incidents and may therefore be influenced by high severity but low frequency incidents. This should therefore be taken as an indication that an incident occurring at such a location does indeed have the potential to cause a significant level of disruption, but the degree to which such an incident represents a typical disruption scenario is difficult to determine in such cases. A trade-off exists between sample size and granularity, whereby combining locations into longer track sections would increase the sample size and thus the reliability of the calculated criticality band but also reduce the localised focus of the methodology and reduce the applicability for city or regional scale rail management.

Identifying outliers, using z-scores of skewness, removes the more extreme incidents but there will always be an influence of rare but high magnitude events. Extending the time series would negate such issues by increasing the sample available for analysis, and as more data is recorded over time future iterations of the criticality assessment methodology would have a greater reliability for single points of failure. For the existing assessment, the interpretation of such locations should be on a case-by-case basis, requiring a forensic analysis of the nature of the incidents occurring at these locations and/or an examination of track and location characteristics. Single points of failure within major lines are generally more reliable, with a higher frequency of failure presenting a more representative sample. For more remote locations on branch lines, a high criticality band indicates a potential problem, but the low sample size means there is no certainty on whether this is a systematic issue or the result of an extreme event.

It is important to understand the caveats to the analysis, and the factors that contribute to a location being rated as highly critical for maintaining train service performance, in order to ensure that the criticality assessment is interpreted and applied in the most useful manner to achieve the aim of improving the efficiency of resource allocation and promoting cost-effective decision making for railway undertakings. The added value of the criticality assessment methodology is in the identification of localised and granular single points of failure, enhancing the understanding of route level train service performance priorities as well as confirming the importance of expected critical locations on mainlines and around major hubs and junctions.

The presented analysis demonstrates a criticality assessment of the Wessex and LNW (South) routes of the GB rail network which can aid the identification of priority locations for maintaining train service levels within a route. The insights gained can inform decision making for a broad range of rail undertakings, with the goal of promoting cost-effective resource allocation. The criticality assessment provides a quantification of the relative importance of locations to maintaining train service performance within a route. Understanding how much more or less critical a location is compared to the rest of the route is essential information for decision making on resource allocation.

3.6 Conclusion

This chapter has presented a network criticality assessment methodology for rail infrastructure, which facilitates a prioritisation scheme for a range of undertakings on the GB rail network. It is demonstrated that the assessment can add value through integration with existing prioritisation schemes by objectively identifying localised single points of failure that are strategically important for maintaining train service performance. Using historical data on train service performance to define network criticality to a high level of spatial granularity leads to the identification of single points of failure within well understood critical lines, such as the WCML, whilst also highlighting more remote critical locations on branch lines. These locations can be used to refine high level financial allocations, translating funding into specific projects, whilst also objectively defining and challenging priorities that currently exist only as subjective tacit knowledge. The enhanced granularity provides a new layer of information for decision making and, whilst the specific application of criticality depends on the scale and timeframe of the decisions involved, all interventions are ultimately local therefore no matter what rail undertaking is in focus, there is a role for localised single points of failure in risk assessments.

The highly complex operational and behavioural mechanisms of the GB rail network are inherently captured in the criticality assessment, yet there is a clear trade-off between the spatial scale of analysis and the sample size available. Coarse track sections would provide a higher frequency of incidents and thus a more reliable indication of criticality, but for route level management using such broad sections that can transcend route boundaries is not adequate for localised decision making. Although demonstrated for two specific routes of the GB rail network, the presented criticality assessment methodology is transferable and can be applied to the entirety of NR's network and could inform decisions made on the 20,000 miles of track and 2,500 stations that NR owns and operates, as well as other international rail networks, dependent on the availability and quality of spatial and operational data.

Overall, the key contribution of this chapter is the formalisation of localised critical locations at the route level of the GB rail network, to inform decision making and promote cost-effective resource allocation. Chapter 4 scales up the complexity of network criticality assessment further to examine the dependencies of an electrified railway on an external electricity distribution system for a traction power supply, and the spatial correlations in criticality between the two networks at the local-scale.

CHAPTER FOUR: **DEPENDENT NETWORK CRITICALITY ASSESSMENT - RAILWAY ELECTRIC TRACTION FEEDER SYSTEM**

4.1 Introduction

In the previous chapter, a railway network criticality assessment was produced, scaling up the complexity of topology and system behaviour. This chapter scales up the complexity of network criticality assessment further to examine the dependencies of an electrified railway on an external electricity distribution system for a traction power supply, and the spatial correlations in criticality between the two networks at the local-scale.

Infrastructure owners and operators have a limited budget and finite resources with which to manage a broad range of activities, including regular maintenance programmes and incident response as well as long-term asset renewals and upgrades. The cost-effective allocation of resources for such activities is a therefore a major network management challenge (Durango-Cohen & Madanat, 2008). Verner et al (2017) suggest that the protection of critical infrastructure should focus on the identification and prioritisation of network failure points based on potential consequence. To this end, a location-based network criticality assessment, identifying such single points of failure (DfT, 2014a), can help to understand the distribution of risk throughout infrastructure networks and prioritise interventions at locations where the greatest service performance improvement would be yielded from the investment.

The criticality of a location within an infrastructure network is a measure of its strategic importance for maintaining service performance, which can be defined by the potential consequence of failure. As the topological characteristics and service flows within infrastructure networks have significant spatial variability, faults or incidents occurring at different locations in networks can have vastly different consequences for service performance, and thus very different measures of network criticality. The prioritisation of critical locations is further complicated by the increasingly interconnected and interdependent nature of infrastructure. There is widespread evidence that interdependencies are important for the planning, design and operation of critical infrastructure and this only set to increase with greater reliance on technology, digital connectivity and power supply (The Resilience Shift, 2018). A systems-of-systems approach to analysing infrastructure is advocated by Hall et al (2013), viewing national infrastructure as a series of interconnected systems, such as transport and energy, which place demands on each other. The concept of infrastructure interdependencies is introduced by Rinaldi et al (2001), where infrastructure systems are mutually dependent as the continued functionality of one infrastructure system depends on the functionality of another infrastructure system and vice versa. This allows the potential for cascading failure to occur, where infrastructure failure and disruption can propagate between systems.

Introducing externalities to a system adds greater complexity to network management activities and thus resource allocation. In order to appreciate a more holistic view of risks to a network and avoid siloed thinking, it is necessary to look beyond the traditional boundaries of that particular system at external assets that may influence the functionality of that system. In this chapter, the focus is on physical dependencies between two connected systems, where one asset depends upon a flow of resources from another external asset (Rinaldi et al, 2001). There is a clear one-way dependency of rail transport systems upon external power distribution systems for a supply of electrical power for various rail sub-systems including traction current, signalling, stations and control centres (RDG, 2017). Within a rail corridor, the most direct application is the supply of traction power for electrified rail to move rolling stock. The electrification of transport networks increases the dependency of transport systems on the energy system, meaning that a significant failure on the electricity network has the potential to cascade onto the transport network with far reaching consequences (Chapman et al, 2013). A recent review of transport resilience to extreme weather (DfT, 2014a) highlighted the resilience of the electricity supply as a specific threat to the continued operation of the rail system. In particular, the failure of key substations can be an unforeseen source of vulnerability during a disruptive event and it is recommended that rail and electricity network managers liaise to trace critical substations and cables through which traction power is supplied and identify single points of failure where resilience improvements can be targeted.

To contribute towards this recommendation, this chapter undertakes a local-scale and high-resolution network criticality assessment of dependent power distribution and electrified railway systems, applied to a case study for the Cross-City railway line (West Midlands, UK) and electricity distribution substation dependencies for traction power. Verner et al (2017) advocate the use of objective criticality measures to avoid reliance on expert or tacit knowledge which may have personal judgement bias and lack appreciation of system-level resilience. Through an evidence-based assessment applying previously underutilised spatial and topological network information in conjunction with historical service performance metrics, real-world system dependencies and network behaviour are captured. A robust prioritisation of locations can aid decision making for localised asset management applications, through the added value of certainty in asset dependencies and reliability of single points of failure identified. The output from such an assessment can promote cost-effective resource allocation whilst identifying opportunities for cross-sector mutual benefit in resilience solutions and enhancements, a priority of the National Needs Assessment for UK infrastructure (Armitt et al, 2016).

4.2 Research Background

Network criticality assessments applied to a single system, such as rail (Pant et al, 2014; NR, 2016d) or electricity (Rosato et al, 2007; Ofgem, 2017a), can provide a detailed picture of spatially distributed risks within that system. However, such assessments often fail to consider external sources of risk beyond the system boundary. Decision making, and resilience enhancements based on single network risk assessments may leave infrastructure managers open to unexpected vulnerabilities during disruptive events, that can have major and far reaching consequences. There is a scarcity of research assessing the vulnerabilities posed by dependencies between railway sub-systems and external systems (RSSB, 2016b) highlighting a significant research gap.

Case studies of past failure events can provide useful insights into the range of vulnerabilities faced by interdependent systems. In particular, key lessons can be learnt from detailed analyses of extreme weather events such as the 2004 hurricane season in Florida (Bigger et al, 2009) and the 2009 heatwave in Melbourne (McEvoy, 2012). Both studies use a combination of literature review and expert interviews to improve understanding of interdependent infrastructure vulnerabilities and aid resilience planning. However, they are limited by their commentary on specific and extreme failure cases. The work of Chang et al (2007) has broader applications, developing a systematic framework for characterising interdependent infrastructure failures, based upon observed power outages from the 1998 Canadian 1998 ice storm. Empirical patterns in a database of power outages are analysed, although there is significant subjectivity in both the source of the database in newspaper articles and the judgement of societal consequences from such events.

Such limitations of qualitative research can be overcome through the objectivity of quantitative methods. Zimmerman & Restrepo (2006) explore how metrics can be used to quantify infrastructure interdependencies, in terms of strength, directionality and cascades, with a metric of relative duration proposed as a potential indicator of cascade risk from a failure event. It is highlighted how useful metrics can be developed despite the challenges of the nature of the data and its availability. Rinaldi (2004) explored the role of modelling and simulation approaches to analysing infrastructure interdependencies, proposing that such approaches are vital to understanding complex infrastructure behaviour under failure conditions.

A review of modelling and simulation methods for interdependent infrastructure systems is presented by Ouyang (2014). Models are grouped into six broad categories; empirical, agent-based, system dynamics, economic theory, network based and others. Whilst all models may provide useful insights into interdependent infrastructure vulnerabilities, for a high-resolution spatial network criticality assessment network modelling approaches are of most interest, where assets are represented as nodes and relationships between assets as edges. Network models are further categorised by Ouyang (2014) as topology or flow-based methods. Johansson & Hassel (2010) propose that in order for a model to be of practical value, interdependent infrastructure should be represented both as network models that describe the structure of physical components using graph theory (topology) and functional models that describe the operational characteristics (flows).

Significant advances in the field of interdependent infrastructure network modelling have been made by the UK Infrastructure Transitions Research Consortium (ITRC), focusing on national-scale multi-infrastructure vulnerabilities. As part of this research programme, Thacker et al (2017a) undertook a network criticality assessment that identified geographic risk hotspots across multiple connected infrastructure systems, using Kernel density estimation to highlight spatial concentrations of assets with a high number of users who would be disrupted should they fail. Thacker et al (2017b) performed a multi-scale disruption analysis for the interdependent domestic flight network and integrated electricity network, defining functional pathways between systems weighted with customer demands. The most pertinent study is that of Pant et al (2016) which developed a vulnerability assessment framework for interdependent infrastructure systems, applied to a case-study of GB rail infrastructure dependencies on external systems. Interdependency mapping models are used to establish cross-infrastructure relationships between assets, with failure consequence defined as a metric of disrupted railway passenger trip flows.

The utility of these approaches is governed by the way in which they model network topology and dependencies, failure scenarios and failure consequence. There is a high degree of similarity between the three studies. In each case, infrastructure network topology is primarily derived from a combination of industry network maps and open source spatial data, such as OS MasterMap. As the exact nature of physical connections between infrastructure systems if often unknown (Thacker et al, 2017a) dependencies are based on geographic proximity and least cost algorithms, where functional pathways are created between an asset and its nearest dependent asset. For example, Pant et al (2016) join electric traction substations to the nearest railway station or track section it is assumed to supply. The generation of failure scenarios varies, with Thacker et al (2017a) testing 200,000 synthetic scenarios whilst Pant et al (2016) obtain flood likelihood maps to apply realistic predicted hazards. Failure consequence is estimated from service demand data and usage statistics where available, such as rail station entries, interchanges and exits (Pant et al, 2016), or in the absence of data techniques such as capacity constrained location allocation algorithms and Voronoi decomposition are employed to estimate the customer demand that would be lost should an asset fail (Thacker et al, 2017a; 2017b).

There are clear advantages to such national-scale network models. A wide range of failure scenarios, infrastructure systems and real-world geographic locations can be simulated, without the burden of computationally expensive low-level detail, offering insights into infrastructure vulnerability across the UK. However, there are limitations to this work when considering the applications for localised asset management. The absence of data and information regarding individual physical asset dependencies, system behaviour and service levels, and the subsequent assumptions highlighted within the research, introduce significant sources of uncertainty to the results. For a methodology that is designed to assess high-level risks and inform national policy, uncertainty can be tolerated, but for decision making surrounding the prioritisation of specific assets at the local-level, uncertainty significantly compromises the applications of such modelling and simulation approaches.

Methods of interdependency analysis based upon geographic proximity do not adequately capture the complex micro-scale dependencies between railway assets and external systems (RSSB, 2016b). There remains the need to identify and assess the influence of infrastructure interdependencies upon system vulnerability to cascading failure and associated disruption, using an evidence-based approach. There is currently an absence of published academic literature that uses evidence of both network disruption and asset dependencies to produce a network criticality assessment for interdependent infrastructure networks. Therefore, this chapter adds value to the existing literature by making progress towards overcoming the challenges of reliability and uncertainty in interdependency analysis by applying previously underutilised data and information sources from infrastructure owners to produce a high resolution and localised dependent infrastructure network criticality assessment.

4.3 Methodology

The approach of this chapter can be distinguished from existing literature regarding interdependent infrastructure network criticality assessment through the focus on a forensic examination of underutilised industry data and information sources for network topologies, asset dependencies and failure consequence in order to evaluate the degree to which such evidence may overcome assumptions and reduce uncertainty. There is a clear trade-off between the scope and complexity of analyses, therefore a local-scale case study is used to undertake a detailed assessment of the spatial distribution of risk across dependent railway and electricity distribution networks, to inform decision making for localised asset management within that geographic area. All asset failures, and thus their consequences, are ultimately at the local-level and so taking an evidence-based approach, analysing high-resolution spatial information and historical performance data can identify specific assets where resilience improvements could be targeted across infrastructure system boundaries with mutual benefits.

4.3.1 Study Area

A local-scale case study of an electrified railway dependent on an external power distribution network for the supply of traction power is used in this chapter (Figure 4.1). Thacker et al (2017a) advocates mapping criticality within urban areas, such as cities, as they are usually the focal point for risk management and resilience interventions, therefore a highly urbanised case study region that contains a major city (Birmingham) is selected for analysis.

The Cross-City railway line is situated in the West Midlands region of the UK, with train services running between the south terminus at Redditch at the north terminus at Lichfield Trent Valley, via the major hub Birmingham New Street. This is a heavily utilised suburban electrified line, with the main traffic being Class 323 Electrical Multiple Units (EMUs) operated by West Midlands Railway. In addition to frequent local services, on the section of the line to south of Birmingham there is significant long-distance traffic to the South West and North West of England, Scotland and Wales as well as numerous freight paths. These trains operate as a combination of Diesel Multiple Units (DMUs) and diesel locomotives. The Cross-City line is an interesting case study due to the variety of service patterns and the contrast between the north and south of the line. Should electrical rolling stock fail, there is high potential for widespread propagation of disruption. Rail infrastructure is owned and maintained by a single infrastructure company (NR), whilst train services are operated by private TOCs and FOCs.

Electric trains operating on the Cross-City line require a supply of electricity from the external power grid for traction power. The ownership and maintenance of electrical substations, cables and towers depends upon the voltage at which electricity is supplied. From generation sites, electricity is transported to GSPs on 400kV/275kV circuits which are the responsibility of NG who maintain the electricity transmission network in the UK. Any assets below these voltages are the responsibility of DNOs which, for the West Midlands, is WPD. 132kV circuits distribute electricity to BSPs which have 33kV circuits to primary substations. As Overhead Line Electrification (OLE) is supplied at 25kV, circuits and substations below this level at 11kV and the LV system at 230V are not of interest for this case study. However, it is acknowledged that lower voltage substations are dependent on the function of a higher voltage substation for their supply, presenting direct internal dependencies within the electricity system.

The complexity of operating the traction power supply for the Cross-City line is clear, with a reliance on multiple assets and multiple agencies at a number of levels across system boundaries. Effective infrastructure management requires the coordination and cooperation of activities between stakeholders, where the results of this chapter can be applied in industry to offer insights into systemic interdependencies, risks and opportunities.

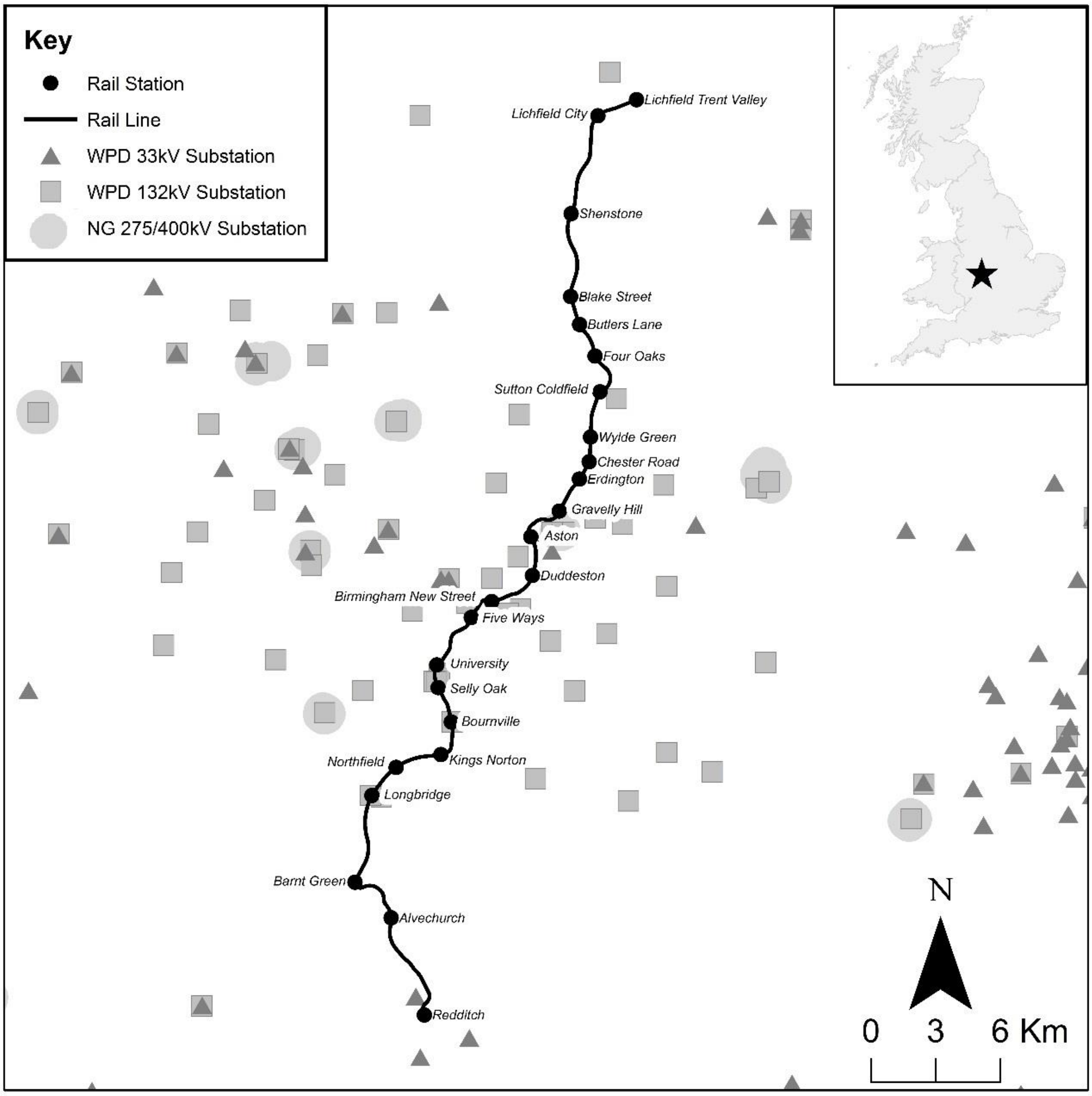


Figure 4.1. The main map shows the Cross-City railway line, transmission substations and distribution substations. The inset map shows the location of the railway and electricity systems within GB.

4.3.2 Data and Metrics

In order to support a detailed local-scale case study, a multi-system evidence base is collated from the sources of data and information outlined in Table 4.1 comprising both spatial and topological elements as well as service performance. Collating and interpreting multiple datasets, for multiple networks from multiple agencies is a challenging and time-consuming task but presents a clear advantage to the methodology in overcoming uncertainty and facilitating a network criticality assessment that can be applied to interdependent real-world systems to prioritise interventions. However, it is important to acknowledge the access restrictions to the data and information sources used in this chapter. Details and metrics of electrical supply systems have confidentiality and security implications; therefore, they are not publicly available.

Table 4.1. Details of data and information sources used in network criticality assessment.

Network	Spatial and Topological	Service Performance
Electricity Distribution and Transmission (Owned by: WPD and NG)	• Distribution assets derived using WPD Area ESRI Shapefile for assets 11kV and above, obtained from WPD Planning Data Portal. • Asset dependencies derived using WPD Network Diagrams, obtained from WPD Planning Data Portal. • Transmission assets derived using NG Transmission Network ESRI Shapefile, obtained from NG website (NG, 2017).	• Distribution service performance consequence metric derived using asset fault database, obtained from WPD for 2009-2014.
Rail Transport (Owned by: NR)	• Rail edges and nodes derived using baseline Mapping database, obtained from NR. • Asset dependencies derived using LNW Alternative Feeding Diagrams (Rugby ECR) document, obtained from NR (NR, 2015b).	• Rail service performance consequence metric derived using TRUST database of train delays, obtained from NR for 2011-2016.

Spatial and topological data is used to map real-world infrastructure assets, edges and nodes offering insights into network topology and system dependencies. This includes a representation of the Cross-City railway line as stations, junctions and track sections using a mapping database from NR and the electricity transmission and distribution networks as substations and cables using mapping data from NG and WCML respectively. Dependencies within and between the two systems can then be determined through examining network diagrams, which avoids geographic proximity-based assumptions, such as the dependency of the railway on geographically closest substations in Pant et al (2016), by allowing the identification of connections between specific assets. The use of network diagrams is a key feature of this chapter, where existing research may have spatial asset data for network topologies there is an omission or simplification of physical asset connections. The feeder stations through which traction power is supplied to the Cross-City railway line are identified, along with the distribution and transmission substations that supply them, therefore tracing through the external assets which present a risk to railway operations. Redacted examples of the network diagrams used in this chapter are included in *Appendix D*.

Service performance data is used to calculate network criticality for both systems, based on the consequence metrics for historical asset failures used in Chapters 2 and 3. For the rail network, NR's TRUST database records incidents that cause delays to trains, reporting a service punctuality metric of *DM* which is defined as the length of time in minutes a train is delayed behind the working timetable. For the electricity distribution network, WPD have a fault database which records individual asset faults, reporting two metrics of consequence for customers connected to the substation. *CA* is the aggregate number of customers without supply due to the fault, and *CML* is the aggregate number of minutes those customers were without supply. By calculating *CML / CA* a metric of *SML* can be obtained per fault, being the actual duration in minutes that a supply was lost from the reported substation.

The metrics used to quantify asset failure consequence are considered appropriate due to their high spatial granularity and similarity, being temporally based. Both metrics are measures of pure network disruption with no pre-defined priorities, for example, railway lines are not weighted by passenger numbers and substations are not weighted by connected customers. In this case, the focus is on one particular 'customer' or user of the electricity network, therefore a metric based on the duration of a power outage is more informative than a measure accounting for all CA. It is recognised that the time series for electricity distribution and rail performance data do not match exactly, however, this was the best available data at the time the analysis was undertaken and there remains significant overlap for the four years from 2011 to 2014.

4.3.3 Network Criticality

Metrics of network criticality are calculated for locations on the Cross-City railway line and local electricity distribution substations, based on service performance metrics from the historical disruption and fault databases obtained. The calculated network criticality bands from Chapters 2 and 3 were combined to assess dependent network criticality in this chapter, applied to the case-study area. To recap, the process for calculating network criticality bands for each network location is described in Figure 4.2.

In order to ensure that the metrics had applications for local-scale asset management, network criticality bands were calculated relative to the distribution of disruption within the network management regions in which the study area is located, namely the LNW (South) route of the railway network and the West Midlands licence area of the electricity distribution network. Network criticality is examined in detail for the case study in focus, spatially filtered for Cross-City line stations, junctions and track sections along with the set of electricity distribution substations that are identified as supplying traction power. The criticality bands and thus the prioritisation of critical locations is relative to all locations within the management regions used in practice.

4.4 Results

4.4.1 Traction Feeder System

Mapping physical connections between the railway system and the external power distribution system facilitates the identification of key substations that supply power to electric trains on the Cross-City railway line. The organisation of the traction power feeder system is described in this chapter but owing to confidentiality and security implications the attributes of substations are anonymised as far as possible.

The traction power feeder system comprises both internal and external elements. Within the railway system, for the majority of the UK traction power is supplied via AC 25kV OLE where trains collect current from overhead lines, suspended by masts and gantries, using a pantograph on the train roof to power on-board electric motors. Such a system is in operation for the Cross-City line, which requires a supply of electrical power from the external energy system.

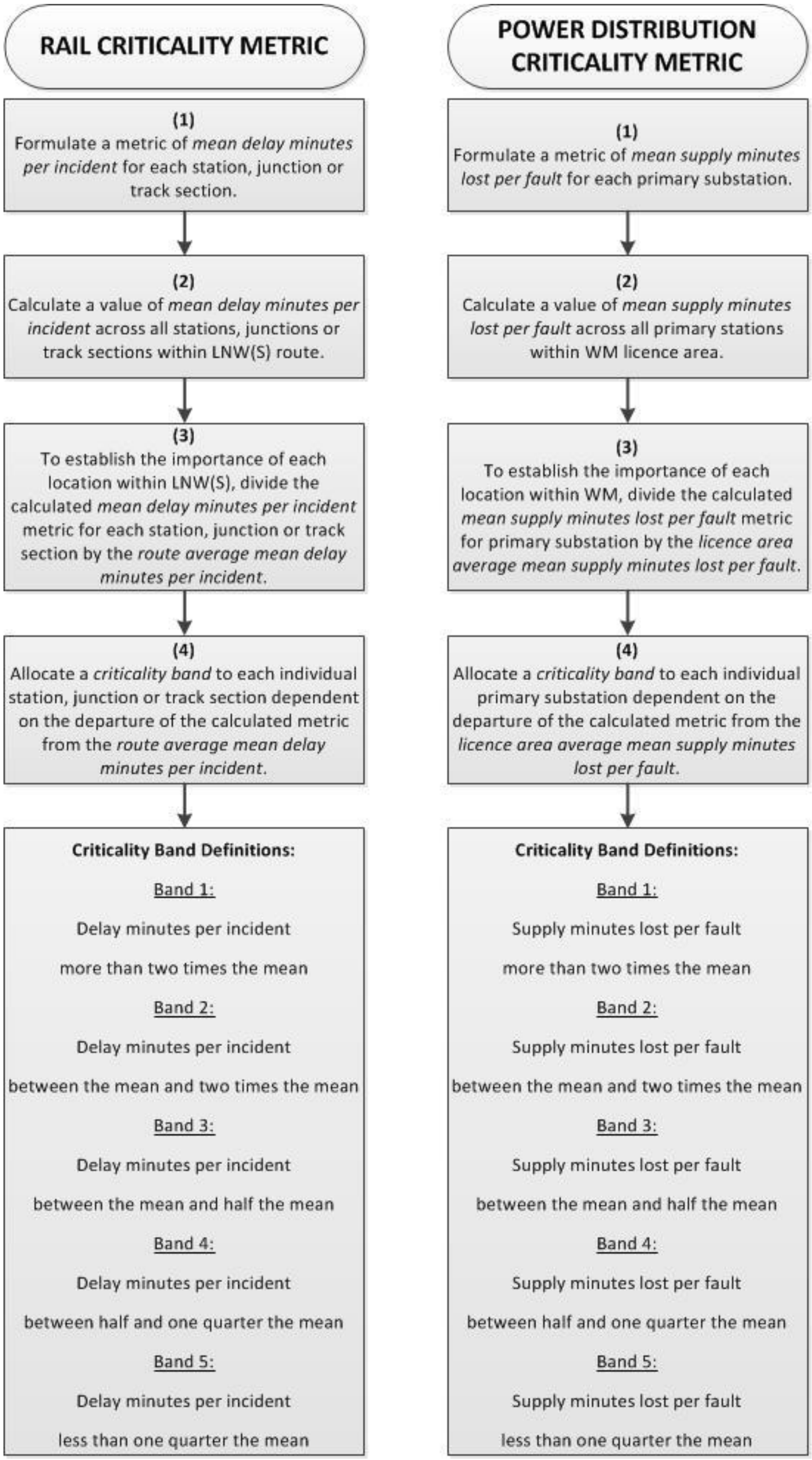


Figure 4.2. Flowchart of Criticality Band calculations.

Traction power feeder stations, situated trackside, receive current from the external electricity transmission and distribution networks. These substations transform the current down to 25kV and supply the internal OLE system. In order to identify the feeder stations that supply traction power to the Cross-City railway line, feeding diagrams were obtained from NR (NR, 2015b) which detail the schematics of the feeder system, including the feeder stations and the circuits they supply under normal operating conditions (all feeder stations operational) and alternate scenarios (loss of supply to one or more feeder stations). The Cross-City line is managed from Rugby Electrical Control Room (ECR) and split into North and South sections at Aston, presenting four possible feeder stations for the line (Figure 4.3). In normal operating conditions, the North section draws from feeder A (primary supply) and the South draws from feeder B, whilst in alternate scenarios the North can draw from feeder A (secondary supply) or C and the South from feeder A or D. This system therefore offers N-2 redundancy as there are two alternative feeder station supplies available to switch and reconfigure the supply, should the normal feed experience a loss of supply. Feeder stations B-C have one outgoing supply circuit, whereas A has two circuits, hence it can provide both normal and alternate supplies to the North section of the line. The normal feeder station supplies for the Cross-City line act as alternate supplies for other lines, just as the alternate supplies normally supply other lines.

Having identified the four traction power feeder stations that supply power to the Cross-City railway line, circuit diagrams for the external electricity distribution network obtained from WPD were used to trace through the substations and cables supplying each feeder station. Feeder stations could be identified in these diagrams as they have a unique identifier and are listed as 25kV substations as opposed to 33kV, supplying only the railway network. As shown in Figure 4.4, the supply to each feeder station was traced through connections to WPD substations at 33kV and 132kV up to NG substations at 275kV. All four feeder stations have similar pathways through the same voltage levels, involving both distribution and transmission assets. Power generation is beyond the scope of this chapter. It is acknowledged that external substations will also have a degree of redundancy and switching/reconfiguration in alternate conditions, however, this information was unavailable and would add significant complexity to interpreting the resultant criticality assessment.

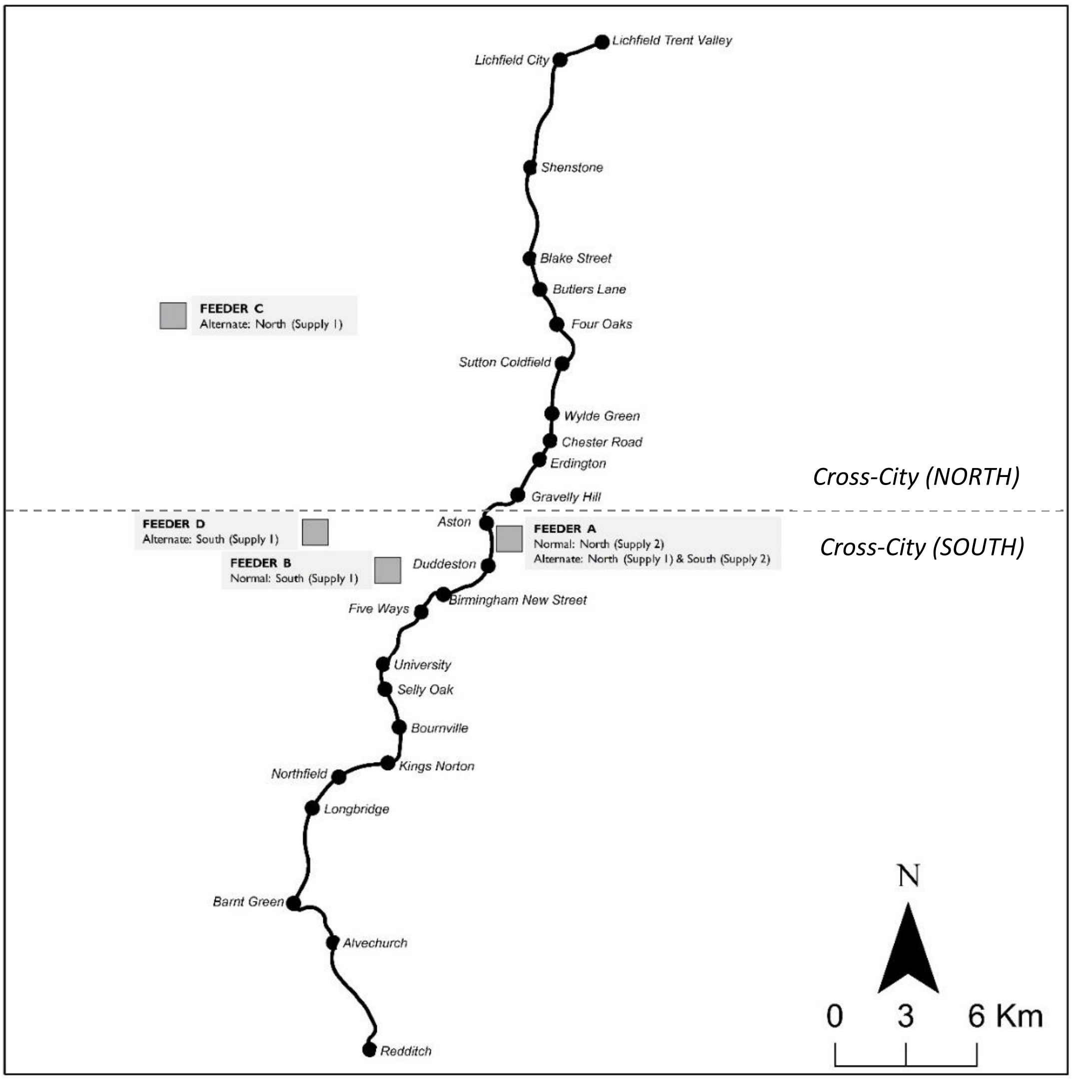


Figure 4.3. Map of traction power feeder stations for North and South sections of the Cross-City railway line.

With an understanding of the traction feeder system for the Cross-City line, including both internal and external elements, a set of specific substations can be defined that may present a risk to the operation of electric rolling stock should they experience a loss of supply. These substations can be mapped in a GIS, alongside railway stations, junctions and track, with network criticality metrics applied in order to understand the distribution of risk across both systems. Uncertainty regarding the physical locations and connections between assets is reduced, negating the need for assumptions on dependencies. It is observed that none of the four feeder stations in focus are trackside to the Cross-City line itself, therefore geographical proximity assumptions would likely be invalid in this case.

4.4.2 Spatial Correlations in Criticality

Network criticality metrics of *DM per incident* for stations, junctions and track sections on the Cross-City railway line along with *SML per fault* for external electricity distribution substations supplying the traction feeder system are mapped in Figures 4.5 and 4.6 respectively. The criticality bands correspond to the relative criticality of a location within the management region, either the LNW (South) route of the railway network or the West Midlands licence area of the electricity distribution network, therefore the actual magnitude of disruption associated with a particular band may be different between management regions and between systems. The distributions of criticality and the resultant prioritisation of locations is described within the individual networks, before the applications of the criticality assessments for prioritising asset management interventions across system boundaries are explored.

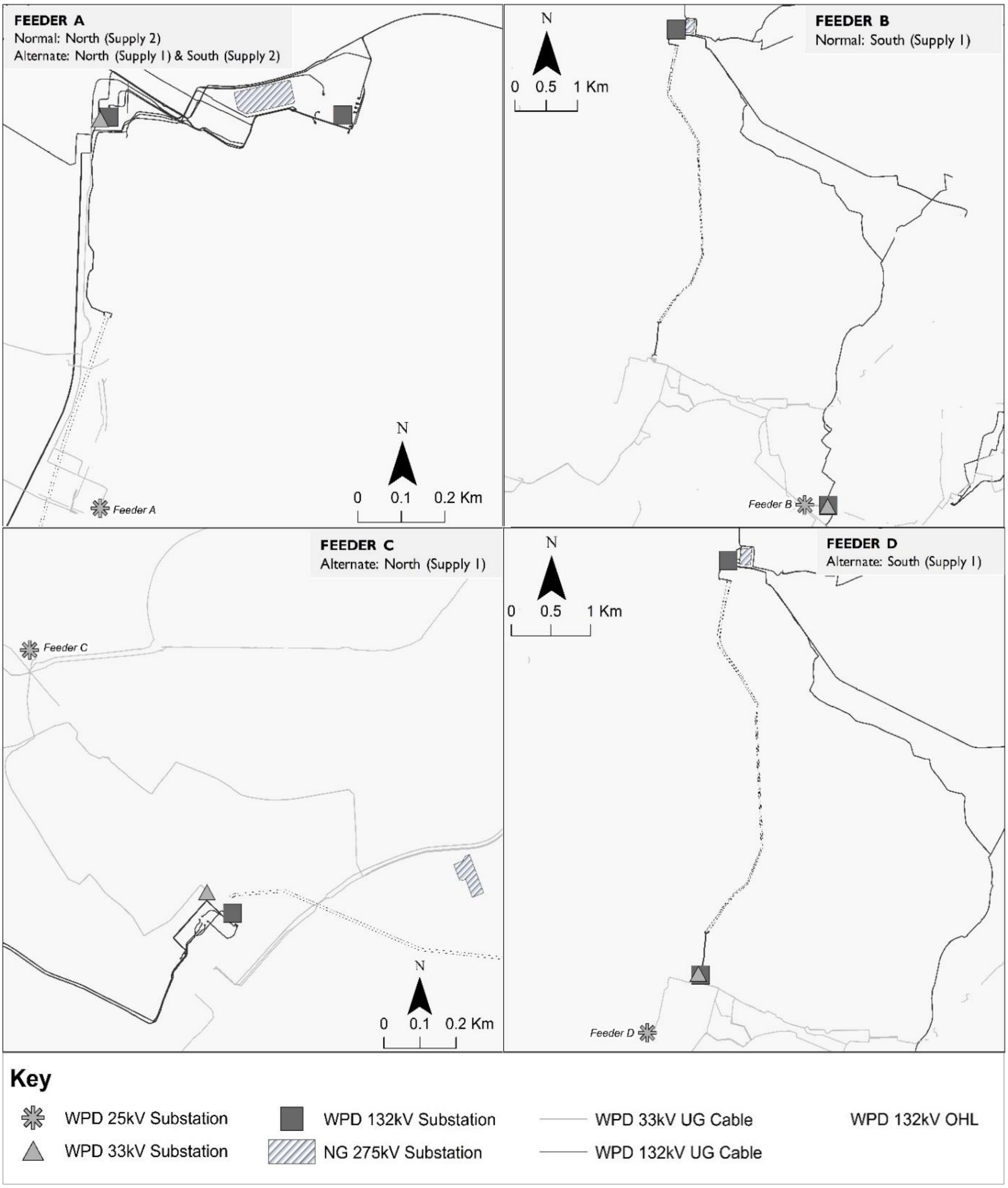


Figure 4.4. Map of external supplies to four traction power feeder stations for the Cross-City railway line.

Focusing on the criticality of electricity distribution substations, an initial observation is the absence of metrics for any of the four 25kV trackside feeder stations, and therefore no calculated criticality band. It is likely the case that as these substations supply only the rail network, they fall beyond the reporting scheme of the database and thus the system boundary. Despite this, metrics were available for all of electricity distribution substations supplying the feeder stations. Based on these metrics, the distribution of criticality has limited variability across the four feeder supplies and that most substations are towards the lower end of the risk spectrum, with criticality bands ranging from 3-5. The network topology and service patterns of the feeder supplies are highly similar and so more uniformity in criticality would be expected. Low criticality metrics could be a factor of the efficiency in response or switching should these substations fail, reducing the duration of supply losses, or the effect of relatively more serious failures elsewhere in the West Midlands dampening the criticality of the substations in the study area. However, low criticality does not immediately translate to low risk as there remains a potential for widespread cascading failure between the energy and railway systems.

It is though possible to distinguish between the four feeder supplies and the individual substations using the calculated criticality bands. Feeders C and D, which are designated as alternate supplies to the North and South of the Cross-City line respectively, are both supplied by substations each ranked at criticality band 5, the lowest risk to supply. Feeder B, the normal supply to the South of the line, has two substations at band 4 and one at band 5, indicating a higher risk. Feeder A, offering normal supply to the North of the line as well as alternate supply to both sections, has the greatest risk with one band 3 substation and two ranked at band 4. Based upon these criticality metrics, the normal supplies would be prioritised first, particularly

Feeder A which has two outgoing supplies. The alternate supplies would seem to be more resilient, which highlights the benefit of redundancy in supply should the normal feeders fail. For individual substations, the 132kV site at criticality band 3 for Feeder A would be greatest priority overall, presenting a clear single point of failure risk to the traction feeder system. However, there is no clear pattern to suggest that higher voltage substations present a greater risk than lower voltage substations across the system, in this application only the connection to the railway system is of interest therefore although 132kV failures would likely impact more customers and connected substations, such consequences do not impact the traction power supply.

Focusing on the criticality of the Cross-City railway line, it is observed that there is significant variability in the distribution of criticality throughout the line and that that most locations are towards the upper end of the risk spectrum, with bands ranging from 1-5. The network topology and service patterns vary along the line and so such differences in criticality would be expected. Higher criticality metrics indicate that the Cross-City railway line overall is a priority within the LNW (South) route, with the majority of the line designated as criticality band 2. However, there is a clear difference between the North and South sections, with the mid-point at Aston corresponding the divisions in traction power feeding. The North section of the line has average criticality band of 3.14, whereas the value for the South section is 2.18. Traffic patterns are significantly different, where the North of the line has only local electric train services the South has more variable traffic of local and long-distance services using diesel and electric traction. More services covering a variety of paths present a greater potential for the accumulation and propagation of delay to trains. The South of the line also presents more localised single points of failure, including key stations and junctions such as

Birmingham New Street and Aston. Longbridge is highlighted as the most critical location, situated on the part of the line between Barnt Green and Kings Norton which is also used by freight trains as well as long and short-distance passenger services.

The presented individual network criticality assessments have a greater value when used in conjunction to assess service performance risks across system boundaries and identify priorities for interventions that may present mutual benefits to both railway and electricity distribution network owners and operators, such as NR and WPD. Taking a holistic view of asset management, the potential consequences to the rail system of failures in the energy system may provide the case for resilience enhancements targeted to traction power feeder substations. Spatial correlations in risk can also influence internal prioritisation schemes for both networks. Based purely on the network criticality metrics, the balance of risk is significantly weighted to the railway system, with a higher magnitude of asset failure consequence overall. At a regional level, the traction power feeder substations would receive less prioritisation whereas the Cross-City line assets would be a higher priority.

However, within the study area, there are correlations of risk. It has been identified that the South section of the Cross-City railway line is highly critical. This section of the line can draw traction feeder power from Feeder B in normal arrangements, or Feeders A or D in alternate conditions. The supply to Feeder B from external electricity distribution substations is the second priority out of the four feeder supplies, whilst the supply to Feeder A is the first priority. Here, there are critical normal and alternate supplies to a highly critical railway line, therefore, there is risk to both systems from connected assets. This is an example of a situation where interventions could be targeted to reduce risk to key substations and railway assets, increasing systemic resilience whether through enhanced protection, response or redundancy.

This information can be used to refine internal prioritisation schemes. Railway system priorities can be refined based on the risk to external substations, whilst energy system priorities can be refined based on the risk to railway locations supplied. The high resolution of the criticality assessments presents granular single points of failure, as electricity substations or railway stations, junctions and track, within the study area. Such locations can further refine prioritisation schemes, for example, specifically targeting Longbridge within the South section of the Cross-City railway line and the connected external band 3 substation supplying Feeder A or the band 4 substations supplying Feeder B.

Prioritisation schemes based solely on single system criticality assessments only account for single system risks, failing to capture interactions and externalities which can present a more complete spectrum of risks to a system. In this case, criticality metrics indicating traction feeder supplies as lower risk do not account for the fact that these substations are supplying highly critical railway. Only by examining metrics from both connected systems can the picture become clearer, providing another layer of information for prioritising asset management actions across system boundaries.

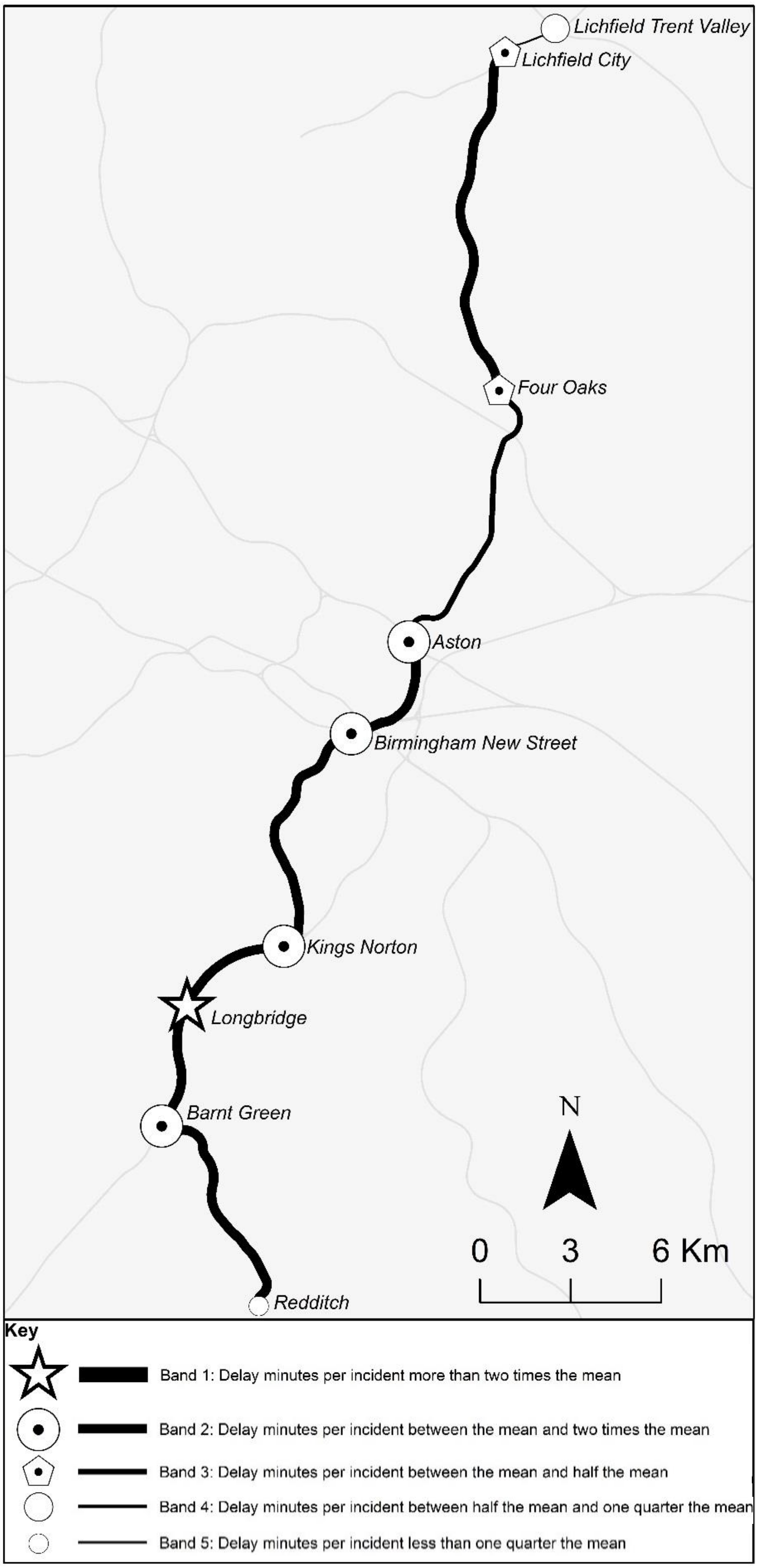


Figure 4.5. Mapped criticality bands for the Cross-City railway line

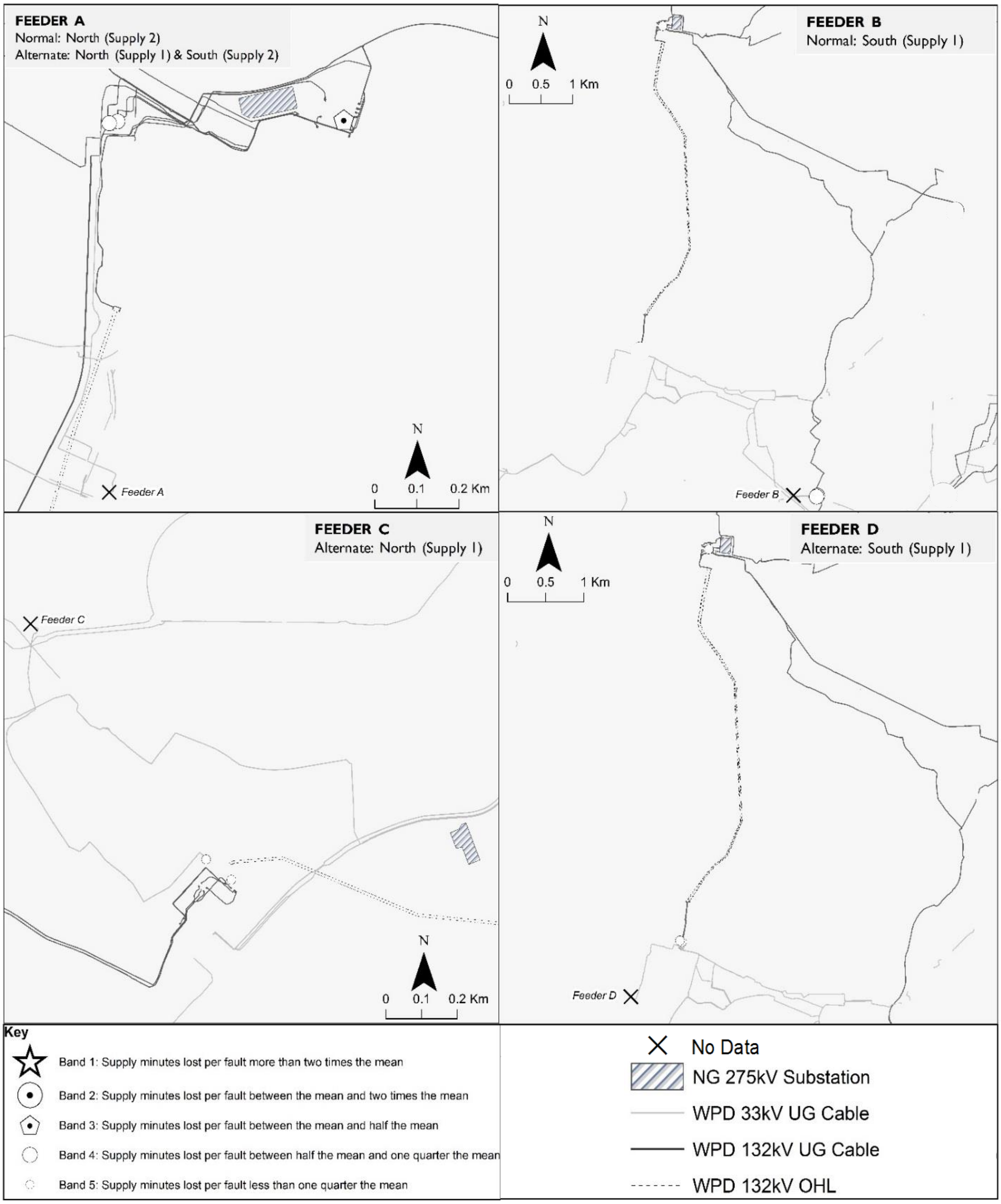


Figure 4.6. Mapped criticality bands for traction power feeder substations.

4.5 Discussion

The results of the criticality assessment have highlighted the overall pattern of network criticality for the Cross-City railway line and traction feeder system supplies, alongside the presence of specific and localised single points of failure. Using network criticality metrics, spatial correlations in risk between the railway and energy systems have been identified which can be used to inform a more holistic prioritisation scheme for interventions to both systems. The interpretation of the criticality assessment requires an evaluation of the evidence base behind the assessment, and the caveats involved, to establish the degree of reliability and uncertainty in the resultant prioritisation.

Two categories of data and information were used to conduct the criticality assessment: spatial/topological and service performance. Focusing on the former, the detail and granularity of information presented in the spatial databases and network diagrams was considered to be sufficient both for understanding network topologies and system dependencies at the local-scale. Precise geographical locations of substations, cables, rail track, stations and junctions alongside specific system connections facilitated a spatial mapping of railway and electricity distribution infrastructure networks. Such data and information provide reliability and certainty to the criticality assessment so long as it is assumed that the sources obtained are accurate and complete. In the absence of extensive site visits and interviews with key management personnel, it is not possible to verify the information and so it is taken as a true reflection of the real-world systems. The information is used for operational applications within NR and WPD, therefore would be subject to internal quality controls and the level of detail is significantly greater than existing criticality assessment literature, overcoming topological assumptions.

With asset dependencies defined, network criticality is derived from service performance databases and metrics which again are used operationally within NR and WPD. Historical records of network disruption provide certainty in the fact that the consequence of incidents or faults has been observed on the real-world network and therefore is evidence of the criticality of an asset and network behaviour, as opposed to simulated failure scenarios and consequence. The caveat to such data sets is that the reliability of a resultant prioritisation can be limited by the presence or absence of faults within the time series obtained and the high spatial resolution presenting issues with low sample sizes for some assets and locations. Therefore, the criticality of a location should be taken as an indication of the potential for a given magnitude of service performance consequence to occur, rather than expecting that exact level of disruption to occur upon every asset failure. The high spatial granularity is however necessary to facilitate a local-level prioritisation scheme, with specific asset connections.

The reporting requirements and attribution for such databases are motivated by their primary purpose in fulfilling regulatory obligations to report network performance to ORR for the railway network and Ofgem for the electricity distribution network. Whilst there is clear value to overlaying service performance metrics from two connected networks, the metrics themselves and thus the reliability of the resultant prioritisation are limited by the definition of what elements and assets on a network fall within the system boundary. A clear omission from the criticality assessment is metrics for any of the four 25kV traction feeder stations in

WPD's fault database. It may be the case that there were no faults at any of these substations within the time series. However, it is more likely that as these substations only have outgoing supplies to an external system, supplying traction power to the railway, they fall beyond the regulatory reporting scheme and thus the system boundary. Traction feeder stations are present in WPD's network diagrams and listed as their assets, but the fault database only contains faults at 11kV, 33kV and 132kV voltage levels. Therefore, a key element of risk in assessing the criticality of traction feeder supplies remains unknown.

Another omission relates to the definition of a 'customer' to the electricity distribution network in the calculation of consequence metrics. By way of an example, a fault reported in WPD's database at one of the 132kV substations supplying Feeder D coincides with an external power failure incident at the feeder site in NR's database. According to the electricity distribution network database, the substation fault had no consequence with the reported metrics of *CA* and *CML* both null. However, for the railway network there was a reported consequence of 12 aggregate *DM* to train services. Whilst this incident had a relatively minor impact on service levels, it is clear that the reporting of the same event across the two systems is not uniform. The impact of the substation fault may have been beyond the system boundary, but still impacted at least one 'customer' in NR along with the passengers on the delayed services. As a result, railway system metrics would appear to consider external risks, yet energy system metrics do not seem to account for external consequence. Prioritising interventions based solely on such single-system metrics could jeopardise the resilience of the traction power supply system overall and highlights the value of considering multi-system metrics.

There are further issues relating to the reporting and attribution of incident or fault causation. Risk can be inferred from the spatial and temporal correlation of events, but this does not necessarily imply causation. Using the available metrics, the criticality of connected assets and locations is defined, however, not all substation faults to traction supplies result in a consequence for the railway supplied just as not all delay incidents on railway sections supplied by the feeders are caused by the failure of those feeders. Such cascading failure events may be high magnitude but occur infrequently, meaning that wider asset failure events are included in the criticality assessment to obtain a more representative sample. It is though helpful to examine to what degree of certainty cascading failure between the two systems can be identified in the evidence base. Returning to the example for Feeder D, the attribution for the railway system provides the information that an external power failure has occurred at a location where there is a trackside feeder station. There is no specific reference to traction power or feeder stations, but with a reasonable degree of certainty it can be assumed that it was the feeder station that experienced a loss of supply. For the electricity distribution network, a cause is attributed to the fault but there is no context or description regarding the external connection or consequence. It is only from consulting the network diagrams that the substation is identified as supplying a traction feeder station. This lack of detail means that there is significant uncertainty and limited evidence for cascading failure pathways and external consequences in the service performance data.

There is also the issue of what is regarded as an ‘asset failure’ on the railway system and the location for reporting external power failures. Railway criticality metrics were based upon asset failure incidents in NR’s database, filtered to a specific set of causation codes used by NR (2016d). However, the code for power supply failure caused by loss of supply from an external supplier (DAB, 2018) was not included in this set. In the case of a loss of supply to a traction feeder station, it is likely that the asset has not physically failed itself, but the external asset failure has resulted in a loss of incoming current. Therefore, external power failures result in consequence for the railway network but the responsibility of restoring the supply to the feeder stations rests with WPD as the failed asset is beyond the system boundary. Furthermore, as none of the four traction feeder stations are trackside to the Cross-City line, if the location of the external power failure on the railway system is reported as the feeder site then these incidents and their consequence would not contribute to the Cross-City line criticality metrics. There is a disparity between the point at which an incident is reported and the widespread power outage that failure has the potential to cause.

Overall, there is clear value in the prioritisation of interventions based upon the criticality assessment in this chapter. The data and information sources used are the best available, as the authors are unware of any cross-system databases currently in use for infrastructure network operations and management. It is important however to understand the various caveats to the data when interpreting and applying the results of the criticality assessment, in particular the omissions and their influence on the reliability and certainty of the prioritisation. The limitations of the data and information sources highlight the need to look beyond traditional and regulatory system boundaries in order to manage the risk of cascading failure and identify opportunities for interventions offering mutual benefits.

The implications of the presented network criticality assessment and interpretation are two-fold. Network criticality metrics can aid the identification of priority locations where interventions can be targeted for a broad range of applications across railway and electricity distribution networks. Also, the insights gained from the evaluation of data and information sources can be used to recommend improvements to service performance and asset failure reporting mechanisms. The ultimate goal of the research is to promote cost-effective and holistic decision making when considering resource allocation for localised asset management. Therefore, the recommendations of this chapter can be applied to drive progress towards this goal.

A combined prioritisation scheme, complementing the existing processes and metrics within NR and WPD with the addition of localised multi-system single points of failure, would likely deliver the most useful applications for network management. The criticality assessment provides an objective and high-resolution prioritisation of locations across two connected networks, which can be used to refine high-level single-system priorities and reinforce information which may only exist as subjective tacit knowledge. The exact application of such a prioritisation scheme depends upon the nature of the intervention in focus and is principally a question of the scale, timeframe and agencies involved.

4.6 Conclusion

This chapter has presented a network criticality assessment methodology for dependent power distribution and electrified railway systems, applied to a local-scale case study for the Cross-City railway line (West Midlands, UK) and electricity distribution substation dependencies for traction power. The resultant criticality assessment can add value through integration with existing prioritisation schemes to inform cost-effective and holistic decision making across system boundaries. Targeting interventions to locations where there is risk to two connected systems can provide mutual benefits through increased resilience and the mitigation of external risks and consequence.

Taking an evidence-based approach, both for identifying system dependencies and calculating network criticality bands, avoids the need for assumptions and simplifications present in existing modelling and simulation approaches. A greater understanding of network criticality at a high-resolution facilitates the identification of localised single points of failure within feeder supplies and railway lines that can be used to refine high level financial allocations, translating funding into specific projects, whilst also objectively defining and challenging priorities that currently exist only as subjective tacit knowledge and raising awareness for unknown failure pathways. The enhanced granularity and cross-system risk provide new layers of information for decision making.

More of the complexity of system dependencies and behavioural mechanisms of the electricity distribution and railway networks are captured in the criticality assessment, yet the reliability of the assessment and resultant prioritisation is dependent upon the reliability of the evidence base. This is ultimately a function of where system boundaries are drawn, influencing reporting requirements and metrics for asset failures. There is clear value in the prioritisation of interventions based upon the criticality assessment in this chapter, with the data and information sources being the best available, but it is important that criticality metrics are interpreted with an understanding of the caveats to the underlying data. Traditional system boundaries are no longer suitable for analysing risks to increasingly interdependent and interconnected infrastructure. Decision making based purely on single-system metrics, without consideration of externalities, may lead to unexpected risks and consequences which would likely incur significant costs in recovery and response after an event.

Although demonstrated for a specific local-scale case study in the UK, the presented criticality assessment methodology is transferable and can be applied to any system but is dependent on the availability and quality of spatial and operational data. Overall, the key contributions of the research are the formalisation of localised critical locations across system boundaries to inform decision making and promote cost-effective and holistic resource allocation, alongside the documentation of the caveats and limitations of the underlying evidence base. Chapter 5 discusses the overall implications of the criticality assessments, exploring how a network criticality layer can be applied and integrated within infrastructure management functions and information systems to inform a variety of resilience interventions, as part of a holistic decision-making process for infrastructure owners and operators.

CHAPTER FIVE: **IMPLICATIONS FOR INFRASTRUCTURE SYSTEM MANAGEMENT**

5.1 Chapter Overview

A series of network criticality assessments have been presented through Chapters 2-4, each covering a different application with different levels of geographic and infrastructure system complexity. Initially, the criticality of a comparatively simple electricity distribution network was explored, before the criticality of a more complex railway transport network was assessed. The two dependent and connected networks were then brought together, to examine more systemic and cross-network criticality, applied to the external electricity supply for an electrified railway traction system. This chapter discusses the overall implications of the criticality assessments, exploring how a network criticality layer can be applied and integrated within infrastructure management functions and information systems to inform a variety of resilience interventions, as part of a holistic decision-making process for infrastructure owners and operators.

5.2 Formalising and Challenging Priorities

An assessment of network criticality has a key role in formalising priority locations through a quantitative and objective prioritisation scheme. It is important to move from ad-hoc prioritisations based on expert or tacit knowledge that may include personal, departmental or sectorial bias to a quantitative and objective approach to network criticality, using value-based metrics (Parlikad & Jafari, 2016: Verner et al 2017). The distribution of network criticality is formalised and mapped for both rail transport and electricity distribution infrastructure, as well as cross-sector dependencies in risk, providing an 'at a glance' picture of which elements or assets warrant prioritisation. Information on the types of substations, track, stations or junctions that are often classified as highly critical can support current understanding, reinforcing subjective tacit knowledge of significant risk sites at the licence area or route level with an objective and formal classification of priorities. For electricity distribution and rail transport, it is understood that supply and demand dynamics influence network criticality, and key areas of high demand/high load centres will likely be known.

However, network criticality may also challenge existing priorities and tacit knowledge, by documenting the low-level details on locations that are classified as highly critical to a high resolution. Using mapped network criticality to discuss and explore the underlying reasons for the important and highly localised single points of failure provides a new layer of information and understanding for decision making and may highlight previously unknown critical locations and network effects. The high resolution of the criticality assessment provides the ability to prioritise interventions within well understood key load centres or main lines, a granularity of detail that may not widely exist as tacit knowledge and focuses resource allocation further. For the rail network, localised risk in more remote locations is particularly important to document, highlighting risk hotspots to investigate further. If local knowledge, particularly for maintenance, does exist it is usually the collective experience of a team of engineers in a geographic area, and is rarely documented. Whilst in this thesis, network criticality is not derived from this information, reliable and detailed tacit knowledge can be an output where objectively defined priorities provide an improved understanding of the distribution of operational risk at the local-scale which is accessible to all levels of an organisation.

Furthermore, network criticality has a knowledge retention function, reducing the risk of key information surrounding priority locations being lost should there be a turnover in personnel as critical locations would be documented. Applying a metric of service performance consequence can standardise prioritisation throughout a licence area or route, whilst also encouraging a more holistic view of risk. The correlations in risk between the two networks have a role in increasing awareness and reinforcing understanding of dependencies for network management personnel. The formalisation and documentation of network criticality can also aid information sharing both between management regions within an organisation, and between organisations/systems overall.

5.3 Infrastructure Management Functions

Infrastructure owners and operators must manage a broad spectrum of activities, at multiple organisational, sectorial and geographic levels, and within the constraints of a limited management budget and finite resources. These activities can include day-to-day maintenance programmes, network operations, incident response, and fault resolution as well as implementing long-term asset renewal and upgrade programmes (WPD, 2014; NAO, 2015). Therefore, both operational functions, managing service levels, and infrastructure functions, managing physical assets and equipment, are required in order to maintain the functionality of infrastructure systems.

Such a broad range of applications across interdependent infrastructure systems from different sectors can be aided by a network criticality assessment. Through the analysis of network performance metrics, priority single points of failure have been identified where resilience interventions can be targeted. The ultimate goal of this research is to promote cost-effective and holistic decision making when considering resource allocation for localised asset management. The criticality assessments in this thesis provide an objective and high-resolution prioritisation of locations within and between two dependent networks, which can be used to refine high-level single-system priorities whilst both reinforcing and challenging information which may only exist as subjective tacit knowledge.

The exact application of such a prioritisation scheme depends upon the nature of the intervention in focus and is principally a question of the scale, timeframe and agencies involved. The difficulty level involved with an application is also a function of the network complexity, and the number of networks or systems involved in the decision making as more complex topologies, flows and management systems need to be considered. However, there is clear commonality in the functions of infrastructure management across systems, highlighting the potential for the transferability and scalability of the methodology as well as the coordination and standardisation of processes across sectors. Potential applications of the criticality assessments are outlined below.

5.3.1 Renewals and Upgrades

For long-term investment in infrastructure projects, the added value of the criticality assessment is through the integration with existing internal prioritisation schemes such as CNAIM (Ofgem, 2017a) and NR's route criticality (NR, 2016d). Investment decisions will require a clear business case for the system(s) in question, and so initially single-system financial costs of power outages and railway delays could be used to allocate funding to broad electrical circuits and track sections at the national-level. The criticality assessment presented in this thesis could refine this prioritisation, translating high level and single-system financial allocations into localised multi-system priorities for specific projects. All interventions are ultimately made at the local-level, therefore a combined approach with layers of financial and service performance metrics is recommended.

Ageing infrastructure assets are a particular issue across multiple sectors, which incur repair costs for public and private sectors whilst increasing the risk of business and supply chain interruptions (Zurich, 2017). Therefore, the like for like replacement of assets at or approaching the end of their lifetime, and the upgrade of assets where capacity improvements or more robust equipment is required, are essential parts of infrastructure management. For electricity distribution, renewal, refurbishment and upgrade projects cover a breadth of activities, mainly centred around improving network capacity and reliability, and a range of assets such as gantries, overhead lines, underground cables and transformers. Key tasks are the design, development, planning and delivery of a combination of larger one-off projects with a greater number of smaller local projects (WPD, 2014). Locally, asset replacement interventions can improve security of supply and reduce the need for maintenance with more modern equipment, whilst reinforcement interventions can reduce faults and increase equipment longevity. Increasing network redundancy can also provide greater resilience through alternate supplies in the event of a fault. The capacity for distributed generation and the installation of smart grid and automation technology are increasingly important concerns for dynamic network control and management. For the rail network, key NR business activities include small renewal projects under the Network Operations division, and the strategic planning and delivery of large projects, renewals (modernising infrastructure) and all upgrades (performance and capacity) under Infrastructure Projects (NAO, 2015). Projects can have a high variability in scale, due to the length of track involved, the complexity of a major project such as resignalling, and the management of major structures such as bridges and tunnels. Furthermore, understanding external risks and consequences helps to avoid unintended consequences, for example, through the degradation of service from a traction feeder substation or using a budget on internal priorities only to experience unexpected cascading failure elsewhere.

5.3.2 Event Response

Real-time decision making for service regulation and incident response is the responsibility of Control Centres within licence areas and Route Control within routes. This includes the implementation of contingency plans including electrical switching/load reconfiguration and emergency timetables, along with the allocation of personnel to investigate and restore failed assets. A multi-system criticality assessment complements existing prioritisation, adding value by identifying localised dependent critical locations, the importance of which may have previously been unknown.

Service management decisions, such as switching and supply restoration, as well as cancellations or amendments to train services, can be made dependent on the expected level of disruption from an incident. For the rail network, train service management can be highly complex due to the number of trains and operators running at different times on different lines. In the case of electricity distribution, there are also vulnerable/priority customers to consider, who are known to WPD. Contingency plans can be simultaneously enacted for both systems to reduce the impact of the disruption. A criticality assessment based upon service performance priorities is particularly useful for incident or emergency response as it provides an indication of the degree of difficulty in managing an incident occurring at a particular location, therefore allocating resources to minimise disruption would be beneficial.

Across all infrastructure systems, the Civil Contingencies Act (2004) provides a framework for civil protection in the UK, defining local arrangements and emergency powers in the event of major incidents. Different categories of responders have different levels of allocated duties, where Category 1 responders are emergency services, health services and local authorities who coordinate the response, whilst Category 2 responders are transport and utility organisations who must cooperate with a joint operation. Mapped criticality provides a visualisation which is easy to interpret and apply for decision making in real time.

A key function of a DNO is dealing with ‘trouble calls’ which involve the resolution of faults causing interruptions to customer supplies (WPD, 2014). Some electrical facilities such as BSPs and primary substations are remotely monitored and controlled from Control Centres. If issues cannot be solved remotely, engineers are on call to respond on site. Real-time information on the network state, combined with a criticality layer, can be used to communicate with and dispatch field teams or helicopter units to electrical sites. A large directly employed workforce helps with contingency arrangements, alongside a generator fleet and bunkered fuel provision. For the rail network, event response and operational management including signalling would be the responsibility of Network Operations within NR (NAO, 2015). Mobile operation managers (MOMs) are on call to respond to incidents and make an initial investigation.

5.3.3 Maintenance Programmes

Inspections and remedial work can be increased for key substations and assets in locations likely to cause a high magnitude of disruption. Maintenance is devolved within routes and licence areas, and at the level of specific assets a high degree of granularity for priority locations is essential. The Brown Review (DfT, 2014a) highlighted simple maintenance as a vital activity, with the routine inspection and maintenance of drainage systems, clearance of vegetation and high-risk trees, and monitoring of structures and embankment slopes all being important tasks in ensuring infrastructure resilience yet historically they have not always been given adequate priority. Funding for ongoing maintenance to reduce risks is essential (ICE, 2009). For electrical substations, inspections can be completed on-site or via remote monitoring, to detect problems developing before they occur. Inspection and maintenance of key assets, as well as regular activities such as tree cutting, are priority tasks for DNOs (WPD, 2014). WPD's helicopter can carry out visual and thermal line patrols, as well as post-fault inspections. For the rail network, almost three quarters of NR's workforce are allocated to Network Operations, including in-house maintenance and day-to-day activities (NAO, 2015). Track access may be an issue with rail maintenance, particularly for more remote sites.

5.4 Assessing Risks to Inform Resilience

With network criticality having applications for a broad range of assets, systems, sectors and activities, it is important to consider how a network criticality layer can both inform the assessment of risks to an infrastructure system and prioritise a range of potential resilience interventions. A combined prioritisation scheme, complementing the existing processes and metrics within NR and WPD with the addition of localised cross-sector single points of failure, would likely deliver the most useful applications for infrastructure management. Network criticality has greater value when integrated within a holistic and systemic risk assessment to inform holistic and systemic resilience interventions.

5.4.1 Risk Assessment

Within a risk assessment, a layer of network criticality adds value to the assessment of consequences from asset failure. However, there are multiple perspectives on consequence. Existing internal prioritisation schemes, such the CNAIM methodology (Ofgem, 2017a) for electricity distribution and NR's internal route criticality (NR, 2016d) for railway transport are based upon a single type of a metric in financial costs, for a single network. Whilst such metrics have their value in isolation, they form part of a broader perspective of network criticality when combined with the service performance metrics used in this thesis, across multiple connected systems.

In the same vein, network criticality fits within a broader spectrum of infrastructure risk assessment. For the rail network, NR (2015a) prioritise risks based on performance and safety impacts, hazards, vulnerability of assets, and consequences, using a "bow tie" risk assessment methodology (Figure 5.1). This method allows an assessment of the adequacy of controls on causes and consequences, with a separate risk assessment per asset group. It is therefore necessary to combine a consequence layer, such as network criticality, with other layers of information such as asset condition, hazard occurrence and vulnerability.

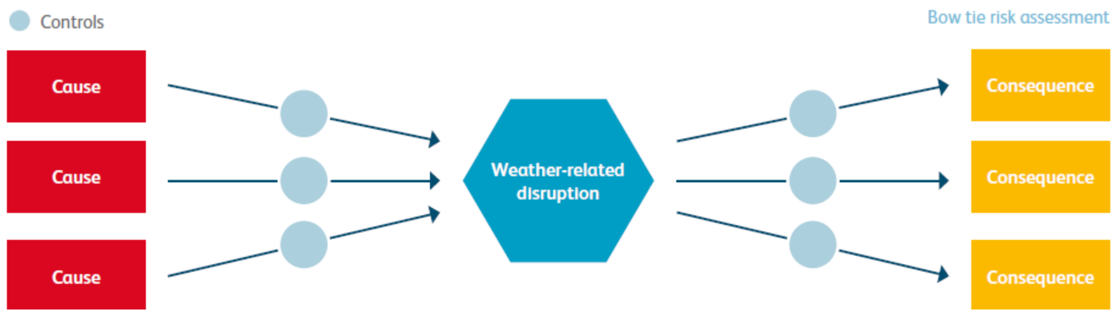


Figure 5.1. NR's "Bow Tie" Risk Assessment (NR, 2015a).

The resolution of network criticality increasingly matches that at which information on hazards and vulnerability is achievably or currently available at, assisting risk-based targeting of decisions. Therefore, specific sites that have a high vulnerability to a hazard and a high potential for disruption or cascading failure can be prioritised. GIS risk mapping is common practice within natural hazard risk assessment, with spatial layers of exposure, vulnerability and consequence. For the rail network, NR (2015a) use data layers for safety risks, performance risks such as Schedule 8 compensation data, localised gridded weather data from proprietary weather stations, weather thresholds for failure rates, and aerial surveys using Light Detecting and Ranging (LIDAR) data for visualising lineside tree risk (Figure 5.2a). The METEX decision-support tool also allow an output of key weather vulnerability statistics for individual routes or maintenance delivery units. For electricity distribution, WPD (2011; 2015) combined asset data and CI profiles with layers of future weather probabilities based on UKCP09 data, Environment Agency fluvial and pluvial flood maps, vegetation management, and UHI impacts. WPD have also been working with Cranfield University and the British Geological Survey to produce a surface map of ground conditions to assess soil properties and geological rock permeability for the risk of ‘drying out’ for earthing infrastructure (Figure 5.2b).

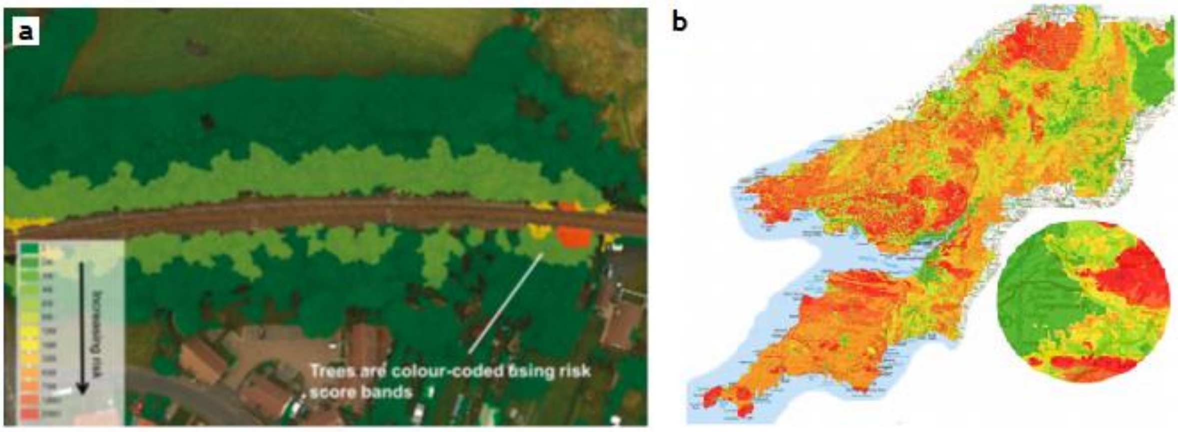


Figure 5.2. (a) Visualisation of lineside tree risk using LIDAR (NR, 2015a) (b) Surface map of soil and geology sensitivity to climate change (WPD, 2015).

5.4.2 Resilience Interventions

Within the process for selecting and implementing resilience interventions, a layer of network criticality adds value to the generation of potential options. As existing internal prioritisation schemes, such the CNAIM methodology (Ofgem, 2017a) for electricity distribution and NR’s internal route criticality (NR, 2016d) for railway transport are designed for a single purpose in prioritising investment in asset renewals and upgrades, and for a single network, their application is limited to increasing resilience through financial investment in the robustness of physical assets. However, with the addition of a network criticality layer based on operational service performance, the applications are extended to a wider range of potential interventions, including more process-based options such as maintenance schedules and event response, across multiple connected systems, facilitating a more holistic approach to resilience. At a broad level, the UK's sector security and resilience plans highlight a range of critical risks and resilience measures (Cabinet Office, 2017).

A highly granular assessment of the potential consequence of an asset failure within and between connected systems has pertinence for the long and short-term protection, preparedness and response to extreme weather. For response during extreme weather events, which may cause asset failures in multiple locations in a short space of time, the criticality assessment can be applied to determine which sites personnel should be dispatched to first. The rail network has a strategic crisis management process to coordinate and aid rapid response to extreme weather events (NR, 2015a). Criticality can also be incorporated in preparedness actions and resource allocation for extreme weather before, during and after a forecast event. For electricity distribution, criticality can be combined with Environment Agency targeted flood warnings and daily bespoke forecasts, to inform how a workforce can be distributed in key locations prior to an event. For the rail network, criticality can also be incorporated in NR's EWAT (Extreme Weather Action Teleconference) procedure which involves a series of teleconferences to define route level preparedness actions and resource allocation for extreme weather before, during and after a forecast event. For long-term response to predicted climate change, adaptation programmes for high risk assets and can be informed by a criticality assessment.

In their climate change adaptation reports for electricity distribution, WPD (2011; 2015) explore a range of options including changes to industry specifications and company directives, altering specifications for pole mounted transformers to improve their resilience to lightning, installation of lightning protection devices as standard, overhead line design requirements for ground clearance and conductor ratings given the predicted rise in temperature, resilient tree cutting near overhead lines, and substation protection through raising equipment above ground level or relocation.

For the rail network, NR (2016c) have developed a coordinated business-wide WRCC programme, involving six sub-programmes and 23 constituent projects (Figure 5.3). This programme involves technical enhancements and adaptations to assets alongside broader operational response to extreme weather events, such as the design of new infrastructure, managing existing assets, third party actions, corporate strategy, asset policies, governance, design standards, risk registers, and long-term planning NR (2015a; 2016c). Specific solutions include the development of a more detailed drainage asset register to improve asset knowledge, better management of earthworks (natural or man-made cuttings, embankments and slopes) located on adjacent land (Outside Party Earthworks) to deliver a susceptibility rating for adjacent land, enhanced vegetation management schemes, structure waterproofing solutions to reduce the risk of icicle formation, and improved weather monitoring capability.

Urban climate resilience is a particular priority, with growing urban populations exposed to increasing extremes (Tyler & Moench, 2012). Chapman et al (2013) highlight the need to adapt to urban heat and UHI impacts, including railway buckling and the degradation of electrical transformers where increased temperatures reduce the efficiency of operation and the subsequent life expectancy of assets. Transformers located in the core areas of the UHI will have significantly shorter life expectancies, whilst the risk of failure is also a function of the transformer loading due to high urban population densities. Network criticality for electricity distribution is also a function of high loadings and demand on substations, therefore combining a criticality layer with a UHI layer would allow the prioritisation of adaptation work to transformers at the city-scale.

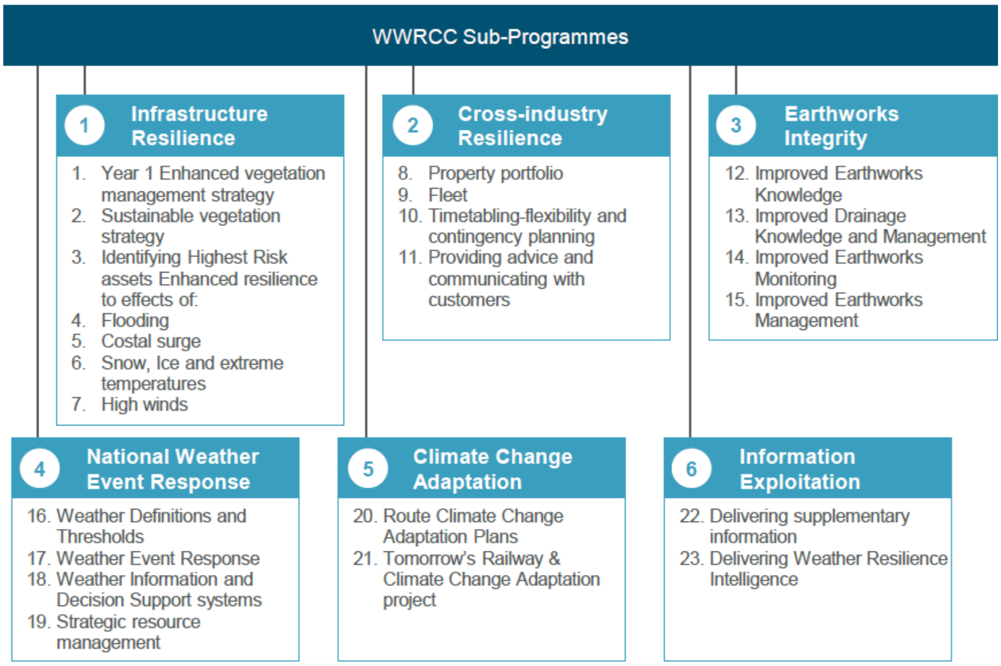


Figure 5.3. The constituent components of NR's WRCC programme (NR, 2016c).

Flood resilience is also a major issue across all infrastructure sectors. The National Infrastructure Assessment (NIC, 2018) recommends that a long-term strategy for flood protection should include a nationwide standard of resilience to flooding, with catchment-based plans. Such plans should explore a full range of options including traditional 'grey' flood defences and 'green infrastructure' (through natural flood management or sustainable drainage). The Pitt Review (Pitt, 2008) advocated a systematic approach to reducing disruption to essential services from flooding, building resilience through improved contingency and local emergency plans. Improved information sharing and cooperative engagement at the local-level can enable more effective emergency planning and response.

The need for a broader approach to flood resilience is demonstrated by the example of the December 2015 floods in Lancaster (Ferranti et al, 2017), both in terms of the variety of interventions required and the cross-system implications. When key substations are out of action, essential services such as communication and transport are affected. Protecting substations with hard flood defences, or 'soft engineering' through blue and green infrastructure are options, but operational resilience measures are also important. Emergency or backup generators could be employed for mobile phone base stations to maintain communications, and at railway stations for heating and lighting, as well as looking at alterative substation sites away from the floodplain. A high-resolution and localised criticality assessment can help to target such interventions to where they are needed most, in conjunction with flood risk maps or projections.

WPD have a significant programme of flood prevention work alongside emergency response procedures for their electrical infrastructure (WPD, 2015) as shown in Figure 5.4. Physical enhancements and adaptations at substation sites include siting equipment on raised plinths above projected flood levels and erecting flood barriers. However, WPD have also developed their capability to respond to flood damage through portable equipment and mobile pumps. A fleet of emergency response vehicles, converted from fire engines, have a combination of high capacity pumps, flood barriers and sandbags operated by trained first response staff. Helicopters can also be used to deliver diesel powered pumps and fuel to remote locations. The protection of substations, and the dispatch of emergency response teams can be aided by network criticality.

Figure 5.4. (a) Raised electrical equipment (b) Flood barriers around a transformer (c) Emergency response vehicle and equipment (WPD, 2015).

It is important that, rather than investing solely in infrastructure that is less likely to fail, there consideration is given to the resilience of the system when assets do fail. Beyond asset robustness, it is important to consider the continuity of service provided by an infrastructure system. The redundancy of system elements and the provision of alternatives is crucial. The Brown Review (DfT, 2014a) highlights the need to reduce the vulnerability of transport networks to extreme weather and speed up the restoration of normal service. Contingency plans for how to manage disruption and clear crisis management procedures are vital preparation for disruption management rapid recovery. For the rail network, this may involve standby buses to transport passengers in the event a line is blocked, standby rolling stock, providing diversionary routes or cross-TOC ticket acceptance, emergency timetables or adaptive train/crew diagrams to recover services should rolling stock, drivers or guards become stranded during extreme weather. Single ticketing options across transport operators and modes can improve system efficiency and resilience, where pressure on certain modes during extreme weather events may be addressed by targeted demand management (Armitt et al, 2016), whilst also providing passengers with the flexibility to choose alternative modes, as is the case with integrated ticket options such as Oyster in London and Swift in the West Midlands. For electricity distribution, this may extend to redundancy of circuits and substations for rerouting power flows, support for energy storage and demand-side generation, backup generators or for longer-term outages, the provision of water, food, sanitation and essential services to vulnerable or isolated communities (Guthrie & Konaris, 2012). Support networks are also vital, similar to the function of the Civil Contingencies Act (2004).

A holistic approach to resilience is particularly important for interdependent infrastructure systems. Traction power feeder systems have an element of redundancy on the supply side, offering alternate substations where current can be drawn from should the normal substation experience a loss of supply. The potential implementation of distributed generation and smart grid technology may help the electricity network to reconfigure. For a more holistic view of resilience, there should also be redundancy on the demand side. Assets can be physically protected to make them more robust to hazards but such measures are unlikely to completely eradicate faults, therefore, contingencies to maintain and recover service levels should be in place. A localised and multi-system criticality layer can inform targeted decision making regarding the locations around which contingencies should be arranged, where the risk of cascading failure and consequence to the railway system is greatest. Redundancy of power sources and alternative fuels would be one way to increase resilience. Uninterruptable Power Supplies (UPS) can be used to provide a backup supply to signalling systems but are not appropriate for high-voltage electrification. If half of the UK's power is provided by renewables by 2030 this will ensure resilience to extreme drought (NIC, 2018), but with localised renewable generation this would also diversify the UK's electricity generation mix and increase resilience should the main electricity grid fail. In densely populated areas, the repurposing of the existing gas grid for hydrogen might also be an option (Armitt et al, 2016).

Diesel rolling stock could be on standby for introduction to service and to rescue stranded EMUs at critical locations should a loss of electric traction supply be experienced. However, more innovative and sustainable solutions may be achieved through alternative fuels such as hydrogen power, bi-mode or battery-powered trains given the desire to decrease reliance on petroleum and plans to phase out diesel trains by 2040 in the UK (Chapman, 2007; Baker, 2018). A battery-powered Bombardier Electrostar Class 379 IPEMU (Independently Powered Electrical Multiple Unit) entered passenger service in the UK in 2015 (Bombardier, 2015) and can be powered via 25kV OLE or on-board batteries, charged from the traction power feed (Figure 5.5). The primary function of the IPEMU is to bridge gaps in existing electrification where the installation of OLE would not be cost-effective, whilst also being more environmentally friendly than diesel-only rolling stock. In the context of risks to electric traction feeds, IPEMUs would be an excellent resilience measure as they would be able to switch to battery power in the event of a loss of external power supply, avoiding stranded stock and offering the capability to at least run a limited service as opposed to suspending service entirely.

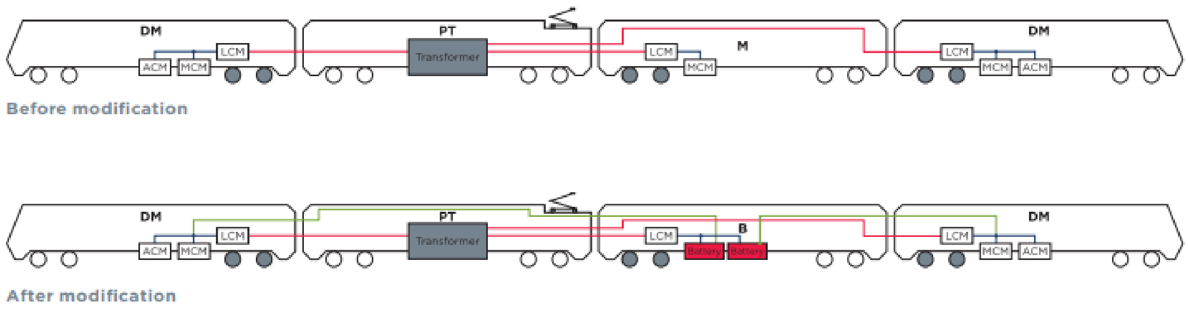


Figure 5.5. Overview of Electrostar IPEMU before and after modification (Bombardier, 2015).

At a broader level, there is no National Power Outage Plan in the UK, but railway organisations should have Business Continuity Plans (BCPs) for managing core business functions (RDG, 2017). These plans may include procedures for electric trains to be 'rescued' by diesel locomotives or substituting electric powered trains for diesel units, however there are practical issues to consider such as signalling systems may not be functioning, spare diesel units may be unavailable, trained drivers may not be available and fuelling diesel trains may be an issue. Therefore, cascading infrastructure failure can lead to systemic issues which requires a systemic and multi-agency solution, beyond physical infrastructure. However, there is little current evidence that there is a general multi-agency approach to power outages within the railway industry (RDG, 2017). Network criticality can help to highlight the need for a coordinated and systemic response to infrastructure risk and resilience.

5.4.3 Climate Services

Network criticality can also be integrated within commercial services for weather and climate resilience, where a company offers a bespoke service to a client which provides them with specific information to help them with their risk-based decision needs. Climate services involve the preparation, interpretation and delivery of information based on climate science, for bespoke requirements across multiple timescales, from months to years, and spatial scales, from global to regional to local (Met Office, 2017).

The Global Framework for Climate Services (GFCS) as shown in Figure 5.6, provides guidance on delivering climate services (WMO, 2014; 2018). Climate services take two forms of information in A) national and international databases of weather variables, risk and vulnerability maps, long-term scenarios and projections along with B) socio-economic variables and non-meteorological data such as agriculture, health and infrastructure indicators to produce an output of bespoke products projections, trends, economic analyses for decision support (WMO, 2018). A layer of network criticality, as non-meteorological data, can be integrated into a Climate Services Information System to provide detailed information on failure consequence and improve the value of the service offered.

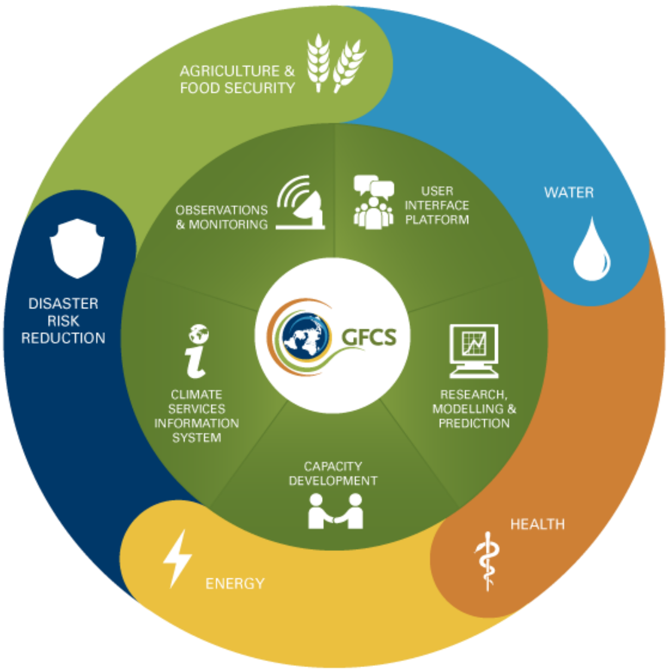


Figure 5.6. Global Framework for Climate Services (WMO, 2018).

By way of an example, Copernicus is the European Union's earth observation programme, comprising a set of systems collecting data from multiple sources, such as satellites and sensors (Copernicus, 2018). These systems process data and provide information services to users. One strand of Copernicus is the Climate Change Service (C3S) which is currently in the development phase but will use climate system observations and climate science for the development of information on past, current and future climates. Key indicators on climate change drivers can support adaptation and mitigation across multiple sectors in Europe, offering economic value through informing policy development, improving planning and adaptation and promoting the development of new services. C3S is also the EU's contribution to WMO's GFCS.

5.5 Holistic Decision Making

Established processes for both risk assessment and the planning of resilience interventions within infrastructure owners and operators can be informed and enhanced by a layer of network criticality. However, activities should not be carried out in isolation, or within different departments of an organisation. Risk and resilience form part of a holistic and systemic decision-making process, which should account for multiple perspectives and types of hazards alongside a range of options for controlling them, across multiple infrastructure systems from different sectors. It is therefore important to consider the 'bigger picture' of how activities and information sources can be coordinated as part of an overall drive for efficiency and resilience of all business functions.

5.5.1 Organisational Standards and Models

At a high-level, international standards developed by the International Organisation for Standardisation (ISO) can provide context and a starting point for the consideration of asset management within an organisation. The ISO 55000 series of standards presents guidance on the fundamentals, management systems, requirements and applications of asset management. ISO 55000 outlines how effective and efficient asset management that is consistent and sustainable over time is required in order for an infrastructure management organisation to realise value from their asset portfolio. A broad range of factors influence an organisation's function, such as the operational context, financial constraints, regulation and legislation, along with stakeholder priorities and thus define the objectives of the organisation. These objectives can be translated into asset-related decisions using a risk-based approach. A prioritisation of asset management interventions would be driven by the need to balance risk, opportunity, costs and performance. Therefore, there is a clear role for network criticality and metrics of performance consequence to help inform overall asset management policy.

It is, however, important to consider the wider decision-making process when looking at the applications of network criticality. A key principal of ISO 55000 is the integration of activities at the organisational level. Asset management can be supported by an asset management system which is a collection of interrelated and interacting elements designed to establish policy, objectives and processes with which to manage an asset portfolio. Such a system can be comprised of tools including information systems, which can help to coordinate activities and functions that would otherwise be conducted in isolation through the organisation and across stakeholders and external service providers. Figure 5.7 outlines the relationship between key elements of an asset management system according to ISO 55000:2014. Network criticality can be integrated as a tool into an asset management system, alongside broader considerations such as the context of the organisation, leadership strategies, planning processes, support, operations, performance evaluation and improvement schemes.

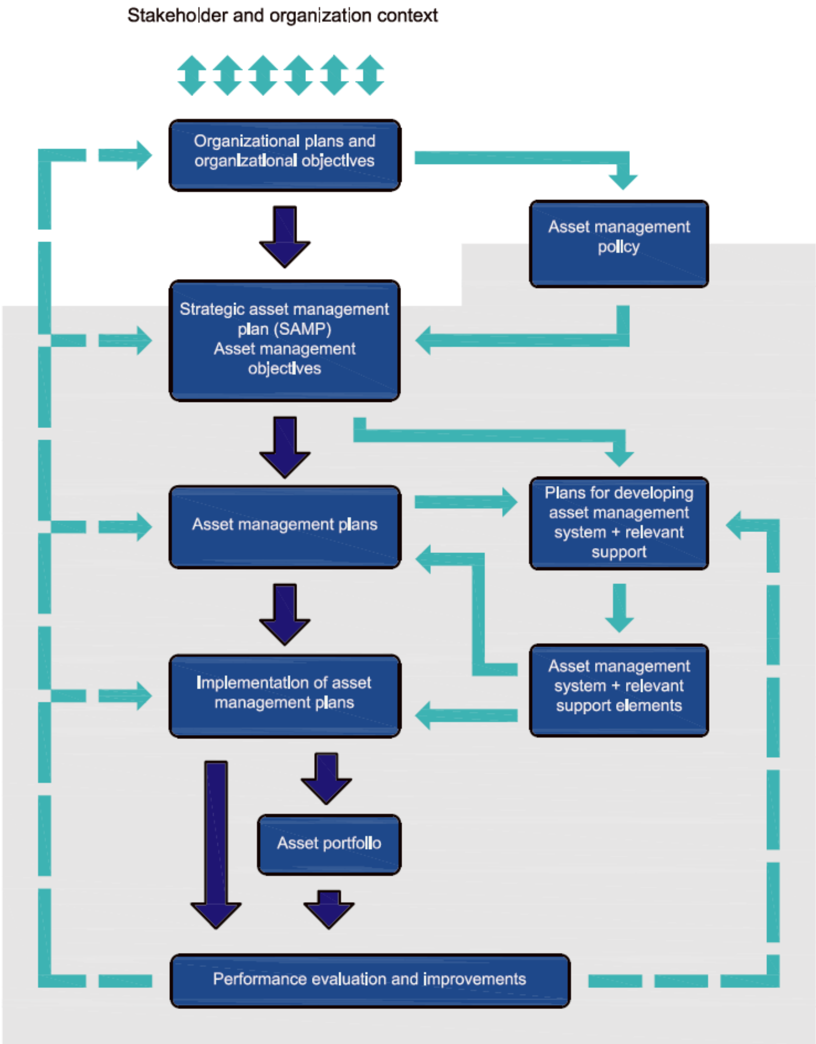


Figure 5.7. Relationship between key elements of an asset management system (ISO 55000:2014).

An asset management system therefore comprises a variety of information sources, systems and people across an organisation and beyond. How such elements are organised, structured and integrated within an infrastructure company influences the potential for realising value from assets. It is therefore important to consider organisational models. Effective decision making requires the effective use and management of information, which must in turn be supported by an effective organisational structure. Beckford (2016) presents an adaptive model of an "Intelligent Organisation" which integrates structure, individuals and information in order to make the best use of new information sources and the increasing volume of information that is generated in modern infrastructure management. Fundamental organisational changes are proposed, shifting to the design of organisations based upon customer, user and decision needs. If people and systems work closer together, and smarter, increasing communication both within a company and with the organisations or individuals who use that company's services, information flows will be more effective. The value of information can be realised when organisations continually adapt, breaking down siloes and recognising the interdependencies of internal systems and externalities, developing an organic rather than rigid structure. Central to the model is the role of information systems and the information they contain. Information systems can enable communication channels and information flows, providing the dual-function of value-generation from existing assets and value-enablement for future assets, together maintaining identity and fulfilling purpose of an organisation (Figure 5.8). An organisation should mirror the structure of the information system and vice versa, comprising operational and strategic levels with appropriate degrees of information and autonomy with which to make the best possible decisions. In the context of this model, a layer of network criticality can be integrated into the information system of an organisation to add value to asset management, but only if that organisation is structured to make effective use of a new information source.

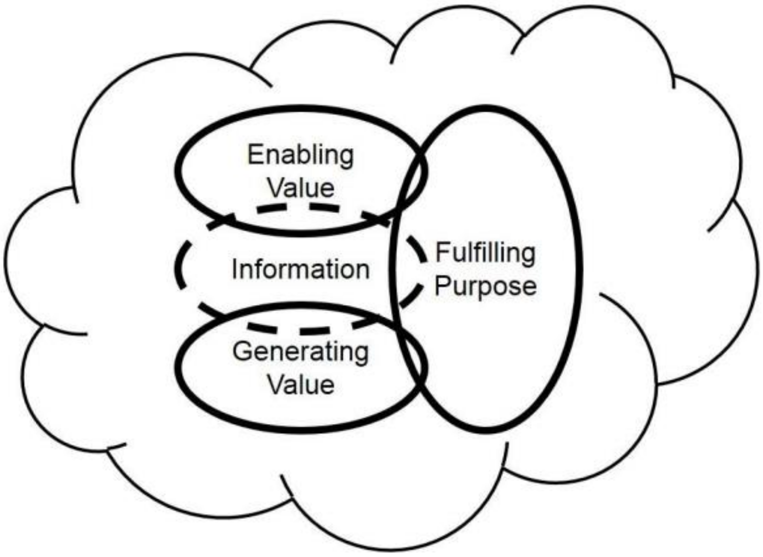


Figure 5.8. The Intelligent Organisation (Beckford, 2016).

5.5.2 Frameworks for Resilient Infrastructure

The broad scope of international standards and organisational models can be refined and focused towards specific sectors and applications through the development of frameworks for decision making. Such frameworks are most mature in the field of natural hazard, extreme weather and climate change resilience, mainly due to the characteristics and experience of such events compared to other hazards. In terms of the comparability of hazards, Golany et al (2009) assessed the contrast in optimal resource allocation policies between probabilistic risks, involving an element of chance, and strategic risks, determined by an adverse interested party. Climate and weather risks are natural phenomenon (although with a degree of anthropogenic forcing) with natural variability in space and time. Other risks such as cyber-attacks and security threats are entirely driven by human decisions and so the distribution of events in space and time is deterministic. Natural events have a degree of predictability based upon an understanding of the physical processes governing climate and earth systems and are experienced more frequently. Human driven events are much more difficult to predict, experienced infrequently, and the information available on the spatiotemporal distribution of hazard likelihood and frequency depends upon the level of intelligence gathered by security organisations. Therefore, Golany et al (2009) recommend that the best policy for probabilistic risk is to target investment and resources towards priority sites which will have the greatest benefit, whereas for strategic risk the optimal policy is to spread resources through a system to decrease the damage potential around the most vulnerable sites. Therefore, the level of information available for decision making is likely to be greater for weather and climate applications, including spatial distributions of likelihood and frequency of events, hence such frameworks are more abundant. However, taking cyber-attacks as an example, there are still facilities that are more and less likely to be targeted and assets or equipment within such facilities that are more and less vulnerable to attack. Therefore, it is possible to extend the application of frameworks developed for natural hazards and climate risk to strategic risks, dependent on the availability of information.

A useful starting point for assessing natural hazard risks to and resilience of infrastructure systems is a framework developed by the UK Cabinet Office (2011) outlining an approach to improving and maintaining the resilience of infrastructure and essential services, supported by practical guidance and advice for owners, operators, emergency responders, industry groups, regulators and government agencies. This is based on the 'Resilience Cycle' (Figure 5.9) comprising segments of risk assessment and resilience building, centred around the sharing of information which is vital for maintaining a continuity of service. Effective communication and information sharing between relevant agencies, with an assessment of external dependencies, is crucial for civil emergency planning, awareness of consequences, and information for service planning. A layer of network criticality can be integrated into the identification and assessment process for risks to infrastructure systems, with an additional function of highlighting dependencies and relevant organisations for information sharing such as rail and electricity network owners and operators.

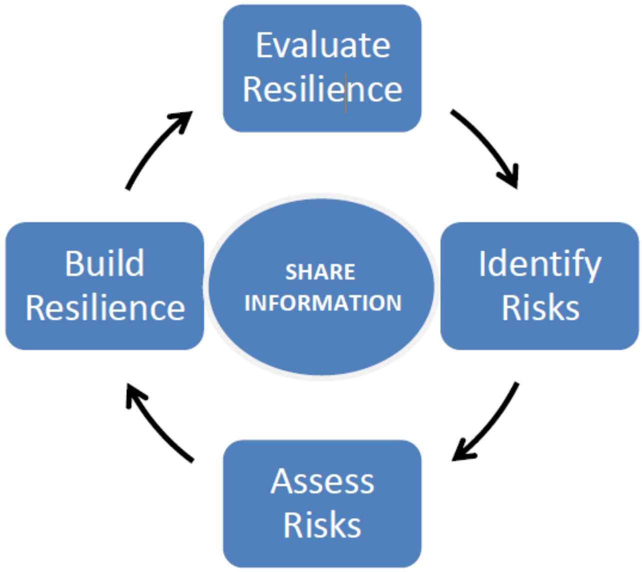


Figure 5.9. Resilience Cycle for Infrastructure Owners (Cabinet Office, 2011).

A comprehensive framework is presented by Quinn et al (2018) with specific applications for the adaptation of transport infrastructure to extreme weather and climate change (Figure 5.10). This framework aligns with the asset management system structure of ISO 55000, and the general cyclical structure of the Cabinet Office (2011) framework. There are two sections: an adaptation strategy and an implementation plan. A two-sided framework helps to break down high-level strategic objectives into specific concerns and interventions for implementation. Network criticality has potential applications for both sides of the framework, informing risk assessment and facilitating a range of resilience options. Although this framework is applied to the transport sector and climate hazards, the processes and elements involved in decision making will be highly similar across any infrastructure sector. The framework includes considerations of factors influencing asset management on both sides, including risk perceptions and stakeholder engagement.

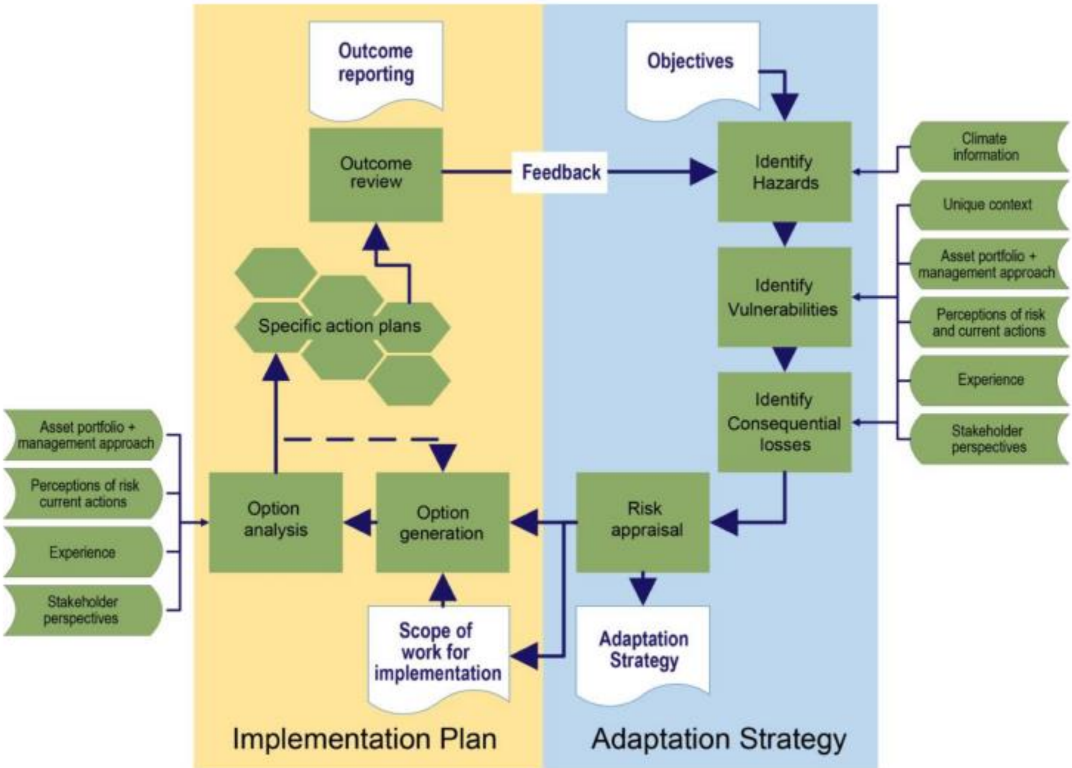


Figure 5.10. Climate-ready transport infrastructure framework (Quinn et al, 2018).

The framework of Quinn et al (2018) is designed to be iterative and circular, incorporating learning alongside new information on risks, vulnerabilities, technology and socioeconomic conditions through each cycle which recognises that the risk landscape is dynamic and not static. Therefore, future revisions of the network criticality assessments with a greater sample size and increased reliability could be integrated. The framework can be used by any organisation, regardless their current knowledge and preparedness levels with aim of embedding adaptation within organisational practices so that it becomes ‘business-as-usual’ and not a separate activity or funding source. The theme of communication and integration is again present, with a desire to bring together disparate activities, systems and information layers to avoid repetition and segregation of organisational functions.

Focusing on risk, the framework developed by the Cabinet Office (2011) involves both the identification of risks (including likelihood, frequency, hazard links, primary impacts, secondary impacts, and vulnerability to risks) and an assessment of the identified risks (including flood resilience, benchmarking, prioritising risks, and the development of standards on the resilience of infrastructure involving asset design, network design, service levels, recovery time, and events). Risk assessment in Quinn et al (2018) comes under the ‘Adaptation Strategy’ side of the framework. The purpose of this strategy is to first define broad high-level objectives which are then used to drive the assessment of potential impacts of climate change on infrastructure through patterns of hazards, vulnerabilities and consequences (economic, social and environmental). Such an assessment can incorporate system performance metrics, meteorological data and localised tacit knowledge. Data needs are driven by input from stakeholders and specialists, with multiple perspectives on consequence, such as the costs of asset repair or delays/cancellations, alongside socioeconomic consequences. These layers of information are used to identify priority risks for adaptation interventions. For a holistic risk assessment, it is necessary to have multiple layers of information on hazards, vulnerabilities and consequence, from multiple perspectives that are both within and external to the organisation. Network criticality based on service performance contributes a consequence layer from the perspective of the infrastructure management company within an information system.

Focusing on resilience, there is recognition in the framework developed by the Cabinet Office (2011) that a range of measures, including improvements in protection, the ability to absorb shocks and recover, and local and national response to emergencies are necessary to achieve resilience. Within the 'Resilience Cycle' there are segments of building resilience (including governance, long-term interests of stakeholders, organisational resilience strategies, strategic leadership and business continuity plans) and evaluating resilience (including sector resilience plans – there is a focus on regular updates and reviews of vulnerability and risk, ambition for continuous improvement, monitoring progress with implementing programmes of measures and updating plans). Resilience interventions in Quinn et al (2018) come under the 'Implementation Plan' side of the framework. The purpose of this plan is to take the scope of work from the adaptation strategy and generate potential options to increase the resilience of the system to each identified risk. Such options must take account of the various constraints imposed upon an organisation (technical, social, environmental and financial) and the finite amount of resources available including budget constraints. An iterative option generation and analysis phase allows the proposition and evaluation of various types of intervention over multiple timescales. Quinn et al (2018) advocate the application of adaptation pathways for phased adaptation, where different options are enacted when risk thresholds are reached rather than at defined time horizons. Resilience options are finally translated into specific action plans, which can be implemented within an infrastructure system. The circular design of the framework allows the evaluation of resilience intervention implementation, in terms of progress and success, with feedback and learning incorporated in subsequent iterations.

Both frameworks have the functionality to consider all components of resilience in the generation of options and action plans, and the influence of multiple perspectives and experience of stakeholders. The evaluation of interventions is also crucial, allowing new information, lessons and socioeconomic context to be incorporated into future decision making. It may be the case that a selected component of resilience is not adding anticipated value, and that a different component and alterative options may be more appropriate. The specific options and interventions selected will differ dependent on the type of risk and hazard in focus. Returning to the assessment of Golany et al (2009) for resource allocation applied to strategic and probabilistic risks, if there is greater confidence in the likely location of failure, such as for extreme weather predictions, hard interventions for that location will be easier to facilitate alongside softer elements such as redundancy and recovery, whereas for strategic risks there is often less confidence in the likely location of attack and so an even greater focus on softer or operational options would be more appropriate.

5.6 Chapter Summary

In summary, this chapter has explored the wider context of network criticality assessment and the overall implications for the decision-making process and infrastructure system management. Network criticality can help to inform prioritisation for resource allocation across multiple geographic scales, multiple systems or combinations of systems, at multiple levels of operational and topological complexity. The role of network criticality within risk assessment and the planning of resilience interventions has been explored, within the context of the broader decision-making process for the implementation of different options. The key principle of this chapter is the realisation of value from infrastructure through the realisation of value from information. This involves the effective and intelligent management of information of various forms through a range of systems, actors and perspectives and the development of information sharing and communication mechanisms for coordinated decision making and actions.

Network criticality is one layer of information that can inform the prioritisation of risks, which has far greater value when integrated with other layers, such as hazards and vulnerabilities as well as multiple perspectives, such as operational and financial. Combined, these layers of information can support the implementation of multiple perspectives on resilience options, from investment in asset robustness to broader options of redundancy and recovery. Risk assessment and resilience interventions should fit within an adaptive decision-making process, with continuous monitoring and evaluation of control measures and the revision of processes based on feedback from implemented projects. Overall, the vision is for holistic decision making where holistic risks inform holistic resilience. This can be achieved through coordinating activities within and between organisations from multiple infrastructure sectors, recognising interdependencies where there is potential to combine efforts for mutual benefit. Local Resilience Forums (LRFs) coordinate multi-agency resilience efforts (Cabinet Office, 2013) under the Civil Contingencies Act (2004) and offer a platform for cross-sector working.

Chapter 6 will provide an evaluation and critique of the methodological approach of this thesis. This includes an interpretation of the characteristics of identified critical locations, an exploration of the advantages and limitations of the data and information sources used to define network criticality along with a series of recommendations for potential improvement of the underlying evidence base.

CHAPTER SIX: **EVALUATION AND RECOMMENDATIONS**

6.1 Chapter Overview

In the previous chapter, the overall implications of the infrastructure network criticality assessments presented in this thesis were explored. This involved the consideration of how a network criticality layer can be applied and integrated within infrastructure management functions and information systems to inform a variety of resilience interventions, as part of a holistic decision-making process for infrastructure owners and operators. This chapter offers a reflection on the overall approach and methodology of the thesis. The nature of the single points of failure identified is explored, including the contribution of the methodological approach to their identification and comparisons to existing literature. A critique of the methodology is then provided, assessing the various benefits and limitations. Finally, recommendations are provided regarding the improvement of the existing network criticality assessment methodology, opportunities for extending the analysis, and a consideration of potential future developments and how they may influence both the distribution of network criticality and the methodology for identifying single points of failure.

6.2 Interpretation of Critical Locations

The nature of the locations identified as highly critical for maintaining service performance within a network are influenced by a combination of network topology, service patterns and flows, and the management of network operations. These factors are driven by the degree of complexity within the network(s) in focus. Criticality assessments were demonstrated for two contrasting management regions within two networks of different levels of complexity; the comparatively less complex GB electricity distribution network in Chapter 2 and the more complex rail transport network in Chapter 3. There are differences in the distribution of criticality between these regions; the West Midlands licence area of the electricity distribution network and the Wessex route of the railway network have more distinct centres of criticality whereas the South West licence area and LNW (South) route have a greater distribution of criticality throughout the respective areas. When comparing the networks overall, it is evident that the railway network has a significantly greater spatial distribution of single points of failure, whereas critical locations on the electricity distribution network are highly concentrated in key areas.

The distribution of network criticality is a function of the degree of connectivity between nodes and edges, and the number of potential source-sink pathways available. Electricity networks have quite a simplistic and hierarchical topology, where power flows from source to sink, from a small number of HV substations to a greater number of lower voltage substations. Flows are, in the majority of cases, unidirectional and the pathways between substations, and thus the footprint of assets are clearly defined. In contrast, railway networks have a more complex topology, where stations can act as both sources and sinks for train services. Flows are multidirectional, and pathways can be created between any pair of stations, dependent on constraints such as traction type, driver training and train-crew diagrams or timetables. Therefore, the key difference between the two networks is the potential for the spatial propagation and dispersion of disruption.

An incident at a relatively minor location on the railway network such as Barnt Green (Figure 6.1) has the potential to disrupt services in the North West and South West of England, and as far north as Scotland (Jaroszweski et al, 2015) due to reactionary delays to long-distance services, whereas a substation failure will typically only impact the substations and customers to which it supplies electricity. Therefore, electricity distribution network criticality is highly concentrated around major towns and cities, whilst single points of failure exist on relatively minor and branch lines of the railway network.

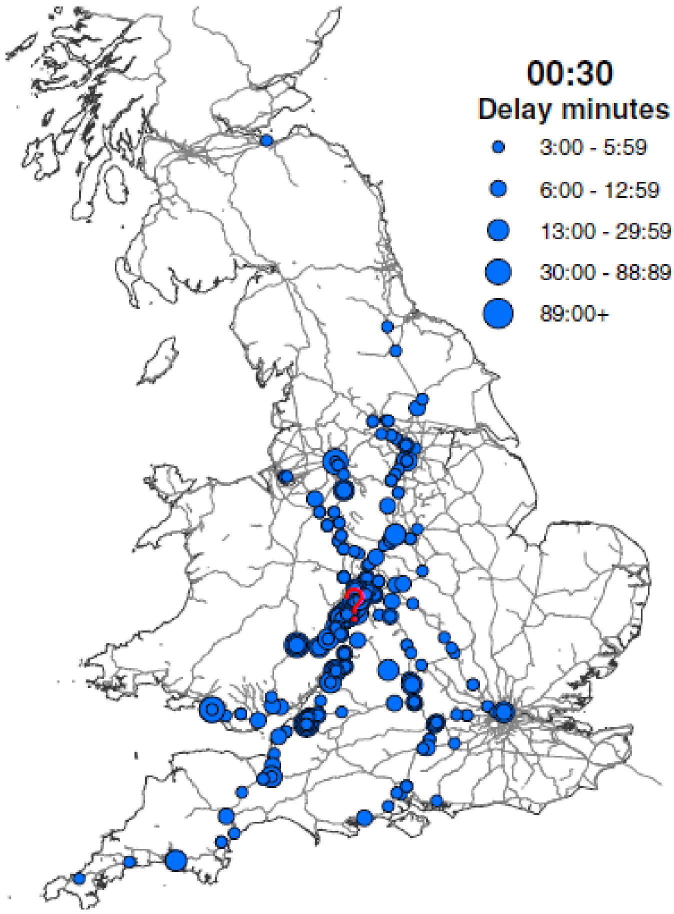


Figure 6.1. Recorded train delays from the TRUST database for a flooding event at Barnt Green. Adapted from Jaroszweski et al (2015).

The variation in the type of locations in a network can also contribute to the distribution of criticality. For the electricity distribution network, only nodes are included in the criticality assessment therefore all locations are substations, distinguished by their voltage level. In contrast, the railway network criticality assessment includes nodes and edges, which have a greater variety in their characteristics, with different categories of track, stations and junctions. There is therefore a greater variability in the types of location classified as highly critical on the relatively complex railway network. Another distinction between the two networks is the complexity of network operation and management. For the electricity network, infrastructure management and service management are combined, falling under the jurisdiction of either the DNO or NG. The railway network has quite distinct infrastructure and operational elements, with NR owning and maintaining the infrastructure whereas train services are operated by TOCs and FOCs. With different operators on the railway, there are competing priorities for traffic management during disruption. It may be the case that trains operating on branch lines are left to accumulate delay whilst services on main lines take priority for restoration, therefore single points of failure occur in more remote locations.

Despite the differences in complexity between the two networks, similar drivers of criticality can be highlighted. Essentially, criticality is a result of network supply and demand dynamics where the network is designed to serve customers or passengers. For the electricity distribution network, highly critical locations are typically concentrated around larger towns and cities, which act as major load centres. Higher voltage substations overall are more critical, supporting a greater load. The identification of such critical locations aligns well with network performance factors used to calculate network criticality under the CNAIM methodology (Ofgem, 2017a) including the number of customers served, amount of load affected, and the time to restore (switching and repair). The added value of the approach in this thesis is that more locally important substations are likely to be identified including industrial connections and renewable energy, compared to CNAIM which is based upon adjusted base costs relative to the national average. However, a direct comparison of mapped network criticality is not possible as the actual calculated criticality bands for assets under CNAIM are held by individual DNOs and are restricted access due to the sensitive nature of the information.

For the railway network, high criticality locations are centred around major hubs, key junctions and mainlines, which are areas of high demand for train services and/or high frequency and volume of traffic. This aligns well with the work of Pant et al (2014) who produced a criticality analysis of the GB rail network with an Origin-Destination trip assignment model, using data on observed passenger flows to estimate and visualise daily passenger trips and thus travel pattern importance. The daily passenger trip flows shown in Figure 6.2 highlight that a small number of lines, mainly in the London area, have significantly greater flows than the remainder of the rail network. It is clear that major urban conurbations and mainlines are highly critical, as identified in this thesis, but the national-scale focus skews the distribution heavily towards these locations and dampens the influence of more locally important single points of failure, which this thesis identifies.

Although the distribution and types of location may differ between the networks, there is commonality in the reasons behind locations being identified as highly critical. The nature of the underlying metrics is also highly similar. Regulatory reporting requirements are the principal reason for recording fault data for electricity distribution, driven by Ofgem, and delay data for the railway network, driven by ORR. The metrics are also temporally based, as a measure of the ‘punctuality’ or ‘continuity’ of service, through electricity SML to customers or railway DM to train services.

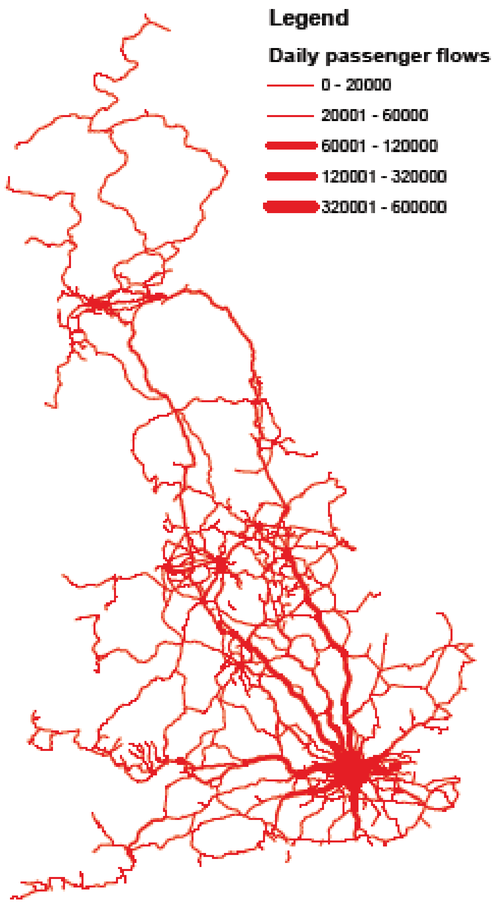


Figure 6.2. Results of trip assignment analysis showing estimates of daily number of passenger trips across individual railway network edges on the GB rail network. Adapted from Pant et al (2014).

The key advantage of the network criticality assessment methodology is the identification of high resolution, and locally specific, single points of failure. The granularity of critical locations is evident within both the electricity distribution and railway networks, particularly at the city-scale. Within cities, the density of both forms of infrastructure increases, as does the demand for services and the loads upon assets. Major substations supplying key residential or business areas exist alongside major railway hubs with a combination of frequent local services and longer distance services. Therefore, whilst key centres of criticality, such as London and Birmingham, may be identified as a whole the high resolution of the assessment provides the ability to determine which substations, track sections, stations and junctions are most critical within these areas.

The added value of the increased resolution and granularity of network criticality assessment can be highlighted through a comparison of the railway network criticality assessment in this thesis and the approach of NR (2016d). Figure 6.3 maps NR's internal route criticality bands for LNW (South), using financial compensation metrics at the SRS-level. The low resolution means that the same level of risk is allocated for long track sections, such as Rugby to London Euston, and the national-scale assessment is, as with Pant et al (2014), heavily skewed towards the WCML. For broad financial allocations such a scale is adequate, yet for localised asset management the benefit of this thesis is the high-resolution single points of failure identified at the STANOX level, for both track sections and individual locations such as stations and junctions.

It is also worth an examination of how the network criticality assessments in this thesis may compare to the prioritisation based upon tacit or expert knowledge within infrastructure owners and operators. An example for the railway network is used in this case for illustration. As part of the stakeholder engagement activity for this thesis, rail experts for the Wessex route including the Route Control Manager (RCM) and Seasons Specialist, based at the former Wessex Integrated Control Centre at Waterloo station in London (now based at the Basingstoke Rail Operating Centre - ROC) were asked to annotate a route map highlighting their priorities based on knowledge and experience.

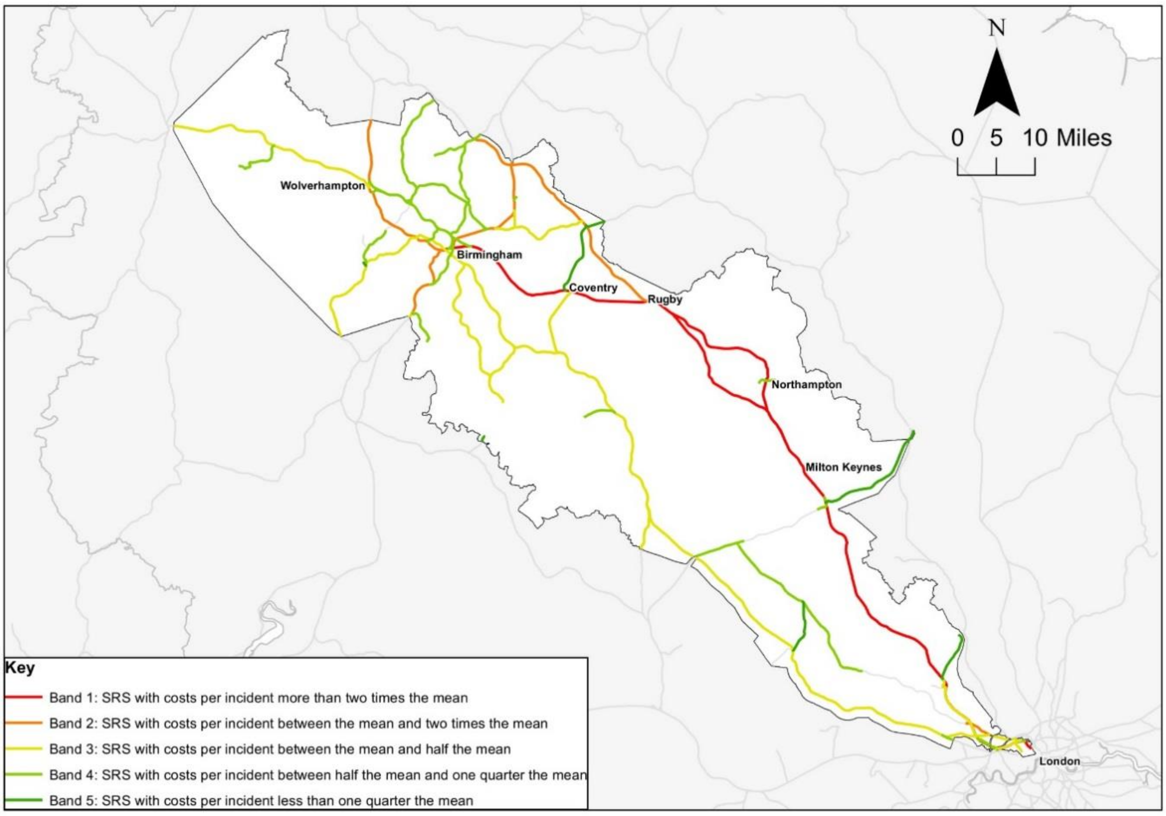


Figure 6.3. Mapped Route Criticality for LNW (South) using criticality bands calculated by NR (2016d).

Figure 6.4 shows the hand-drawn map produced, with locations of different priorities indicated. The most critical section, highlighted in orange, is between Clapham Junction and Woking. A line is drawn across the map from Reading to indicate the boundary between 'inner' and 'outer' lines which are managed as distinct units with different characteristics. Of the 'outer' lines, the most critical are highlighted in pink, around the South Coast including Basingstoke, Southampton, Salisbury and Portsmouth. Green locations are classified as 'isolated' and received less prioritisation during disruptive events. The general pattern identified is represented well through the network criticality assessment in this thesis, including the importance of London Waterloo to Woking and the lines to Southampton, along with the general trend of decreasing criticality from North East to South West. This indicates that the methodology applied in this thesis is representative of current understanding within infrastructure organisations and could be applied document priorities. However, this thesis also challenges tacit knowledge with the identification of localised single points of failure, particularly in the London area, that are classified as low priority by route personnel. An examination of such locations can enhance current prioritisation and target resilience interventions to limit the impact of potential asset failure.

Figure 6.4. Hand-drawn map of perceived network criticality by operations team at Wessex Integrated Control Centre.

The granularity of critical locations is even more evident when undertaking an interdependent infrastructure network criticality assessment. The external electricity supply to the traction feeder system for the Cross-City railway line was used as a local-scale case-study to demonstrate a cross-system criticality assessment. The complexity of criticality increases further, with single points of failure incorporating elements of network topology, service patterns and flows across the electricity distribution network and the railway network. For individual cases of feeder station supplies to specific sections of railway, the criticality of a feeder pathway and an electrified track section can be identified, as well as the criticality of substations within that pathway and locations within the track section. With connections between individual assets used to bring consequence metrics on both networks together, a high spatial resolution is paramount.

When the criticality assessment is scaled up to include two connected networks, criticality depends upon both internal and external factors. The footprint of an electricity substation is extended to include the sections of the railway network it supplies, with the consequence being a factor of DM as well as SML. Sources on the electricity distribution network have sinks on the railway network. Alongside cross-network flows, cross-network management is required between multiple agencies including DNOs, NR, TOCs, FOCs and NG. Examining the criticality of connected networks presents a greater variety of types of critical location to interpret and understand in combination. However, the underlying drivers of criticality remain the same. A highly loaded substation supplying a section of track with frequent and high-volume rail traffic presents a risk to service performance across both networks. The distribution of criticality is more variable within and weighted more towards the railway network, with a distinction between the north and south of the Cross-City line, whereas the substations that supply traction feeder power to the line exhibit very similar characteristics and therefore have fairly uniform criticality.

Across different infrastructure, management regions, and applications of varying complexity, different spatial distributions of network criticality are likely to be produced. As the complexity increases, through network characteristics or the addition of multiple networks, the behaviour of the system and subsequent management of operations becomes increasingly complex. The more connected networks become, the larger an asset footprint becomes, increasing the potential for disruption to propagate or cascade and thus the number of single points of failure identified is likely to increase. However, despite such differences in the geographical distributions, the drivers of criticality in supply and demand dynamics remain the same, with major demand centres and high frequency and volume of flows influencing the location of single points of failure. Therefore, although the criticality assessments in this thesis have been applied to selected management regions and case-studies, the overall understanding of network criticality in terms of the types of critical locations, network behaviour, and system dynamics can be applied nationally, across an entire network, to inform the targeted prioritisation of locations for resource allocation and resilience interventions. Across infrastructure systems, it is the city-scale interdependencies that are most crucial, highlighting the presence of and the need to account for external sources of risk and consequence in any prioritisation of interventions.

6.3 Critique of Methodology

It is necessary to interpret the results of the network criticality assessments with respect to the limitations of the underlying data and information sources, so as to understand the impact such limitations may have on the conclusions drawn. Essentially, the caveats to the criticality assessments influence the reliability and certainty of the single points of failure identified.

The electricity distribution and railway transport network criticality assessments, presented in Chapters 2 and 3, are based upon similar historical fault and disruption databases for a single system. The main limitation with the databases is the sample size constraint, with five-year time series of both electricity supply interruptions and railway delays. Whilst this sample provides an adequate volume and variety of events for analysis, any historical sample remains a 'snapshot' of the wider distribution of events. Therefore, the presence or absence of failures along with network and operational changes within a time series influence the single points of failure identified. This is particularly evident for the electricity distribution network, with a high number of substations and thus potential failure points overall. There is also the general rarity of power cuts at a single location to consider, as the normal state of the electricity distribution network is for power to flows between all substations and from source to sink at all times. As a result, the calculated criticality bands for the majority of substations are based upon the service performance consequence of a single fault, although the distribution of consequence magnitude per failure is likely to be quite narrow due to the defined asset footprint of a substation. For the railway network, there is a significantly greater variety in the sample size of incidents at individual locations. Most of the major locations, such as main lines and key hubs, have very high incident counts whereas the more isolated locations, such as branch lines, tend to have low incident counts. Whilst there may be fewer potential failure points, with track sections including a range of assets, failures are more common overall due to the complexity of the system and the range of sub-systems required for a railway to function. Incident occurrence and magnitude is also more variable as this largely depends on train service patterns, which are highly variable in frequency and volume between locations.

With low sample sizes at the majority of electrical substations and more remote railway locations, the reliability of allocated criticality band may be reduced requiring careful interpretation of the characteristics of a particular location. However, the reliability of a criticality band depends upon how representative a single event is of the wider distribution at a location. Although the criticality of an electricity distribution substation may be based on one fault, the asset footprint and thus the potential consequence for connected substations and customers is quite clearly defined. For the railway network, the consequence of failure at a particular location is likely to be more variable due to the spatiotemporal variability of train service patterns and the potential for propagation and dispersion of disruption. The management of the railway network is also more complex, with personnel issues causing propagation of delays if, for example, train crew become delayed and cannot operate the subsequent service they were scheduled for.

Therefore, the low sample sizes at more remote railway locations present more of an issue than the single failures at electrical substations. Such locations should be interpreted on a case-by-case basis, with a more forensic examination of the nature of the location. The location of critical electrical substations in towns and cities aligns with common understanding of priority areas, whereas understanding of single points of failure on railway branch lines is less common. It is for this reason that locations with high Z-scores and only one observation were omitted from the railway network criticality assessment, whereas such locations were retained for the electricity distribution network criticality assessment. The removal of substations with a single observation would have reduced the number of substations included in the assessment to such a low number that an analysis of criticality would not have been worthwhile.

The caveats to the analysis become increasingly complex with an interdependent infrastructure network criticality assessment, presented in Chapter 4. Evaluating criticality across two connected networks involves integrating both service performance databases and spatial information from different infrastructure companies from different infrastructure systems. The degree of reliability and certainty within the resultant criticality assessment depends upon the commonality between the data and information sources. In this case, granularity of the evidence base is essential when assessing the connectivity of individual assets between systems. The spatial information supporting the criticality assessment is assumed to be accurate and complete, having been obtained from the infrastructure companies directly. The information is adequate for tracing pathways between external electricity substations and railway track sections without any issues. It is the service performance databases that present issues with integration between systems. As with the single system criticality assessments, the same issues surrounding sample sizes, low frequency high severity events and remote single points of failure remain. However, the principal issue in this case is the definition from regulators of what infrastructure elements fall within the system boundaries for fault reporting requirements.

It was found that, in general, there is very limited consideration of externalities in both causation and consequence across the reporting of electricity supply interruptions and train delays. The only direct reference is the ‘external power failure’ delay reason code in the railway delay database. Fault or incident reporting requirements define what types of assets and what types of failures are recorded. For electricity distribution, traction feeder connections to the railway network at 25kV appear to fall beyond the system boundary, where the railway network is not regarded as a ‘customer’ and so the service performance metric reported fails to account for external consequences. Tracing failure pathways from source to sink, and from asset failure to consequence, is a major challenge with the limited amount of information reported. There is a significant overlap between the metrics, where spatial correlations can provide an indication of the potential for cascading failure, but ultimately only internal consequences are quantified.

Ultimately, the limitations and caveats to an infrastructure network criticality assessment methodology, both for this thesis and the existing literature, are a factor the scale of application, in terms of geography and systems. Network criticality assessments for single and dual networks use similar methodological approaches. They are largely based on modelling and simulation, involving Complex Network Analysis (CNA) with topological (graph theory) and system-based (supply and demand flows) methodologies (Pagani & Aiello, 2013; Ouyang, 2014; Mattsson & Jenelius, 2015). Such models are useful for incorporating a range of hazards, vulnerabilities and risks across multiple connected systems at the national-scale, to provide general direction on infrastructure planning and provision. However, there is a trade-off between the scope of analysis and the detail and reliability of the output.

Evaluating vulnerability using purely topological metrics can be misleading (Hines et al, 2010), whilst a number of assumptions on networks flows and behaviour are, quite necessarily, made for simplification when analysing multiple complex networks for the whole of GB. Thacker et al (2014) assessed the vulnerability of present and future configurations of the GB electricity network to climate hazards using a model of national-scale transmission and distribution, assuming that electricity follows the shortest path between two points. Thacker et al (2017b) performed a multi-scale disruption analysis for the interdependent domestic flight network and integrated electricity network, estimating customer demands from flight and population statistics, and assuming connections between airports and substations based on geographic proximity. Pant et al (2016) also assume geographic dependencies between electrical substations and railway lines in order to undertake a vulnerability assessment of GB rail infrastructure dependencies on external electricity systems.

Given the simplifications made, there are challenges when downscaling the output and examining local-level network criticality. For example, Thacker et al (2017a) undertook a network criticality assessment of interdependent critical infrastructure in England and Wales, identifying geographic hotspots to target investments and enhance network resilience. At the national-scale, the mapped hotspots (Figure 6.5) are useful for highlighting areas where resilience interventions are most in need, such as the periphery of urban areas where there are large highly loaded facilities or central urban areas where several critical infrastructure networks are concentrated in one location presenting major demand hubs. However, when local-scale output is assessed, with criticality metrics calculated for 1km x 1km grid squares (Figure 6.6), the assumptions made on infrastructure demand and shortest path flows reduce the reliability of results to a level where decision making around specific assets is not particularly viable. Pant et al (2016) assess flood vulnerability of railway and electrical infrastructure using NaFRA flood likelihood maps intersected with infrastructure maps. Spatial intersections can identify assets in flood risk areas, but the consequence of failure from those assets and their interdependencies is not as reliable at the local-level, as there is no certainty regarding whether a particular substation supplies power to a track section in reality. Therefore, modelling and simulation approaches have applications at a high-level but present a case for more focused assessments of locally important single points of failure.

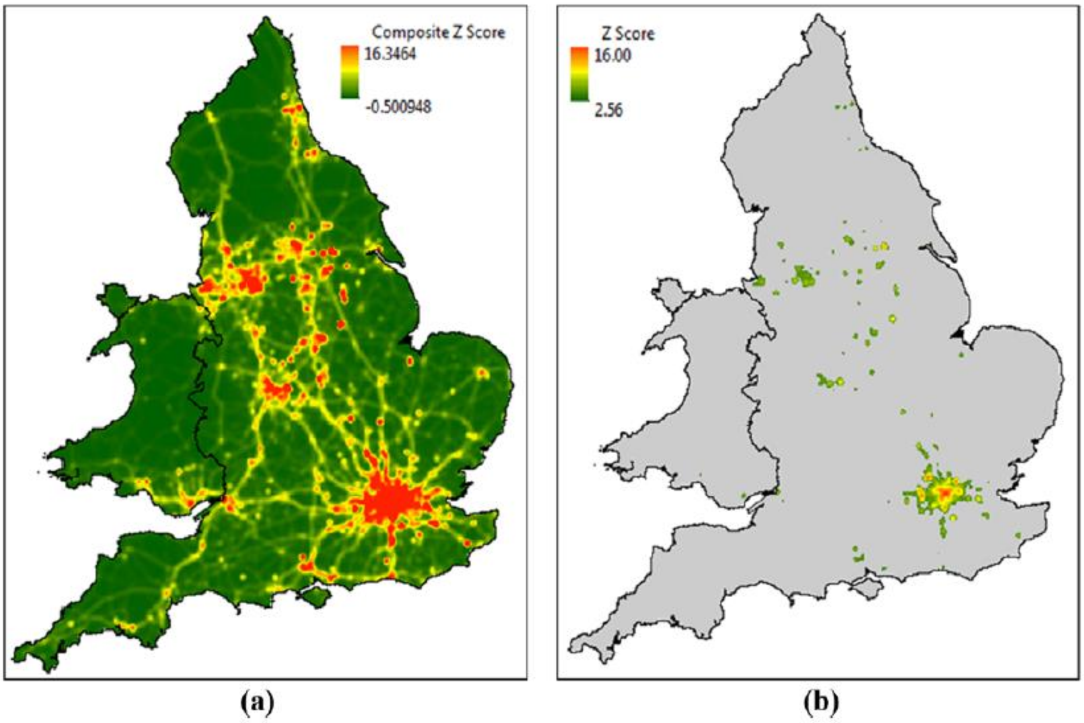


Figure 6.5. (a) Composite Z-scores of user demand and disruption of assets, electric network, rail, and road. (b) Statistically significant composite hotspots at a 99% significance level (Z-score > 2.56) (Thacker et al, 2017a).

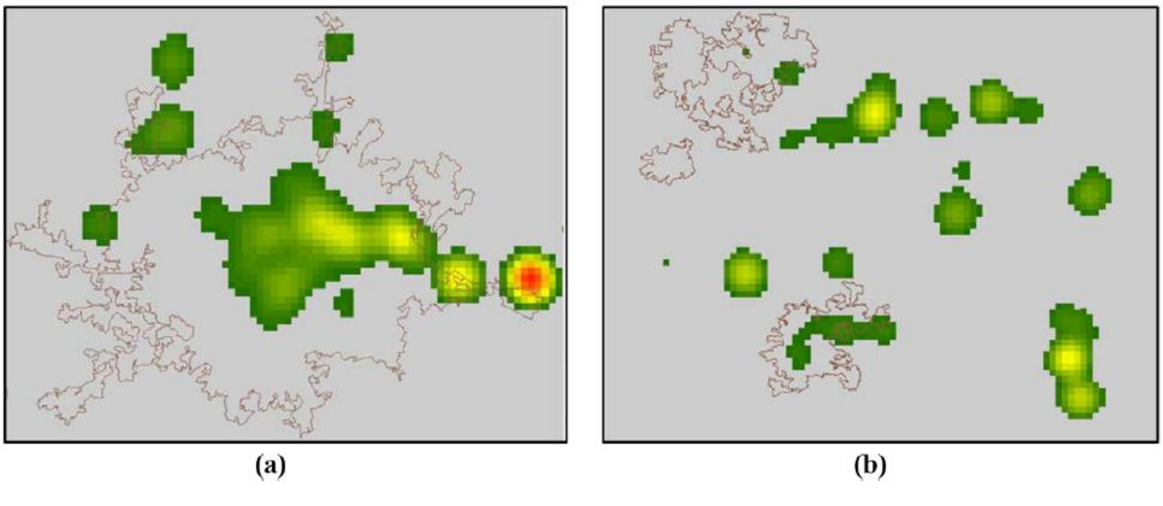


Figure 6.6. (a) London's electricity infrastructure asset user demand hotspots at a 99% significance level (Z-score > 2.56). (b) Electricity infrastructure asset user demand hotspots at a 99% significance level (Z-score > 2.56) for south Yorkshire (Thacker et al, 2017a).

This thesis has therefore contributed towards a research gap in assessing localised single points of failure across dependent infrastructure systems using industry data and information sources. There is a different set of caveats for this thesis compared to the literature, regarding the data and information sources used which, despite being the best available, mean that the single points of failure identified require careful interpretation. There is clear trade-off between spatial resolution and sample size, whilst when the complexity of the criticality assessment increases through the integration of multiple networks and data sets, the definition of system boundaries presents challenges for interpretation. However, there is clear value in the prioritisation of interventions based upon the criticality assessments presented in this thesis. Whilst the existing literature presents criticality methodologies that are designed for national-scale applications, a methodology specifically designed for local-scale asset management has reduced the degree of uncertainty and improved reliability in targeting resilience interventions.

6.4 Recommendations

6.4.1 Opportunities for Improving Network Criticality Assessment

Given the limitations identified, potential improvements to the data and information sources used would enhance the evidence base upon which the network criticality assessment is established. Ideally, with historical service performance databases, longer time series would increase the sample size of faults or incidents at locations, providing a more reliable indication of whether a particular criticality band, particularly for more localised single points of failure, is based upon a systematic issue or an ‘extreme’ event by assessing the distribution of events. Extending the time series would also be likely to increase the spatial distribution of events and increase the geographic coverage of a criticality assessment within a management region, whilst accounting for more variation in network developments and service patterns. For infrastructure interdependencies, a longer time series may provide more reliable evidence of cascading failure pathways and consequences, whilst increasing the potential for scalability. In the same vein, obtaining electricity transmission performance data from NG would help to complete a more systemic assessment of risk for the electricity sector and connections to the rail network.

However, there are more fundamental issues with the data and metrics that need to be addressed. A recommendation of the National Infrastructure Assessment (NIC, 2018) is that long-term decisions can be improved through robust analysis of the quality and performance of existing infrastructure, and that the information supporting this analysis should be as detailed and systemic as possible. If the reporting requirements for asset failures and consequence metrics are driven by regulation, then Tran et al (2014) suggest that regulators have the opportunity to drive improvements in this area, through improving the quality of data recorded, reforming policies and contradictory incentives between regulators from different sectors and increasing the potential for data-sharing agreements and cooperation between organisations. It is recommended that the UK government adopt an integrated approach to governing infrastructure interdependencies, involving more proactive incentives and facilitating urban-scale intermediary platforms for coordination within and between infrastructure sectors and stakeholders. Sharing information is crucial for local-level emergency planning, maintaining essential services and emergency services assistance (Cabinet Office, 2011) in line with statutory guidance from the Civil Contingencies Act (2004) for establishing effective relationships between responders and infrastructure owners and operators. The National Security Strategy and Strategic Defence and Security Review (HM Government, 2015b) also suggests that the sharing and improvement of information is important, with the Government working with infrastructure owners and operators to create a regulatory framework to ensure that infrastructure is resilient to future threats and that responsibilities for integrated infrastructure policing are shared across a number of organisations with different levels of capability and capacity.

Progress towards this goal has been made by the UKRN (UK Regulators Network) which was launched in March 2014 and brings together CEOs from different regulators across different sectors, including Ofgem and ORR, to discuss common issues and projects (UKRN, 2018). UKRN have a cross-sector project looking at making better use of non-financial vulnerability data involving collaboration between energy and water sectors for the purpose of identifying and responding to vulnerable customers (UKRN, 2017). The same principles could be applied to sharing vulnerability data between other sectors, such as the non-financial railway delay and electricity fault databases. Regulatory reporting requirements should be changed to reflect the increasing sources of external risk and consequence, and the flexible nature of system boundaries. This can be achieved by improving consequence metrics to account for impacts to external assets, as well as more detailed fault reporting and attribution to acknowledge external sources of risk and allow cascading failure pathways to be traced. Either the reporting should be extended or the system boundary itself should be extended.

For spatial and topological data, more detailed low-level information such as LV electricity assets and connections to external networks i.e. railway signalling would allow a more systemic assessment of criticality. There is also a key role for initiatives such as Level 3 BIM

(Building Information Modelling) as part of the Digital Built Britain strategy which would improve the level of detail regarding information recorded for construction of buildings and infrastructure (HM Government, 2015a). Making better use of infrastructure data would help to understand dependencies, realise value from assets, assess their health and criticality, and inform planning for resilience interventions.

For the rail network in particular, the Joint Rail Data Action Plan (DfT, 2018) is centred around making better use of the increasing amounts of data that are available, removing barriers to collaboration between rail and other sectors, with new initiatives between transport modes, and between the rail and technology sectors promoting open sharing of non-personal data to drive innovation. Furthermore, the Data and Analytics Facility for National Infrastructure (DAFNI) is under development which will collate and host datasets on national infrastructure for detailed simulation and analysis (DAFNI, 2018). The system architecture, outlined in Figure 6.7, will provide the UK with a national facility to both host infrastructure datasets and facilitate detailed analysis using a system science driven modelling platform. They key resource to come from DAFNI will be the National Infrastructure Database (NID) due by 2021, which would provide a centralised repository of infrastructure data that could significantly enhance network criticality assessment and decision making at multiple scales for multiple systems.

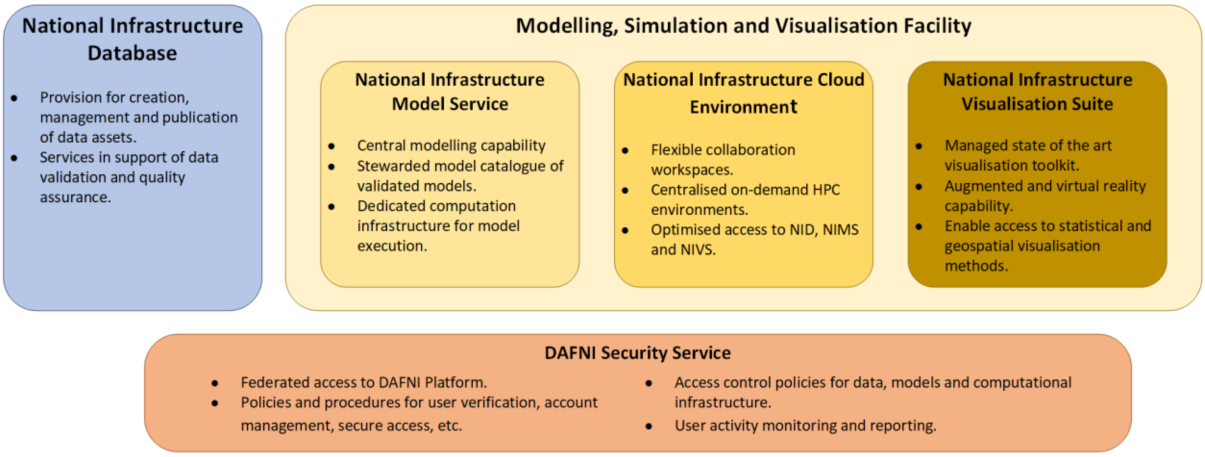


Figure 6.7. DAFNI Architecture (DAFNI, 2018).

Ultimately, the utility of any evidence base for analysing interdependencies is determined by where the system boundaries are drawn. If data and metrics, and in turn network owners and operators do not consider external risks and consequence the management of the national infrastructure system is jeopardised. This thesis presents a criticality assessment using the best available data, which can inform future network management. Improved decision making, both locally and holistically focused, is required alongside developments in the data and metrics used to underpin those decisions.

6.4.2 Opportunities for Extending Network Criticality Assessment

The infrastructure network criticality assessment methodology presented in this thesis has several natural extensions. Focusing on the consequence metrics used, network criticality was calculated based upon one perspective, from the infrastructure owner or operator, and one type of performance metric, relating to service levels in terms of delays to trains and the duration of power outages. However, as has been highlighted in this thesis, there are a variety of different performance metrics, including financial costs (e.g. NR, 2016d) and service demand (e.g. Pant et al, 2014) and a broad range of stakeholders involved with the planning and operation of infrastructure, with different viewpoints. Therefore, a network criticality assessment methodology could be developed that incorporates several different candidate metrics, with layers of criticality developed in conjunction with different organisations and stakeholders, to progress towards a more holistic assessment of risk. ISO 55000:2014 on Asset Management highlights that the needs and expectations of an organisation and its stakeholders, as well as external service providers, influence rules for consistent decision making and general organisational objectives.

In this thesis, such candidate metrics were not explored as they were beyond the scope of the research, with a focus on network effects and pure service disruption dynamics, as well as there being issues with the reliability and availability of data to inform such metrics. A key factor in the originality of the network criticality assessment methodologies developed in Chapters 2-4 is the use of observed data on service performance for both railway transport and electricity distribution. However, in order to calculate metrics based on, for example, the number of passengers on delayed trains or the electric load carried, observed data is either not recorded or difficult to access. Weighting links by user numbers would involve estimations such as the O-D trip assignment model used by Pant et al (2014) which would impact upon the reliability of metrics, unless such data was recorded by other means i.e. travel diaries, questionnaires or interviews (Hayden et al, 2017).

Furthermore, there is the potential to translate the service disruption metrics in this thesis into financial costs yet similar limitations apply. A user-focused approach might explore the cost of disruption to rail passengers and electricity customers, however, defining the cost of what and to whom presents a major challenge as individual circumstances can be vastly different. For the economic appraisal of transport projects, values of travel time for road transport can be translated into financial values, based on evidence of 'willingness-to-pay' for travel time savings (DfT, 2014b). There is also a GB national average cost of a delay minute on the railway network of £73.47 (Burr et al, 2008) which relates to the economic impact per passenger. However, using such arbitrary values fails to capture the unique circumstances of users, such as whether they are travelling for business or leisure, or whether a power cut is experienced to a residential property and the associated vulnerability of residents, or to a non-residential property, and the nature of the function or business. Such complexity would be difficult to observed and capture, involving an extensive research programme, and raises a question over the prioritisation of different user groups.

Accounting explicitly for different types of hazards would also enhance the application of network criticality in different scenarios, such as extreme weather contingency planning and climate change adaptation. However, individual hazards were not assessed in this thesis due to sample size limitations as, for example, weather-related incidents comprise approximately 1% of NR's TRUST database, and issues surrounding the reliability of coding and attribution of such incidents, as some delays associated with an extreme weather event may not be attributed to that event if the initial cause of failure is unclear. There is, however, the potential for the integration of weather and climate information into the overall decision-making process for the resilience and adaptation of infrastructure. A layer of network criticality, along with weather forecasts, asset condition, natural hazards and climate projections, presents the opportunity for a more holistic assessment of infrastructure and environmental risk. As shown in Figure 6.8, relationships between specific asset categories and weather variables can be incorporated into such an assessment, supported by ongoing research at the University of Birmingham (UoB) (Fisher et al, 2018) which aims to define a series of failure pathways for railway infrastructure, by using fault data from all railway asset types with a range of weather variables to quantify the role of 'day-to-day', extreme and antecedent temperatures and precipitation in the causation of faults to inform better decision making for asset resilience.

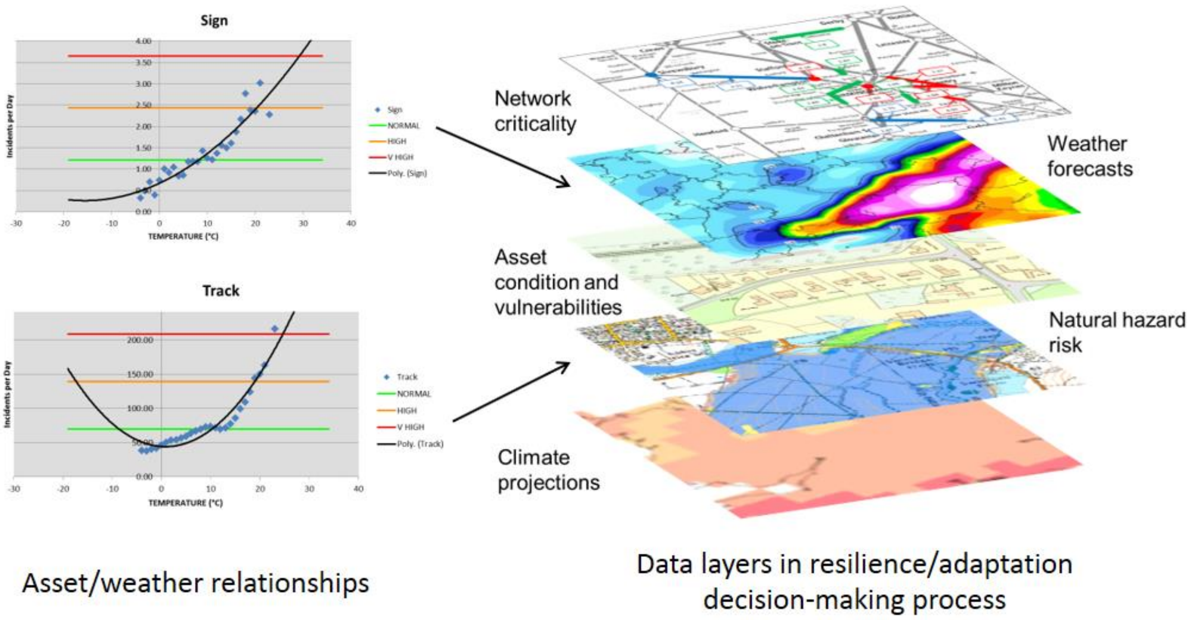


Figure 6.8. Data layers and asset/weather relationships in the decision-making process for resilience and adaptation of infrastructure to extreme weather and climate change.

It is clear that there are benefits to 'scaling up' a network criticality assessment, in terms of both geography and infrastructure systems, provided that the limitations outlined can be overcome or reduced. Geographically, network criticality could be extended nationally within GB to assess the spatial distribution of risk within other management regions. To explore further licence areas of the electricity distribution network, initially all DNOs were contacted regarding the provision of data for this thesis, yet only one responded positively (WPD), therefore extending the assessment is possible but relies upon the cooperation and willingness to share data of individual DNO companies. However, all DNOs must report performance data to the regulator Ofgem, with most using NaFIRS to achieve this, so every DNO should have an equivalent data set to WPD. For exploring other routes of the railway network, this thesis obtained NR's TRUST database for the entire GB rail network, therefore the only inhibiting factor is the time required to manually digitise STANOX track sections in GIS. Increasing spatial coverage of network criticality would examine the transferability of the methodology and have benefits for decision making across a variety of different types of management regions. The principal issues with increasing the geographic coverage of network criticality would be with access to detailed information on interdependencies, such as traction feeding diagrams and electricity network diagrams, and the subsequent time required to both interpret this information and examine spatial correlations between cross-sector metrics.

It would also be beneficial to both understand how infrastructure network criticality assessment is approached internationally, and to assess the transferability of the methodology in this thesis to networks overseas. During the literature review process for this thesis, international examples of network criticality were identified in the academic literature, but no examples were found of the internal processes within infrastructure owners and operators. It is likely that this information is restricted, commercially sensitive, or there is no formalised process with a reliance on tacit knowledge for less developed infrastructure systems. In terms of transferability of the methodology, international applications may in fact be simpler than in GB, in cases where performance monitoring systems and data architecture were developed alongside the construction of infrastructure. For example, it is likely that the Shinkansen high-speed rail system in Japan has greater levels of documentation and understanding of the dependencies on external electrical traction substations, as well as more streamlined reporting systems for delay reporting, given the drive for efficiency and the fact that trains are timed to the second.

The network criticality assessment methodology could also be extended to include further interdependent infrastructure systems, such as water, waste and ICT. Initially, a case-study of an urban conurbation, such as Birmingham, would be useful with multiple transport modes across rail, road, metro and air alongside electricity transmission and distribution, ICT and communications networks, water and waste. An assessment could follow a similar evidence-based approach to this thesis, assessing the availability, accessibility, and quality of both performance databases and spatial information from multiple infrastructure owners and operators and the potential degree of reliability and certainty these sources would present. Different data sets from different sectors may present different challenges for integration, therefore a case-study would present a useful scoping exercise, with progress towards a common reporting format for infrastructure faults across sectors. There is the potential to combine metrics, and associated criticality bands, if they are in a similar format with different weightings for infrastructure systems and assets. To facilitate such a 'scaling up' of infrastructure systems, it would be helpful to understand more about the evolution and cascades of disruption between assets on an event basis. It has been highlighted in this thesis that tracing interdependent failure pathways, using consequence metrics, is a challenge due to the differences in fault reporting and definitions of system boundaries between sectors. However, if enhanced data were available, tracing cascades of failure through interdependent infrastructure systems, from the initial asset failure to propagation of disruption, there would be a better understanding of the behaviour of system, the failure mechanisms, and thus how response measures could control or limit disruption. Furthermore, with a longer time series and thus greater sample sizes, a more detailed forensic examination of the distribution of incidents originating at single points of failure could occur. Locations influenced by extreme events can be separated from locations where incidents are systematically problematic.

The spatial distribution, or propagation, of reactionary disruption through a network has been investigated by Jaroszweski et al (2015) particularly for rail transport, who advocate that future research could involve analyses of ensembles of historical incidents at single points of failure to understand the spatial disruption profile from each location, accounting for delay propagation mechanisms. Locations could therefore be categorised, building upon a metric of aggregate service level disruption (train delay or power cut duration), by the spatial extent or dispersion of disruption originating from an asset failure, whether typically dispersed or contained. Metrics could be developed dependent on the actual distance over which 'knock-on' disruption spreads and/or weightings for the geographic areas into which disruption spreads, for example, prioritising locations that propagate disruption across management regions and increase the complexity of incident management. Different locations will have different spatial profiles of disruption dependent upon the service patterns and flows through that location, for example, a railway asset failure on the WCML or the failure of an electricity transformer at a HV substation are likely to spread disruption further than railway branch lines or 11kV local electricity substations. Locations that are net importers and exporters of disruption, particularly at route or licence area boundaries, would be of significant interest to infrastructure owners and operators.

A layer of network criticality, as developed in this thesis, has a role in the validation of models and simulations in order to assess the degree to which real-world network behaviour and dynamics are represented and/or improve the model input by providing a baseline and training simulations towards more realistic output. The Birmingham Centre for Railway Research and Education (BCRRE) at UoB have developed the Birmingham Railway Virtual Environment (BRaVE) which is a suite of software tools featuring a microscopic simulator that can provide a virtual laboratory for exploring the influence of new technologies, timetables and train routing for railway operations, with the option to insert various disruption scenarios and examine the impact on train movements and performance (Dai, 2016).

6.4.3 Implications of Future Developments for Network Criticality Assessment

It is important to explore the range of potential future developments that may either influence the distribution of network criticality or enhance and direct the methodological approach to identifying single points of failure. Infrastructure networks contain assets that have long lifetimes, therefore, they are likely to be influenced by high-level long-term trends in infrastructure supply and demand, including population and demographic change (such as population growth, ageing, migration and urbanisation), macroeconomic drivers (such as national and regional economies, economic growth and energy prices) and societal change (such as governance, devolution and behavioural change) (Tran et al, 2014; Armitt et al, 2016). Environmental change also presents the need to for protection and adaptation of infrastructure, through the general warming of the global climate system, which is highly likely to be driven by anthropogenic greenhouse gas emissions (Jenkins et al, 2008) with projections for the UK of warmer and wetter winters, hotter and drier summers, rising sea levels and more extreme storms (Murphy et al, 2009). Dawson et al (2016) highlights how projections of increasing sea levels are likely to increase days with line restrictions by up to 1170% and lead to repair costs in the £10s of millions as well as socio-economic costs.

The political and governance landscape could change significantly, dependent on the outcome of negotiations surrounding the Withdrawal Agreement for implementing the UK's Exit from the European Union, scheduled for March 2019. The Department for Transport (DfT) and the Department for Business, Energy and Industrial Strategy are assessing potential outcomes for transport users and energy programmes (NAO, 2017; 2018). The devolution of responsibility within transport owners and operators to local business units (NR, 2017a) and from central government to local authorities (TfWM, 2018) has implications for the way in which infrastructure is managed and funded. More localised responsibility for infrastructure heightens the need for localised assessment of network criticality and interdependent failure pathways, with greater potential to highlight and act upon single points of failure within management regions and local government.

The most direct influence on network criticality and the spatial distribution of operational service risk comes from the introduction of new technologies to an infrastructure system. For the rail network, NR's Upgrade Plan (NR, 2017b) involves a range of developments such as rebuilding stations and opening new lines such as the upcoming Elizabeth Line (Crossrail) for London and the South East. Changing the design of the network and creating or modifying service paths can influence the potential for propagation of disruption and the distribution of single points of failure. Electrification of existing lines is also a priority, such as the extension of the Cross City line, used as a case-study in this thesis, between Barnt Green and Bromsgrove

(WMR, 2018b). Electrification enhances service levels with shorter journey times, but also increases the need for efficiency of operation, with less headway between services. The resilience of the external electricity supply is also crucial, with greater redundancy and capacity required. The future introduction of High Speed Two (HS2) in the UK, connecting London to Birmingham, Manchester, the East Midlands and Leeds (HS2, 2018), will increase capacity but also present a major change to supply and demand dynamics and service patterns of the rail network as a whole, given that a large proportion of HS2 will run on the existing infrastructure, and present a challenge for the electricity transmission network and NG in providing electrical capacity and security for traction power supply.

Perhaps the most significant development is the increasing digitalisation of infrastructure systems. Infrastructure is becoming increasingly reliant upon IT and communications systems to enhance the efficiency and capacity of operations, through technological advances and the increased amount of data available, with the analytical capability that presents. Modern transport systems are dependent upon ICT systems for the operation of services (such as smart motorways, railway signalling systems and air traffic control) and the management of transport system users through stations and terminals, on to trains and planes (DfT, 2014a). The digitalisation of railway transport is demonstrated through the Digital Railway Strategy (Digital Railway, 2018) which is designed to overcome the capacity challenges of full trains and limited train paths through the replacement of conventional systems with digital signalling, operations and train control. The vision is for technology to be embedded across the rail system, including real-time train control, mainly through the European Train Control System (ETCS). ETCS will allow trains to run closer together, moving from traditional fixed block signalling to a moving block model, increasing capacity as trains can travel at their optimum speed with less headway. Traditional signal aspects will also be replaced with in-cab signalling, placing greater reliance on communications. The increased efficiency of operation will remove bottlenecks and relieve pressure and 'pinch points' on the network, but the consequence of the system failing is significantly greater. Across the railway system, the Rail Technical Strategy Capability Delivery Plan (RSSB, 2017) outlines twelve key capabilities, shown in Figure 6.9, all of which are enabled by digital technology, such as greater efficiency in passenger flows and energy use.

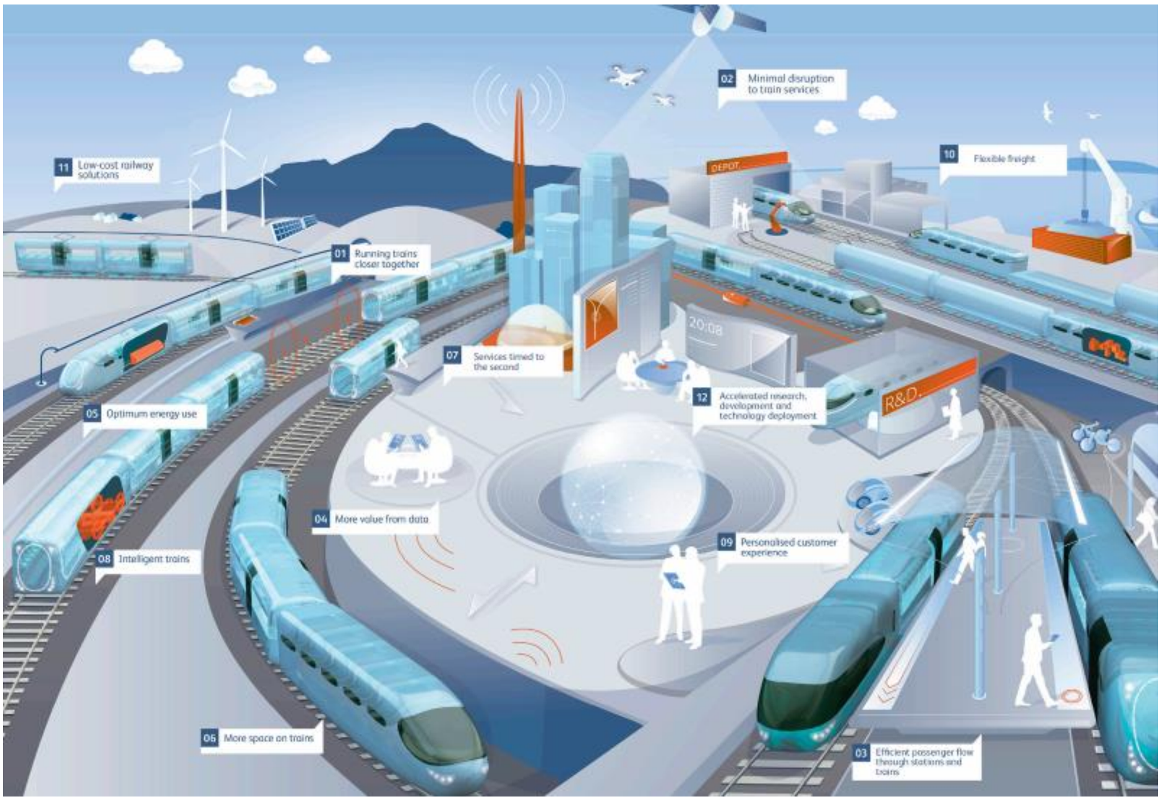


Figure 6.9. Twelve Key Capabilities of Rail Technical Strategy Capability Delivery Plan (RSSB, 2017).

The digitalisation of electricity distribution is exemplified by the transition of WPD from a Distribution Network Operator (DNO) to a Distribution System Operator (DSO), as shown in Figure 6.10, in order to move towards a low carbon future, integrating more renewable generation and new technologies such as electric vehicles (WPD, 2017). The introduction of smart meters, distributed generation and demand side management (DSM) are key technologies (POST, 2011). Distributed generation involves the decentralisation of generation sites, from large power stations to more localised and renewable sources, often on a small scale at residential or commercial premises. Challenges include the greater complexity of reverse power flows and the intermittent nature of generation. This thesis has demonstrated that connections to distributed generation sites can present localised single points of failure. Such challenges can be managed by smart grids, which have the ability to forecast and manage power flows through a system, moving from passive operation to active management through increased sensing and technical mechanisms (WPD, 2017).

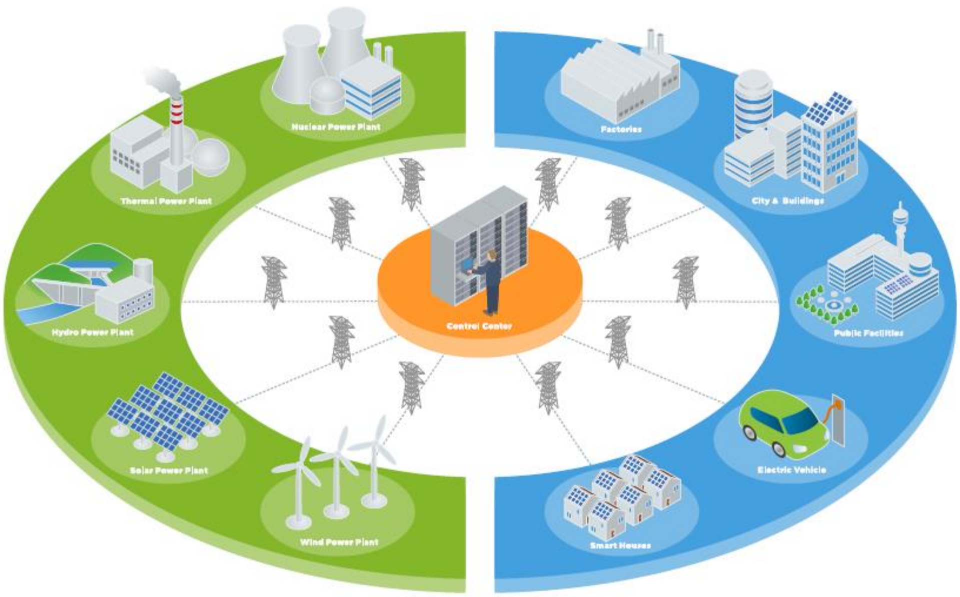


Figure 6.10. Distribution System Operations (WPD, 2017).

However, whilst such technological advancements may increase efficiency and capacity, they also step-up the complexity and diversity of infrastructure systems, increasing the number of 'moving parts'. A greater dependence on external ICT and communications infrastructure heightens the need for system-wide resilience. The proliferation of digital systems increases the vulnerability to cyber-attacks. Cyber security also becomes even more essential against the threat of malware, hacking, botnets and phishing which can have widespread impacts such as electricity blackouts and disruption to water supply control systems (BT, 2017). As a result, it is important that the future direction of network criticality assessment focuses upon ICT systems, assessing the distribution of risk within ICT infrastructure, such as fibre broadband, and single points of failure in systems embedded within other infrastructure, such as digital signalling, accounting for their dependence on external assets.

ICT and digital systems also influence the methodological approach to network criticality assessment, through the quantity and resolution of data recorded and processed. Smart infrastructure is a transformative technology that facilitates the functionality of systems through improved collection and use of data (The Resilience Shift, 2018). As shown in Figure 6.11, increasing the ‘smartness’ of infrastructure presents both opportunities and vulnerabilities. Digital systems have the potential to increase resilience through, for example, smart grids regulating power flows or remotely restoring and maintaining substations, as well as presenting a greater need for backup or alternative methods of operation should digital systems fail. For applications in network criticality assessment, the power of the data collected by these systems can also be harnessed to help to inform resilient decision making through analysis and communication of information.

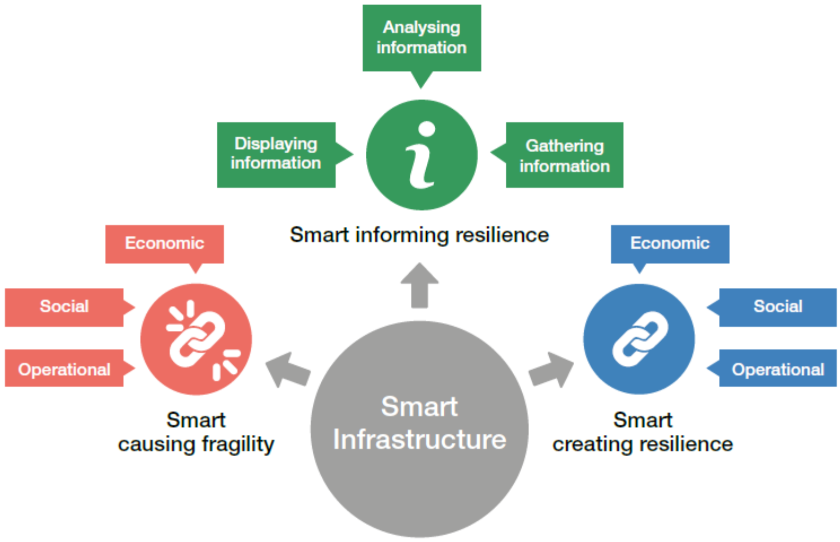


Figure 6.11. The different ways in which smart infrastructure solutions can impact on the resilience of infrastructure and the people who use and operate it (The Resilience Shift, 2018).

Looking at the 'bigger picture' of network criticality assessment, improved data sets and monitoring of infrastructure can greatly improve the evidence-base available upon which single points of failure are based, improving both reliability and certainty in targeting resilience interventions. The National Infrastructure Assessment (NIC, 2018) advocates a move towards a 'digital society' centred around data and digital connectivity and enabled by full fibre broadband, artificial intelligence (AI), virtual reality (VR) and internet of things (IoT) technology. In particular, IoT technology drives smart infrastructure, through connecting 'things' or 'objects' (in this case infrastructure assets) to the internet and each other (Evans, 2011) using electronic internet-enabled devices and sensors. Urban-scale sensor technology has the potential to improve the whole-life approach to infrastructure management and cutting costs by, for example, identifying leaks in water mains (Armitt et al, 2016). Assets can 'talk' to one another and communicate with a control centre to facilitate service regulation and maintenance interventions based upon the information being collected, such as asset loadings and sensor-based condition monitoring.

The data collected and used by smart infrastructure sensors and observations can be described as ‘big data’ due to the complexity, high volume, accessibility and spatiotemporal resolution, providing a digital reflection of the physical world which enables the management and prediction of disruptive events (Jin et al, 2015). ‘Big data’ is stored on servers, either owned by an infrastructure company or using a cloud-based system, which can be used for analysis both in near real-time or as a historical data set. Smart infrastructure also fits in with the smart cities agenda and forms part of Birmingham City Council’s ICT and Digital Strategy, which proposes a whole-system and evidence-based approach to targeting key priorities for decision making using emerging technologies such as IoT, 5G communications, robotics, autonomous vehicles and virtual reality (Birmingham City Council, 2016). The data collected through smart infrastructure systems can therefore be integrated within a network criticality assessment, either as a static assessment of single points of failure or as a dynamic decision-making tool.

IoT technology has particular applications in enhancing the resilience of urban infrastructure to extreme weather and climate change. Chapman et al (2013) advocate the implementation of high resolution monitoring and sensor networks to identify localised city-scale issues on infrastructure networks, with increasing temperatures and associated energy use impacting electrical transformers and resulting in cascades of failure for transport and ICT networks. Therefore, internet-enabled sensors can be used to monitor weather conditions, located either on infrastructure assets, or within infrastructure corridors, integrating meteorological and non-meteorological information. Urban climate resilience is a significant issue, as cities are concentrations of both people and infrastructure with many highly loaded assets. A demonstration of a high-resolution urban meteorological sensor network is the Birmingham Urban Climate Laboratory (BUCL) involving the installation of 84 low-cost air temperature sensors [more information available in Young et al (2014)] to model the impact of Birmingham's UHI on local infrastructure and provide a test-bed for high-density low-cost urban meteorological sensor networks (Chapman et al, 2015). Figure 6.12 provides examples of interpolated UHI maps, based on data from the wireless air temperature sensors. For a heterogeneous urban environment, with significant variations in meteorological conditions and infrastructure systems, high-resolution data on weather-related hazards and network criticality can be overlaid in order to undertake a more robust risk assessment at the local-scale and identify locations with intersections of both a high risk to infrastructure service performance, such as highly loaded substations, and a higher meteorological risk, such as high air temperature, where resilience interventions can be targeted.

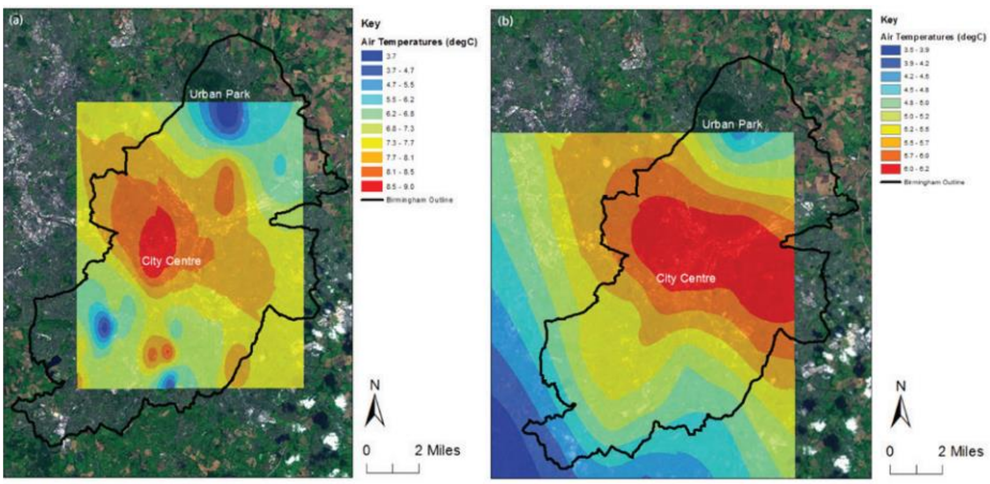


Figure 6.12. (a) Interpolated UHI map at 0100 LT 6 May 2013 (based on available data from 18 sensors) plus aerial imagery, (b) interpolated UHI map at 0100 LT 19 Feb 2014 (based on available data from 3 sensors) plus aerial imagery. Aerial images from OpenStreetMap.

Further projects at UoB highlight the range of applications for deploying self-contained low-cost IoT meteorological sensors at a high resolution in an urban area, and potential integration with a layer of infrastructure network criticality. Low-cost infra-red (IR) thermopile sensors can be attached to street furniture to measure high resolution thermal variations in road surface temperatures, informing selective salting and dynamic routing for gritters in winter (Chapman & Bell, 2016) or used to measure railway track temperatures to assess the risk of track buckling in summer (Ferranti et al, 2016). Also, leaf wetness sensors on the railway network can measure moisture levels, which are important for anticipating autumn leaf-fall related adhesion issues of SPADs (signals passed at danger) and platform over-runs (Chapman et al, 2016). Network criticality could be combined with adhesion forecasts and buckling vulnerability information to inform the implementation of speed restrictions, targeting specific track sections and avoiding the need for blanket speed restrictions.

Beyond IoT sensors, crowdsourcing of data could change the way in which measurements are collected. Chapman et al (2017) explored the potential of using data from low-cost Netatmo weather stations to quantify the UHI in London. It was found that there are quality issues to resolve, but the results are promising for the future direction of urban meteorology. Furthermore, 'big data' can also be sourced from social networks or focus on flows of people, such as in transport corridors, providing large, complex data sets (Jin et al, 2015). In particular, the use of mobile phone data is an emerging area of research for travel behaviour to identify movements and flow patterns across transport modes (Wang et al, 2018). Mobility can be determined by multiple positioning systems from mobile devices, such as cell triangulation, GPS and wi-fi access. If high-resolution weather data can be combined with existing network criticality, based on operational service risk, and 'user criticality' derived from trends on how transport system users behave in different weather conditions, a more resilient transport system could be realised that not only focuses on physical infrastructure and operations, but aligns more with user needs and requirements.

Ultimately, the benefits of any future developments are only realised with stakeholder engagement and cooperation. Mattsson & Jenelius (2015) advocate more cross-disciplinary collaborations to create practical strategies for resilience between agencies and stakeholders and to translate the learning and knowledge from research into actions. This is particularly pertinent when considering the range of agencies and stakeholders involved with the provision and operation of infrastructure systems, such as local and national government, regulators, infrastructure owners and service operators. System level resilience is compromised if infrastructure is designed for one purpose and funded by one agency (The Resilience Shift, 2018). Decision making and thus network interventions should be holistic, considering external risks to assets and external consequences for connected networks, and locally driven.

The importance of visualising data and effective communication with key organisations, particularly at the local-level, cannot be underestimated. A novel concept is described by Eckersley et al (2018) of Newcastle City Council's use of 'decision theatres' for simulating the potential impacts of extreme weather on urban infrastructure services. Local partners were invited to interactive workshops held in a dedicated room, with large screens, where computer models of different scenarios and their consequences were visualised. Stakeholders were invited to change the model inputs and explore how different interventions would influence disruption across sectors in real-time, with the aim of triggering discussions between key local actors to develop a common understanding of challenges and a collective business case for interventions. The 'decision theatre' workshops could integrate the various sources of data outlined above, from IoT sensors, crowdsourcing and mobile phones, along with a layer of network criticality to provide an evidence-based and high-resolution assessment of consequence. As well as using network criticality to inform stakeholders, the feedback from stakeholders could also be used to refine the network criticality assessment methodology and learn more about local-scale infrastructure interdependencies.

6.5 Chapter Summary

In summary, this chapter has provided a reflection on the overall methodological approach of the thesis. The nature of the single points of failure identified was explored, finding that whilst differences in complexity and propagation potential exist between sectors, similar drivers and types of critical locations were found to exist. The criticality assessments in this thesis are generally representative of those in the existing literature, particularly for rail, and criticality defined by tacit knowledge. This information is however challenged by the high resolution and localised single points of failure in urban areas, a key contribution of the thesis. A critique of the methodology was then provided, highlighting the limitations of low sample sizes and system boundary definitions with their influence on fault reporting and performance metrics. The methodological caveats depend mainly on the scale of analysis, with a trade-off between national-scale analysis and a low level of detail in the existing literature and a trade-off between a high resolution and a low sample size in this thesis.

Recommendations were provided regarding the improvement of the existing network criticality assessment methodology, principally through obtaining a longer time series for the performance databases and enhanced fault reporting and cooperation between organisations from different sectors, driven largely by regulators. There are a variety of opportunities for extending the analysis, such as including a greater variety of stakeholder perspectives of criticality, scaling the assessment up to cover national and international management regions, as well as further interdependent networks including ICT infrastructure, and a more detailed event-based assessment of disruption evolution and propagation. Finally, potential future developments were considered in terms of how they may influence both the distribution of network criticality and the methodology for identifying single points of failure. High level drivers such as political and governance change can alter the way in which infrastructure is managed and funded, whilst the most direct impact will be the introduction of new technologies, mainly through the digitalisation of infrastructure and an increased reliance on IT and communications systems. The growth in 'big data' from IoT technology and sensors, for both smart infrastructure and weather conditions, allows the potential for integration of high resolution information at the local-scale.

Chapter 7 will highlight the key findings and overall conclusions of the thesis. The contribution of the thesis to the fulfilment of the stated aim and objectives will be described.

CHAPTER SEVEN: **CONCLUSIONS**

7.1 Chapter Overview

Within this thesis, Chapter 1 has provided an introduction and overall background to the research, Chapters 2-4 have presented network criticality assessments for three different infrastructure applications (electricity distribution, rail transport and railway traction power dependencies on external electricity feeder substations), Chapter 5 has explored the implications of calculated network criticality for infrastructure system management within the decision-making process whilst Chapter 6 has evaluated the output and methodological approach of the network criticality assessments, providing recommendations on potential improvements, extensions and the influence of projected future developments for the nature and identification of single points of failure. In this chapter, the overall conclusions and key findings of the thesis are outlined, organised by the five specific objectives of the research, as described in Chapter 1.

7.2 Fulfilment of Aim and Objectives

The overall aim of this thesis was ***to develop and demonstrate a local-scale and high-resolution network criticality assessment methodology for the evidence-based identification of single points of failure within infrastructure systems of different scales of complexity and dependency***. A series of specific objectives were designed to facilitate the achievement of this aim.

7.2.1 Objective One

To evaluate network criticality for a relatively less complex infrastructure system – electricity distribution.

Chapter 2 presented a network criticality assessment for electricity distribution infrastructure, identifying single points of failure that can inform a prioritisation scheme for the targeted delivery of a range of resilience interventions across GB DNOs. The existing literature in the field mainly involves large national-scale models and simulations of electricity network vulnerability, either based purely on network topology or including system supply and demand dynamics, such as power flows and substation loadings. However, the scale of the models necessitates simplifications of network behaviour, including the assumption that electricity follows the shortest path between two points. Therefore, due to the inherent uncertainty in existing models, an evidence-based approach to quantifying network criticality was required, using historical DNO performance data to capture the complex behavioural mechanisms of the electricity distribution network and increase the reliability and certainty of the resultant prioritisation scheme. Performance metrics can be used to identify single points of failure, however the current approach within the electricity industry is to use high-level financial costs of disruption relative to the national average. To facilitate a more localised and high-resolution assessment of network criticality, historical asset fault data was obtained for WPD's South West and West Midlands licence areas between 2009 and 2014, with a pure service-level metric of SML applied to quantify and map network criticality within the two management regions, with a criticality band assigned to each substation reflecting the average duration of a power outage experienced should equipment at that substation site fail.

The resultant network criticality assessment demonstrated that a data-driven methodology was able to define highly localised single points of failure for a relatively low complexity electricity distribution network, particularly within urban areas, that can add value to the current understanding of priority substations, as well as highlighting the overall pattern of operational service risk, with commonly appreciated centres of high criticality, at high-voltage substations in major conurbations. There is a contrast in the spatial distribution of criticality between the two licence areas, mainly influenced by geography, with the South West having a broad coverage of critical locations with an influence of renewable generation sites, whilst the West Midlands has more focused clusters of criticality, influenced by heavy industrial sites. There is, however, commonality between the licence areas in that the majority of critical substations are concentrated around major urban areas, such as Bristol and Birmingham, with a higher concentration of infrastructure supplying a higher population density resulting in higher substation loadings. City-scale networks are clearly evident, with the relative criticality of substations within the boundaries of an urban area providing a detailed layer of information for decision making. There are clear advantages through defining criticality bands within single licence areas, allowing the identification of locations that may not feature as prominently in a national assessment but are very important regionally, whilst a service-level performance metric treats all power outages of the same magnitude equally, identifying the influence of industrial and distributed generation connections which would be unlikely to be identified using a financial metric. However, the caveats and limitations to the performance data must be recognised, with the general rarity of power cuts at a single site resulting in small sample sizes for most locations. There is a clear trade-off between spatial granularity and sample size, but for licence area level management a high resolution of analysis is essential despite the limitations.

7.2.2 Objective Two

To evaluate network criticality for a relatively more complex infrastructure system – railway transportation.

Chapter 3 presented a network criticality assessment for railway transport infrastructure, identifying single points of failure that can inform a prioritisation scheme for the targeted delivery of a range of resilience interventions across the routes of the GB rail network. The existing literature in the field mainly involves large national-scale models and simulations of transport network vulnerability, either based purely on network topology or including system supply and demand dynamics, such as passenger flows and timetables. However, the scale of the models necessitates simplifications of network behaviour, with the omission of highly complex elements such as TOC prioritisations and train-crew diagrams. Therefore, due to the inherent uncertainty in existing models, an evidence-based approach to quantifying network criticality was required, using historical performance data from NR to capture the complex behavioural mechanisms of the railway network and increase the reliability and certainty of the resultant prioritisation scheme. Performance metrics can be used to identify single points of failure, however the current approach within the rail industry is to use high-level financial compensation costs of disruption relative to the national average, and at a coarse spatial resolution. To facilitate a more localised and high-resolution assessment of network criticality, historical train delay data was obtained from NR's TRUST system for the Wessex and LNW (South) routes of the GB rail network between 2011 and 2016, with a pure service-level metric of DM applied to quantify and map network criticality within the two routes, with a criticality band assigned to each track section, station, junction or siding reflecting the average magnitude of delay to services experienced should equipment at that location fail.

The resultant network criticality assessment demonstrated that a data-driven methodology was able to define highly localised single points of failure for a comparatively more complex rail transport network, particularly within urban areas, that can add value to the current understanding of priority locations, as well as highlighting the overall pattern of operational service risk, with commonly appreciated centres of high criticality, in major conurbations, on mainlines and at key junctions. There is a contrast in the spatial distribution of criticality between the two routes, mainly influenced by connectivity and service patterns, with Wessex having quite distinct critical clusters dominated by London and the South Coast given that the west of the route is quite isolated, whilst LNW (South) is dominated by the WCML and has more long-distance services leading to a greater coverage of critical locations through the route. There is, however, commonality between the routes in that the majority of critical locations have similar attributes, such as freight lines, key junctions, major hubs and depots. City-scale networks are clearly evident, particularly for London and Birmingham, with the relative criticality of locations within the boundaries of an urban area providing a detailed layer of information for decision making. The same is true for mainlines, which may be worthy of prioritisation in their entirety but still have more and less critical sections. There are clear advantages through defining criticality bands within single routes, allowing the identification of locations that may not feature as prominently in a national assessment but are very important regionally, whilst a service-level performance metric treats all delays of the same magnitude equally, identifying the influence of more isolated single points of failure which would be unlikely to be identified using a financial metric. The granularity of critical locations is particularly apparent for a highly complex network, where locations away from traditional criticality centres are also identified as highly critical, on branch lines and at relatively minor stations, highlighting the contribution of an increase spatial resolution. The increased granularity is highlighted by the fact that of the 41 Band 1 critical locations across both routes, 23 are track sections, with 18 sections less than 10km in length. Using shorter track sections allows prioritisation of resource allocation to have a much more localised focus, targeting more specific locations and saving time and money. However, the caveats and limitations to the performance data must be recognised, as the sample size of incidents at different locations can vary significantly, for example, there are generally smaller sample sizes for branch lines and greater sample sizes for mainlines. There is a clear trade-off between spatial granularity and sample size, but for route level management a high resolution of analysis is essential despite the limitations. Some of the more minor single points of failure may require careful interpretation to separate systematic issues from rare yet high impact events.

7.2.3 Objective Three

To evaluate network criticality for two dependent infrastructure systems – traction feeder supplies to an electrified railway.

Chapter 4 presented a network criticality assessment for two dependent infrastructure systems. A case-study of a traction feeder system for an electrified railway was used the illustrate the dependency of railway infrastructure on external electricity distribution infrastructure, identifying single points of failure that can inform a cross-system prioritisation scheme for the targeted delivery of a range of resilience interventions across both DNOs and

NR. The existing literature on interdependent infrastructure network vulnerability takes a similar methodological approach to single-system studies, involving large national-scale network models and simulations incorporating both topological and operational characteristics. Therefore, the scale of the models necessitates similar simplifications of network behaviour, principally regarding network dynamics by modelling demand through passenger and population statistics. However, with interdependent network criticality there is also a need to model the connectivity between infrastructure, either through their co-location in the same geographic corridor or through physical asset connections. Increasing the complexity of analysis amplifies the issues regarding uncertainty and reliability. When there are also simplifications of dependencies, such as proximity-based assumptions where pathways are created between an asset and its nearest dependent asset. For example, it is assumed that the geographically closest electrical substation is the source of the power supply to airports and traction power to railway lines. Uncertainty in both system behaviour and dependencies means that the application of such methods for local-level infrastructure management is significantly compromised.

As a result, an evidence-based approach was required for both identifying cross-system dependencies and quantifying dependent network criticality. To achieve the latter, the electricity distribution network criticality bands calculated in Chapter 2 and the railway network criticality bands from Chapter 3 were applied to a localised case-study of the Cross City railway line (West Midlands, UK) and electricity distribution substation dependencies for traction power. To overcome the assumptions in the existing research, specific dependencies between track sections and substations were identified using information supplied by WPD and NR, examining electricity distribution network diagrams and traction feeder diagrams along with GIS mapping data for both networks. The sources of information used were found to be highly detailed and valuable for identifying dependences at a high resolution. It was found that traction power to the Cross City line is supplied by four possible external feeder substations, including normal and alternate supplies offering an N-2 degree of redundancy. These substations are then directly supplied by a series of substations in WPD's distribution network and ultimately a higher voltage substation in NG's transmission network. It was also observed that none of the four feeder stations are trackside to the Cross-City line itself, therefore geographical proximity assumptions would likely be invalid in this case.

The resultant dependent network criticality assessment demonstrated that a data-driven methodology was able to define highly localised spatial correlations in single points of failure across two connected infrastructure systems, that can add value to the current understanding of prioritisation within networks by assessing external risk and consequence. Whilst the distribution of criticality had limited variability across the four feeder supplies, with most substations towards the lower end of the risk spectrum, it was possible to distinguish between the four feeder supplies and the individual substations using the calculated criticality bands to suggest the order in which they should be prioritised. The alternate supplies seem to be more resilient, which highlights the benefit of redundancy in supply should the normal feeders fail. There are clear advantages to an evidence-based assessment of dependent network criticality at the local-scale, providing a high-resolution prioritisation of specific assets or locations with increased certainty of asset dependencies, highlighting the need for cross-system resilience interventions. However, the definition of system boundaries presents a reliability challenge when combining performance databases designed for single-sector use and identifying cascading failure pathways. The sample size caveats to the electricity distribution and railway transport network criticality bands remain, but the main issue in this case is the lack of coordination between the two metrics used, for example, failures at feeder stations have no reported consequence in WPD's database yet they have a consequence for railway operations in terms of delay to services. Therefore, whilst it is possible to examine spatial correlations between the metrics, the difference in fault reporting and attribution between infrastructure sectors is identified as an area for potential improvement, with greater coordination required between infrastructure owners and operators to move towards a common cross-network reporting scheme.

7.2.4 Objective Four

To explore the practical implications of the presented network criticality assessments for infrastructure system management.

Chapter 5 explored the wider context of network criticality assessment and the overall implications for the decision-making process and infrastructure system management. Network criticality can help to inform prioritisation for resource allocation across multiple geographic scales, multiple systems or combinations of systems, at multiple levels of operational and topological complexity. A key role of network criticality is in the formalisation of priorities, within and between infrastructure systems, through the documentation of objectively defined critical locations. Information on the types of locations classified as highly critical can reinforce existing tacit knowledge, whilst the high resolution single points of failure can also challenge the existing understanding of criticality. Network criticality also has a broad applicability across a range of infrastructure management functions. By calculating the network criticality bands based upon service-level risk, as opposed to financial costs, a measure of the likely degree of operational management difficulty resulting from incidents occurring at each location is attained. Therefore, network criticality has applications for day-to-day functions such as event response, maintenance as well as longer-term investment in infrastructure renewals and upgrades.

The role of network criticality within risk assessment and the planning of resilience interventions was also explored, within the context of the broader decision-making process for the implementation of different options. Network criticality is one layer of information that can inform the prioritisation of risks, which has far greater value when integrated in a risk assessment with other layers, such as hazards, vulnerabilities including defined asset-weather relationships and asset condition as well as multiple organisational and stakeholder perspectives, such as passengers and finance. The resolution of network criticality increasingly matches that at which information on hazards and vulnerability is achievably or currently available at, assisting risk-based targeting of decisions using GIS risk mapping. Combined, these layers of information can support the implementation of multiple types of resilience options, from investment in asset robustness to broader options of redundancy and recovery. Criticality can be incorporated in preparedness actions and resource allocation for extreme weather before, during and after a forecast event, for example, should asset failures occur in multiple locations simultaneously, the criticality assessment can be applied to determine which sites personnel should be dispatched to first. Practical interventions such as lightning protection for electrical transformers and railway vegetation management can also be targeted more efficiently. Urban climate resilience is a particular priority and combining a criticality layer with a UHI layer, for example, would allow the prioritisation of adaptation work to transformers at the city-scale. There is also a need for more operational resilience measures, particularly for cascades of failure, involving interventions such as the installation of backup generators at mobile phone base stations to maintain communications should they experience a loss of power. Contingency plans for how to manage disruption and clear crisis management procedures are vital preparation for disruption management rapid recovery, such as having buses on standby at railway stations to transport passengers in the event a line is blocked. A localised and multi-system criticality layer can inform targeted decision making regarding the locations around which contingencies should be arranged, where the risk of cascading failure and consequence to a system is greatest. Diesel rolling stock could be on standby for introduction to service and to rescue stranded EMUs at critical locations should a loss of electric traction supply be experienced, as well as the introduction of IPEMUs.

An overall vision for holistic decision making, where holistic risks inform holistic resilience, is based upon the realisation of value from infrastructure through the realisation of value from information. This involves the effective and intelligent management of information of various forms through a range of systems, actors and perspectives and the development of information sharing and communication mechanisms for coordinated decision making and actions. A specific example is the role of Climate Services, integrating meteorological information and non-meteorological information, such as network criticality, to provide bespoke services to organisations based on their individual decision needs. At a high level, international standards and organisational models can inform a decision-making process by highlighting the range of factors that influence an organisation's asset management approach and offering direction for the application and design of information systems for integrating activities within and between organisations. The broad scope of international standards and organisational models can be refined and focused towards specific sectors and applications through the development of frameworks for decision making. Such frameworks involve elements of risk assessment and the generation of resilience options, providing the functionality to consider all components of resilience and the influence of multiple perspectives and experience of stakeholders. The cyclical nature of frameworks also allows for continuous development of system resilience, through the evaluation of interventions which incorporates new information, learning and socioeconomic context into future decision making.

7.2.5 Objective Five

To evaluate the contribution of the developed network criticality assessment methodology and explore future directions for the quantification of infrastructure network criticality.

Chapter 6 provided a reflection on the overall methodological approach of the thesis. An interpretation of the single points of failure identified was provided, highlighting the influence of the differences in complexity between the railway and electricity distribution sectors on their respective criticality distributions. The railway network has significantly greater operational difficulty, complex service patterns and disruption propagation potential, and therefore has a significantly greater spatial distribution of single points of failure compared to the electricity distribution network where critical locations tend to be concentrated in key areas. However, similar drivers and types of critical locations were found to exist between infrastructure systems. Essentially, criticality is a result of network supply and demand dynamics, therefore, critical substations tend to be within or around larger towns and cities, which act as major load centres, and critical railway locations tend to be around major hubs, key junctions and mainlines, which are areas of high demand for train services and/or high frequency and volume of traffic. The criticality assessments in this thesis were found to be generally representative of those in the existing literature and of criticality defined by tacit knowledge, particularly for rail where direct comparisons were possible. The main difference is that the larger national-scale simulations and tacit knowledge either do not identify the high resolution and localised single points of failure in urban areas, or do not recognise the importance of these locations - a key contribution of the thesis is the definition of these localised priorities. The granularity of critical locations is even more evident when undertaking a dependent infrastructure network criticality assessment, with connections between individual assets used to bring consequence metrics on both networks together a high spatial resolution is paramount.

A critique of the methodology was provided, highlighting the main limitations with the network criticality assessments. The low sample size constraints of the service performance databases used influence the reliability of the results and therefore careful interpretation of the characteristics of more localised single points of failure is recommended. However, the low sample sizes at more remote railway locations present a greater issue than the single failures at electrical substations, due to the greater variability in asset footprints. Furthermore, for dependent infrastructure network criticality, system boundary definitions influence fault reporting and performance metrics. In general, there is very limited consideration of externalities in both causation and consequence across the reporting of electricity supply interruptions and train delays. The methodological caveats depend mainly on the scale of analysis, with a trade-off between national-scale analysis and a low level of detail in the existing literature and a trade-off between a high resolution and a low sample size in this thesis. Therefore, downscaling existing models and simulations and upscaling the single point of failure methodology in this thesis would present a different set of challenges.

Recommendations were provided regarding the improvement of the existing network criticality assessment methodology. Obtaining a longer time series for the performance databases would provide a greater distribution of event magnitudes, increase the spatial coverage of network criticality, and provide more reliable evidence of cascading failure pathways and consequences. Enhanced fault reporting and cooperation between organisations from different sectors, driven largely by regulators, would increase the level of detail in the information provided and a greater appreciation of system-wide consequences. This can be achieved by improving consequence metrics to account for impacts to external assets, as well as more detailed fault attribution to acknowledge external sources of risk and allow cascading failure pathways to be traced. This thesis presents a criticality assessment using the best available data, which can inform future network management. Improved decision making, both locally and holistically focused, is required alongside developments in the data and metrics used to underpin those decisions.

There are a variety of opportunities for extending the analysis. Including a greater variety of stakeholder perspectives of criticality would help progress towards a more holistic assessment of risk. Scaling the assessment up to cover national and international management regions, as well as further interdependent networks including ICT infrastructure, would improve the application and transferability methodology, provided that data of the appropriate quality was available and accessible. A more detailed event-based assessment of disruption evolution and propagation would provide more information for infrastructure owners and operators to allow them to adapt their response and contingency plans further. Potential future developments were also considered in terms of how they may influence both the distribution of network criticality and the methodology for identifying single points of failure. High level drivers including political and governance change, such as Brexit and devolution, can alter the way in which infrastructure is managed and funded. The most direct impact on infrastructure network criticality will be the introduction of new technologies and network developments, such as railway electrification and electric vehicle usage. The main transformation is likely to be the increasing digitalisation of infrastructure and the reliance on IT and communications systems, such as ETCS signalling on the railway network as part of the Digital Railway Strategy and smart grids for electricity distribution as DNOs transition to DSOs. Whilst such technological advancements may increase efficiency and capacity, they also heighten the need for system-wide resilience. A major benefit of digital technology is the growth in 'big data' from IoT technology and sensors, for both smart infrastructure and weather conditions, alongside mobile phone or social network data which allows the potential for integration of high resolution information at the city-scale. Ultimately, the benefits of any future developments are only realised with stakeholder engagement and cooperation, therefore visualisations and tools can be used to encourage stakeholder interaction and coordinated planning for disruptive events across multiple infrastructure sectors.

7.3 Concluding Remarks

Overall, this thesis has achieved its aim by ***developing and demonstrating a local-scale and high-resolution network criticality assessment methodology for the evidence-based identification of single points of failure within infrastructure systems of different scales of complexity and dependency*** through the fulfilment of the five research objectives. The utility of the network criticality assessments in this thesis is not only through the direct application of mapped single points of failure for the prioritisation of resource allocation and targeted resilience interventions, but also through the influence of the limitations and opportunities identified. The recommendations of this thesis can help to promote the improvement of data and information systems within and between infrastructure owners and operators, increasing the potential for cross-sector collaboration in network criticality assessment and the planning and delivery of resilience measures. The ultimate vision is for a local-scale, high-resolution and holistic systems-of-systems analysis of interdependent infrastructure, to be informed by robust, current and accessible data on hazards, vulnerability and consequence alongside accurate information for asset dependencies and cascading failure pathways.

REFERENCES

Ackoff, RL. (2001) *A brief guide to interactive planning and idealized design* [Online] https://www.ida.liu.se/~steho87/und/htdd01/AckoffGuidetoIdealizedRedesign.pdf [Accessed 11/2/2019].

African Development Bank, (2018). Financing Africa's Infrastructure: New Strategies, Mechanisms, and Instruments, Chapter 4, p95-124 in African Development Bank (eds.) *Financing Africa's Infrastructure* [online] https://www.afdb.org/fileadmin/uploads/afdb/Documents/Publications/2018AEO/African_Economic_Outlook_2018_-_EN_Chapter4.pdf [Accessed 20/7/2018].

Armitt, J. Baggs, M. Baveystock, N. Dalton, G. Dickie, J. Hall, J. Holliday, S. Kelly, R. Lamonte, J. Mair, R. Owen, R. Threlfall, R. and Williams, G. (2016) *National Needs Assessment - A Vision for UK Infrastructure* [online] https://www.ice.org.uk/getattachment/news-and-insight/policy/national-needs-assessment-a-vision-for-uk-infrastr/National-Needs-Assessment-PDF-(1).pdf.aspx#_ga=2.222494995.946978139.1528376974-335235961.1523267290 [Accessed 3/5/2018].

Asian Development Bank, (2017). Meeting Asia's Infrastructure Needs [online] https://www.adb.org/sites/default/files/publication/227496/special-report-infrastructure.pdf [Accessed 25/7/2018].

Association for Project Management, (2018). *Systems thinking: How is it used in project management?* Research Fund Series [Online] https://www.apm.org.uk/media/17308/systems-thinking_final.pdf [Accessed 11/2/2019].

Augutis, J. Joksas, B. Krikstolaitis, R. and Urbonas, R. (2016) The assessment technology of energy critical infrastructure. *Applied Energy*, 162, 1494-1504.

Azevedo, JA. Chapman, L. and Muller, CL. (2016) Urban heat and residential electricity consumption: A preliminary study. *Applied Geography*, 70, 59-67.

Baker, CJ. Chapman, L. Quinn, A. Dobney, K. (2010) Climate change and the railway industry: a review. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science,* 224, 519-527

Baker, J. (2018) The UK's Diesel Phase-Out and Rail Innovation. *FutureRail*, 61 [online] https://rail.nridigital.com/future_rail_may18/the_uk_s_diesel_phase-out_and_rail_innovation [Accessed 1/6/2018].

Baruah, PJ. Eyre, N. Qadrdan, M. Chaudry, M. Blainey, S. Hall, J. Jenkins, N. and Tran, M. (2014) Energy system impacts from heat and transport electrification. *Proceedings of the Institution of Civil Engineers – Energy*, 167 (3), 139-151.

Beckford, J. (2014) *The Railway System*. Beckford Consulting. Presentation [Online] http://beckfordconsulting.com/wp-content/uploads/2014/03/The-Railway-System-TRACCA.pdf [Accessed 2/5/2018].

Beckford, J. (2016). *The Intelligent Organisation: Realising the Value of Information*; Routledge: Abingdon, UK.

Bier, VM. Haphuriwat, N. Haphuriwat, J. Zimmerman, R. and Culpen, AM. (2008) Optimal Resource Allocation for Defense of Targets Based on Differing Measures of Attractiveness. *Risk Analysis*, 28 (3), 763-770.

Bigger, JE. Willingham, MG. and Krimgold, F. (2009) Consequences of critical infrastructure interdependencies: lessons from the 2004 hurricane season in Florida. Int. J. Critical Infrastructures, 5(3), 199-219.

Birmingham City Council, (2016). *Information Communication Technology & Digital Strategy 2016 – 2021* [online] https://www.birmingham.gov.uk/download/downloads/id/5029/birmingham_city_council_ict_and_digital_strategy_2016-2021.pdf [Accessed 10/8/2018].

Blockley, D. and Godfrey, P. (2017) *Doing it Differently: Systems for rethinking infrastructure*, Second edition, ICE Publishing. London, UK.

Bollinger, LA. And Dijkema, GPJ. (2016) Evaluating infrastructure resilience to extreme weather – the case of the Dutch electricity transmission network. *EJTIR*, 16 (1), 214-239.

Bombardier, (2015). *Battery-driven Bombardier Electrostar Electrical Multiple Unit* [online] https://www.bombardier.com/content/dam/Websites/bombardiercom/Projects/supporting-documents/BT_Battery-Driven-Bombardier-Electrostar_LowRes.pdf [Accessed 5/6/2018].

British Telecom, (2017). *Protecting the UK's Critical National Infrastructure Defence and Security Information Circle* [online] https://business.bt.com/content/dam/bt/business/PDFs/solutions/BT_DSIC_white_paper.pdf [Accessed 11/8/2018].

BS ISO 55000:2014. *Asset management – Overview, principles and terminology*, BSI Standards Publication.

Buldyrev, SV. Parshani, R. Paul, G. Stanley, HE. and Havlin, S. (2010) Catastrophic cascade of failures in interdependent networks. *Nature*, 464, 1025-1028.

Burr, T. Merrifield, S. Duffy, D. Griffiths, J. Wright, S. and Barker, G. (2008) Reducing passenger rail delays by better management of incidents, National Audit Office for the Office of Rail Regulation [online] https://publications.parliament.uk/pa/cm200708/cmselect/cmpubacc/655/655.pdf [Accessed 19/8/2018].

Cabinet Office, (2011). *Keeping the Country Running: Natural Hazards and Infrastructure - A Guide to improving the resilience of critical infrastructure and essential services* [online] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/61342/natural-hazards-infrastructure.pdf [Accessed 20/7/2018].

Cabinet Office, (2013). *The role of Local Resilience Forums: A reference document* [online] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/62277/The_role_of_Local_Resilience_Forums-_A_reference_document_v2_July_2013.pdf [Accessed 23/7/2018].

Cabinet Office, (2017). *Public Summary of Sector Security and Resilience Plans 2017* [online] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/678927/Public_Summary_of_Sector_Security_and_Resilience_Plans_2017__FINAL_pdf__002_.pdf [Accessed 6/7/2018].

Carbno, C. (1999) Optimal Resource Allocation for Projects. *Project Management Journal*, 30 (2), 22-31.

Cardona, OD. van Aalst, MK. Birkmann, J. Fordham, M. McGregor, G. Perez, R. Pulwarty, RS. Schipper, ELF. and Sinh, BT. (2012) Determinants of risk: exposure and vulnerability. In: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation [Field, CB. Barros, V. Stocker, TF. Qin, D. Dokken, DJ. Ebi, KL. Mastrandrea, MD. Mach, KJ. Plattner, GK. Allen, SK. Tignor, M. and Midgley, PM. (eds.)]. *A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC)*. Cambridge University Press, Cambridge, UK, and New York, NY, USA, p 65-108.

Cats, O. Yap, M. and van Oort, N. (2016) Exposing the role of exposure: Public transport network risk analysis. *Transportation Research Part A – Policy and Practice*, 88: 1-14.

Centre for the Protection of National Infrastructure (2018) *Critical National Infrastructure* [online] https://www.cpni.gov.uk/critical-national-infrastructure-0 [Accessed 26/7/2018].

Chang, SE. McDaniels, TL. Mikawoz, J. and Peterson, K. (2007) Infrastructure failure interdependencies in extreme events: power outage consequences in the 1998 Ice Storm. *Natural Hazards*, 41(2), 337-358.

Chapman, L. (2007) Transport and climate change: a review. *Journal of Transport Geography*, 15, 354-367.

Chapman, L. and Bell, SJ. (2016) Low-cost Road Surface Temperature sensing enabled by the Internet of Things. *Proceedings of the 18th SIRWEC Conference*, 28th-30th April 2016, Fort Collins, Colorado.

Chapman, L. Azevedo, JA. and Prieto-Lopez, T. (2013) Urban heat and critical infrastructure networks: a viewpoint. *Urban Climate*, 3, 7-12.

Chapman, L. Bell, C. and Bell, S. (2017) Can the crowdsourcing data paradigm take atmospheric science to a new level? A case study of the urban heat island of London quantified using Netatmo weather stations. *International Journal of Climatology*, 37, 3597-3605.

Chapman, L. Muller, CL. Young, DT. Warren, EL. Grimmond, CSB. Cai, X-M. and Ferranti, EJS. (2015) The Birmingham Urban Climate Laboratory: An open meteorological testbed and challenges of the smart city. *Bulletin of the American Meteorological Society*, 96, 1545-1560.

Chapman, L. Warren, EL. and Chapman, VL. (2016) Using the internet of things to monitor low adhesion on railways. *Transport*, 169, 1-9.

Checkland, P. (2000) Soft systems methodology: A thirty year retrospective. *Systems Research and Behavioral Science*, 17, S11-S58.

Civil Contingencies Act, (2004). [online] https://www.legislation.gov.uk/ukpga/2004/36/pdfs/ukpga_20040036_en.pdf [Accessed 22/7/2018].

Copernicus, (2018). *Copernicus Climate Change Service* [online] https://climate.copernicus.eu/ [Accessed 21/7/2018].

Curtis, S. Fair, A. Wistow, J. Val, DV. and Oven, K. (2017) Impact of extreme weather events and climate change for health and social care systems. *Environmental Health*, 16(Suppl 1):128, 23-32.

Dai, L. (2016) *Intelligent Real-Time Train Rescheduling Management for Railway System*. A thesis submitted to the University of Birmingham for the degree of Doctor of Philosophy, School of Engineering, Birmingham, UK.

Data and Analytics Facility for National Infrastructure, (2018). *Homepage* [online] http://www.dafni.ac.uk/ [Accessed 3/6/2018].

Dawson, D. Shaw, J. and Gehrels, WR. (2016) Sea-level rise impacts on transport infrastructure: The notorious case of the coastal railway line at Dawlish, England. *Journal of Transport Geography*, 51, 91-109.

Dawson, RJ. Thompson, D. Johns, D. Wood, R. Darch, G. Chapman, L. Hughes, PN. Watson, GVR. Pauslon, K. Bell, S. Gosling, SN. Powrie, W. and Hall, JW. (2018) A systems framework for national assessment of climate risks to infrastructure. *Phil. Trans. R. Soc. A*, 376.

Delay Attribution Board, (2018). *Delay Attribution Principles and Rules* [online] http://www.delayattributionboard.co.uk/documents/dag_pdac/April%202018%20DAPR.pdf [Accessed 1/6/2018].

Department for Transport, (2014a). *Transport Resilience Review – A review of the resilience of the transport network to extreme weather events* [online] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/335115/transport-resilience-review-web.pdf [Accessed 10/4/2018].

Department for Transport, (2014b). *Values of Time and Vehicle Operating Costs, TAG Unit 3.5.6, Transport Analysis Guidance* (TAG) [online] http://webarchive.nationalarchives.gov.uk/20140304110038/http:/www.dft.gov.uk/webtag/documents/expert/pdf/U3_5_6-Jan-2014.pdf [Accessed 17/8/2018].

Department for Transport, (2016). *Rail Cyber Security, Guidance to Industry* [online] https://www.rssb.co.uk/Library/improving-industry-performance/2016-02-cyber-security-rail-cyber-security-guidance-to-industry.pdf [Accessed 2/5/2018].

Department for Transport, (2018). *Joint Rail Data Action Plan - Addressing Barriers to Make Better use of Rail Data* [online] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/733043/joint-rail-data-action-plan-2018.pdf [Accessed 12/8/2018].

Dey, P. Mehra, R. Kazi, F. Wagh, S. and Singh, NM. (2016) Impact of Topology on the Propagation of Cascading Failure in Power Grid. *IEEE Transactions on Smart Grid*, 7 (4), 1970-1978.

Digital Railway, (2018). *Digital Railway Strategy April 2018* [online] http://digitalrailway.co.uk/wp-content/uploads/2018/05/Digital-Railway-Strategy.pdf [Accessed 10/8/2018].

Dobney, K. Baker, CJ. Chapman, L. and Quinn, AD. (2010) The Future Cost to the UK's Railway Network of Heat Related Delays and Buckles Caused by the Predicted Increase in High Summer Temperatures Due to Climate Change. *Proc IMechE Part F- J Rail and Rapid Transit*, 224(1), 25-34.

Dobney, K. Baker, CJ. Quinn, AD. and Chapman, L. (2009) Quantifying the Effects of High Summer Temperatures due to Climate Change on Buckling and Rail Related Delays in south-east UK. *Meteorol Appl*, 16(2), 245-251.

Dunn, S. and Wilkinson, SM. (2013) Identifying Critical Components in Infrastructure Networks Using Network Topology. *Journal of Infrastructure Systems*, 19 (2), 157-165.

Durango-Cohen, PL. and Madanat, SM. (2008) Optimization of inspection and maintenance decisions for infrastructure facilities under performance model uncertainty: A quasi-Bayes approach. *Transportation Research Part A: Policy and Practice*, 42, 1074–1085.

Eckersley, P. England, K. and Ferry, L. (2018) Sustainable development in cities: collaborating to improve urban climate resilience and develop the business case for adaptation. Public Money & Management, 38 (5), 335-344.

Eddowes, MJ. Waller, D. Taylor, P. Briggs, B. Meade, T. and Ferguson, I. (2003) *Rail Safety and Standards Board: Safety Implications of Weather, Climate and Climate Change*. Issue 2, Report no. AEAT/RAIR/76148/R03/005 [online] http://www.climate-change-uk.info/sites/RailSafetyclimatechange.pdf [Accessed 2/3/2018].

Ellis, I. (2010) *Ellis' British Railway Engineering Encyclopaedia*, Second Edition, Self-Published, UK.

Energy Networks Association, (2012). *Instructions for Reporting to the National Fault and Interruption Reporting Scheme.* Engineering Recommendation G43, Issue 3, Amendment 1, 2012.

Engineering Council, (2011). *Guidance on Risk for the Engineering Profession* [Online] https://www.engc.org.uk/engcdocuments/internet/Website/Guidance%20on%20Risk.pdf [Accessed 13/2/2019].

Evans, D. (2011) *The Internet of Things: How the Next Evolution of the Internet Is Changing Everything*, Cisco Internet Business Solutions Group (IBSG) White Paper [online] https://www.cisco.com/c/dam/en_us/about/ac79/docs/innov/IoT_IBSG_0411FINAL.pdf [Accessed 10/8/2018].

Faramondi, L. Setola, R. Panzieri, S. Pascucci, F. and Oliva, G. (2018) Finding critical nodes in infrastructure networks. *International Journal of Critical Infrastructure Protection*, 20, 3-15.

Farrell, D. Gebre, B. Hudspeth, C. and Sellgren, A. (2013) Risk-based resource allocation – Focusing regulatory and enforcement efforts where they are needed the most, *McKinsey Working Papers on Risk*, Number 42, McKinsey & Company.

Ferranti, E. Chapman, L. and Whyatt, D. (2017) A Perfect Storm? The collapse of Lancaster's critical infrastructure networks following intense rainfall on 4/5 December 2015. *Weather*, 72 (1), 3-7.

Ferranti, E. Chapman, L. Lowe, C. McCulloch, S. Jaroszweski, D. and Quinn, A. (2016) Heat-Related Failures on Southeast England's Railway Network: Insights and Implications for Heat Risk Management. *Wea. Climate Soc,* 8, 177-191.

Fisher, R. Quinn, A. and Jaroszweski, D. (2018) *Hazardous Weather, Susceptible Infrastructure and Vulnerable Railways*, School of Engineering, University of Birmingham, UK. Academic Poster.

Frontier Economics, (2012). *Systemic Risks and Opportunities in UK infrastructure* [online] https://www.frontier-economics.com/documents/2013/10/frontier-report-systemic-risk-and-opportunities-in-uk-infrastructure-2.pdf [Accessed 5/7/2018].

Golany, B. Kaplan, EH. Marmur, A. and Rothblum, UG. (2009) Nature plays with dice – terrorists do not: Allocating resources to counter strategic versus probabilistic risks. *European Journal of Operational Research*, 192, 198-208.

Guthrie, P. and Konaris, T. (2012) Infrastructure Resilience, Report produced for the Government Office of Science, Foresight project 'Reducing Risks of Future Disasters: Priorities for Decision Makers [online] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/286993/12-1310-infrastructure-and-resilience.pdf [Accessed 30/7/2018].

Hall, J. Thacker, S. Ives, M. Cao, Y. Chaudry, M. Blainey, S. and Oughton, E. (2017) Strategic analysis of the future of national infrastructure. *Proceedings of the Institution of Civil Engineers - Civil Engineering*, 170 (1), 39-47.

Haughwout, AF. (2001) Infrastructure and social welfare in metropolitan America. *FRBNY Economic Policy Review*, December 2001.

Hayden, A. Tight, M. and Burrow, M. (2017) Is Reducing Car Use a Utopian Vision? *Transportation Research Procedia*, World Conference on Transport Research - WCTR 2016 Shanghai. 10-15 July 2016, 25C, 3948-3960.

Heathcote, C. (2017) *Infrastructure demand: A major global challenge*, Global Infrastructure Hub Blog [online] https://www.gihub.org/blog/global-infrastructure-demands/ [Accessed 25/7/2018].

Hickman, AL. Baker, CJ, Cai, X. Delgado-Saborit, JM. and Thornes, JE. (2018) Evaluation of air quality at the Birmingham New Street Railway Station. *Proc IMechE Part F: J Rail and Rapid Transit*, 232 (6), 1864-1878.

High Speed Two, (2018). *Realising the potential* [online] https://s3-eu-west-2.amazonaws.com/1042421-static-assets-production/wp-content/uploads/2018/07/17154802/22403_Realising_the_potential_WEB.pdf [Accessed 12/8/2018].

Hines, P. Cotilla-Sanchez, E. and Blumsack, S. (2010) Do topological models provide good information about electricity infrastructure vulnerability? *Chaos*, 20 (3), 033122.

HM Government, (2015a). *Digital Built Britain Level 3 Building Information Modelling – Strategic Plan* [online] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/410096/bis-15-155-digital-built-britain-level-3-strategy.pdf [Accessed 3/4/2018].

HM Government, (2015b). *National Security Strategy and Strategic Defence and Security Review 2015 - A Secure and Prosperous United Kingdom* [online] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/478933/52309_Cm_9161_NSS_SD_Review_web_only.pdf [Accessed 27/7/2018].

HM Treasury, (2013). *National Infrastructure Plan 2013* [online] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/263159/national_infrastructure_plan_2013.pdf [Accessed 8/9/2014].

Hodgkinson, S. Jaroszweski, D. Quinn, A. and Chapman, L. (in review) Single point of failure assessment methodology for evaluating railway network criticality. Manuscript submitted for publication to *Transportation Research Part A – Policy and Practice*.

Howell, L. (2013) Resilience: What it is and why it's needed. *Resilience: A journal of strategy and risk*, p5-7 [online] https://www.pwc.com/gx/en/governance-risk-compliance-consulting-services/resilience/publications/pdfs/issue3/what_it_is_and_why_its_needed.pdf [Accessed 20/7/2018].

Hutchen, A. Gibson, S. and Taylor, K. (2016) Using a Risk Framework - Applying the Common Network Asset Indices Methodology in practice. *Asset Management Conference (AM 2016)*, London, 2016, p1-15.

iBUILD, (2018). *Closing the Gap: Local infrastructure business models to support inclusive growth*, iBUILD Research Centre Final Report, Newcastle University [Online] http://www.ibuild.ac.uk/2018finalreport [Accessed 14/2/2019].

International Council on Systems Engineering, (2018). About Systems Engineering [Online] https://www.incose.org/about-systems-engineering [Accessed 11/2/2019].

Infrastructure and Projects Authority, (2017). *Analysis of the National Infrastructure and Construction Pipeline* [online] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/665332/Analysis_of_National_Infrastructure_and_Construction_Pipeline_2017.pdf [Accessed 5/7/2018].

Institution of Civil Engineers, (2009). *The state of the nation, defending critical infrastructure* [online] https://www.ice.org.uk/getattachment/news-and-insight/policy/state-of-the-nation-critical-infrastructure-2009/SoN_DCIreport_final_web.pdf.aspx [Accessed 12/5/2018].

Institution of Engineering and Technology, (2013). *Electricity Networks - Handling a shock to the system* [online] https://www.theiet.org/factfiles/energy/elec-shock-page.cfm?type=pdf [Accessed 25/6/2018].

International Electrotechnical Commission, (2015). *Strategic asset management of power networks – White Paper* [online] http://www.iec.ch/whitepaper/pdf/iecWP-assetmanagement-LR-en.pdf [Accessed 5/7/2018].

Intergovernmental Panel on Climate Change, (2012). *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK, and New York, NY, USA, 582 pp.

Independent Television, (2018). *Power cut hits Birmingham's Bull Ring and New Street Station* [online] http://www.itv.com/news/central/2018-04-10/power-cut-hits-birminghams-bull-ring-and-new-street-station/ [Accessed 25/6/2018].

Jaroszweski, D. Hooper, E. Baker, C. Chapman, C. and Quinn, A. (2015) The impacts of the 28 June 2012 storms on UK road and rail transport. *Meteorol Appl*, 22, 470-476.

Jenkins, GJ. Perry, MC. and Prior, MJ. (2008) *The climate of the United Kingdom and recent trends*, Met Office Hadley Centre, Exeter, UK [online] https://ukcip.ouce.ox.ac.uk/wp-content/PDFs/UKCP09_Trends.pdf [Accessed 9/8/2018].

Jin, X. Wah, BW. Cheng, X. and Wang, Y. (2015) Significance and Challenges of Big Data Research. *Big Data Research*, 2, 59-64.

Johansson, J. and Hassel, H. (2010) An approach for modelling interdependent infrastructures in the context of vulnerability analysis. *Reliability Engineering and System Safety*, 95, 1335-1344.

Jonsson, H. Johansson, J. and Johansson, H. (2008) Identifying critical components in technical infrastructure networks. *Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability*, 222 (2), 235-243.

Khaled, AA. Jin, M. Clarke, DB. and Hoque, MA. (2015) Train design and routing optimization for evaluating criticality of freight railroad infrastructures. *Transportation Research Part B – Methodological*, 71, 71-84.

Kitching, C. (2015) *Operation Stack turns M20 into lorry park and tailbacks stretch 20 MILES as Channel Tunnel travel chaos enters sixth day* [online] http://www.dailymail.co.uk/travel/travel_news/article-2921376/Channel-Tunnel-power-supply-crisis-enters-SIXTH-day-Eurostar-delays-20-mile-tailbacks-M20-turned-lorry-park.html [Accessed 28/7/2018].

Koc, Y. Raman, A. Warnier, M. and Kumar, T. (2016) Structural Vulnerability Analysis of Electric Power Distribution Grids. *International Journal of Critical Infrastructures*, 12 (4), 311-330.

Leviakangas & Saarikivi (2012) *D6 European Extreme Weather Risk Management – Needs, Opportunities, Costs and Recommendation, Extreme weather impacts on European networks of transport* (EWENT) [online] http://ewent.vtt.fi/Deliverables/D6/Ewent_D6_SummaryReport_V07.pdf [Accessed 25/7/2018].

Li, H. Liu, Y. and Peng, K. (2018) Characterizing the relationship between road infrastructure and local economy using structural equation modelling. *Transport Policy*, 61, 17-25.

London Economics, (2013). *The Value of Lost Load (VoLL) for Electricity in Great Britain* [online] https://www.ofgem.gov.uk/ofgem-publications/82293/london-economics-value-lost-load-electricity-gbpdf [Accessed 2/7/2018].

Lu, L. Wang, X. Ouyang, Y. Roningen, J. Myers, N. and Calfas, G. (2018) Vulnerability of Interdependent Urban Infrastructure Networks: Equilibrium after Failure Propagation and Cascading Impacts. *Computer-Aided Civil and Infrastructure Engineering*, 33, 300-315.

Mattson, LG. and Jenelius, E. (2015) Vulnerability and resilience of transport systems – A discussion of recent research. *Transportation Research Part A – Policy and Practice*, 81, 16-34.

McColl, L. Palin, EJ. Thornton, HE. Sexton, DMH. Betts, R. and Mylne, K. (2012) Assessing the potential impact of climate change on the UK's electricity network. *Climatic Change*, 115, 821-835.

McEvoy, D. Ahmed, I. and Mullett, J. (2012) The impact of the 2009 heat wave on Melbourne's critical infrastructure. *Local Environment: The International Journal of Justice and Sustainability*, 17(8), 783-796.

Met Office, (2017). *Climate services* [online] https://www.metoffice.gov.uk/services/climate-services [Accessed 21/7/2018].

Ministry of Housing, Communities & Local Government, (2018). National Planning Policy Framework [online] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/728643/Revised_NPPF_2018.pdf [Accessed 30/7/2018].

Montesinos-Valera, J. Aragonés-Beltrán, P. and Pastor-Ferrando, JP. (2017) Selection of maintenance, renewal and improvement projects in rail lines using the analytic network process. *Structure and Infrastructure Engineering*, 13(11): 1476-1496.

Murphy, JM. Sexton, DMH. Jenkins, GJ. Boorman, PM. Booth, BBB. Brown, CC. Clark, RT. Collins, M. Harris, GR. Kendon, EJ. Betts, RA. Brown, SJ. Howard, TP. Humphrey, KA. McCarthy, MP. McDonald, RE. Stephens, A. Wallace, C. Warren, R. Wilby, R. Wood, RA. (2009) *UK Climate Projections Science Report: Climate change projections*, Met Office Hadley Centre, Exeter [online] http://ukclimateprojections.metoffice.gov.uk/media.jsp?mediaid=87894&filetype=pdf [Accessed 12/8/2018].

Murrant, D. Quinn, A. Chapman, L. and Heaton, C. (2017a) Water use of the UK thermal electricity generation fleet by 2050: Part 1 identifying the problem. *Energy Policy*, 108, 844-858.

Murrant, D. Quinn, A. Chapman, L. and Heaton, C. (2017b) Water use of the UK thermal electricity generation fleet by 2050: Part 2 quantifying the problem. *Energy Policy*, 108, 859-874.

National Audit Office, (2015). *A Short Guide to Network Rail* [online] https://www.nao.org.uk/wp-content/uploads/2015/08/Network-rail-short-guide1.pdf [Accessed 20/7/2018].

National Audit Office, (2017). *Implementing the UK's Exit from the European Union*, Department for Business, Energy & Industrial Strategy, Report by the Comptroller and Auditor General, HC 608, Session 2017-2019 [online] https://www.nao.org.uk/wp-content/uploads/2017/11/Implementing-the-UKs-exit-from-the-European-Union-Department-for-BEIS.pdf [Accessed 8/8/2018].

National Audit Office, (2018). *Implementing the UK's Exit from the European Union*, Department for Transport, Report by the Comptroller and Auditor General, HC 1125, Session 2017-2019 [online] https://www.nao.org.uk/wp-content/uploads/2018/07/Implementing-the-UKs-Exit-from-the-European-Union.pdf [Accessed 8/8/2018].

National Grid, (2003). *Investigation Report into the Loss of Supply Incident affecting parts of South London at 18:20 on Thursday, 28 August 2003* [online] http://www.geocities.jp/ps_dictionary/blackout/London28082003.pdf [Accessed 12/4/2018].

National Grid, (2017). *Transmission network shapefiles* [online] https://www.nationalgrid.com/uk/about-grid/our-networks-and-assets/gas-and-electricity-network-routes [Accessed 6/4/2018].

National Infrastructure Commission, (2017). *Congestion, Capacity, Carbon: Priorities for national infrastructure – Consultation on a National Infrastructure Assessment* [online] https://www.nic.org.uk/wp-content/uploads/Congestion-Capacity-Carbon_-Priorities-for-national-infrastructure.pdf [Accessed 15/4/2018]

National Infrastructure Commission, (2018). *National Infrastructure Assessment* [online] https://www.nic.org.uk/wp-content/uploads/CCS001_CCS0618917350-001_NIC-NIA_Accessible.pdf [Accessed 20/7/2018].

Network Rail, (2015a). *Climate Change Adaptation Report 2015* [online] https://cdn.networkrail.co.uk/wp-content/uploads/2016/11/Climate-Change-Adaptation-Report-2015_FINAL.pdf [Accessed 30/7/2018].

Network Rail, (2015b). *LNW Alternative Feeding Diagrams Rugby ECR*. Issue 05.

Network Rail, (2016a). *Delivering a better railway for a better Britain, Network Specification 2016 London North Western* [online] https://cdn.networkrail.co.uk/wp-content/uploads/2016/11/Network-Specification-2016-London-North-Western.pdf [Accessed 5/5/2018].

Network Rail, (2016b). *Delivering a better railway for a better Britain, Network Specification 2016 Wessex* [online] https://cdn.networkrail.co.uk/wp-content/uploads/2016/11/Network-Specification-2016-Wessex.pdf [Accessed 5/5/2018].

Network Rail, (2016c). *Route Weather Resilience and Climate Change Adaptation Plans – London North Western* [online] https://cdn.networkrail.co.uk/wp-content/uploads/2016/11/LNW-Route-WRCCA-Plan.pdf [Accessed 30/7/2018].

Network Rail, (2016d). *SRS criticality update Based on 10/11 to 14/15 TRUST records*. Issue 2, Draft 2.

Network Rail, (2017a). *Network Rail's Transformation Plan* [online] https://cdn.networkrail.co.uk/wp-content/uploads/2017/09/Transformation-Plan-Update-Sept-2017.pdf [Accessed 10/8/2018].

Network Rail, (2017b). *Railway Upgrade Plan 2017/18* [online] https://cdn.networkrail.co.uk/wp-content/uploads/2017/08/Railway-Upgrade-Plan-Update-2017-2018.pdf [Accessed 2/4/2018].

Network Rail, (2017c). *Smarter, more Efficient Electrification* [online] https://cdn.networkrail.co.uk/wp-content/uploads/2017/03/Challenge-Statement-EP-Challenge-Statement-3-Smarter-more-Efficient-Electrification.pdf [Accessed 25/4/2018].

Office of Rail and Road, (2016). *Rail Statistics Compendium, Great Britain, 2015-16 Annual* [online] http://orr.gov.uk/__data/assets/pdf_file/0013/23323/rail-statistics-compendium-2015-16.pdf [Accessed 5/4/2018].

Office of Rail and Road, (2017). *Freight Rail Usage, 2016-17 Q4 Statistical Release* [online] http://orr.gov.uk/__data/assets/pdf_file/0007/24892/freight-rail-usage-2016-17-quarter-4.pdf [Accessed 5/4/2018].

Office of Rail and Road, (2018). *Passenger & Freight Rail Performance: Quality and Methodology Report* [online] http://orr.gov.uk/__data/assets/pdf_file/0007/22795/performance-quality-report.pdf [Accessed 15/8/2018].

Office of Rail Regulation, (2015). *Performance regime* [online] http://orr.gov.uk/__data/assets/pdf_file/0005/17618/track-access-guidance-performance-regime.pdf [Accessed 5/5/2018].

Ofgem, (2015). *RIIO-ED1 regulatory instructions and guidance: Annex F – Interruptions* [online] https://www.ofgem.gov.uk/ofgem-publications/95354/annexfinterruptions-pdf [Accessed 28/6/2018].

Ofgem, (2017a). *DNO Common Network Asset Indices Methodology, Health & Criticality – Version 1.1* [online] https://www.ofgem.gov.uk/system/files/docs/2017/05/dno_common_network_asset_indices_methodology_v1.1.pdf [Accessed 6/5/2018].

Ofgem, (2017b). *Guide to the RIIO-ED1 electricity distribution price control* [online] https://www.ofgem.gov.uk/system/files/docs/2017/01/guide_to_riioed1.pdf [Accessed 12/6/2018].

Ofgem, (2018). *Map: who operates the electricity distribution network?* [online] https://www.ofgem.gov.uk/key-term-explained/map-who-operates-electricity-distribution-network [Accessed 5/7/2018].

Ouyang, M. (2014) Review on modelling and simulation of interdependent critical infrastructure systems. *Reliability Engineering and System Safety*, 121, 43-60.

Oxera, (2015). *What is the contribution of rail to the UK economy?* Report for the Rail Delivery Group, September 2015 [online] https://www.oxera.com/wp-content/uploads/2018/07/RDG-booklet-Final-Sept-15.pdf [Accessed 5/7/2018].

O'Rourke, TD. (2007) Critical Infrastructure, Interdependencies, and Resilience. *The Bridge*, p22-29, 37 (1).

Pagani, GA. and Aiello, M. (2013) The Power Grid as a complex network: A survey. *Physica A*, 392, 2688-2700.

Pant, R. Blainey, S. Hall, J. and Preston, J. (2014) Assessing Risks to Inform Resilience: A Criticality Assessment of the British Railway Network. In*: International Symposium for Next Generation Infrastructure Conference Proceedings (eds. T Dolan and B Collins)*, International Institute of Applied Systems Analysis (IIASA), Schloss Laxenburg, Vienna, Austria, 30 September - 1 October 2014, 117-121.

Pant, R. Hall, J. and Blainey, S. (2016) Vulnerability assessment framework for interdependent critical infrastructures: case-study for Great Britain's rail network. *EJTIR,* 16(1), 174-194.

Panteli, M. Pickering, C. Wilkinson, S. Dawson, R. and Mancarella, P. (2017) Power System Resilience to Extreme Weather: Fragility Modeling, Probabilistic Impact Assessment, and Adaptation Measures. *IEEE Transactions on Power Systems*, 32 (5), 3747-3757.

Parliamentary Office of Science & Technology, (2011). *Future Electricity Networks*, POSTNOTE, Number 372 [online] https://www.parliament.uk/documents/post/postpn_372-future-electricity-networks.pdf [Accessed 10/8/2018].

Parliamentary Office of Science and Technology, (2017). *Cyber Security of UK Infrastructure, POSTNOTE, Number 554* [online] http://researchbriefings.files.parliament.uk/documents/POST-PN-0554/POST-PN-0554.pdf [Accessed 20/6/2018].

Parlikad, AK. and Jafari, M. (2016) Challenges in infrastructure asset management. *IFAC-PapersOnLine 49-28*, 185-190.

Pitt, M. (2008) Learning lessons from the 2007 floods: An independent review [online] http://webarchive.nationalarchives.gov.uk/20100812084907/http://archive.cabinetoffice.gov.uk/pittreview/_/media/assets/www.cabinetoffice.gov.uk/flooding_review/pitt_review_full%20pdf.pdf [Accessed 3/7/2018].

Pollitt, M. (2005) The role of efficiency estimates in regulatory price reviews: Ofgem's approach to benchmarking electricity networks. *Utilities Policy*, 13, 279-288.

Pregnolato, M. Ford, A. Robson, C. Glenis, V. Barr, S. Dawson, R. (2016) Assessing urban strategies for reducing the impacts of extreme weather on infrastructure networks. *R. Soc. open sci*, 3, 160023.

Quinn, AD. Ferranti, EJS. Hodgkinson, SP. Jack, ACR. Beckford, J. and Dora, JM. (2018) Adaptation Becoming Business as Usual: A Framework for Climate-Change-Ready Transport Infrastructure. *Infrastructures*, 3(10).

Rail Delivery Group, (2017). *Guidance Note - Contingency Planning for Power Outages* [online] RDG-GN037, 1 https://www.rssb.co.uk/rgs/oodocs/RDGGN037%20Iss%201.pdf [Accessed 30/4/2018].

Railway Safety and Standards Board, (2016a). *Tomorrow's Railway and Climate Change Adaptation: Final Report, Task 3: Metrics evaluation appendices* [online] https://www.rssb.co.uk/research-development-and-innovation/research-reports-catalogue/pb024347 [Accessed 1/6/2018].

Railway Safety and Standards Board, (2016b). *Tomorrow's Railway and Climate Change Adaptation: Final Report, Task 4: Systems modelling appendices* [online] https://www.rssb.co.uk/research-development-and-innovation/research-reports-catalogue/pb024352 [Accessed 1/6/2018].

Railway Safety and Standards Board, (2017). *Rail Technical Strategy Capability Delivery Plan* [online] https://www.rssb.co.uk/rts/Documents/2017-01-27-rail-technical-strategy-capability-delivery-plan-brochure.pdf [Accessed 10/8/2018].

Rinaldi, SM. (2004) Modeling and simulating critical infrastructures and their interdependencies. In: *Proceedings of the 37th Annual Hawaii International Conference on System Sciences - 2004*.

Rinaldi, SM. Peerenboom JP. and Kelly, TK. (2001). Identifying, understanding, and analyzing critical infrastructure interdependencies. *Control Systems, IEEE*, 21(6): 11-25.

Rodriguez-Nunez, E. and Garcia-Palomares, JC. (2014) Measuring the vulnerability of public transport networks. *Journal of Transport Geography*, 35, 50-63.

Rosato, V. Bologna, S. and Tiriticco, F. (2007) Topological properties of high-voltage electrical transmission networks. *Electric Power Systems Research*, 77, 99-105.

Royal Academy of Engineering, (2011). *Infrastructure, engineering and climate change adaptation - ensuring services in an uncertain future* [online] www.raeng.org.uk/adaptation [Accessed 14/5/2018].

Royal Academy of Engineering, (2014). *Counting the cost: the economic and social costs of electricity shortfalls in the UK - A report for the Council for Science and Technology* [online] https://www.raeng.org.uk/publications/reports/counting-the-cost [Accessed 7/5/2018].

Sapkota, JB. (2018) Access to infrastructure and human well-being: evidence from rural Nepal. *Development in Practice*, 28:2, 182-194.

Senge, PM. (1990). *The Fifth Discipline: Art and Practice of the Learning Organization*; New York, Doubleday.

Severn Trent Water, (2015). Severn Trent Water's climate change adaptation report [online] https://www.stwater.co.uk/content/dam/stw/about_us/documents/Full-Climate-change-adaptation-report-2015-2020.pdf [Accessed 25/6/2018].

Solomon, D. (2013) *Securing our economy: The case for infrastructure* [online] https://www.ceca.co.uk/wp-content/uploads/2018/05/Securing-our-economy-The-Case-For-Infrastructure.pdf [Accessed 28/7/2018].

Thacker, S. Barr, S. Pant, R. Hall, JW. And Alderson, D. (2017a) Geographic Hotspots of Critical National Infrastructure. *Risk Analysis*, 37(12), 2490-2505.

Thacker, S. Pant, R. and Hall, JW. (2014) Characterizing the Vulnerability of Future Configurations of Great Britain's Electricity Network Infrastructure to Climate-related Hazards. *2nd Int. Conf. on Vulnerability, Uncertainty and Risk*, ASCE, Reston, VA, 648-657.

Thacker, S. Pant, R. and Hall, JW. (2017b) System-of-systems formulation and disruption analysis for multi-scale critical national infrastructures. *Reliability Engineering and System Safety*, 167, 30-41.

The Resilience Shift, (2018). *Critical Infrastructure Resilience - Understanding the landscape* [online] http://resilienceshift.org/wp-content/uploads/2017/10/The-Resilience-Shift-Understanding-the-Landscape-March-2018_1.pdf [Accessed 20/5/2018].

Thornes, J. Rennie, M. Marsden, H. Chapman, L. (2012) *Climate Change Risk Assessment for the Transport Sector* [online] http://randd.defra.gov.uk/Document.aspx?Document=CCRAfortheTransportSector.pdf [Accessed 4/8/2014].

Thornes, JE. Davis, BW. (2002) Mitigating the impact of weather and climate on railway operations in the UK. *Proceedings of the 2002 ASME/IEEE Joint Rail Conference in Washington DC*, April 23-25, 2002.

Thornes, JE. Hickman, A. Baker, C. Cai, X. and Delgado Saborit, JM. (2017) Air quality in enclosed railway stations. *Proceedings of the Institution of Civil Engineers – Transport*, 170 (TR2), 99-107.

Thywissen, K. (2006) *Components of Risk, A Comparative Glossary. UNU-EHS, SOURCE Publication Series, No. 2/2006* [Online] http://collections.unu.edu/eserv/unu:1869/pdf4042.pdf [Accessed 13/2/2019].

Tran, M. Hall, J. Hickford, A. Nicholls, R. Alderson, D. Barr, S. Baruah, P. Beavan, R. Birkin, M. Blainey, S. Byers, E. Chaudry, M. Curtis, T. Ebrahimy, R. Eyre, N. Hiteva, R. Jenkins, N. Jones, C. Kilsby, C. Leathard, A. Manning, L. Otto, A. Oughton, E. Powrie, W. Preston, J. Qadrdan, M. Thoung, C. Tyler, P. Watson, J. Watson, G. and Zuo, C. (2014) *National infrastructure assessment: Analysis of options for infrastructure provision in Great Britain, Interim results*. Environmental Change Institute, University of Oxford.

Transport for West Midlands, (2018). *About Us* [online] https://www.tfwm.org.uk/about-us/ [Accessed 11/8/2018].

Tyler, S. and Moench, M. (2012) A framework for urban climate resilience. *Climate and Development*, 4 (4), 311-326.

UK Regulators Network, (2017). *Making better use of data: identifying customers in vulnerable situations* [online] http://www.ukrn.org.uk/wp-content/uploads/2017/10/Making-better-use-of-data-identifying-customers-in-vulnerable-situations.pdf [Accessed 2/5/2018].

UK Regulators Network, (2018). *The UK Regulators Network* [online] http://www.ukrn.org.uk/ [Accessed 2/5/2018].

Ukkusuri, SV. and Yushimito, WF. (2009) A methodology to assess the criticality of highway transportation networks. *J Transp Secur*, 2, 29-46.

United Nations, (2015). *Resolution adopted by the General Assembly on 25 September 2015 - 70/1. Transforming our world: the 2030 Agenda for Sustainable Development*, General Assembly, Seventieth session, Agenda items 15 and 116, A/RES/70/1 [online] http://www.un.org/en/development/desa/population/migration/generalassembly/docs/globalcompact/A_RES_70_1_E.pdf [Accessed 20/7/2018].

United Nations, (2016). Report of the open-ended intergovernmental expert working group on indicators and terminology relating to disaster risk reduction. General Assembly, Seventy first session, Agenda item 19c, A/71/644 [Online] https://www.preventionweb.net/files/50683_oiewgreportenglish.pdf [Accessed 13/2/2019].

Verner, D. Kim, K. and Petit, F. (2017) Incorporating Prioritization in Critical Infrastructure Security and Resilience Programs. In: *10th Anniversary Homeland Defense/Security Education Summit* [online] Arlington, VA, US. https://www.osti.gov/servlets/purl/1364653 [Accessed 15/5/2018].

Vespignani, A. (2010) The fragility of interdependency. *Nature*, News & Views, Complex Networks, p984-985, 464.

Voltes-Dorta, A. Rodriguez-Deniz, H. and Suau-Sanchez, P. (2017) Vulnerability of the European air transport network to major airport closures from the perspective of passenger delays: Ranking the most critical airports. *Transportation Research Part A – Policy and Practice*, 96, 119-145.

von Ferber, C. Berche, B. Holovatch, T. and Holovatch, Y. (2012) A tale of two cities - Vulnerabilities of the London and Paris transit network. *J Transp Secur*, 5 (3), 199-216.

Wang, JYT. (2015) "Resilience thinking" in transport planning. *Civ. Eng. Environ. Syst,* 32, 180-191.

Wang, Z. He, SY. and Leung, Y. (2018) Applying mobile phone data to travel behaviour research: A literature review. *Travel Behaviour and Society*, 11, 141-155.

Wei, C. Minghua, H. Bin, D. Yanjun, W. and Cheng, F. (2016) Empirical analysis of airport network and critical airports. *Chinese Journal of Aeronautics*, 29 (2), 512-519.

West Midlands Railway, (2018a). *Train Times 20 May to 8 December 2018 Redditch – Bromsgrove – Longbridge – Birmingham – Sutton Coldfield – Lichfield* [online] https://www.westmidlandsrailway.co.uk/sites/default/files/assets/download_ct/20180502/O2jija9noo27WMB_XI3_cXaSdaxBXvp9cEnmrv-tBvc/wm01_may_2018_revised.pdf [Accessed 30/7/2018].

West Midlands Railway, (2018b). *Up to three extra trains per hour for Bromsgrove* [online] https://www.westmidlandsrailway.co.uk/about-us/news-desk/three-extra-trains-hour-bromsgrove [Accessed 10/8/2018].

Western Power Distribution, (2011). *Adaptation to Climate Change Report* [online] https://www.westernpower.co.uk/docs/social-responsibility/Environment/Climate-Change-Adaptation.aspx [Accessed 22/7/2018].

Western Power Distribution, (2014). *2015-2023 RIIO-ED1 BUSINESS PLAN SA-08 Supplementary Annex – Business Performance, Efficiency and Benchmarking* [online] https://www.westernpower.co.uk/docs/About-us/Stakeholder-information/Our-future-business-plan/Seperate-documents/Business-Efficiency.aspx [Accessed 20/7/2018].

Western Power Distribution, (2015). *Adaptation to Climate Change Second Round Report* [online] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/474340/climate-adrep-western-power.pdf [Accessed 2/8/2018].

Western Power Distribution, (2016). Shaping Subtransmission to 2030 - South West [online] https://www.westernpower.co.uk/docs/About-us/Our-business/Our-network/Strategic-network-investment/Shaping-Subtransmission-to-2030-South-West-2016-v1.aspx [Accessed 5/7/2018].

Western Power Distribution, (2017). *DNO Transition December 2017 Update* [online] https://www.westernpower.co.uk/docs/About-us/Our-business/Our-network/Strategic-network-investment/DSO-Strategy/DSO-Transition-Strategy.aspx [Accessed 11/8/2018].

Western Power Distribution, (2018). Shaping Subtransmission to 2030 – West Midlands [online] https://www.westernpower.co.uk/docs/About-us/Our-business/Our-network/Strategic-network-investment/West-Midlands/Shaping-Subtransmission-to-2030-West-Midlands-2018.aspx [Accessed 5/7/2018].

World Economic Forum, (2013). *Insight Report – Global Risks 2013 – Eighth Edition* [online] http://www3.weforum.org/docs/WEF_GlobalRisks_Report_2013.pdf [Accessed 21/7/2018].

World Meteorological Organisation, (2014). *Implementation Plan of the Global Framework for Climate Services* [online] http://www.wmo.int/gfcs/sites/default/files/implementation-plan//GFCS-IMPLEMENTATION-PLAN-FINAL-14211_en.pdf [Accessed 21/7/2018].

World Meteorological Organisation, (2018). *GFCS – Global Framework for Climate Services* [online] http://www.wmo.int/gfcs/ [Accessed 21/7/2018].

Wright, D. Kelly, A. and Stuart, A. (2016) *Electricity Transmission Network Output Measures Methodology* [online] https://www.ofgem.gov.uk/ofgem-publications/99518 [Accessed 23/6/2018].

Young, DT. Chapman, L. Muller, CL. Grimmond, CSB. Cai, X. (2014) Evaluating the performance of a 'low-cost' wireless temperature sensor. *Journal of Atmospheric & Oceanic Technology*, 31, 938-944.

Zimmerman, R. (2001) Social Implications of Infrastructure Network Interactions. *Journal of Urban Technology*, 8:3, 97-119.

Zimmerman, R. (2004) Decision-making and the vulnerability of interdependent critical infrastructure. In: *Proceedings of the 2004 IEEE international conference on systems, man and cybernetics*, 4059–63

Zimmerman, R. and Restrepo, CE. (2006) The next step: quantifying infrastructure interdependencies to improve security. *Int. J. Critical Infrastructures*, 2(2/3), 215-230.

Zuo, L. Xiahou, T. and Liu, Y. (2018) Evidential network-based failure analysis for systems suffering common cause failure and model parameter uncertainty. *Proc IMechE Part C: J Mechanical Engineering Science*, 0 (0), 1–11.

Zurich, (2017). Challenges of our nation's aging infrastructure - The pressing need to maintain critical systems [online] https://www.zurichna.com/_/media/dbe/zna/docs/kh/infrastructure/aging-infrastructure-whitepaper-april-2017.pdf [Accessed 25/7/2018].

APPENDIX A: MANUSCRIPT SUBMITTED TO JOURNAL

Single point of failure assessment methodology for evaluating railway network criticality

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Abstract

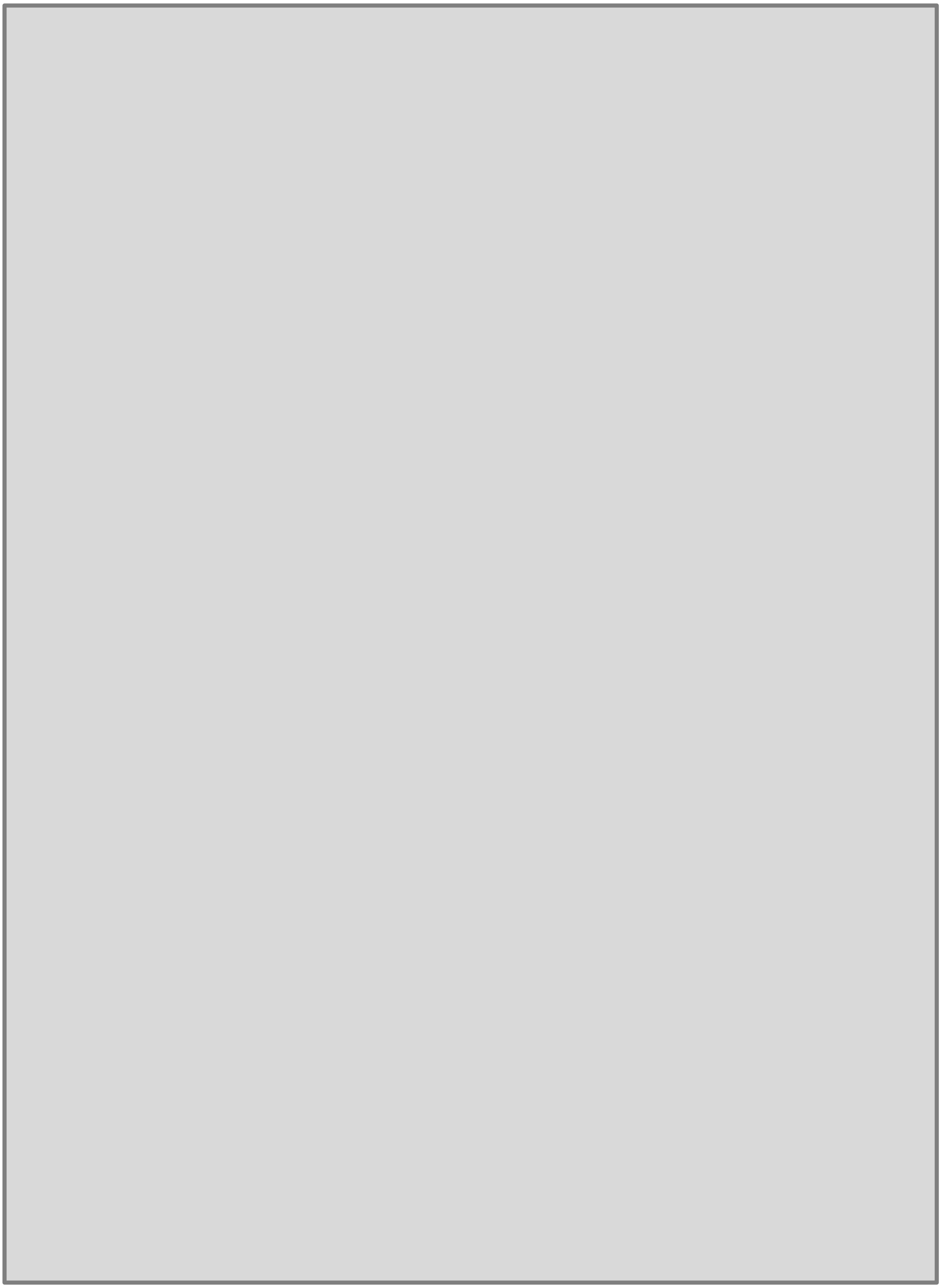
Asset failures that occur at strategically important or critical locations on a rail network have the potential to result in widespread disruption to train services. On a heavily utilised network approaching full capacity, with constrained management budgets there is a need for cost-effective resource allocation. The decision-making process for a range of railway undertakings can be informed by a location based network criticality assessment. This paper presents a data driven methodology which prioritises GB rail network locations based upon the average magnitude of train service disruption per asset failure, in the form of delay minutes extracted from Network Rail's TRUST system for the period 2011-2016. Using historical data incorporates real world network behaviour and facilitates a criticality assessment capable of identifying very localised single points of failure. Detailed criticality maps are presented and discussed for two contrasting routes of the GB rail network; Wessex and London North Western (South). The results demonstrate the benefits of defining network criticality at a high granularity and regional scale, adding value through integration with existing prioritisation schemes for maintenance programmes, upgrade or renewal projects and incident response applicable in GB and internationally.

Keywords

Criticality, performance, metric, prioritisation, railways, disruption.

Declarations of Interest

The author(s) declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.



APPENDIX B: ELECTRICITY DISTRIBUTION NETWORK CRITICALITY BANDS

Table of Criticality Bands allocated to substations for the South West licence area, ranked in descending order of disruption magnitude.

BAND	District	Asset Type	Voltage (Up/Down)	Faults	SML	SML per fault
1	Bodmin	BSP	132/33	1	620.0	620.0
1	Redruth	BSP	132/33	2	674.0	337.0
1	Redruth	BSP	132/33	3	777.7	259.2
1	Exeter	Primary	33/11	2	324.1	162.1
1	Plymouth	Primary	33/11	1	117.8	117.8
1	Barnstaple	BSP	132/33	2	220.5	110.3
1	Barnstaple	BSP	132/33	2	186.0	93.0
1	Bristol	Primary	33/11	1	69.2	69.2
1	132 kV	GSP	400-275/132	1	65.0	65.0
1	Projects	BSP	132/33	1	63.0	63.0
1	Bristol	Primary	33/11	5	308.4	61.7
1	Bristol	Primary	33/11	1	60.0	60.0
1	132 kV	GSP	400-275/132	1	55.7	55.7
1	Bristol	Primary	33/11	1	55.2	55.2
1	Redruth	BSP	132/33	1	52.0	52.0
1	Plymouth	Primary	33/11	1	51.7	51.7
1	Plymouth	Primary	33/11	1	51.0	51.0
1	Bristol	Primary	33/11	1	48.0	48.0
1	Redruth	Primary	33/11	2	94.1	47.1
1	Redruth	Primary	33/11	1	46.8	46.8
1	Exeter	Primary	33/11	1	45.3	45.3
1	Plymouth	Primary	33/11	1	45.1	45.1
1	Bristol	Primary	33/11	1	44.0	44.0
1	Weston	Primary	33/11	1	40.0	40.0
1	Bristol	Primary	33/11	3	119.6	39.9
1	Bath	Primary	33/11	2	72.8	36.4
1	Bristol	Primary	33/11	1	34.7	34.7
1	Bristol	Primary	33/11	1	32.5	32.5
1	Bristol	Primary	33/11	1	32.1	32.1
1	Projects	BSP	132/33	1	31.5	31.5
1	Taunton	Primary	33/11	8	244.6	30.6
1	Plymouth	Primary	33/11	1	30.5	30.5
1	Bristol	Primary	33/11	1	28.5	28.5
1	Plymouth	Primary	33/11	3	80.7	26.9
1	Plymouth	Primary	33/11	1	25.4	25.4
1	Bristol	Primary	33/11	2	48.0	24.0
2	Bristol	Primary	33/11	2	46.9	23.5
2	Bristol	Primary	33/11	2	46.3	23.2
2	Bristol	Primary	33/11	2	44.7	22.4
2	Weston	Primary	33/11	3	64.5	21.5
2	Plymouth	Primary	33/11	2	42.8	21.4
2	Bristol	Primary	33/11	2	42.0	21.0
2	Redruth	Primary	33/11	14	288.2	20.6

2	Plymouth	Primary	33/11	3	58.8	19.6
2	Exeter	Primary	33/11	3	55.8	18.6
2	Taunton	BSP	132/33	5	87.0	17.4
2	Bristol	Primary	33/11	3	50.2	16.7
2	Plymouth	Primary	33/11	2	33.5	16.7
2	Bristol	Primary	33/11	2	31.5	15.7
2	Taunton	Primary	33/11	15	232.9	15.5
3	Bodmin	BSP	132/33	3	33.8	11.3
3	Bristol	Primary	33/11	3	33.7	11.2
3	Bristol	Primary	33/11	8	82.6	10.3
3	Taunton	Primary	33/11	7	69.2	9.9
3	Taunton	BSP	132/33	4	39.6	9.9
3	Torquay	Primary	33/11	4	39.4	9.8
3	Plymouth	Primary	33/11	3	29.2	9.7
3	Exeter	Primary	33/11	3	28.6	9.5
3	Bath	Primary	33/11	5	47.0	9.4
3	Bath	BSP	132/33	4	37.2	9.3
3	Plymouth	Primary	33/11	5	46.2	9.2
3	Plymouth	Primary	33/11	2	17.8	8.9
3	Plymouth	Primary	33/11	4	35.3	8.8
3	Bristol	Primary	33/11	5	42.3	8.5
3	Bristol	Primary	33/11	4	33.8	8.5
3	Bristol	Primary	33/11	4	32.7	8.2
3	Bodmin	Primary	33/11	7	56.6	8.1
3	Redruth	Primary	33/11	30	237.4	7.9
3	Taunton	Primary	33/11	17	133.9	7.9
3	Bath	Primary	33/11	6	46.7	7.8
3	Bath	Primary	33/11	6	46.4	7.7
3	Exeter	Primary	33/11	24	182.7	7.6
3	Plymouth	Primary	33/11	7	52.4	7.5
3	Bristol	Primary	33/11	5	36.7	7.3
3	Bristol	Primary	33/11	6	43.7	7.3
3	Bristol	Primary	33/11	5	35.4	7.1
3	Bristol	Primary	33/11	5	35.0	7.0
3	Taunton	Primary	33/11	26	171.8	6.6
3	Weston	Primary	33/11	5	31.7	6.3
3	Bristol	Primary	33/11	7	44.0	6.3
3	Weston	Primary	33/11	5	31.2	6.2
3	Exeter	Primary	33/11	5	31.1	6.2
3	Bath	Primary	33/11	9	55.6	6.2
3	Taunton	Primary	33/11	14	85.3	6.1
3	Bath	Primary	33/11	6	36.3	6.1
3	Exeter	Primary	33/11	15	90.7	6.0
3	Bristol	Primary	33/11	3	17.9	6.0
4	Barnstaple	Primary	33/11	24	139.9	5.8
4	Redruth	Primary	33/11	30	162.6	5.4
4	Bristol	Primary	33/11	5	27.0	5.4
4	Bristol	Primary	33/11	3	15.7	5.2
4	Exeter	Primary	33/11	5	25.7	5.1
4	Exeter	Primary	33/11	6	30.5	5.1
4	Bristol	Primary	33/11	8	40.4	5.0
4	Exeter	Primary	33/11	8	40.2	5.0

4	Bristol	BSP	132/33	1	5.0	5.0
4	Bristol	Primary	33/11	5	24.8	5.0
4	Torquay	Primary	33/11	7	34.1	4.9
4	Exeter	Primary	33/11	7	33.8	4.8
4	Taunton	BSP	132/33	1	4.8	4.8
4	Taunton	Primary	33/11	15	72.0	4.8
4	Bristol	Primary	33/11	6	28.6	4.8
4	Taunton	Primary	33/11	35	165.2	4.7
4	Exeter	Primary	33/11	24	111.9	4.7
4	Weston	Primary	33/11	11	49.8	4.5
4	Bristol	Primary	33/11	6	27.1	4.5
4	Torquay	Primary	33/11	9	39.5	4.4
4	Bath	Primary	33/11	19	83.3	4.4
4	Torquay	Primary	33/11	6	26.3	4.4
4	Plymouth	Primary	33/11	6	25.9	4.3
4	Taunton	Primary	33/11	28	120.3	4.3
4	Torquay	Primary	33/11	21	90.2	4.3
4	Bodmin	Primary	33/11	16	68.6	4.3
4	Exeter	Primary	33/11	30	127.5	4.3
4	Exeter	Primary	33/11	14	59.0	4.2
4	Exeter	Primary	33/11	22	92.5	4.2
4	Bath	Primary	33/11	12	50.3	4.2
4	Torquay	BSP	132/33	2	8.1	4.1
4	Exeter	Primary	33/11	18	72.8	4.0
4	Weston	Primary	33/11	15	60.0	4.0
4	Exeter	Primary	33/11	10	39.6	4.0
4	Plymouth	Primary	33/11	8	31.1	3.9
4	Bristol	Primary	33/11	10	38.8	3.9
4	Barnstaple	BSP	132/33	7	27.1	3.9
4	Taunton	Primary	33/11	24	90.6	3.8
4	Taunton	Primary	33/11	9	33.8	3.8
4	Exeter	BSP	132/33	1	3.7	3.7
4	Barnstaple	Primary	33/11	24	88.9	3.7
4	Torquay	Primary	33/11	22	81.5	3.7
4	Barnstaple	Primary	33/11	13	47.5	3.7
4	Bath	Primary	33/11	14	49.8	3.6
4	Bristol	Primary	33/11	5	17.8	3.6
4	Plymouth	Primary	33/11	5	17.7	3.5
4	Bristol	Primary	33/11	7	24.3	3.5
4	Taunton	Primary	33/11	10	34.2	3.4
4	Bristol	Primary	33/11	6	20.4	3.4
4	Bristol	Primary	33/11	7	23.7	3.4
4	Taunton	Primary	33/11	28	94.3	3.4
4	Weston	Primary	33/11	19	63.8	3.4
4	Taunton	Primary	33/11	11	36.8	3.3
4	Taunton	Primary	33/11	15	50.1	3.3
4	Taunton	Primary	33/11	31	102.5	3.3
4	Bodmin	Primary	33/11	19	62.2	3.3
4	Bristol	Primary	33/11	9	29.4	3.3
4	Weston	Primary	33/11	25	81.5	3.3
4	Plymouth	Primary	33/11	19	61.8	3.3
4	Bodmin	Primary	33/11	42	134.2	3.2

4	Exeter	Primary	33/11	30	95.0	3.2
4	Taunton	Primary	33/11	19	59.2	3.1
4	Redruth	Primary	33/11	13	40.5	3.1
4	Taunton	Primary	33/11	35	108.7	3.1
4	Torquay	Primary	33/11	9	27.7	3.1
4	Plymouth	Primary	33/11	34	104.2	3.1
4	Bodmin	Primary	33/11	25	76.3	3.1
4	Taunton	Primary	33/11	24	72.6	3.0
4	Exeter	Primary	33/11	53	159.5	3.0
4	Bodmin	Primary	33/11	1	3.0	3.0
4	Exeter	Primary	33/11	14	42.0	3.0
4	Redruth	Primary	33/11	20	59.4	3.0
5	Bristol	Primary	33/11	23	67.7	2.9
5	Bristol	Primary	33/11	7	20.6	2.9
5	Bristol	Primary	33/11	13	38.1	2.9
5	Taunton	BSP	132/33	2	5.9	2.9
5	Plymouth	Primary	33/11	28	81.3	2.9
5	Plymouth	Primary	33/11	33	95.5	2.9
5	Torquay	Primary	33/11	14	40.4	2.9
5	Exeter	Primary	33/11	14	40.1	2.9
5	Taunton	Primary	33/11	19	54.4	2.9
5	Barnstaple	Primary	33/11	14	40.0	2.9
5	Redruth	Primary	33/11	24	67.6	2.8
5	Plymouth	Primary	33/11	34	95.2	2.8
5	Bath	Primary	33/11	28	77.5	2.8
5	Exeter	Primary	33/11	29	79.9	2.8
5	Taunton	Primary	33/11	27	73.6	2.7
5	Bristol	Primary	33/11	18	49.0	2.7
5	Taunton	Primary	33/11	32	86.0	2.7
5	Redruth	Primary	33/11	65	172.0	2.6
5	Bath	Primary	33/11	16	42.3	2.6
5	Redruth	Primary	33/11	20	52.3	2.6
5	Exeter	Primary	33/11	13	33.8	2.6
5	Torquay	Primary	33/11	18	46.7	2.6
5	Barnstaple	Primary	33/11	34	87.2	2.6
5	Taunton	Primary	33/11	28	71.5	2.6
5	Taunton	Primary	33/11	38	95.1	2.5
5	Bodmin	Primary	33/11	35	86.4	2.5
5	Torquay	Primary	33/11	17	42.0	2.5
5	Barnstaple	BSP	132/33	37	90.7	2.5
5	Taunton	Primary	33/11	35	85.5	2.4
5	Weston	Primary	33/11	26	63.4	2.4
5	Weston	Primary	33/11	21	51.1	2.4
5	Taunton	Primary	33/11	25	60.6	2.4
5	Weston	BSP	132/33	7	16.9	2.4
5	Bath	Primary	33/11	33	79.7	2.4
5	Torquay	Primary	33/11	13	31.2	2.4
5	Redruth	Primary	33/11	30	70.6	2.4
5	Torquay	Primary	33/11	27	63.4	2.3
5	Taunton	Primary	33/11	45	103.0	2.3
5	Bodmin	Primary	33/11	22	50.1	2.3
5	Bodmin	BSP	132/33	8	18.2	2.3

5	Bodmin	Primary	33/11	44	99.3	2.3
5	Bristol	Primary	33/11	14	31.5	2.3
5	Barnstaple	Primary	33/11	34	76.1	2.2
5	Taunton	Primary	33/11	45	100.4	2.2
5	Exeter	Primary	33/11	38	84.7	2.2
5	Redruth	Primary	33/11	52	115.5	2.2
5	Bristol	Primary	33/11	11	24.4	2.2
5	Redruth	Primary	33/11	35	77.6	2.2
5	Redruth	Primary	33/11	29	63.8	2.2
5	Barnstaple	Primary	33/11	36	79.1	2.2
5	Bodmin	Primary	33/11	23	50.5	2.2
5	Exeter	Primary	33/11	17	37.2	2.2
5	Exeter	Primary	33/11	31	67.2	2.2
5	Weston	Primary	33/11	33	70.8	2.1
5	Exeter	Primary	33/11	34	72.5	2.1
5	Bodmin	Primary	33/11	39	82.8	2.1
5	Bodmin	Primary	33/11	39	82.4	2.1
5	Taunton	Primary	33/11	22	46.3	2.1
5	Redruth	Primary	33/11	63	132.4	2.1
5	Weston	Primary	33/11	18	37.7	2.1
5	Exeter	BSP	132/33	2	4.1	2.1
5	Redruth	Primary	33/11	101	204.6	2.0
5	Redruth	BSP	132/33	3	6.0	2.0
5	Bristol	Primary	33/11	12	24.1	2.0
5	Bodmin	BSP	132/33	2	4.0	2.0
5	Bodmin	Primary	33/11	53	106.2	2.0
5	Exeter	Primary	33/11	43	85.5	2.0
5	Bodmin	Primary	33/11	47	93.4	2.0
5	Bodmin	Primary	33/11	38	74.6	2.0
5	Torquay	Primary	33/11	25	48.7	1.9
5	Redruth	Primary	33/11	63	122.6	1.9
5	Weston	Primary	33/11	27	52.4	1.9
5	Bodmin	Primary	33/11	47	90.5	1.9
5	Bodmin	Primary	33/11	42	80.8	1.9
5	Weston	Primary	33/11	30	57.2	1.9
5	Weston	BSP	132/33	2	3.8	1.9
5	Plymouth	Primary	33/11	42	78.8	1.9
5	Plymouth	BSP	132/33	6	11.2	1.9
5	Taunton	Primary	33/11	33	61.4	1.9
5	Torquay	Primary	33/11	18	33.3	1.9
5	Bath	Primary	33/11	20	36.9	1.8
5	Redruth	Primary	33/11	36	65.4	1.8
5	Taunton	Primary	33/11	36	64.0	1.8
5	Exeter	Primary	33/11	30	53.1	1.8
5	Bodmin	Primary	33/11	45	79.5	1.8
5	Redruth	Primary	33/11	44	77.7	1.8
5	Exeter	Primary	33/11	39	68.8	1.8
5	Barnstaple	Primary	33/11	24	42.3	1.8
5	Plymouth	Primary	33/11	42	73.6	1.8
5	Taunton	Primary	33/11	37	64.2	1.7
5	Bodmin	Primary	33/11	49	82.9	1.7
5	Taunton	Primary	33/11	15	25.3	1.7

5	Redruth	Primary	33/11	38	63.5	1.7
5	Plymouth	Primary	33/11	40	64.9	1.6
5	Exeter	Primary	33/11	57	91.6	1.6
5	Redruth	Primary	33/11	31	49.3	1.6
5	Bodmin	Primary	33/11	48	76.1	1.6
5	Bodmin	Primary	33/11	30	46.9	1.6
5	Redruth	Primary	33/11	66	102.5	1.6
5	Bath	Primary	33/11	25	38.7	1.5
5	Weston	Primary	33/11	39	60.1	1.5
5	Plymouth	Primary	33/11	41	62.8	1.5
5	Weston	Primary	33/11	34	52.1	1.5
5	Bodmin	Primary	33/11	38	57.9	1.5
5	Taunton	Primary	33/11	32	48.7	1.5
5	Taunton	Primary	33/11	40	60.8	1.5
5	Taunton	Primary	33/11	37	56.0	1.5
5	Bristol	Primary	33/11	13	19.7	1.5
5	Bath	Primary	33/11	32	48.4	1.5
5	Bristol	Primary	33/11	21	31.4	1.5
5	Barnstaple	Primary	33/11	35	51.5	1.5
5	Barnstaple	BSP	132/33	4	5.9	1.5
5	Plymouth	Primary	33/11	61	89.1	1.5
5	Exeter	Primary	33/11	57	83.1	1.5
5	Plymouth	Primary	33/11	42	60.1	1.4
5	Weston	Primary	33/11	43	61.5	1.4
5	Barnstaple	Primary	33/11	49	69.7	1.4
5	Taunton	Primary	33/11	33	46.6	1.4
5	Bodmin	Primary	33/11	56	79.0	1.4
5	Exeter	Primary	33/11	44	61.8	1.4
5	Bristol	Primary	33/11	22	30.8	1.4
5	Redruth	Primary	33/11	37	51.8	1.4
5	Taunton	Primary	33/11	48	67.1	1.4
5	Exeter	Primary	33/11	30	41.1	1.4
5	Plymouth	Primary	33/11	53	71.2	1.3
5	Bodmin	Primary	33/11	45	60.2	1.3
5	Bath	Primary	33/11	44	58.1	1.3
5	Bodmin	Primary	33/11	40	52.2	1.3
5	Torquay	Primary	33/11	65	84.7	1.3
5	Weston	Primary	33/11	35	45.6	1.3
5	Torquay	Primary	33/11	55	71.0	1.3
5	Bath	Primary	33/11	31	40.0	1.3
5	Bristol	Primary	33/11	14	18.0	1.3
5	Weston	Primary	33/11	25	32.0	1.3
5	Barnstaple	Primary	33/11	39	49.8	1.3
5	Exeter	Primary	33/11	43	54.8	1.3
5	Plymouth	Primary	33/11	44	56.0	1.3
5	Bath	Primary	33/11	38	48.2	1.3
5	Plymouth	Primary	33/11	72	88.0	1.2
5	Weston	Primary	33/11	59	71.6	1.2
5	Exeter	Primary	33/11	58	70.1	1.2
5	Exeter	Primary	33/11	39	47.0	1.2
5	Taunton	Primary	33/11	38	44.2	1.2
5	Barnstaple	Primary	33/11	56	65.1	1.2

5	Plymouth	Primary	33/11	58	67.0	1.2
5	Barnstaple	Primary	33/11	32	36.5	1.1
5	Barnstaple	Primary	33/11	62	70.4	1.1
5	Torquay	Primary	33/11	19	20.9	1.1
5	Bath	Primary	33/11	44	47.9	1.1
5	Redruth	Primary	33/11	57	61.4	1.1
5	Barnstaple	Primary	33/11	69	74.0	1.1
5	Bath	Primary	33/11	32	34.2	1.1
5	Redruth	Primary	33/11	39	41.2	1.1
5	Bodmin	Primary	33/11	64	67.3	1.1
5	Bodmin	Primary	33/11	67	70.3	1.0
5	Redruth	Primary	33/11	66	68.0	1.0
5	Bath	Primary	33/11	34	35.0	1.0
5	Exeter	Primary	33/11	43	44.1	1.0
5	Barnstaple	Primary	33/11	78	78.4	1.0
5	Taunton	Primary	33/11	67	67.0	1.0
5	Weston	Primary	33/11	34	33.8	1.0
5	Weston	Primary	33/11	32	31.5	1.0
5	Redruth	Primary	33/11	84	81.6	1.0
5	Plymouth	Primary	33/11	62	59.5	1.0
5	Redruth	Primary	33/11	63	59.5	0.9
5	Redruth	Primary	33/11	71	66.8	0.9
5	Torquay	Primary	33/11	27	25.2	0.9
5	Exeter	Primary	33/11	66	58.5	0.9
5	Bodmin	Primary	33/11	44	38.7	0.9
5	Bodmin	Primary	33/11	81	69.5	0.9
5	Bodmin	Primary	33/11	57	48.3	0.8
5	Bodmin	Primary	33/11	79	66.5	0.8
5	Redruth	Primary	33/11	92	76.7	0.8
5	Exeter	Primary	33/11	56	46.5	0.8
5	Barnstaple	Primary	33/11	95	78.2	0.8
5	Bristol	Primary	33/11	33	26.6	0.8
5	Plymouth	Primary	33/11	104	82.6	0.8
5	Torquay	Primary	33/11	49	38.2	0.8
5	Torquay	Primary	33/11	84	63.7	0.8
5	Plymouth	Primary	33/11	74	54.6	0.7
5	Barnstaple	Primary	33/11	75	54.4	0.7
5	Bodmin	Primary	33/11	64	46.2	0.7
5	Redruth	Primary	33/11	91	59.4	0.7
5	Barnstaple	Primary	33/11	71	46.3	0.7
5	Plymouth	Primary	33/11	82	53.4	0.7
5	Taunton	Primary	33/11	68	44.2	0.7
5	Barnstaple	Primary	33/11	82	51.8	0.6
5	Barnstaple	Primary	33/11	47	29.0	0.6
5	Barnstaple	Primary	33/11	74	45.0	0.6
5	Plymouth	Primary	33/11	90	54.4	0.6
5	Barnstaple	Primary	33/11	93	56.0	0.6
5	Weston	Primary	33/11	84	47.6	0.6
5	Barnstaple	Primary	33/11	118	44.5	0.4
5	Barnstaple	Primary	33/11	80	26.7	0.3

Table of Criticality Bands allocated to substations for the West Midlands licence area, ranked in descending order of disruption magnitude.

BAND	District	Asset Type	Voltage (Up/Down)	Faults	SML	SML per fault
1	Tipton	GSP	400-275/132	1	421.0	421.0
1	Stoke	BSP	132/33	1	263.0	263.0
1	Gloucester	Primary	33/11	1	197.0	197.0
1	Tipton	Primary	33/11	1	118.0	118.0
1	Tipton	BSP	132/33	1	97.0	97.0
1	Stoke	BSP	132/33	1	71.0	71.0
1	Birmingham	Primary	33/11	3	188.5	62.8
1	Stoke	Primary	33/11	1	54.0	54.0
1	Gloucester	BSP	132/33	5	210.0	42.0
1	Tipton	BSP	132/33	1	25.0	25.0
1	Gloucester	BSP	132/33	1	21.3	21.3
2	Birmingham	Primary	33/11	5	63.2	12.6
2	Major Projects West	GSP	400-275/132	1	12.2	12.2
2	Birmingham	Primary	33/11	9	93.8	10.4
2	Worcester	Primary	33/11	11	94.4	8.6
2	Birmingham	Primary	33/11	8	66.4	8.3
2	Birmingham	Primary	33/11	11	87.6	8.0
3	Telford	BSP	132/33	2	15.7	7.8
3	Tipton	GSP	400-275/132	1	7.4	7.4
3	Telford	BSP	132/33	4	23.8	6.0
3	Tipton	Primary	33/11	7	41.4	5.9
3	Tipton	Primary	33/11	1	5.2	5.2
3	Birmingham	Primary	33/11	20	98.6	4.9
3	Birmingham	Primary	33/11	15	73.2	4.9
3	Birmingham	Primary	33/11	15	67.1	4.5
3	Telford	Primary	33/11	8	34.8	4.4
3	Birmingham	Primary	33/11	9	39.0	4.3
3	Birmingham	Primary	33/11	15	62.0	4.1
4	Gloucester	Primary	33/11	34	128.2	3.8
4	Birmingham	Primary	33/11	19	66.1	3.5
4	Birmingham	Primary	33/11	23	77.1	3.4
4	Birmingham	Primary	33/11	19	62.1	3.3
4	Worcester	Primary	33/11	27	85.6	3.2
4	Gloucester	Primary	33/11	30	95.1	3.2
4	Stoke	Primary	33/11	24	71.9	3.0
4	Birmingham	Primary	33/11	23	68.4	3.0
4	Stoke	Primary	33/11	38	108.2	2.8
4	Birmingham	Primary	33/11	14	38.8	2.8
4	Stoke	Primary	33/11	41	111.9	2.7
4	Tipton	Primary	33/11	42	113.8	2.7
4	Stoke	Primary	33/11	24	64.7	2.7
4	Birmingham	Primary	33/11	25	66.4	2.7
4	Telford	Primary	33/11	34	87.8	2.6
4	Birmingham	Primary	33/11	28	72.2	2.6
4	Stoke	BSP	132/33	5	12.8	2.6
4	Birmingham	Primary	33/11	24	60.3	2.5
4	Worcester	Primary	33/11	35	83.6	2.4
4	Telford	Primary	33/11	38	89.1	2.3

4	Major Projects West	GSP	400-275/132	3	7.0	2.3
4	Telford	Primary	33/11	34	78.7	2.3
4	Stoke	Primary	33/11	19	43.2	2.3
4	Birmingham	Primary	33/11	31	68.4	2.2
4	Stoke	BSP	132/33	31	68.1	2.2
4	Birmingham	Primary	33/11	22	47.2	2.1
4	Birmingham	Primary	33/11	30	63.5	2.1
4	Telford	Primary	33/11	17	35.7	2.1
4	Stoke	Primary	33/11	20	40.9	2.0
4	Telford	Primary	33/11	23	46.8	2.0
4	Birmingham	Primary	33/11	28	56.0	2.0
4	Stoke	Primary	33/11	32	64.0	2.0
4	Tipton	Primary	33/11	17	33.9	2.0
4	Telford	Primary	33/11	30	59.4	2.0
4	Stoke	Primary	33/11	19	37.6	2.0
5	Worcester	Primary	33/11	46	89.5	1.9
5	Gloucester	Primary	33/11	58	112.8	1.9
5	Gloucester	Primary	33/11	49	91.6	1.9
5	Stoke	Primary	33/11	42	78.1	1.9
5	Gloucester	Primary	33/11	26	48.3	1.9
5	Gloucester	Primary	33/11	44	79.6	1.8
5	Telford	Primary	33/11	21	38.0	1.8
5	Stoke	Primary	33/11	41	73.6	1.8
5	Tipton	Primary	33/11	22	39.0	1.8
5	Gloucester	Primary	33/11	47	83.1	1.8
5	Worcester	Primary	33/11	59	104.0	1.8
5	Worcester	Primary	33/11	32	56.1	1.8
5	Stoke	Primary	33/11	55	95.4	1.7
5	Worcester	Primary	33/11	37	63.9	1.7
5	Worcester	Primary	33/11	67	115.7	1.7
5	Stoke	Primary	33/11	33	56.6	1.7
5	Hereford & Ludlow	Primary	33/11	53	88.5	1.7
5	Telford	Primary	33/11	29	48.2	1.7
5	Gloucester	Primary	33/11	38	62.8	1.7
5	Stoke	Primary	33/11	51	84.1	1.6
5	Telford	Primary	33/11	49	79.1	1.6
5	Worcester	Primary	33/11	42	67.3	1.6
5	Stoke	Primary	33/11	24	38.4	1.6
5	Worcester	Primary	33/11	74	117.4	1.6
5	Stoke	Primary	33/11	89	140.1	1.6
5	Telford	Primary	33/11	63	97.9	1.6
5	Telford	Primary	33/11	25	38.1	1.5
5	Hereford & Ludlow	Primary	33/11	63	95.6	1.5
5	Tipton	BSP	132/33	4	6.0	1.5
5	Gloucester	Primary	33/11	57	85.7	1.5
5	Gloucester	Primary	33/11	31	45.5	1.5
5	Birmingham	Primary	33/11	32	46.9	1.5
5	Telford	Primary	33/11	64	93.0	1.5
5	Hereford & Ludlow	Primary	33/11	65	94.0	1.4
5	Worcester	Primary	33/11	57	82.4	1.4
5	Telford	Primary	33/11	45	64.9	1.4
5	Stoke	Primary	33/11	42	59.9	1.4

5	Hereford & Ludlow	BSP	132/66	9	12.8	1.4
5	Birmingham	Primary	33/11	47	66.1	1.4
5	Gloucester	Primary	33/11	34	47.7	1.4
5	Stoke	Primary	33/11	35	48.5	1.4
5	Telford	Primary	33/11	47	63.5	1.4
5	Worcester	Primary	33/11	40	53.9	1.3
5	Gloucester	Primary	33/11	29	38.9	1.3
5	Telford	Primary	33/11	67	89.3	1.3
5	Tipton	Primary	33/11	36	47.9	1.3
5	Gloucester	Primary	33/11	27	35.7	1.3
5	Tipton	Primary	33/11	32	41.3	1.3
5	Stoke	Primary	33/11	16	20.4	1.3
5	Gloucester	Primary	33/11	41	51.7	1.3
5	Hereford & Ludlow	Primary	33/11	81	101.0	1.2
5	Gloucester	Primary	33/11	54	66.7	1.2
5	Stoke	Primary	33/11	54	65.9	1.2
5	Worcester	Primary	33/11	56	68.0	1.2
5	Gloucester	Primary	33/11	60	72.7	1.2
5	Gloucester	Primary	33/11	48	57.9	1.2
5	Stoke	Primary	33/11	39	46.1	1.2
5	Hereford & Ludlow	Primary	33/11	45	52.9	1.2
5	Gloucester	Primary	33/11	71	83.3	1.2
5	Worcester	Primary	33/11	53	61.9	1.2
5	Hereford & Ludlow	Primary	33/11	78	91.1	1.2
5	Gloucester	Primary	33/11	63	72.2	1.1
5	Stoke	Primary	33/11	58	66.3	1.1
5	Hereford & Ludlow	Primary	33/11	66	75.4	1.1
5	Stoke	Primary	33/11	74	84.5	1.1
5	Tipton	Primary	33/11	38	43.2	1.1
5	Hereford & Ludlow	Primary	33/11	88	99.0	1.1
5	Birmingham	Primary	33/11	46	51.4	1.1
5	Worcester	BSP	132/33	37	41.3	1.1
5	Gloucester	Primary	33/11	73	81.4	1.1
5	Gloucester	Primary	33/11	68	75.5	1.1
5	Worcester	Primary	33/11	46	50.6	1.1
5	Tipton	Primary	33/11	56	61.0	1.1
5	Hereford & Ludlow	Primary	33/11	109	118.7	1.1
5	Gloucester	Primary	33/11	91	98.5	1.1
5	Worcester	Primary	33/11	68	73.4	1.1
5	Tipton	Primary	33/11	49	52.6	1.1
5	Stoke	Primary	33/11	56	58.7	1.0
5	Tipton	Primary	33/11	35	36.4	1.0
5	Worcester	Primary	33/11	44	45.6	1.0
5	Hereford & Ludlow	Primary	33/11	68	69.7	1.0
5	Gloucester	Primary	33/11	63	63.8	1.0
5	Gloucester	Primary	33/11	42	42.5	1.0
5	Stoke	Primary	33/11	30	29.6	1.0
5	Hereford & Ludlow	Primary	33/11	87	85.2	1.0
5	Birmingham	Primary	33/11	59	57.7	1.0
5	Hereford & Ludlow	Primary	33/11	69	67.3	1.0
5	Telford	Primary	33/11	52	50.6	1.0
5	Telford	Primary	33/11	70	68.0	1.0

5	Telford	Primary	33/11	74	71.6	1.0
5	Stoke	Primary	33/11	34	32.7	1.0
5	Worcester	Primary	33/11	65	62.0	1.0
5	Telford	Primary	33/11	35	33.1	0.9
5	Gloucester	Primary	33/11	62	58.6	0.9
5	Hereford & Ludlow	Primary	33/11	69	65.0	0.9
5	Birmingham	Primary	33/11	74	69.5	0.9
5	Gloucester	Primary	33/11	46	43.1	0.9
5	Telford	Primary	33/11	45	42.1	0.9
5	Telford	Primary	33/11	83	77.5	0.9
5	Hereford & Ludlow	Primary	33/11	64	58.2	0.9
5	Birmingham	Primary	33/11	27	24.5	0.9
5	Hereford & Ludlow	Primary	33/11	91	82.0	0.9
5	Tipton	Primary	33/11	46	41.1	0.9
5	Hereford & Ludlow	Primary	33/11	69	59.8	0.9
5	Worcester	Primary	33/11	59	50.8	0.9
5	Tipton	Primary	33/11	64	55.0	0.9
5	Stoke	Primary	33/11	58	48.8	0.8
5	Birmingham	Primary	33/11	94	79.1	0.8
5	Gloucester	Primary	33/11	66	54.9	0.8
5	Tipton	Primary	33/11	83	69.0	0.8
5	Gloucester	Primary	33/11	60	49.7	0.8
5	Tipton	Primary	33/11	66	53.4	0.8
5	Worcester	Primary	33/11	70	56.5	0.8
5	Hereford & Ludlow	Primary	33/11	70	56.4	0.8
5	Worcester	Primary	33/11	64	50.7	0.8
5	Worcester	Primary	33/11	80	62.0	0.8
5	Tipton	Primary	33/11	56	42.9	0.8
5	Worcester	Primary	33/11	81	61.7	0.8
5	Stoke	Primary	33/11	61	46.2	0.8
5	Hereford & Ludlow	Primary	33/11	59	43.1	0.7
5	Hereford & Ludlow	Primary	33/11	65	47.5	0.7
5	Worcester	Primary	33/11	65	47.2	0.7
5	Birmingham	Primary	33/11	60	43.2	0.7
5	Worcester	Primary	33/11	82	58.4	0.7
5	Telford	Primary	33/11	78	55.3	0.7
5	Birmingham	Primary	33/11	78	54.5	0.7
5	Birmingham	Primary	33/11	78	54.4	0.7
5	Worcester	Primary	33/11	50	34.4	0.7
5	Tipton	Primary	33/11	78	52.1	0.7
5	Worcester	Primary	33/11	113	75.4	0.7
5	Tipton	Primary	33/11	61	40.2	0.7
5	Stoke	Primary	33/11	92	60.4	0.7
5	Tipton	Primary	33/11	68	44.0	0.6
5	Stoke	GSP	400-275/132	48	31.1	0.6
5	Gloucester	Primary	33/11	38	24.0	0.6
5	Tipton	Primary	33/11	50	31.4	0.6
5	Tipton	Primary	33/11	72	45.2	0.6
5	Gloucester	Primary	33/11	116	69.9	0.6
5	Hereford & Ludlow	Primary	33/11	101	60.1	0.6
5	Worcester	Primary	33/11	91	52.1	0.6
5	Gloucester	Primary	33/11	41	23.4	0.6

5	Hereford & Ludlow	Primary	33/11	101	55.2	0.5
5	Tipton	Primary	33/11	50	26.6	0.5
5	Stoke	Primary	33/11	74	38.3	0.5
5	Gloucester	Primary	33/11	142	72.9	0.5
5	Tipton	Primary	33/11	81	41.1	0.5
5	Gloucester	Primary	33/11	100	50.7	0.5
5	Gloucester	Primary	33/11	115	57.7	0.5
5	Hereford & Ludlow	Primary	33/11	86	43.0	0.5
5	Stoke	Primary	33/11	84	41.9	0.5
5	Tipton	Primary	33/11	77	38.3	0.5
5	Worcester	Primary	33/11	84	41.5	0.5
5	Hereford & Ludlow	Primary	33/11	112	53.7	0.5
5	Hereford & Ludlow	Primary	33/11	112	50.8	0.5
5	Worcester	Primary	33/11	118	50.5	0.4
5	Stoke	Primary	33/11	74	28.6	0.4
5	Stoke	Primary	33/11	113	39.7	0.4
5	Stoke	Primary	33/11	73	23.7	0.3
5	Stoke	Primary	33/11	147	43.7	0.3
5	Stoke	Primary	33/11	72	21.3	0.3

APPENDIX C: RAILWAY NETWORK CRITICALITY BANDS

Table of Criticality Bands allocated to locations for the Wessex route, ranked in descending order of disruption magnitude.

BAND	Location	Incidents	DM	DM per Incident
1	Strawberry Hill C.S.D. to Teddington	2	1504.6	752.3
1	Motspur Park to Tolworth SDGS	2	945.8	472.9
1	Nine Elms Jn to Vauxhall	5	1607.5	321.5
1	Clapham Junction to Vauxhall	36	10512.6	292.0
1	Fratton to Portcreek Jn	63	17983.9	285.5
1	Clapham Junction to Wimbledon	88	23787.4	270.3
1	New Malden	31	8103.8	261.4
1	Andover to Romsey	4	1042	260.5
1	Northam C.S.D.	6	1482.5	247.1
1	Earlsfield to Wimbledon	29	7128.2	245.8
1	Clapham Junction to London Waterloo	202	46136.7	228.4
1	Winchester	44	9175.6	208.5
1	Andover	2	416	208.0
1	Eastleigh to St Denys	127	26286.3	207.0
1	Earlsfield	23	4753.1	206.7
1	Fawley Esso	3	567	189.0
1	Winchester to Worting Jn	346	61683.8	178.3
1	London Waterloo to Nine Elms Jn	15	2646.2	176.4
1	Fratton	47	8250	175.5
1	Basingstoke to Worting Jn	11	1861.9	169.3
1	Southampton Eastern Docks	3	505.4	168.5
1	Kingston	8	1341.4	167.7
1	Bramley (Hants)	27	4483.6	166.1
2	Eastleigh	125	20143.3	161.1
2	Surbiton to Woking	132	21206.3	160.7
2	Effingham Junction to Guildford	5	800.2	160.0
2	Clapham Junction to Earlsfield	24	3813.4	158.9
2	New Malden to Surbiton	76	12043.4	158.5
2	Portsmouth & S'Sea D.C.S to Portsmouth & Southsea	44	6953.5	158.0
2	St Denys	44	6932.9	157.6
2	Surbiton to Weybridge	117	17898.9	153.0
2	Wimbledon	89	12589.8	141.5
2	Eastleigh to Winchester	160	22143.9	138.4
2	Motspur Park to Wimbledon	64	8854.6	138.4
2	Redbridge	45	6123.9	136.1
2	Millbrook Hants..F.L.T.	9	1185.4	131.7
2	Effingham Junction to Surbiton	2	258.4	129.2
2	Virginia Water	27	3475	128.7

2	New Malden to Wimbledon	110	13469.1	122.4
2	Wishford to Wylye Ahb	18	2197	122.1
2	Fareham to St Denys	136	16470.5	121.1
2	Alton to Farnham	123	14664.2	119.2
2	Southampton Western Docks to Southampton Central	2	238	119.0
2	Brockenhurst to Redbridge	130	15385.7	118.4
2	Vauxhall	48	5641.6	117.5
2	Leatherhead	27	3154.6	116.8
2	Cosham	32	3705.5	115.8
2	Bournemouth to Brockenhurst	173	19830.6	114.6
2	Reading Spur Jn to Wokingham	83	9219.6	111.1
2	Ash to Guildford	40	4427.8	110.7
2	Wokingham	44	4779	108.6
2	London Waterloo	595	64396.4	108.2
2	Fratton C.S.D.	9	964.5	107.2
2	Aldershot	73	7790.5	106.7
2	Barnes	67	7090.8	105.8
2	Redbridge to Southampton Central	173	18280.3	105.7
2	Cosham to Portcreek Jn	33	3447.9	104.5
2	Basingstoke	194	19412.9	100.1
2	Andover to Salisbury	75	7404.5	98.7
2	Southampton Eastern Docks to St Denys	3	295	98.3
2	Cosham to Havant	36	3437	95.5
2	Southampton M.C.T.	25	2291	91.6
2	Southampton Central to Southampton M.C.T.	11	1001	91.0
2	London Waterloo to Vauxhall	115	10352.1	90.0
2	Feltham	30	2690.4	89.7
2	Feltham to Twickenham	86	7633	88.8
2	Gillingham (Dorset) to Templecombe	10	885.5	88.6
2	Maiden Newton to Yeovil Pen Mill	27	2299	85.1
2	Cosham to Fareham	46	3873.5	84.2
2	Fratton to Portsmouth & Southsea	64	5301.7	82.8
2	Clapham Junction	185	15315.5	82.8
2	Southampton Central to St Denys	222	18247.4	82.2
3	Eastleigh East Yard	21	1674	79.7
3	Portsmouth Harbour	103	8036.7	78.0
3	Wool	18	1401	77.8
3	Tolworth SDGS	5	389	77.8
3	Surbiton	42	3259.4	77.6
3	Nine Elms Jn	8	620.8	77.6
3	Dorchester West to Maiden Newton	35	2710	77.4
3	Brockenhurst	70	5403.3	77.2
3	Staines	61	4692.6	76.9
3	Romsey to Salisbury	275	20918.3	76.1

3	Alton	36	2729.8	75.8
3	Guildford	109	8137.1	74.7
3	Clandon to Effingham Junction	28	2063.2	73.7
3	Ash Vale	33	2429.6	73.6
3	Redbridge to Romsey	35	2566.4	73.3
3	Worting Jn	21	1538	73.2
3	Ash to Wokingham	107	7691.9	71.9
3	Farnham	40	2847.9	71.2
3	Kingston to Teddington	12	854.2	71.2
3	Addlestone	9	617.8	68.6
3	Epsom	69	4683.4	67.9
3	Salisbury	79	5263.8	66.6
3	Portcreek Jn	5	333	66.6
3	Havant to Petersfield	135	8979.1	66.5
3	Havant to Portcreek Jn	93	6159.3	66.2
3	Weybridge	37	2413.6	65.2
3	Farnborough (Main) to Woking	148	9424.8	63.7
3	Weybridge to Woking	74	4707.4	63.6
3	Staines to Virginia Water	126	7928.8	62.9
3	Botley to Fareham	56	3481.1	62.2
3	Twickenham	44	2691.2	61.2
3	Woking	133	8091.9	60.8
3	Fareham	59	3588.5	60.8
3	Haslemere	71	4263	60.0
3	Soton W Docks Shed 107	4	240	60.0
3	Basingstoke to Bramley (Hants)	36	2148	59.7
3	Haslemere to Petersfield	261	15521.5	59.5
3	Branksome	19	1128.4	59.4
3	Clapham Junction to Nine Elms Jn	123	7276.3	59.2
3	Barnes to Putney	21	1226.2	58.4
3	Ascot to Ash Vale	80	4645.8	58.1
3	Chard Jn. S.B to Honiton	94	5162	54.9
3	Honiton	13	707	54.4
3	Yeovil Junction	16	865.5	54.1
3	Farncombe to Haslemere	158	8542	54.1
3	Gillingham (Dorset) to Salisbury	119	6377	53.6
3	Aldershot to Ash Vale	44	2352.2	53.5
3	Motspur Park	19	980.6	51.6
3	Addlestone to Woking	16	816.6	51.0
3	Wimbledon Park	7	352.6	50.4
3	Templecombe	13	651	50.1
3	Chessington South to Motspur Park	86	4292	49.9
3	Guildford to Woking	62	3082.4	49.7
3	Teddington	5	246.6	49.3

3	Southampton Central	134	6603.9	49.3
3	Bournemouth	101	4970	49.2
3	Dorchester South to Weymouth	119	5849.2	49.2
3	Epsom to Motspur Park	70	3432.8	49.0
3	Wareham to Wool	79	3838.6	48.6
3	Barnes to Brentford	111	5346.6	48.2
3	Dorchester South to Wool	139	6614.8	47.6
3	Poole	54	2565.5	47.5
3	Basingstoke to Farnborough (Main)	170	8065.8	47.4
3	Aldershot to Ash	28	1311	46.8
3	Effingham Junction	28	1297.9	46.4
3	Botley	29	1336.5	46.1
3	Salisbury to Wishford	27	1236	45.8
3	Feltham to Staines	76	3454.8	45.5
3	Kingston to New Malden	37	1680	45.4
3	Fawley Esso to Redbridge	21	952	45.3
3	Clandon to Guildford	24	1076.4	44.9
3	Botley to Eastleigh	50	2235.2	44.7
3	Weymouth	50	2230.4	44.6
3	Farncombe	22	971	44.1
3	Fulwell to Teddington	15	655	43.7
3	Yeovil Pen Mill	17	739	43.5
3	Havant	117	5050.5	43.2
3	Clapham Yard	16	687.8	43.0
3	Chard Jn. S.B to Yeovil Junction	64	2748.5	42.9
3	Portsmouth & Southsea	77	3189	41.4
3	Templecombe to Yeovil Junction	61	2516.9	41.3
3	Petersfield	33	1343	40.7
3	Claygate to Effingham Junction	57	2306.2	40.5
3	Bracknell to Wokingham	68	2745.4	40.4
4	Andover to Worting Jn	41	1651	40.3
4	Putney	14	562	40.1
4	Hounslow	16	626.6	39.2
4	Claygate	4	156	39.0
4	Wareham	16	623	38.9
4	Ash Vale to Woking	27	1045.5	38.7
4	Poole to Wareham	61	2361.8	38.7
4	Branksome to Poole	46	1759.9	38.3
4	Epsom to Leatherhead	84	3212.8	38.2
4	Brentford to Hounslow	52	1983.8	38.2
4	Surbiton to Virginia Water	2	76	38.0
4	Eastleigh to Romsey	46	1710.5	37.2
4	Lymington Pier	8	286.6	35.8
4	Hampton Court	34	1205.6	35.5

4	Farnborough (Main)	27	951	35.2
4	Northam C.S.D. to St Denys	3	104	34.7
4	Fulwell to Strawberry Hill	2	67	33.5
4	Romsey	29	964.9	33.3
4	Shepperton to Sunbury	8	263	32.9
4	Dorchester South	34	1107.8	32.6
4	Addlestone to Chertsey	20	648	32.4
4	Strawberry Hill to Teddington	19	615.4	32.4
4	Feltham to Hounslow	32	1024	32.0
4	Gillingham (Dorset)	16	510.5	31.9
4	Bournemouth to Branksome	52	1611.8	31.0
4	Dorchester West to Weymouth	15	463.7	30.9
4	Brentford	5	154	30.8
4	Clapham Junction to Putney	74	2237.6	30.2
4	Redbridge to Southampton M.C.T.	3	90	30.0
4	Chessington South	10	299.2	29.9
4	Sunbury	10	295.6	29.6
4	Ascot	45	1304.8	29.0
4	Hounslow to Twickenham	18	521	28.9
4	Ascot to Virginia Water	47	1296.6	27.6
4	Hampton Court to Surbiton	28	761.8	27.2
4	Staines to Windsor & Eton Riverside	55	1481.8	26.9
4	Windsor & Eton Riverside	25	668.6	26.7
4	Aldershot to Farnham	28	738.8	26.4
4	Hampton	13	330	25.4
4	Strawberry Hill	34	862.8	25.4
4	Shepperton	29	686.2	23.7
4	Ash	19	418	22.0
4	Strawberry Hill to Twickenham	15	329.8	22.0
4	Virginia Water to Woking	13	276	21.2
5	Ascot to Bracknell	24	470	19.6
5	Dorchester West	12	232.5	19.4
5	Effingham Junction to Leatherhead	26	457	17.6
5	Epsom - Up Sidings	5	87.4	17.5
5	Addlestone to Weybridge	16	278	17.4
5	Chertsey to Virginia Water	11	182	16.5
5	Clapham Junction to Wimbledon Park	11	179.8	16.3
5	Fulwell to Hampton	7	112.2	16.0
5	Brockenhurst to Lymington Pier	16	245.4	15.3
5	Clandon	7	104.6	14.9
5	Fulwell	24	350.2	14.6
5	Hampton to Sunbury	14	194	13.9
5	Chertsey	11	152	13.8
5	Chard Jn. S.B	6	82	13.7

5	Maiden Newton	10	130	13.0
5	Shalford	6	75	12.5
5	Guildford U.C.H.S. to Woking	2	24	12.0
5	Claygate to Surbiton	14	160	11.4
5	Bracknell	2	21	10.5
5	Yeovil Junction to Yeovil Pen Mill	6	59	9.8
5	Millbrook Hants..F.L.T. to Southampton Central	4	32	8.0
5	Hamworthy T.C. to Poole	2	14	7.0
5	Ash to Guildford U.C.H.S.	2	11	5.5
5	East Putney to Wimbledon Park	2	9	4.5
5	Fratton C.S.D. to Portsmouth & Southsea	2	8	4.0

Table of Criticality Bands allocated to locations for the LNW (South) route, ranked in descending order of disruption magnitude.

BAND	Location	Incidents	DM	DM per Incident
1	Rowley Regis	4	4157	1039.3
1	Princes R'Boro Ace	3	2446.3	815.4
1	Weedon	5	3778	755.6
1	Kingsbury Jn to Kingsbury SDGS	2	1285	642.5
1	Bescot Up Engineers SDGS to Perry Barr North Jn	2	1218.5	609.3
1	Ledburn Jn	64	27871.5	435.5
1	Harrow & Wealdstone	24	10203.5	425.1
1	Longbridge	28	11645.5	415.9
1	Hanslope Jn to Weedon	133	55278.1	415.6
1	Hanslope Jn	59	22727.8	385.2
1	Kingsbury Jn to Park Lane Jn	6	2302	383.7
1	Galton Jn to Wolverhampton Steel Term	9	3251.5	361.3
1	Bescot Holding Sidings to Walsall	2	645	322.5
1	Harrow & Wealdstone to Watford Junction	224	63578.3	283.8
1	Ledburn Jn to Tring	76	21474.5	282.6
1	Harrow & Wealdstone D.C. to Willesden Jn Low Level	199	55682.3	279.8
1	Aynho Jn	10	2701.6	270.2
1	Birmingham New Street to Galton Jn	169	43990.3	260.3
2	Kingsbury Jn	34	8240	242.4
2	Harrow & Wealdstone to Willesden West Londn Jn	524	126578.8	241.6
2	Watford Junction	133	31418.3	236.2
2	Aston	34	8014	235.7
2	Wolverhampton	145	32823	226.4
2	Galton Jn to Wolverhampton	199	44109	221.7
2	Birmingham International to Coventry	162	34434.9	212.6
2	Calvert	6	1268.8	211.5
2	Kings Norton to Longbridge	48	9769	203.5

2	Stechford	10	2009	200.9
2	Aston to Birmingham New Street	92	18451	200.6
2	Barnt Green	20	3971.5	198.6
2	Galton Jn	18	3535.5	196.4
2	Hatton	18	3380.9	187.8
2	Birmingham New Street to Kings Norton	126	23546.7	186.9
2	Leamington Spa	53	9583.3	180.8
2	Dorridge to Hatton	29	5155.6	177.8
2	Kings Norton	29	5098.5	175.8
2	Bordesley Jn	4	702	175.5
2	Hanslope Jn to Northampton	80	13914.8	173.9
2	Castle Bromwich Jaguar to Landor Street Jn	3	520	173.3
2	Birmingham Moor Street to Tyseley	54	9193.1	170.2
2	Birmingham New Street to Stechford	91	15302.3	168.2
2	Bushbury Jn to Wolverhampton	72	12039	167.2
2	Harrow & Wealdstone D.C.	44	7278	165.4
2	Bletchley to Ledburn Jn	230	36995.7	160.9
2	Queens Park (Dc)	47	7546.5	160.6
2	Hanslope Jn to Milton Keynes Central	190	30232.4	159.1
2	Queens Park (Dc) to Willesden Jn Low Level	83	13099	157.8
2	Willesden West Londn Jn	43	6427.3	149.5
2	Birmingham International	51	7418.8	145.5
2	Kingsbury Jn to Landor Street Jn	191	26927	141.0
2	Barnt Green to Redditch	13	1829	140.7
2	Coventry	93	12875	138.4
2	Nuneaton to Whitacre Jn	77	10655	138.4
2	Stratford-Upon-Avon to Whitlocks End	19	2605.3	137.1
2	Barnt Green to Longbridge	24	3233	134.7
2	Birmingham New Street	558	74589.9	133.7
2	Whitlocks End	2	266	133.0
2	London Euston to Willesden West Londn Jn	272	35984.5	132.3
2	St Albans Abbey to Watford Junction	52	6836.6	131.5
2	Lawley Street F.L.T.	25	3280	131.2
2	Birmingham International to Stechford	50	6506.8	130.1
2	Four Oaks to Lichfield City	58	7433.5	128.2
2	Birmingham Snow Hill to Rowley Regis	92	11728.4	127.5
2	South Ruislip	15	1871.7	124.8
3	Rugby to Weedon	176	21861.6	124.2
3	St Albans Abbey	2	245	122.5
3	Harrow & Wealdstone to Willesden Euroterminal	4	487	121.8
3	Northampton to Rugby	205	24628.3	120.1
3	Madeley Jn (Salop)	5	598	119.6
3	Landor Street Jn	37	4365	118.0
3	Willesden Euroterminal	4	468	117.0

3	Bletchley	112	12552.1	112.1
3	Madeley Jn (Salop) to Wolverhampton	99	10749	108.6
3	Willesden Jn Low Level	45	4840	107.6
3	Tring	64	6834.8	106.8
3	Birmingham Moor Street to Birmingham Snow Hill	6	635	105.8
3	Nuneaton	97	10127	104.4
3	Stourbridge Junction	37	3808.2	102.9
3	Four Oaks	13	1330	102.3
3	Harrow & Wealdstone D.C. to Watford Junction	5	511	102.2
3	London Euston to Queens Park (Dc)	29	2945	101.6
3	Gerrards Cross to High Wycombe	81	8137.2	100.5
3	Hatton to Leamington Spa	49	4803.4	98.0
3	Birmingham New Street to Landor Street Jn	62	5919	95.5
3	Lichfield City	14	1330	95.0
3	Mitre Bridge Jn	42	3977.3	94.7
3	Perry Barr North Jn to Walsall	188	17773	94.5
3	Rugby	133	12567.1	94.5
3	Bushbury Jn	24	2261	94.2
3	Coventry to Rugby	168	15786.9	94.0
3	Camden C.S.D. to London Euston	2	187.8	93.9
3	Dorridge	28	2618.5	93.5
3	Tyseley	18	1679.5	93.3
3	Nuneaton to Rugby	260	24130.5	92.8
3	Madeley Jn (Salop) to Wellington (Shropshire)	24	2219.5	92.5
3	Banbury to Leamington Spa	126	11391.7	90.4
3	Milton Keynes Central	89	7880.4	88.5
3	Aston to Four Oaks	67	5812	86.7
3	Aston to Perry Barr North Jn	43	3721	86.5
3	Wembley Eur Frt Ops Cntre to Willesden West Londn Jn	4	341	85.3
3	Tyseley to Whitlocks End	16	1363.5	85.2
3	Park Lane Jn	5	419	83.8
3	Gerrards Cross to South Ruislip	81	6655	82.2
3	Park Lane Jn to Walsall	73	5973.5	81.8
3	London Euston	146	11933.4	81.7
3	Bescot Down Side to Walsall	11	886	80.5
3	London Marylebone	95	7607.1	80.1
3	Coventry to Leamington Spa	59	4649	78.8
3	Bletchley C.S.	9	702.8	78.1
3	Bescot Down Side to Perry Barr North Jn	5	377	75.4
3	Portobello Jn (West Mids)	6	449	74.8
3	Northampton	138	10183.2	73.8
3	Bletchley to Milton Keynes Central	179	12872.9	71.9
3	Camden C.S.D.	2	141	70.5
3	Birmingham New Street to Soho L.M.D.	7	491	70.1

3	Bordesley Jn to Tyseley	19	1332	70.1
3	Birmingham Moor Street	49	3417.9	69.8
3	Aynho Jn to Banbury	86	5801	67.5
3	Birmingham New Street to Bordesley Jn	65	4328.5	66.6
3	Perry Barr North Jn	23	1492.5	64.9
3	Tyseley L.M.D.	4	256	64.0
3	Landor Street Jn to Whitacre Jn	120	7596	63.3
4	Stonebridge Park Depot to Willesden Jn Low Level	3	182	60.7
4	Bordesley Jn to Landor Street Jn	15	892	59.5
4	Stonebridge Park Depot	5	296	59.2
4	Bescot Down Side	13	759	58.4
4	Dorridge to Tyseley	86	5015.3	58.3
4	Banbury	126	7336.3	58.2
4	Rowley Regis to Stourbridge Junction	39	2270.5	58.2
4	Lichfield Trent Valley Hl	25	1428	57.1
4	Dorridge to Stratford-Upon-Avon	4	222	55.5
4	Wembley Eur Frt Ops Cntre	16	885	55.3
4	Landor Street Jn to Hams Hall Reception Line	2	109	54.5
4	Hednesford	20	1073.5	53.7
4	Bletchley C.S. to Milton Keynes Central	10	534	53.4
4	Aynho Jn to Heyford	24	1258	52.4
4	Aynho Jn to Bicester North	38	1925.8	50.7
4	Bordesley Jn to Kings Norton	30	1445	48.2
4	Hednesford to Rugeley Town	35	1685	48.1
4	Castle Bromwich Jaguar	2	94	47.0
4	Kidderminster to Stourbridge Junction	56	2631	47.0
4	Hednesford to Walsall	135	6216	46.0
4	Landor Street Jn to Park Lane Jn	13	593	45.6
4	Walsall	39	1744	44.7
4	Gerrards Cross	36	1605.5	44.6
4	Kidderminster	52	2308.8	44.4
4	Bescot Up Engineers SDGS	8	346	43.3
4	Watford Junction Dc	20	848.6	42.4
4	Birmingham Snow Hill	38	1609.1	42.3
4	Galton Jn to Perry Barr North Jn	6	254	42.3
4	Aylesbury	46	1892.6	41.1
4	Bordesley Jn to Tyseley L.M.D.	10	400.5	40.1
4	Aston to Stechford	7	280	40.0
4	Whitacre Jn	7	274	39.1
4	Perry Barr North Jn to Portobello Jn (West Mids)	36	1393	38.7
4	Birmingham New Street to Perry Barr North Jn	32	1211	37.8
4	Walsall Freight Terminal to Walsall	2	68	34.0
4	Soho L.M.D.	2	68	34.0
4	Coventry to Nuneaton	49	1638	33.4

4	Hatton to Stratford-Upon-Avon	15	500.5	33.4
4	Bescot Up Engineers SDGS to Walsall	3	94	31.3
5	Rugeley Town	14	432	30.9
5	Wellington (Shropshire)	17	514	30.2
5	Kingsbury Jn to Lawley Street F.L.T.	3	87	29.0
5	Harrow & Wealdstone to Wembley Eur Frt Ops Cntre	8	228	28.5
5	Amersham to Aylesbury	34	938	27.6
5	High Wycombe	18	487.7	27.1
5	Portobello Jn (West Mids) to Walsall	17	447	26.3
5	Amersham	2	50	25.0
5	Lawley Street F.L.T. to Whitacre Jn	22	515	23.4
5	Perry Barr North Jn to Soho L.M.D.	8	179	22.4
5	Kingsbury Jn to Whitacre Jn	8	176	22.0
5	Northampton Castle Yard	2	44	22.0
5	Park Lane Jn to Whitacre Jn	6	129	21.5
5	Galton Jn to Rowley Regis	19	396	20.8
5	Willesden Brent Sidings	4	74	18.5
5	Stratford-Upon-Avon	9	165	18.3
5	Redditch	8	146	18.3
5	Northampton Emd to Northampton	3	52	17.3
5	Harrow & Wealdstone D.C. to Watford Junction Dc	54	904	16.7
5	Round Oak to Stourbridge Junction	11	184	16.7
5	Bicester North	21	337	16.0
5	Mitre Bridge Jn to Willesden West Londn Jn	13	206	15.8
5	Bushbury Jn to Portobello Jn (West Mids)	13	201	15.5
5	Portobello Jn (West Mids) to Wolverhampton	9	134	14.9
5	Lichfield City to Lichfield Trent Valley Hl	16	225	14.1
5	Landor Street Jn to Lawley Street F.L.T.	3	41	13.7
5	Wembley Lmd	5	64	12.8
5	Aston to Galton Jn	7	85	12.1
5	Bedworth Murco SDGS to Nuneaton	2	22	11.0
5	Bushbury Jn to Madeley Jn (Salop)	5	49	9.8
5	Birmingham Moor Street to Tyseley L.M.D.	2	8	4.0
5	Banbury to Fenny Compton M.O.D.	2	6	3.0

APPENDIX D: EXAMPLES OF NETWORK DIAGRAMS

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Example of WPD network diagram (REDACTED).

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Example of NR traction feeder diagram (REDACTED).