Climate change resilience beyond the mainline railway

Fisher, Rachel; Ferranti, Emma; Greenham, Sarah; Quinn, Andrew

DOI:
10.1680/jcien.23.00101

Accepted manuscript

As a service to our authors and readers, we are putting peer-reviewed accepted manuscripts (AM) online, in the Ahead of Print section of each journal web page, shortly after acceptance.

Disclaimer

The AM is yet to be copyedited and formatted in journal house style but can still be read and referenced by quoting its unique reference number, the digital object identifier (DOI). Once the AM has been typeset, an ‘uncorrected proof’ PDF will replace the ‘accepted manuscript’ PDF. These formatted articles may still be corrected by the authors. During the Production process, errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal relate to these versions also.

Version of record

The final edited article will be published in PDF and HTML and will contain all author corrections and is considered the version of record. Authors wishing to reference an article published Ahead of Print should quote its DOI. When an issue becomes available, queuing Ahead of Print articles will move to that issue’s Table of Contents. When the article is published in a journal issue, the full reference should be cited in addition to the DOI.

Accepted manuscript
doi: 10.1680/jcien.23.00101

Submitted: 01 June 2023

Published online in 'accepted manuscript' format: 04 November 2023

Manuscript title: Climate change resilience beyond the mainline railway: a review

Authors: Rachel Fisher[1], Emma Ferranti[1], Sarah Greenham[2], Andrew Quinn[1]

Affiliations: [1]School of Engineering, University of Birmingham, Birmingham, UK. [2]Geography, Earth and Environmental Sciences University of Birmingham, Birmingham, UK.

Corresponding author: Rachel Fisher, School of Engineering, University of Birmingham, Birmingham, UK.

E-mail: r.s.fisher@bham.ac.uk

Abstract

The UK's national railway network has evaluated climate change impacts, risks and adaptation solutions. This review establishes the case for greater attention to be given to the vulnerability rail transport beyond the mainline network. By considering the resilience of high-speed rail, mass rapid transit systems and light rail transit systems, the overall resilience of journeys can be improved. To this end, this review establishes current knowledge, practice and policy relating to rail beyond the mainline and outlines the next steps to achieve resilience. By providing this overview of advances, challenges and opportunities, practitioners and academics alike will be stimulated to pursue further resilience.

Accepted manuscript
doi: 10.1680/jcien.23.00101

1. Introduction

In 2010, Baker *et al*. provided the seminal review of climate change and the UK rail industry (Baker *et al*., 2010). The review considered the role of the railway industry in reducing greenhouse gas emissions, and the changes that would be required to enable this (climate change mitigation). It also considered the impact of climate change on the railways, such as more frequent extreme weather, and how they could become more resilient to current and projected hazards (climate change adaptation).

Baker's 2010 consideration of the impacts of climate change on railways formed the beginning of the academic dialogue on resilience and adaptation to climate change within the sector. Prior to this, the discussion had primarily revolved around the role of railways in the mitigation of climate change through reducing emissions and creating a modal shift to rail. Since 2010, there has been significant progress on climate adaptation and resilience thinking within the transport sector, in part enabled through improved understanding of climate science.

1.1 Advancements in climate science

Since 2010 there has been increased scientific research on climate change leading to a more detailed understanding of the meteorological and atmospheric processes, and improved future climate projections, particularly at regional and local levels. Globally, the International Panel on Climate Change (IPCC) collates scientific evidence in regular assessment reports under three broad headings: physical science; impacts, adaptation and vulnerability; and mitigation. The synthesis of the Sixth Assessment Report (AR6) has now been published. While there are many headline statements relating to the state of the climate, in this context it is particularly concerning that the IPCC is warning that the window of opportunity for climate resilient development is closing (Mukherji *et al*., 2023).

The UK Climate Projections Programme (UKCP) provides climate observations and projections for the UK. Baker *et al*. (2010) utilised the climate data from UKCIP02 (Hulme, 2002) although acknowledged that the most recent development at the time of publishing, UKCP09 (Murphy *et al*., 2009) provided greater in-depth data for analysis. Since then, UKCP18 (Lowe *et al*., 2018) has further advanced the capability to investigate the scale of climate change and its impacts.

Current products include 2.5 km resolution climate projections for the UK until 2100, for different emission scenarios, or representative concentration pathways (RCP). The RCPs link mitigation and adaptation agendas, enabling end-users to understand the scale of climate impacts for different emissions reduction ambitions.

Building on experience gained during UKCP09 (Steynor *et al*., 2012), UKCP18 involved significant stakeholder co-creation, and end-user testing and development to ensure the final products were suitable for the decision-making requirements of a range of bodies, including infrastructure operators, environmental organisations and local government.

1.2 Political landscape

In the past decade there has been increased political awareness and action to address climate change. In 2015, the United Nations World Conference on Disaster Risk Reduction (Sendai) and the United Nations Sustainable Development Summit (New York) led up to the Paris

Agreement at COP 21 in Paris (Paris Agreement, 2015). The Sustainable Development Goals (SDG) were adopted at the New York Summit (SDG Fund, 2015); of these, Climate Action (SDG13) takes urgent action to combat climate change and its impacts, including building resilience, adaptive capacity, implementing measures into policy, and raising awareness at all levels of society.

The SDGs combined with the Sendai Framework for Disaster Risk Reduction (UNISDR (United Nations International Strategy for Disaster Reduction), 2015) have provided coherent frameworks for collaborative global action. In combination, these international agreements and increased scientific understanding has enabled assessment of the role of infrastructure in both mitigating and resisting climate change.

In the UK, infrastructure adaptation is mandated by the 2008 Climate Change Act. Government must undertake a climate change risk assessment (CCRA) (HM Government UK, 2022), which feeds into a national adaptation programme (NAP) (Department for Environment, Food and Rural Affairs, 2023) (for details of this legislative approach see (Jude *et al*., 2017)).

Under the adaptation reporting power (ARP3), major infrastructure operators and owners are required to report on climate risks and opportunities and the measures they are taking. Over 80 organisations submitted responses to the third round of adaptation reporting, 80% of the organisations invited to report. While reviews of the previous rounds have found the process increases awareness, transparency, and action to address climate change (Hayman *et al*., 2017), 20% of invited organisations did not submit a report and half of these are organisations that have participated in ARP2 (Climate Change Committee, 2022).

Furthermore, the National Infrastructure Commission (NIC), has assessed the impacts of climate change on critical national infrastructure including transport infrastructure, focusing on resilience of infrastructure in one of their latest reports (National Infrastructure Commission, 2020). An overview of the UK mainline railway climate change adaptation policy landscape is shown in Figure 1.

1.3 Railway resilience research

Alongside national assessments conducted by government bodies, there has been an increase in academic research interrogating the role of infrastructure and the impact of climate change on these assets in the future (Figure 2), although this is only a small proportion of the overall research (Clarivate Analytics, 2021). Moreover, resilience to weather and climate is only a small proportion of transport resilience research (Figure 3).

Over the course of a decade, the research has matured and enabled work to be conducted at the interface between academics and practitioners (for example Ferranti *et al*., 2016; Greenham *et al*., 2023a, 2020; and Quinn *et al*., 2018). This has resulted in exploration of areas such as interdependencies between different infrastructure networks and decision-centric approaches to adaptation (Ranger *et al*., 2013), and the role of adaptation pathways to create long-term resilience (Ferranti *et al*., 2021 and Haasnoot *et al*., 2013).

Although in development since the early 2000s, the urgency to address the issue was accelerated in part due to number of extreme weather events including widespread snowfall in the winter of 2009/10 (Department for Transport, 2010), summer storms in 2012 (Jaroszweski *et al*., 2015) , storms over the winter of 2013/14 (Department for Transport, 2014) and extreme

doi: 10.1680/jcien.23.00101

heat in the summer of 2015 (Ferranti *et al*., 2018). However, these incidents continue to happen, such as washouts on the Conwy Valley Line (Figure 4) and notably, 40°C being exceeded in the UK for the first time (Kendon, 2022).

The most comprehensive assessment of knowledge of the relationships to date forms part of the Tomorrow's Railways and Climate Change Adaptation (TRaCCA), which investigated the resilience of the UK rail network to future climates, highlighting vulnerabilities and consequently made recommendations for both the academic community and the rail industry (Marteaux, 2016). TRaCCA identified knowledge gaps across four areas

- operational threshold analysis of railway systems
- knowledge about impacts on the rail network
- knowledge about procedures, risk mitigation and solutions
- design thresholds, standards and other research (RSSB, 2015).

The core of the research systematically explored and consolidated the knowledge established with regards to each weather–rail-system relationship and the associated operational thresholds, impacts, risks and design standards (RSSB, 2015).

1.4 Resilience beyond the mainline railway

There has been significant progress over the last decade relating to the resilience of the mainline UK rail network. However, it is short-sighted to consider the railway network in isolation as the resilience of passenger journeys is dependent on other types of rail-based transport systems as well. To achieve whole journey resilience, the role of rail systems beyond the mainline, such as high speed and urban rail transit systems is critical.

It is particularly important when considering the need for modal shift to low-emissions modes at both the inter- and intra- city scales to mitigate climate change. However, CCRA approaches are siloed and focused on national networks leaving an adaptation gap at regional levels. Although the climate emergency is a global problem, the impacts of future climates will be felt internationally, nationally, regionally and even at a local level (Lowe *et al*., 2018).

The risks to the mainline network are considered at a national and route level, while regional and local impacts to journeys is much less considered. There is an urgent need for a step change in the approach to the resilience of rail systems beyond the mainline as the window for adaptation closes (Mukherji *et al*., 2023) and as the likelihood of exceeding +1.5°C (even temporarily) by 2027 increases (World Meteorological Organization, 2023).

Consequently, this review brings together the current state-of-the-art research, policy and strategy focusing on the resilience of rail transit beyond the mainline railway in Britain. The following sections outline the advances, challenges and opportunities for high-speed rail (HSR), mass rapid transit systems (MRTS) and light rail transit systems (LRTS).

2. High-speed rail resilience

In the UK there is currently only one operational HSR known as High Speed One (HS1), which connects the Channel Tunnel to St Pancras International Station. High Speed 2 (HS2) is now under construction with a planned route between London and Birmingham. The HSR network in Britain is limited compared to that of other countries such as China, France, Germany and Japan (Nunno, 2018). Consequently, there has been limited research into the impacts of weather and climate change on HSR in Britain, however, this section outlines the current

doi: 10.1680/jcien.23.00101

approaches for HSR and climate change adaptation.

2.1 High Speed 1

HS1 is 109 km in length and the infrastructure is owned by Network Rail and managed by HS1 Limited (HS1 Limited, 2022). The railway is maintained and operated by Network Rail (High Speed) (HS1 Limited, 2023). Due to its age, the HS1 route does not experience the same challenges as the mainline network in Britain, however this does not make it immune to the impacts of extreme weather (Arup, 2022; Kent County Council, 2020).

Climate change is a priority for HS1 according to their latest sustainability strategy, outlining targets to reduce emissions and stating that they will produce a CCRA under the ARP3 (HS1 Limited, 2021). While it is highlighted that this process will enable HS1 to create adaptation plans, scheduled for delivery in 2024–25 (HS1 Limited, 2021), the HS1 ARP3 contribution has still not been delivered (Climate Change Committee, 2022).

However, there is now significant precedence in the UK rail industry for developing dedicated rail weather resilience and climate change adaptation strategies and this gap should be addressed as a priority to ensure the resilience of the railway network in the south-east of England.

2.2 High Speed 2

Before the construction of High Speed 2 (HS2), assessment of climate change adaptation for the proposed scheme is required by European directives (HS2 Limited, 2019). The assessment considers climate hazards and the risk they pose to rail assets and identifies the measures

doi: 10.1680/jcien.23.00101

outlined at the early stages of the design to create a resilient HSR.

For example, to reduce future flood risks the proposed scheme will incorporate a 1m freeboard above the 1-in-1000 year annual probability of flooding, the capacity of drainage systems will accommodate 1-in-100 year events and include an additional 30% capacity to account for climate change. These measures will be extended as the design process proceeds and the extreme weather risks during construction will be mitigated through the Code of Construction Practice.

In the future, operation and management plans will be outlined to ensure the continued resilience of the assets (HS2 Limited, 2013). This assessment has been conducted in greater detail for the second phase of the route considering the specific impacts of different climate variables on different types of assets, the associated risk, their mitigation and allowance for future measures and monitoring (HS2 Limited, 2017).

Now that HS2 is under construction they have participated in the third round of the adaptation reporting power. This outlines how their well-considered approach to addressing climate change resilience at all stages of the delivery of HS2 will deliver a future proof HSR. To achieve this, HS2 has established The Climate Change Design Impact Assessment, Climate Change Resilience and Interdependencies Assessment and Climate Change Adaptation and Resilience Reporting for contractors. In addition, its ARP3 contribution demonstrates consideration of interdependencies which is a complex task in itself (HS2 Limited, 2021).

HS2’s approach has been developed through application of ISO 14,090:2019—Adapting to climate change which outlines general principles and processes to be applied to achieve resilience. One of these principles is transparency (International Standards Organisation, 2019), and whilst the process to achieving resilience is clear for HS2, this is in complete contrast to HS1. While improvements to the HS1 process (or the transparency of their process) could be made, the preparation to create a resilient high-speed route with HS2 is promising.

3. Rapid transit resilience

Rail-based rapid transit provides low emissions intra-urban public transport and can be found in cities around the world. However, the most commonly known is, of course, the London Underground (LU) which, along with MerseyRail in Liverpool, are the only MRTS in the UK to date.

Due to increasing city populations and the need for sustainable transport for the last mile of passenger journeys, there has been a rise in the number of LRTSs across the UK in recent years. The number of systems currently stands at 11 (UK Tram, 2022), but the consideration given to the climate change impacts on light rail operation and infrastructure is questionable.

3.1 Mass rapid transit systems

Unlike mainline railways, infrastructure for MRTSs is almost entirely within the confines of urban areas. Consequently, metro systems are more exposed to the effects of urban heat islands (UHIs) and high temperatures present a key risk, both to passengers and infrastructure. In addition, due to pressures on space in urban areas, many MRTSs are partially or entirely underground and therefore at significant risk of flooding.

3.1.1 Heat risks

High temperatures are a risk to the thermal comfort of passengers particularly on underground metro networks such as LU. The extent of factors affecting the thermal environment of deep tube tunnels are complex and the LU deep tube tunnel lining and surrounding ground has substantially increased over a century (Botelle *et al*., 2010). Heat gains are primarily through train braking in tunnels and passengers body heat, consequently increased ventilation is necessary to lower tunnel heat (Ampofo *et al*., 2004). The effects of crowding also exacerbate passenger thermal experience physiologically and psychologically (Kelly, 2011). This can be particularly challenging when delays further exacerbate crowding.

There is also a relationship between the mean number of asset-related delays on the LU and the mean daily temperature, increasing both underground and at surface level (though at different rates) as the mean daily temperature increases (Greenham *et al*., 2020). Near-complete passenger thermal discomfort has been estimated across some sections of the deep tube part of the LU network under a high emissions climate change scenario by 2050, thus more needs to be done to prevent future heat related infrastructure damage (Jenkins *et al*., 2014).

In a significant development to simulate the current thermal properties of the LU network, Greenham is undertaking further research to utilise models developed to calculate tunnel temperatures (Kimura *et al*., 2018). The research adapted the developed methodology to LU tunnels to improve the understanding of the relationship between ambient air temperatures and tunnel temperatures for underground metro systems. In addition, it was extended to provide

doi: 10.1680/jcien.23.00101

estimations of potential future tunnel temperatures under a range of projected climate scenarios (Greenham, 2023; Greenham *et al*., 2023b).

3.1.2 Flooding risks

Whether above ground or underground, MRTS are vulnerable to flooding particularly where the metropolitan area they serve is coastal or estuarial. The LU has a long history of navigating the risks associated with co-location with the Thames estuary, and has the first tunnel built under a body of water (The Thames Tunnel) within its network.

London benefits from the protection of the Thames Barrier, a tidal flood defence however, the LU is still susceptible to surface water flooding. Surface water flooding causes significant disruption to the LU such as the 28 station closures after thunderstorms in august 1994 (Parker and Tapsell, 1995) through to the more recent closure of 30 stations in July 2021 (Transport for London, 2023).

However, there is progress towards resilience, through the combined efforts of Transport for London in its Climate Change Adaptation Plan (Transport for London, 2023) and the Environment Agency's Thames Estuary 2100 Plan (Department for Environment, Food & Rural Affairs and Environment Agency, 2023) and the application of adaptation pathways.

3.2 Light rail transit systems

All LRTSs are uniquely designed to serve their metropolitan area, and there is currently no overarching climate change adaptation strategy for LRTSs, nor a requirement for operators to report under the ARP. In addition, academic literature is largely absent concerning the impact of climate change on LRTSs (Walsh and O'Mahony, 2022). As with MRTSs, LRTSs may be susceptible to the effects of heat, with risks such as overhead line sag and track buckling likely to affect LRTS infrastructure. However, this has yet to be documented in the UK context. In addition, surface water flooding in urban areas also presents a risk to LRTS. Surface water flooding affected the LRTS managed by Transport for London known as the Docklands Light Railway (DLR) in July 2021, leading to station closure and service suspension (Transport for London, 2021).

To address these risks Transport for London has developed a climate change adaptation plan and has extensive experience from managing and operating rail networks, overground LRTS, as well as underground and overground MRTS (Transport for London, 2023, 2021). However, many other LRTSs in the UK do not have dedicated, or regional transport adaptation plans and are instead presumably covered by their local climate change adaptation strategy (Glasgow City Council, 2022).

Following the recent publication of guidance for LRTS operators relating to extreme weather management (LRSSB, 2023) further work is needed to establish the risk of climate change to LRTSs and mechanisms to increase their resilience and adaptation to climate change.

4. Next steps

It has been established that the level of preparedness for extreme weather events and climate change varies across rail modes beyond the mainline railway network in the UK. A summary of these findings can be seen in Figure 5. To address these gaps HSR, MRTS and LRTS owners, managers and operators can learn from the progress already achieved in the journey to

Accepted manuscript
doi: 10.1680/jcien.23.00101

resilience for mainline railway networks. There are three key ways to do this: 1) develop knowledge of risks; 2) develop adaptation frameworks; and 3) deliver robust climate change resilience reporting to evaluate progress on the previous two mechanisms.

4.1 Rail system resilience knowledge

There is a large body of research relating to the impact of weather and climate change on railway networks. As many of the assets and systems are common between mainline railways LRTS, MRTS and HSR there are likely to be shared risks and consequently opportunities to learn from current best practice. For example, many LRTSs are powered by overhead lines which are known to be vulnerable to high temperatures, especially in urban areas (Ferranti *et al*., 2016). Undertaking a review of identified risks to mainline railways and considering their applicability to other rail systems could provide a valuable starting point to establish the needs of different rail systems to increase their resilience to climate change.

While extensive risk assessments have been undertaken for mainline railway networks, LRTS, MRTS and HSR infrastructure managers and operators can begin by evaluating the impact of extreme weather impacts on their systems. Analysis of discrete extreme weather impacts can provide valuable insights to understand system vulnerability.

A recent comparison of approaches used to explore the impacts of weather has suggested that when investigating the relationships between weather and railway infrastructure faults, discrete extreme weather events still dominate the investigation and results (Fisher, 2021). Therefore, investigating discrete weather events is a useful approach to further improve understanding of extreme and complex weather events on rail transport of all types.

doi: 10.1680/jcien.23.00101

4.2 Rail system adaptation frameworks

To facilitate the process of understanding risks and identifying adaptation actions, HSR, MRTS and LRTS infrastructure managers should engage with an adaptation framework to guide this process. An adaptation framework for railways has been established through the Rail Adapt project, shown in Figure 6.

The flexible framework was developed by bringing together rail stakeholders from across the world to support decision-making activities to inform adaptation of railways and the implementation of adaptation strategies. It is the current state of the art for adaptation approaches. It was developed by considering both technical processes as well as the role of asset management decision making to develop and inform the consequent adaptation framework through consultation with stakeholders and critically reviewing existing procedures. It offers the rail industry a practical iterative process to support decision makers in their activities while also encouraging evaluation of progress and the incorporation of arising information and data.

Overall the framework provides the means for the rail industry to be prepared for the impacts of climate change and implement strategies and adaptations to improve the resilience of rail transport systems ensuring that ‘climate adaptation actions become part of business as usual’. However, for this to be successful it is critical that climate adaptation actions are integrated within best-practice asset management procedures rather than being siloed or managed by a separate team (Quinn *et al*., 2018). In other words, adaptation of the rail industry to climate change is everyone’s responsibility, not just a part-time role for a select few.

4.3 Adaptation reporting for rail systems

To systematically improve the process of embedding climate change resilience across all types of rail transport, it would be beneficial to implement evaluation and reporting mechanisms across the industry. This could be achieved by utilising the application of an adaptation framework in combination with a consistent reporting mechanism such as that undertaken through the ARP process.

While participation in the ARP process was initially mandatory under the 2008 Climate Change Act, it is now voluntary for the present participants (Climate Change Committee, 2022). This risks a lack of engagement, however as this is a process that organisations are invited to participate in, there may be willingness from MRTS, LRTS and HSR organisations to participate. Primarily the invitation should be extended to LRTS managers to extend the governments understanding of the resilience of transport networks to regional rail transport. This expansion is critical to achieving resilient and sustainable journeys.

5. Conclusion

This review establishes the need for rail transport systems beyond the mainline to evaluate their resilience to extreme weather events and climate change. To improve overall journey resilience, LRTS, MRTS and HSR systems need to increase their knowledge of weather and climate change impacts on their networks to inform adaptation action for resilience.

The current progress of system operators and infrastructure managers in the UK are outlined. Crucially, next steps are identified which will advance current knowledge and practice to accelerate adaptation and progression towards resilient systems. These next steps are improving knowledge of risks, application of adaptation frameworks and the role of policy in the form of ARP participation.

By pursuing the above activities, vulnerability of rail transport modes beyond the mainline can be addressed, supporting the delivery of resilient and sustainable mobility for the future.

Acknowledgements

Rachel Fisher's time on this research was in part funded by NERC Fellowship NE/X001938/1.

Emma J. S. Ferranti acknowledges EPSRC Fellowship EP/R007365/1.

Accepted manuscript
doi: 10.1680/jcien.23.00101

References

Ampofo, F., Maidment, G., Missenden, J., 2004. Underground railway environment in the UK Part 2: Investigation of heat load. Appl. Therm. Eng. 24, 633–645.

Arup, 2022. High Speed 1: Laying the tracks for transformation.

Baker, C., Chapman, L., Quinn, A., Dobney, K., 2010. Climate change and the railway industry: a review. Proc. Inst. Mech. Eng. Part C J. Mech. Eng. Sci. 224, 519–528.

Botelle, M., Payne, K., Redhead, B., 2010. Squeezing the heat out of London's Tube. Presented at the Proceedings of the Institution of Civil Engineers-Civil Engineering, Thomas Telford Ltd, pp. 114–122.

Clarivate Analytics, 2021. Web of Science Core Collection.

Climate Change Committee, 2022. Understanding climate risks to UK infrastructure: Evaluation of the third round of the Adaptation Reporting Power. UK.

Department for Environment, Food & Rural Affairs, Environment Agency, 2023. Thames Estuary 2100 (TE2100) [WWW Document]. URL https://www.gov.uk/government/collections/thames-estuary-2100-te2100

Department for Environment, Food and Rural Affairs, 2023. The Third National Adaptation Programme (NAP3) and the Fourth Strategy for Climate Adaptation Reporting.

Department for Transport, 2014. Transport Resilience Review: A review of the resilience of the transport network to extreme weather events.

Department for Transport, 2010. The Resilience of England's Transport Systems in Winter - An Independent Review.

Ferranti, E., Chapman, L., Lee, S., Jaroszweski, D., Lowe, C., McCulloch, S., Quinn, A., 2018. The hottest July day on the railway network: insights and thoughts for the future. Meteorol. Appl. 25, 195–208.

Ferranti, E., Chapman, L., Lowe, C., McCulloch, S., Jaroszweski, D., Quinn, A., 2016. Heat-related failures on southeast England's railway network: Insights and implications for heat risk management. Weather Clim. Soc. 8, 177–191.

Ferranti, E., Greenham, S., Wood, R., 2021. Adaptation Pathways for Infrastructure Operators and Policymakers.

Fisher, R.S., 2021. Quantifying the vulnerability of GB rail to temperature and precipitation in order to improve resilience. University of Birmingham.

Glasgow City Council, 2022. Glasgow's Adaptation Plan 2022-2030.

Greenham, S., 2023. Quantifying the Impact of Heat and Climate Change on London Underground's Infrastructure. University of Birmingham.

Greenham, S., Ferranti, E., Powell, R., Drayson, K., Quinn, A., 2023a. The impact of heat on London Underground infrastructure in a changing climate. Weather 78, 170–175.

Greenham, S., Ferranti, E., Quinn, A., Drayson, K., 2020. The impact of high temperatures and extreme heat to delays on the London Underground rail network: An empirical study. Meteorol. Appl. 27, e1910. https://doi.org/10.1002/met.1910

Greenham, S., Quinn, A.D., Ferranti, E.J.S., 2023b. Validation of a simple tunnel temperature estimation model on the London Underground network to project the impact of future climate change. Draft.

Haasnoot, M., Kwakkel, J.H., Walker, W.E., Ter Maat, J., 2013. Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world. Glob. Environ. Change 23, 485–498.

Hayman, V., Street, R., Wilkins, T., 2017. Understanding the value of the Adaptation Reporting Power process to the reporting organisations involved. Underst. Value Adapt. Report. Power Process Report. Organ. Involv.

HM Government UK, 2022. UK Climate Change Risk Assessment 2022.

HS1 Limited, 2023. About Us [WWW Document]. Site Name. URL https://highspeed1.co.uk /about-us/ (accessed 5.26.23).

HS1 Limited, 2022. 2023 HS1 Network Statement.

HS1 Limited, 2021. Delivering the Green Gateway to Europe.

HS2 Limited, 2021. Climate Change Adaptation and Resilience Adaptation Reporting Power (ARP) Report December 2021.

HS2 Limited, 2019. Climate change adaptation and resilience.

HS2 Limited, 2017. High Speed Rail (West Midlands - Crewe) Environmental Statement Volume 5: Technical appendices Climate Results of climate change assessments.

HS2 Limited, 2013. HS2 Phase One: London-West Midlands Environmental Statement Volume 5 | Technical Appendices Resilience to impacts from climatic conditions (CL-003-000) Climate.

Hulme, M., 2002. Climate change scenarios for the United Kingdom: the UKCIP02 scientific report. Tyndall Centre for Climate Mental Sciences University.

International Standards Organisation, 2019. ISO 14,090:2019—Adapting to climate change — Principles, Requirements and Guidelines.

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

Jenkins, K., Gilbey, M., Hall, J., Glenis, V., Kilsby, C., 2014. Implications of climate change for thermal discomfort on underground railways. Transp. Res. Part Transp. Environ. 30, 1–9.

Jude, S.R., Drew, G.H., Pollard, S.J.T., Rocks, S.A., Jenkinson, K., Lamb, R., 2017. Delivering organisational adaptation through legislative mechanisms: Evidence from the Adaptation Reporting Power (Climate Change Act 2008). Sci. Total Environ. 574, 858–871. https://doi.org/10.1016/j.scitotenv.2016.09.104

Kelly, L.K., 2011. Thermal comfort on train journeys.

Kendon, M., 2022. Unprecedented extreme heatwave, July 2022.

Kent County Council, 2020. Climate Change Risk and Impact Assessment for Kent and Medway Part 2 Transport Sector Summary.

Kimura, K., Shibata, K., Sato, M., Tanita, N., Yagi, H., Kondo, Y., 2018. Simple Estimation Formula of Air Temperature in Tunnels: Estimation method for cooling load caused by train wind in an underground station: part 2 (in Japanese). J Env. Eng Trans. AIJ. https://doi.org/10.3130

Lowe, J.A., Bernie, D., Bett, P., Bricheno, L., Brown, S., Calvert, D., Clark, R., Eagle, K., Edwards, T., Fosser, G., 2018. UKCP18 science overview report. Met Off. Hadley Cent.

Exeter UK.

LRSSB, 2023. Weather and Climate Resilience Guidance.

Marteaux, O., 2016. Tomorrow's Railway and Climate Change Adaptation: Executive Report.

Mukherji, A., Thorne, P., Cheung, W.W.L., Connors, S.L., Garschagen, M., Geden, O., Hayward, B., Simpson, N.P., Totin, E., Blok, K., Eriksen, S., Fischer, E., Garner, G., Guivarch, C., Haasnoot, M., Hermans, T., Ley, D., Lewis, J., Nicholls, Z., Niamir, L., Szopa, S., Trewin, B., Howden, M., Méndez, C., Pereira, J., Pichs, R., Rose, S.K., Saheb, Y., Sánchez, R., Xiao, C., Yassaa, N., 2023. Synthesis Report of the IPCC Sixth Assessment Report (AR6).

Murphy, J., Sexton, D., Jenkins, G., Boorman, P., Booth, B., Brown, C., Clark, R., Collins, M., Harris, G., Kendon, E., 2009. UK Climate Projections Science Report: Climate change projections–Met Office Hadley Centre. Exeter UK.

National Infrastructure Commission, 2020. Anticipate, React, Recover: Resilient Infrastructure Systems.

Nunno, R., 2018. Fact Sheet | High Speed Rail Development Worldwide | White Papers | EESI.

Paris Agreement, 2015. Paris agreement. Presented at the Report of the Conference of the Parties to the United Nations Framework Convention on Climate Change (21st Session, 2015: Paris). Retrived December, HeinOnline, p. 2017.

Parker, D., Tapsell, S., 1995. Hazard transformation and hazard management issues in the London megacity. GeoJournal 37, 313–328.

Quinn, A.D., Ferranti, E.J.S., Hodgkinson, S.P., Jack, A.C.R., Beckford, J., Dora, J.M., 2018.

Adaptation Becoming Business as Usual: A Framework for Climate-Change-Ready Transport Infrastructure. Infrastructures 3, 10. https://doi.org/10.3390/infrastructures 3020010

RSSB, 2015. Tomorrow's railway and climate change adaptation: Work Package 1 Summary Report.

SDG Fund, 2015. Sustainable development goals.

Steynor, A., Gawith, M., Street, R., 2012. Engaging users in the development and delivery of climate projections: the UKCIP experience of UKCP09.

Transport for London, 2023. Climate Change Adaptation Plan 2023.

Transport for London, 2021. TfL Adaptation Reporting Power Submission 2021.

UK Tram, 2022. Strategy for Light Rail.

UNISDR (United Nations International Strategy for Disaster Reduction), 2015. Sendai framework for disaster risk reduction 2015–2030. UNISDR, Geneva.

Walsh, G., O'Mahony, M., 2022. Analysing the Effects of Weather on Light Rail Transit Performance in Dublin, Ireland.

World Meteorological Organization, 2023. WMO Global Annual to Decadal Climate Update.

Accepted manuscript
doi: 10.1680/jcien.23.00101

Figure 1. The UK mainline railway climate change adaptation policy landscape highlighting legislation, policy, guidance and Network Rail's own strategic documents and guidance relating to weather resilience and climate change adaptation (source: WRCCA)

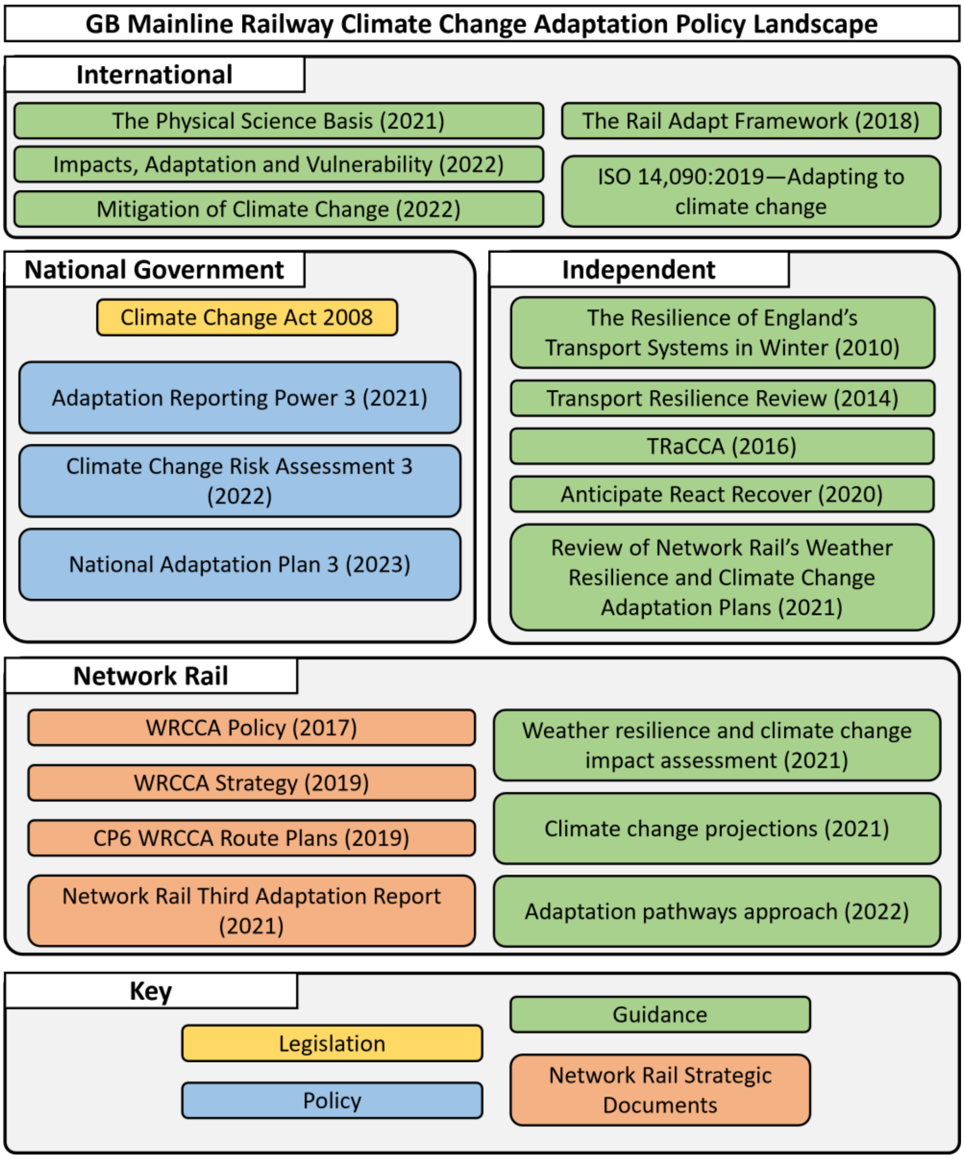
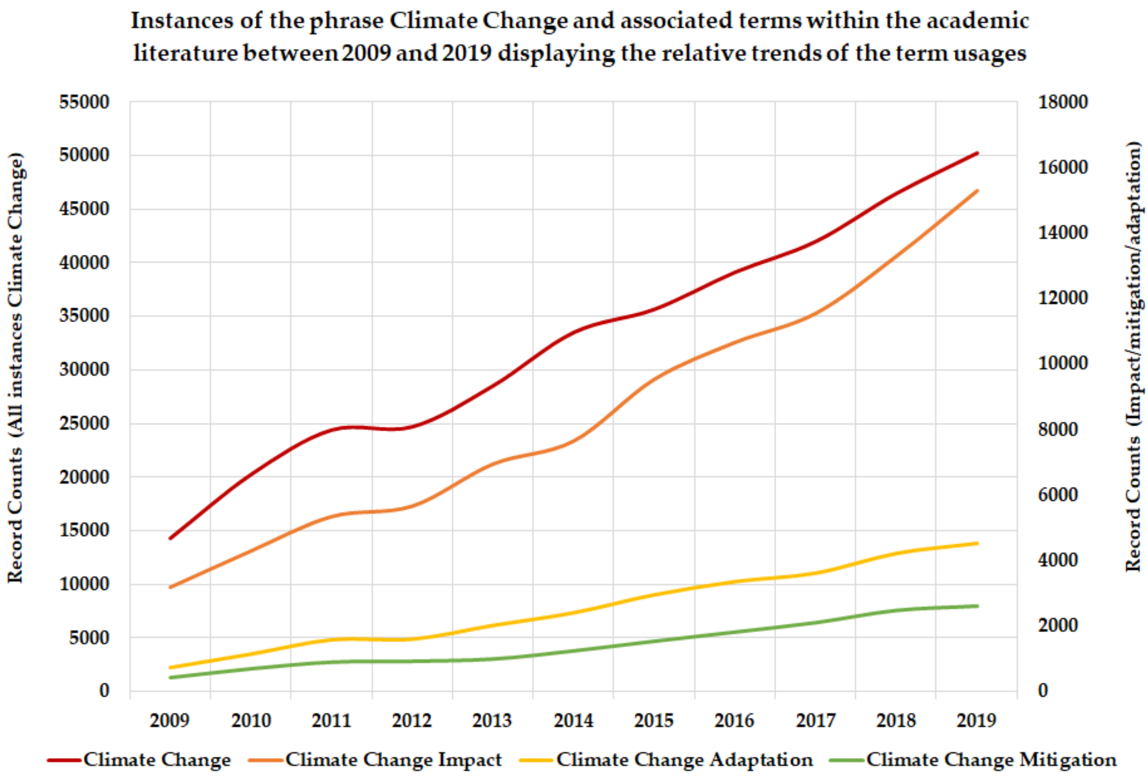
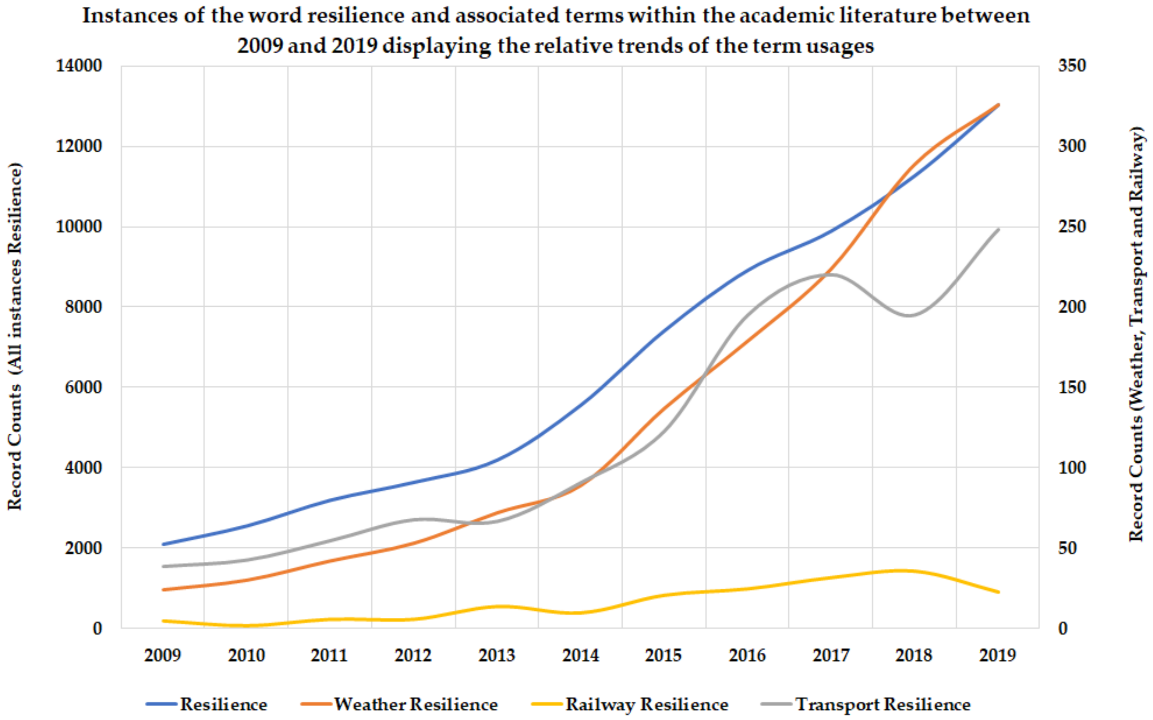


Figure 2. Trends for instances of climate change and associated terms in academic literature (source: Clarivate Analytics, 2021)



Accepted manuscript
doi: 10.1680/jcien.23.00101

Figure 3. Trends for instances of Resilience and associated terms in academic literature (source: Clarivate Analytics, 2021)



doi: 10.1680/jcien.23.00101

Figure 4. Washouts in 2020 leading to suspended track on the Conwy Valley Line (source: Network Rail)

Accepted manuscript
doi: 10.1680/jcien.23.00101

Figure 5. Climate change resilience strategic documents present for UK mainline rail

Comparison of climate change resilience strategic documents across rail modes

	Mainline	HRS	MRTS	LRTS
Policy	●	○	○	⊘
Strategy	●	○	○	⊘
Planning	●	○	○	⊘
Guidance	●	⊘	○	○
Risk Assessment	●	○	○	○
ARP3	●	○	○	⊘

Key

Present	●	Limited Evidence	⊘
Some Evidence	○		

doi: 10.1680/jcien.23.00101

Figure 6. Rail Adapt Framework (source: Quinn et al, 2018 with permission)