Chapter 6

How does the UK transport system respond to the risks posed by climate change? An analysis from the perspective of adaptation planning

Tianni Wang[a,b,c], Zhuohua Qu[a], Zaili Yang[b], Adolf K.Y. Ng[d]
[a]*Liverpool Business School, Liverpool John Moores University, Liverpool, United Kingdom,* [b]*Liverpool Logistics, Offshore and Marine Research Institute, Liverpool John Moores University, Liverpool, United Kingdom,* [c]*Transport College, Shanghai Maritime University, Shanghai, China,* [d]*Department of Supply Chain Management, Asper School of Business, University of Manitoba, Winnipeg, MB, Canada*

1 Introduction

In the United Kingdom, the transport sector is recognized as one of six key departments which is the most vulnerable to the risks posed by climate change (McKenzie Hedger et al., 2000). The country has a network covering 422,100 km of paved roads with different quality and capacity (Department for Transport, 2017; Department for Infrastructure, 2017). A unified road numbering system is used to classify and identify all the roads in the United Kingdom. Cooperated with the Department for Transport, Highways England (HE), for example, operates, maintains, and improves motorways and major "A" roads in England (Highways England, 2018a).

The United Kingdom opened locomotive-hauled public passenger railways in 1825. As the oldest railway system in the world, it has a network of 15,760 km of standard-gauge lines, including 5272 km electrified lines today (Wikinow, n.d.). The majority of railway track is managed and maintained by Network Rail (NR). Also, there are some services on public rail-based mass transit systems run by local authorities and an undersea rail link to France called the Channel Tunnel operated by Getlink. Some short tourist rail lines are managed by private railways.

Maritime Transport and Regional Sustainability. https://doi.org/10.1016/B978-0-12-819134-7.00006-X

The rapid rate of climate change challenges the infrastructure, operation, and policy-making in the context of transport systems. The transport-related activities are vulnerable to heterogeneous weather extremes, which include variations in temperature, precipitation, winds, sea-level/other-water levels, thunderstorms, fog period or visibility, frost, and thaw (e.g., Wang et al., 2019; Schweikert et al., 2014; Love et al., 2010). In the United Kingdom, the inland transport systems are threatened by four primary climate change hazards, namely high temperature, heavy precipitation and flooding, high wind and storms, and sea-level rise (SLR) (Wang et al., 2018a,b, 2019). The frequently occurring flooding events in Cumbria and heavy storms in Devon, for example, have caused catastrophic infrastructural and financial losses and casualties due to a variety of impacts including roads and rail line closure, bridges' deterioration, traffic disruption, service cancellation, and delays (e.g., BBC News, 2015a,b, 2017; Devon County Council, 2014a; Devon Maritime Forum, 2014).

Some reviews have been conducted to investigate the impacts of climate change on the British roads and railways in recent years (e.g., Wang et al., 2018b, 2019; Koetse and Rietveld, 2009). However, research on climate impacts on road and rail freight in the United Kingdom has remained relatively unexplored (Jaroszweski, 2015). It is only recently that more attention has been given to the impacts of climate change on roads and railways (e.g., Hooper and Chapman, 2012; Wang et al., 2018b, 2019). Current action plans in British roads have not been developed from a published, detailed, and official adaptation plan but mainly focus on internal technical documents within the relevant business areas (Committee on Climate Change, 2014). Likewise, the existing adaptation plan of NR mainly concerns with the identification of several climate thresholds and selection of the best risk scenario, owing to the uncertainties of long-term climate change risks and insufficiency of data on change rate and extreme events (Network Rail, 2015). Indeed, a comprehensive adaptation plan covering every aspect has not been published in either British road or rail networks.

The failure of implementing adaptation plans in the transport systems may potentially be attributed to the deficiency of precise data on climate change impacts and cost-benefit analysis of adaptation planning (e.g., Koetse and Rietveld, 2012). Accordingly, there have been considerable studies assessing climate risks and cost-effectiveness of adaptation measures in diverse transport modes (e.g., ports, roads, railways) (Ng et al., 2018; Yang et al., 2018; Wang et al., 2018b, 2019). Nevertheless, current published reports rarely cover the "hidden" problems in climate adaptation planning, such as planning methods, procedure, time horizon, and public participants. Understanding such, in this chapter, we conduct a comparative study on the UK road and railway networks to reveal the state-of-the-art understanding on how the two transport systems adapt to the risks of climate change, including the primary climate risks, adaptation options, and the implementation and development of adaptation plans.

This chapter performs an analysis of multicase studies via in-depth interviews with affiliated senior experts in the UK transport systems. The outcomes provide researchers, transport planners, and decision makers with an innovative thinking pattern from the identification of climate hazards to the implementation of climate adaptation planning, in order to bridge the research gaps and facilitate climatic adaptation in the inland transport industries.

2 Methodology

A qualitative approach is used to get access to a considerable amount of unpublished qualitative information, to analyze relationships and social process, which could be hard to achieve by only using quantitative methods (such as modeling) especially when data is scarce (Miles and Huberman, 1984). In addition to documental review, we conducted five semistructured, in-depth interviews with the associated domain experts from HE, NR, Transport for London (TfL), Environment Agency (EA), and Devon County Council (DCC) in early 2018. Their positions included policymakers, transport planners, environmental specialists, and climate change advisors.[a]

The interview, as a commonly used qualitative method, was used to collect data in four case studies. These data were expected to reveal some "hidden" problems (e.g., the key factors, processes, and references in a climate change adaptation plan) in adapting to the risks posed by climate change in the UK transport systems. Besides the primary threats posed by the climate change, the interviews attempted to figure out the current risk assessment and planning processes, as well as the crucial elements and dilemmas in current and future adaptation planning for climate change. The primary interview questions were

(1) What are the significant risks and uncertainties posed by climate change? Do road/rail stakeholders have an adaptation plan and measures to cope with such climate risks?
(2) How are these climate risks assessed in their entities? Is there a risk analysis system for climate change? What are the priorities and fundamental principles for adaptation planning in short- and long-terms?
(3) How do road/rail decision makers conceive the unique conditions of their entities? What kind of recourses, information, and references have been used or would be used for adaptation planning?
(4) What are the perceptions of road/rail decision makers on climate adaption planning? Who are the involved participants or will be involved in the climate adaptation planning process?
(5) What is the planning horizon of climate adaptation planning? What are the critical factors influencing the success of an effective climate adaptation plan?

These interview questions were semistructured and open-ended in terms of their expected answers. The five corresponding issues were: Part A, identifying

a. The basic information of interviewees can be found in the Appendix.

the vulnerabilities of rail and road posed by climate change; Part B, assessing risk and planning priorities; Part C, recognizing the characteristics and differences between rail and road's conditions; Part D, analyzing the preparation, environment, and stakeholders involving an adaptation plan; Part E, implementing an adaptation plan and developing adaptation strategies.[b]

All the interviewees were asked similar major questions based on a preset framework, which gave interviewees enough time to prepare their answers and allowed us to cover all questions adequately. However, we (as interviewers) did not strictly limit them only to answer the above questions but encouraged them to express their views freely to reflect their "real thinking" on climate risks and adaptation planning. After that, we integrated multisource evidence for triangulation, including the interviews, official reports, and local news and archival data, to enhance the validity of our understanding. The interview data were coded by a thematic coding analysis approach, which provided a practical and flexible approach to categorize and summarize the key characteristics of various qualitative data (Braun and Clarke, 2006).

Finally, both within-case (i.e., EA and TfL in London) and cross-case (e.g., NR and HE) analyses were undertaken to compare and contrast the similarities and differences of the organizations' adaptation plan, which also reinforced the external and internal validity (Yin, 2003). First, in a single case, within-case analysis allows us to recognize the existing and potential climate risks and adaptation strategies by hearing diverse voices from different entities in a specific region (i.e., London). Cross-case analysis facilitates the development of a comprehensive view on how the rail and road adapt to the risks posed by climate change respectively, so as to reveal the common issues and potential collaborative opportunities in an integrated inland transport system.

3 Adapting planning for climate change in the UK road and rail systems

3.1 Highways England

Formerly known as the Highways Agency, Highways England (HE) became a new government company in 2015 responsible for the operation, maintenance, and improvement of England's strategic road network covering more than 4300 of miles motorways and major A-class roads (Highways England, 2018a,b).

The Highways Agency initiated its first *Climate Change Adaptation Strategy and Framework* in 2009, aiming to recognize and assess the impacts posed by climate change on the road network to generate preferred adaptation options (Highways Agency, 2009). Through a comprehensive review, the *Highways Agency's Adaptation Framework Model (HAAFM)* was developed by setting up a detailed seven-stage adaptation process from "*define objectives*

b. The interview question framework can be provided as a request.

and decision making criteria" to "*adaptation programme review*". By 2014, a variety of climate risk assessment and adaptation action plans had been produced, with specific reports on flooding and winter adaptation, but few gaps in climate adaptation on roads remained unexplored (Highways England, 2016). The Committee on Climate Change (2014) commented that neither information on resilience spending plans nor reported progress of implementing resilience measures were publicly available. However, the *Transport Resilience Review* (Department for Transport, 2014) contained recommendations for improving climate resilience such as the management of high-sided vehicles due to high winds, drainage management for flooding, and roadside infrastructure for winter driving.

The latest *Climate Adaptation Risk Assessment Progress Update* (Highways England, 2016) set up an overview of climate adaptation in the 2015–2020 (Road Investment Strategy 1) period. HE identified the existing primary climate change hazards in its 2016 report. The trend of climate change included increased average and maximum temperature, more frequent and intense rainfalls in summer, high winds, and SLR. For instance, the variations in precipitation, such as flooding, storm surges, and groundwater level changes, could pollute and deteriorate transport asset as well as influence the design, operation, and maintenance of drainage, foundations, and skid. High temperature may modify bearings' layout and expansion joints. In addition, high winds may slightly affect structure and gantries but could result in severe disruption of construction work. Cascade failure risk is being talked about in infrastructure circles and will potentially be an issue in the future (Interviewee 1, January 26, 2018).

Still using the *HAAFM* methodology, HE's 2016 report highlighted current adaptation action plans. The existing climate risk evaluation takes account of four main factors, including the rate of climate change, the severity of disruption, uncertainties, and the extent of disruption (Conference of European Programme of Roads, 2010). The management of drainage, road pavements, and structures are still the primary focus, with the highest risk scores, which is the same as the results in the risk assessment 2011 (Highways Agency, 2011), whereas other potential climate vulnerabilities will be continuously monitored by HE.

Under the Adaptation Reporting Power in the Climate Change Act, HE is required to report to the British government on a 5-year basis. Current time horizons of road asset life/activity are assessed against two broad categories: short-term (less than 30 years) and long-term (more than 30 years). However, HE (Highways England, 2016) considers that the time horizon for climate change effects to become material can be divided into short-term (present-2020), mid-longer term (2020–2080), and longer term (beyond 2080).

Due to the uncertain nature of climate change, a longer time horizon might be required in future adaptation planning. This planning horizon can be referred to asset lifecycles up to 120 years (Interviewee 1, January 26, 2018). Road planning is a complicated procedure that involves geography, asset condition, and financial budgets. Also, different routes might have diverse time horizon because of its project-based feature. Hence, an appropriate time horizon for climate adaptation planning needs to be set up on a multifaceted basis (e.g., asset lifecycle, likelihood, frequency, severity of climate change and infrastructure resilience, route conditions, and adaptation costs, etc.).

In future adaptation planning, one of the critical challenges, as an interviewee mentioned ((Interviewee 1, January 26, 2018), is how to find an approach to embed climate change in standards. This might start with reviewing relevant road technical specifications (e.g., Design Manual for Roads and Bridges). A long-term plan with specific adaptation actions will be carried out, but how to deliver it to all the staff is yet to be addressed (Highways England, 2016). With the publication of UKCP18, a new-round review of derived products within the British road sector is required (Interviewee 1, January 26, 2018). Moreover, other mitigation measures should be supplementary with adaptation measures to reduce CO_2 emission owing to high temperature, which is a primary concern as stressed in *Highways England Delivery Plan (2015–2020)* (Highways England, 2015) and from our interviews. Still, risk analysis should be a significant component of road planning for climate adaptation. It will benefit from a standardized mechanism constructed by diverse road stakeholders, such as from the UKCP18 Government User Group.

3.2 Network Rail

Network Rail (NR) owns and operates the national railway infrastructure covering 20,000 miles of track, 30,000 bridges and viaducts, as well as thousands of tunnels, signals, level crossings, and points across England, Wales, and Scotland (Network Rail, 2018a). Its strategic national network has been divided into nine routes, including Anglia, Freight and National Passenger Operations, London North Eastern and East Midlands, London North Western, Scotland, South East, Wales, Wessex, and Western line since 2015. Although local train and freight operators run each route, they are supported by NR's national services and functions to maintain its safety and efficiency (Network Rail, 2018b).

Climate change adaptation and weather resilience are two mainstreams in environmental development in NR. Though climate adaptation and weather resilience initiatives have been prepared since 2012, an official *Climate Change Adaptation Report* was not published until 2015. Afterward, *Route Weather Resilience Plans* specialized for each route were produced in 2016 (Network Rail, 2018c,d). In the Western Route Plan, for instance, flooding, wind, and landslips were considered to be the highest priority risk and likely to cost a lot to repair.

The 2015 Adaptation Report (Network Rail, 2015) summarized the understanding of NR as to the existing and potential impacts posed by climate change on its rail performance and safety and the implementation of adaptation actions to deal with them. This included the identification of climate risks, thresholds and uncertainties, knowledge sharing, existing adaptation barriers and opportunities, and planned actions. A few significant climate hazards on rail infrastructure were recognized through an internal risk analysis supported by METeorological data EXplorer (METEX) and geographic information system (GIS) tools. These included changes in temperature and precipitation, increased flooding, high winds, SLR, extreme weather, lightning, and seasonal changes. For example, cold weather, such as snow and ice, would threaten overhead line equipment and block rail lines; heat may increase rail bucking and derailment risk; heavy rainfall and flooding could cause scour of embankment material and damage electricity equipment (Interviewee 2, April 6, 2018). Furthermore, *Tomorrow's Railway and Climate Change Adaptation Report*, as a part of the T1009 programme funded by the Rail Safety and Standards Board (RSSB), established an adaptation framework containing four action steps for the management of summer conditions, winter conditions, and flooding risk by drawing on the experiences of other countries in weather resilience and climate change adaptation (RSSB, 2016).

In the meantime, NR has been responding to the challenges of extreme weather in its daily operation (Network Rail, 2018c). The latest published *Weather Resilience & Climate Change (WRCC) Adaptation Policy* and *Weather Resilience and Climate Change Adaptation Strategy 2017–2019* (Network Rail, 2017a,b) laid solid foundation for the delivery of resilience plans of each route through setting up the context and funding values of specific adaptation actions. The *WRCC* reports (Network Rail, 2017a,b) set out NR's approach to creating a safer and more resilient network for future weather impacts. A four-pillared method included the following components: "analysis risk and costs," "integrate into business as usual," "streamline operational weather management," and "proactive investment" in its *2020 Review and Revise Strategy*.

Overall, NR has constructed a relatively comprehensive framework for adapting to climate change and extreme weather, with supplementary specific route plans and a professional resilience steering group (e.g., RSSB, 2016). The current adaptation report runs on a 5-year basis. However, the time horizon for rail adaptation planning may look at the next 30 years and beyond 2100 in a longer term depending upon the lifespan of specific assets and geographical conditions. There are four primary steps in real adaptation implementation, including risk assessment in place, data analysis, asset investment, and influence and discussion with stakeholders (Interviewee 2, April 6, 2018). Nevertheless, owing to the uncertainties of long-term climate change impacts and insufficiency of precise data on climate change rate and extreme events (Network Rail, 2015), the existing plan still focuses on the identification of several climate thresholds and selection of the best risk scenario (Interviewee 2, April 6, 2018). The quantification of climate risks and costs is still at an embryonic phase (Network Rail, 2017a).

Several gaps have been investigated in the last 5 years, including weather and climate-related thresholds, management of wet weather, and standards' design of uppertemperature thresholds (RSSB, 2016). Meanwhile, the need for asset investment funding to take account of the whole-life cycle of the rail network, as well as the cost-benefit analysis, was mentioned in the interview (Interviewee 2, April 6, 2018). As part of the process of preparing its climate adaptation strategy, NR has researched exceptional experience and suggestions from local transport authorities, such as TfL, as well as data analysis from EA, consultants, and scholars. To be successful, further plans should also incorporate stakeholder views, including public engagement. Besides, NR should continuously receive legislative and regulatory support from the Office of Road and Rail (ORR) and Department for Transport (DfT), and other relevant government bodies. Successful climate adaptation planning might mean that climate adaptation can be finally written into every business plan and become "business as usual" (Interviewee 2, April 6, 2018).

3.3 London (Transport for London & Environment Agency)

3.3.1 Transport for London

Transport for London (TfL), as a local transport authority, is responsible for the daily operations of the capital's public transport and road system (Transport for London, 2018a). Through delivering the transport strategy and policies from the Mayor of London, it commits to develop and maintain integrated, secure, efficient, and economical transportation infrastructure and various services mainly covering London Underground, Surface Transport, London Rail, and Emirates Air Line Cable Car (Transport for London, 2018a,b).

TfL started its climate risk assessment on London's transport networks based on the UK Climate Impact Programme's projections of the potential climate risks and opportunities due to flooding, drought, and overheating. It possesses mechanisms in managing extreme weather events and identifying the requirement to replace critical assets to make them more resilient to climate change (Greater London Authority, 2011). *Managing Extreme Weather at Transport for London* (Woolston, 2014) reviewed a series of local documents in climate adaptation in London, such as the London Underground's comprehensive flood risk review and EA's Thames Estuary 2100 Project, and attempted to establish a long-term flood risk management plan by a flexible "threshold" planning approach.

The recently published report *Providing Transport Service Resilience to Extreme Weather and Climate Change* (Transport for London, 2015) updated the findings in the 2011 report and provided an overview of existing risk assessment by TfL regarding operation and services. According to this report, the primary trend of climate change impacts to Greater London included the increased temperature in summer, flooding, and more frequent and intensive winter storms by 2080s. Flooding, high winds, and heating were deemed to be the main risks that affect the delays on the road network, the safety of surrounding buildings and infrastructure, as well as the comfort and health of passengers on trains, respectively.

Some extreme weather events were also reviewed by TfL, exemplified by a lightning strike at Docklands Light Railway Crossharbour in 2012, a hail storm at the Fore Street tunnel in 2013, and cloudburst flooding and localized rainfall in several spots in summer 2014 (Transport for London, 2015). Combined with the discussion results from an interviewee, the summary is that roads are less vulnerable to climate risk as they have alternative routes and modes to adapt to climate change; but rail and underground are usually more vulnerable due to lack of flexibility in asset construction. The wind is considered as one of the critical threats at present, while the published UKCP18 has changed the status quo by integrating additional factors, such as SLR (Interviewee 3, January 17, 2018; UK Climate Projections, 2018).

A critical scoring risk assessment method has been developed by TfL. The TfL Board initially develops a "top-down" risk appetite factor before each business area (London Rail, London Underground and Surface Transport) produces its own scoring scheme to reflect the local differences (the bottom up factor) (Transport for London, 2015). The strategic risk map primarily considers the likelihood and impacts of climate change. For instance, in London Underground, overheating was expected to pose "very high" impacts to key track, signals, and communications assets, as well as the comfort of staff and passengers. Current risk management of TfL is based on its day-to-day operations, asset management plans, and also infrastructure design and scheme planning in the long term. The forecast bulletins and daily real-time monitoring help identify temperature and precipitation changes to enable the corresponding adaptation options. For example, TfL would apply salt and grit to the road surface, bus station approaches, and platforms if cold weather and icy conditions are being forecasted. Meanwhile, its asset management framework sets out the high-level principles and specific strategies for every asset group with regard to required asset performance, conditions, and maintenance.

Established in 2003, the London Climate Change Partnership (LCCP) Transport Group committed to raising the awareness of the risks of climate change in the transport sector via the development of guidance and adaptation measures. Several projects, such as London Underground's cooling the tube and "Drain London," have offered pioneering trials in climate adaptation (Woolston, n.d.). Nevertheless, existing adaptation methods to climate change are still at an embryonic stage, and no comprehensive adaptation plans have been proposed to TfL. This could partially be due to uncertainties in forecasting and insufficient understanding of climate vulnerabilities and thresholds. Current risk assessment tends to rely on qualitative evidence rather than on a systematic quantitative method. Hence, priorities should be given to how to best utilize scientific data, as well as how to translate climate forecasts into meaningful scenarios.

As an integrated transport provider with financial support from the government, TfL has advantages in developing a holistic adaptation plan to make a resilient network in the future. Even so, gaining political interest is still a potential barrier. This would require TfL to continually provide substantial evidence on the level of risks alongside other factors to enable decision-making. In future adaptation plans, appropriate time horizons will vary for each project and different transport mode and its asset strategy. The future plan of climate adaptation can be led by TfL. The planners can draw on the adapting experience of NR and LCCP, while attracting the engagement of transport providers and utility providers (e.g., Thames Water, Environment Agency and Met Office) to further increase the likelihood of success of adaptation planning (Interviewee 3, January 17, 2018).

3.3.2 Environment Agency

In water transport, the Thames Barrier in London is one of the few moveable flood barriers in the world, which is run and maintained by the Environment Agency (EA). EA examines the barrier monthly and tests it at a high spring tide each year. Supported by its internal computer models and data from Met Office and the UK National Tide Gauge Network, it forecasts the risks up to 36 hours in advance to inform a decision on when the barrier should be closed. The closure of the Thames Barrier happens under a storm surge condition in order to protect London from the sea, depending upon the height of the tide and the tidal surge as well as the river flow entering the tidal Thames. Since 1982, the barrier has been closed over 170 times to protect against tidal and fluvial flooding (Environmental Agency, 2014).

The Thames Estuary 2100 (TE2100) Project, established by EA in 2002, is the first primary flood risk project in the United Kingdom to put climate change adaptation at its core. The plan mainly looked at tidal flooding, though other sources of flooding including high river flow as a result of heavy rainfall, and surface water flooding are simultaneously considered. Based on the prediction of SLR from 90 cm up to 2.7 m by 2100, the plan was designed to provide strategic guidance for adapting to flooding in the Thames Estuary over the next 100 years. A key driver is to consider how the tidal flood is likely to change in response to future change in climate, and how this would impact people and property in the floodplain. Additionally, there is a consensus that many existing flood walls, embankments, and barriers are getting older and would need to be raised or replaced to manage SLR (Interviewee 4, February 1, 2018).

The *Safeguarding London Transport* (Environmental Agency, 2008) comprehensively evaluated the risks that potential flooding pose to the London transport system and the Thames Estuary. Using Geographic Information System (GIS) and Key Performance Indicators (KPIs), it assessed the vulnerability of different assets in several transport networks (e.g., age of station, elevation, flood warning, and distance from the defenses). Generally, London Underground was most vulnerable to the risks of flooding as it was widely located in tunnels underneath the ground, though roads, generally at ground level, can also be extensively affected. However, the rail network had the lowest level of vulnerability because stations and rail tracks were usually located above the ground. Adaptation costs and network resilience were considered in responding to flooding risks.

A typical cost of installing a set of points and their related signals could be expected to be between British pounds (£) 175,000 and £250,000 (Environmental Agency, 2008). The resilience was measured by the recovery capacity of the transport network, including the scope to use other alternative routes or modes to bypass the partial closure of this system. London Underground, owing to its natural underground location and interconnected tunnels with a high possibility for water ingress, might be the least resilient to climate risks. In the worst flood risk scenario, a majority of the sections could be closed for an extended period, and the repair cost could be massive. With an updating requirement of a 5-year short-term review and a 10-year full review, the latest *TE2100 5-year review*, used historical data and report analysis to examine the results of ten indicators (e.g., sea level, peak surge level, asset condition, barrier operation, habitat, and public attitudes to flood risk, etc.) (Environmental Agency, 2016).

One of the significant challenges is the mismatch of aging flooding barrier infrastructure and a higher SLR rate where many flood defenses were built 30 years ago when SLR was 8 mm per year but now becomes 11 mm per year (Environmental Agency, 2017). Existing data are incapable of measuring wave conditions at a peak surge level and the amount of intertidal habitat in the Estuary. Meanwhile, the asset condition has declined in recent years in some areas, especially the outer Estuary. More funding is needed for asset improvement and maintenance and increasing the proportion of assets rating as fair and reasonable (Environmental Agency, 2016).

Nevertheless, the TE2100 Plan is believed to be on the right track with a broad range of stakeholders and public engagement, as an interviewee stated. Having had two earlier consultations in 2005 and 2008 on the critical findings of the project supported by a programme of public meetings and a web-based consultation, EA undertook its public consultation on the draft TE2100 Plan in 2009. These included 15 local workshops and public meetings across the Estuary, over 50 meetings with key organizations, to provide stakeholders (e.g., Greater Local Authority) with an opportunity to feedback and ask questions on any aspect of the Plan or its recommendations, as well as receiving 120 written responses (Interviewee 4, February 1, 2018). In future planning, it is expected to have more new and cost-effective barriers further downstream and tidal flood defenses for tackling more severe SLR and storm surges (Environmental Agency, 2017).

3.4 Devon County Council

Flooding is one of the critical issues for UK transport systems. A significant number of heavy storms in recent years have broken historical records since 2000 in the United Kingdom, and there are more frequent events projected in the future (Devon County Council, 2014a).

Dawlish Warren is a coastal spit on the south Devon coast of England. The cumulative effect of the rapid succession of over significant storms in winter

2012/2014 had the most severe impacts in the United Kingdom since the 1950s (Devon Maritime Forum, 2014). The South West main rail network was mainly affected with the collapse of the multisectional seawall at Dawlish, as well as a significant impact on transport resilience and the local economy of the South West Peninsula due to extreme weather (Devon County Council, 2014a; Devon Maritime Forum, 2014). Up to 46 m of railway track was swept away with part of the seawall in early February 2014, restricting the service linking Cornwall and much of Devon with the rest of the United Kingdom. Dawlish station was damaged, and the main rail line from Exeter to Newton Abbot was closed. In total, the storms had resulted in the 2-month closure of the mainline and over 7000 services canceled (Devon Maritime Forum, 2014).

NR estimated that the damage would take “at least” six weeks to recover, and an extra £100m was provided for flood repairs across the country (BBC News, 2014a, 2015c). A storm occurred again in early 2017, crashed into trains and over flood barriers as 50ft waves smashed the coasts. Boats, lighthouses, and seafront rail track were impaired by surges, and the gales caused temporary cancellation of some trains at Plymouth and between Newton Abbot and Exeter St David’s (The Sun, 2017).

Devon County Council (DCC) is responsible for the maintenance and repair of 12,800 km of the public road network (not including Strategic Road Network) in Devon. On the basis of the UK Climate Impact Programme’s projections, the potential impacts on Devon’s roads include increased temperature, SLR and the changes in rainfall patterns, and humidity variations. DCC initiated its Weather Impacts Assessment in 2010 and introduced an Impact Assessment Tool (IAT) in 2011. The risks posed by climate change were evaluated through the “Devon Way for Risk Management” matrix, where the impact and likelihood of risks were identified as three scenarios (“low,” “medium,” and “high”) in different timescales (the 2020s, 2050s, and 2080s).

In the *Extreme Weather Resilience Report* (Devon County Council, 2014a), a few risks on highways maintenance and connectivity posed by extreme weather events were documented after the 2013/2014 storm. These mainly contributed to the collapse of the sea wall at Dawlish, severe road deterioration, and road closures in multiple sections of “A” road, backlog in the carriageway, increases in potholes, fallen trees, and branches (Devon County Council, 2014a). £3 m initial clear-up was followed by more than £700 m for climate risk maintenance.

In April 2014, the main railway line through Dawlish in Devon was reopened, rebuilt by a 300-strong team from NR at a cost of £35 m (BBC News, 2014b). By Dec. 2016, the government had commissioned NR to make a further £10 m plan to protect coastal lines from storms, which included moving the line and strengthening the cliffs above the line connecting Devon and Cornwall with the rest of the United Kingdom (BBC News, 2016). NR has outlined the ongoing maintenance for the regional rail network in Control Period 6 of its 5-year plan (2019–2024) (Devon Live, 2018).

Led by DCC, the Flood Recovery Coordination Group was established to provide operational and financial support for the affected communities threatened by flooding (Devon Maritime Forum, 2014). Since 2012, DCC has spent over £12 m on the storm-related emergency plan for highways, together with extensive drainage works implemented due to the 2013 storms. Nevertheless, a continual modification for existing design and operation and maintenance are required to adapt against further climate change (Devon County Council, 2014b).

More recently, an assessment of the risks posed by climate change to DCC's Highways Management Service was completed in April 2014 in coordination with Highways Agency and Department for Environment, Food & Rural Affairs (DEFRA). DCC, as a part of the South West partnership, including Somerset County Council and Wiltshire Council, has campaigned for government investment to enhance the strategic resilience of the A303/A30/A358 corridor (Devon County Council, 2014b). Meanwhile, the South West Peninsula Rail Task Force, made up of local authorities, enterprise, and academia, provided cross-sector support for guaranteeing a £7 m investment to develop a more resilient rail network (Devon Maritime Forum, 2014). Therefore, further collaboration between roads and railways is expected to deal with the potential risks posed by storms and other extreme weather events.

The modal shift solution from the road to rail may not fit the case of DCC, as pointed out by an interviewee (Interviewee 5, February 8, 2018). First, rail is more vulnerable to the variation of weather, as it is easier to identify alternative routes for an affected road. Second, the capacity of trains cannot meet the demand for emergency evacuation of cars on the road. For instance, the capacity of a train that can carry 500 people is only equivalent to 250 cars. Alternatively, as an emergency plan, the National Express provided five new "rail replacement" coach services, and Flybe had put on three extra flights from Newquay to Gatwick each day during that period (Transport Committee, 2014). Most importantly, since 2014, a solution proposed by NR to tackle storms is the reinstatement of the old Tavistock line, along the Great Western Railway Teign Valley route, and a new railway with five alternative routes to avoid the coastal section through Dawlish (BBC News, 2014c,d). More recently, the Peninsula Rail Task Force implemented the Dawlish Additional Line as a long-term priority in the 20-year plan, by reconnecting Okehampton to Plymouth route to make the network more resilient to extreme weather (Devon Live, 2018).

Although NR's efforts in storm adaptation are remarkable concerning rapid repairing capacity and replacement services, the condition of the coastlines and their connectivity to the diverse region are still inexplicit in the long term with the occurrence of more frequent and intense extreme weather events (Devon Maritime Forum, 2014). Overall, there is no comprehensive adaptation strategy for climate change at DCC, which may be associated with the kaleidoscopic nature of climate change itself. Currently, climate adaptation has been integrated into the risk management, by which DCC is primarily identifying the risks posed by climate change and working closely with NR to make specific adaptation measures for each risk. With more than £10m being put into drainage management, a near-sight plan (the 2020s) is to alleviate flooding and keep the water level as low as possible. One of the advantages in developing a holistic adaptation strategy in the future is that DCC is well aware of the risks of climate change via a bottom-up mechanism to collect local information and a top-down mechanism to deliver the governmental policy. Even so, a long-term adaptation plan still needs enough financial support and cross-party engagement to ensure its effective implementation (Interviewee 5, February 8, 2018).

4 Discussion and conclusion

This chapter explores the existing adaptation planning in the road and railway systems by exemplifying four typical case studies in the United Kingdom. A qualitative research method is utilized, including document review and five in-depth interviews with domain transport experts from HE, NR, EA, TfL, and DCC. By doing so, the evolvement of climate risk assessment and adaptation actions, current advantages, and potential challenges are dissected for each organization. To compare the similarities and differences of adaptation plans among different organizations, within-case (e.g., London) and cross-cases analyses (e.g., NR and HE) are further explained to strengthen the external and internal validity.

Table 1 summarizes the primary progress of the UK road and rail sectors in adapting to climate change based on the Committee on Climate Change's latest report (2017b) and the new findings from the studied cases.

In the cases of HE and NR, a series of climate risk and adaptation reports have been published on the basis of the UK Climate Projections (UKCP09) and relevant legal guidance (e.g., Committee on Climate Change, 2017a,b; Department for Transport, 2014). Although fewer weather-related delays in England occurred in recent years, regional extremes are still witnessed and will potentially trigger significant costs due to the uncertainties of climate change. In the road and rail sectors, the facilitation of flood resilience is a shared priority with over £100 million funding being allocated by the government (HM Treasury, 2016). Meanwhile, the Committee on Climate Change's ARP2 and DfT's Transport Resilience Review have provided HE, NR, and other local authorities with specific guidance for improving climate resilience on their transport networks.

Simultaneously, the road and rail systems face many challenges in adapting to climate change risks. Overall, rail and underground are more vulnerable to the impacts of climate change due to the limited flexibility and complexity in rail infrastructure construction. Compared with roads, a strategic rail adaptation plan covering all the nine national routes (exclude the Freight and National Passenger Operators route but add the West of Exeter route) has been prepared (Network Rail, 2017a,b; Rail Safety and Standards Board, 2016). However,

TABLE 1 Primary progress of the UK road and rail sectors in climate adaptation.

Similarities	**Risks to infrastructure**	Increased frequency and severity of flooding (will double the number of assets exposed to climate change by 2080s); temperature and precipitation changes; increased maximum wind speeds; other uncertainties such as fog, storms, and lightning (Dawson et al., 2016)
	Vulnerability	Fewer weather-related delays in England in recent years
		The road is less vulnerable to climate risk as having alternative routes and modes to adapt to climate change; rail and underground are more vulnerable due to the limited flexibility and complexity in rail infrastructure construction (e.g., in cases of London and Devon)
	Risk assessment	*TfL—Providing Transport Service Resilience to Extreme weather and Climate* Change (2015): A scoring risk assessment method considering likelihood and impacts of climate change at each business area in London Rail, London Underground and Surface Transport has been developed
		EA—TE2100 5-Year Review (2016): Evaluated the flooding risks based on identified 10 KPIs
	Funding	*The Autumn Statement 2016 transport projects*: Announced £150 m governmental funding for flood resilience improvement with £10 m on roads and £50 m on rails (HM Treasury, 2016)
		London: several £million has invested for Docklands Light Railway, and an estimated cost of at least £1m is required to carry out a sustainability assessment for pathways in TfL (Transport for London, 2015); delivering £308 m of investment on tidal flood defense improvements across the Tidal Thames for the Thames Estuary Asset Management programme (Institution of Civil Engineering, 2017)
		Devon: Over £12 m storm emergency plan in highways from DCC and a further £10 m plan for protecting the coastal line from storms for NR (BBC News, 2016); £7 m investment for establishing a resilient rail network from The South West Peninsula Rail Task Force (2016)
	Guidance	*The UK Climate Projections (UKCP09)* provided comprehensive evidence for risk assessment; the new *UKCP18* projections may change the level of climate risks
		The second round of the Adaptation Reporting Power (ARP2) for 2015-2020 (2017a): HE and NR's reports
		DfT—Transport Resilience Review: A review of the resilience of the transport network to extreme weather events (2014): provided HE and NR with the specific recommendation for improving climate resilience

Continued

TABLE 1 Primary progress of the UK road and rail sectors in climate adaptation—cont'd

Railways	*RRSB—Tomorrow's Railway and Climate Change Adaptation Report (2016)*: Established an adaptation framework for climate change
	NR—An internal audit of weather resilience and climate change (2016): Recognized the demand for setting up strategic targets, and standardizing risk management and decision making.
	NR—Weather Resilience and Climate Change Strategy (2017): Covered all national routes (including West of Exeter); risk analysis and site-specific actions (focusing on embankments, bridge stability, and coastal defenses)
	Implementation: NR has cooperated with the Energy Network Association to investigate the electricity substations; aging railway infrastructure is a challenge
Roads	*HE—Climate Change Adaptation Strategy and Framework (2009)*: Initiated the HHAFM by setting up a seven-stage adaptation process
	HE—Climate Adaptation Risk Assessment Progress Update (2016): Embarked a flood risk analysis through utilizing EA's flood risk maps and other data; recognized high risk and very high-risk hotspots and culverts and reduced floods at 124 flooding hotspots and culverts
	DCC—Service Resilience in a Changing Climate Highways Management (Devon County Council, 2014b): Developed a "Devon Way for Risk Management" matrix for evaluating the impact and likelihood
	Implementation: HE has improved drainage and flood resilience to climate change on some regional routes; some local authorities have increased its strategic planning and investment in resilience

Based on "Progress in preparing for climate change 2017 Report to Parliament" (Committee on Climate Change, June 2017a).

the existing adaptation plan of NR mainly focuses on the identification of various climate thresholds (Network Rail, 2015). Sometimes climate adaptation is regarded as part of risk management, where the attention focuses on risk assessment for the road system with specific extreme weather adapting plans (Interviewee 5, February 8, 2018). The absence of a holistic adaptation strategy might reflect the deficiency of scientific data (e.g., SLR for TE2100), cost-benefit analysis, and understanding of climate vulnerabilities and thresholds (Interviewee 3, January 17, 2018), and these gaps reflect the findings in the literature (e.g., Koetse and Rietveld, 2012). Hence, a new set of climate projections (UKCP18) published in November 2018 by the UK government is believed to offer clear guidance for dealing with the challenges of estimation and selection of risk scenarios under various climate conditions.

One of the significant challenges revealed by the case of the TE2100 is that the aging flooding infrastructure might not be able to catch up with the higher SLR (Environmental Agency, 2017), while aging infrastructure could be a standard issue for the whole railway industry owing to the increasing rate of climate change. Furthermore, there is an ambiguous time horizon for road and rail adaptation planning. For the majority of cases, adaptation reports run on a 5-year basis (Interviewee 1, January 26, 2018; Interviewee 2, April 6, 2018; Interviewee 4, February 1, 2018); thereafter, the time horizon for a long-term adaptation plan is undetermined: it may look at next 30 years and beyond 2100 (Interviewee 2, April 6, 2018) or 100 years (Interviewee 3, January 17, 2018) for railways and up to 120 years for roads. It can be linked to the diverse lifespan of specific assets, geographic conditions, climate change prediction, financial budgets, etc. In the future, climate adaptation planning needs to be regularized and written into every business plan (Interviewee 3, January 17, 2018), embedded in technical standards and delivered to all staff seamlessly (Interviewee 1, January 26, 2018). A successful adaptation plan must be aware of budgetary constraints and strike a balance between corporate priorities and technical requirements (Wang et al., 2019).

The establishment of several partnerships, on behalf of the London Climate Change Partnership (LCCP) Transport Group and the South West Peninsula Rail Task Force, has offered a chance to deal with regional climate change issues. However, in practice, owing to the project-based characteristics in most adaptation cases, as per several interviewees, road and rail stakeholders usually only consult each other but undertake projects separately. A modal shift strategy has been successfully applied into practice, for instance, where road traffic was converted to rail by establishing a rail platform and offering a new rail service in Workington, Cumbria in a quick response (Ace Geography, n.d.), and a rail replacement service by increasing buses and flights from Newquay to London due to seawall damage in Dawlish, Devon (Transport Committee, 2014). More extensive and efficient cooperation between roads and railways is expected, but the development of an integrated inland transport system requires thorough consideration of multiple factors, such as mode capacity, the severity of consequences, and geographic conditions. The trans-mode and cross-sectoral collaborations in the future should enable planners to create a new blueprint for climate adaptation, effectively facilitated by governmental regulation (e.g., ORR, DfT), broader stakeholder management, and public engagement from decision-making to adaptation implementation.

Finally, we believe that this chapter contributes to further studies in climate change, risk assessment, transport planning, policy making, and other interdisciplinary areas. The all-around data analysis from interviews will facilitate interviewees in the case studies to better understand the impacts posed by climate change in decision-making and to recognize their strengths and barriers in future adaptation planning. Also, an integrated thinking pattern concerning roads and railways in an integrated inland transport will enlighten transport planners to consider the consistency and resiliency of diverse modes in a systematic transport network in future planning.

Appendix. Basic information of interviewees

Interviewee	Position	Organization	Interview date
Interviewee 1	Middle	Highways England	January 26, 2018
Interviewee 2	Middle	Network Rail	April 6, 2018
Interviewee 3	Senior	Transport for London	January 17, 2018
Interviewee 4	Middle	Environmental Agency	February 1, 2018
Interviewee 5	Senior	Devon County Council	February 8, 2018
Remarks: "Senior" means policy maker, transport planner, etc. "Middle" means environmental specialist, climate adaptation advisor/manager, etc.			

References

Ace Geography (n.d.). Flooding Case Studies: Cockermouth, UK - Rich Country (MEDC). Retrieved from: http://www.acegeography.com/flooding-case-studies-gcse.html. 20 December 2017.

BBC News, 2014a. Devon and Cornwall Storm Causes 'Devastation'. Retrieved from: http://www.bbc.com/news/uk-england-26044323. (Accessed June 10, 2018).

BBC News, 2014b. Storm-Hit Dawlish Rail Line Compensation Payout Revealed. Retrieved from: https://www.bbc.co.uk/news/uk-england-devon-27055780. (Accessed June 10, 2018).

BBC News, 2014c. UK Storms Destroy Railway Line and Leave Thousands Without Power. Retrieved from: http://www.bbc.com/news/uk-26042990. (Accessed June 10, 2018).

BBC News, 2014d. How Do You Fix the Dawlish Problem?. Retrieved from: https://www.bbc.co.uk/news/uk-26068375. (Accessed June 10, 2018).

BBC News, 2015a. Cumbria Hit by Flooding After Heavy Rain. Retrieved from: http://www.bbc.com/news/uk-england-cumbria-35003649. (Accessed August 9, 2017).

BBC News, 2015b. Storm Desmond: Defences Against Indefensible Floods. Retrieved from: http://www.bbc.com/news/science-environment-35028180. (Accessed December 20, 2017).

BBC News, 2015c. Dawlish Rail Line: Closure 'Costs Economy up to £1.2bn'. Retrieved from: http://www.bbc.com/news/uk-england-devon-31140192. (Accessed June 11, 2018).

BBC News, 2016. Dawlish Railway Line: £10m Pumped Into Saving Coastal Route. Retrieved from: https://www.bbc.co.uk/news/uk-england-devon-38012833. (Accessed June 11, 2018).

BBC News, 2017. Flooding Closes Cumbria Roads and Schools. Retrieved from: http://www.bbc.com/news/uk-england-cumbria-41582974. (Accessed December 20, 2017).

Braun, V., Clarke, V., 2006. Using thematic analysis in psychology. Qual. Res. Psychol. 3 (2). 77–101, 474, 486.

Committee on Climate Change, 2014. Managing climate risks to well-being and the economy. Adaptation Sub-Committee Progress Report 2014.

Committee on Climate Change, 2017a. Progress in preparing for climate change. . 2017 Report to Parliament.

Committee on Climate Change, 2017b. The Second Round of the Adaptation Reporting Power (ARP2) for 2015-2020.

Conference of European Directors of Roads, 2010. Retrieved from http://www.fehrl.org/index.php?m=32&mode=download&id_file=10736, Accessed 20 May 2018.

Dawson, R.J., Thompson, D., Johns, D., Gosling, S., Chapman, L., Darch, G., Watson, G., Powrie, W., Bell, S., Paulson, K., Hughes, P., Wood, R., 2016. UK Climate Change Risk Assessment Evidence Report: Chapter 4, Infrastructure. Report prepared for the Adaptation Sub-Committee of the Committee on Climate Change, London.

Department for Infrastructure, 2017. Northern Ireland Transport Statistics 2016-2017. . UK Government (Crown copyright).

Department for Transport, 2014. Transport Resilience Review: A Review of the Resilience of the Transport Network to Extreme Weather Events. Retrieved from: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/335115/transport-resilience-review-web.pdf. (Accessed July 4, 2017).

Department for Transport, 2017. Road Lengths in Great Britain 2016. DfT Statistical Release. UK Government (Crown copyright).

Devon County Council, 2014a. Extreme Weather Resilience Report. Devon County Council, Devon. May 2014.

Devon County Council, 2014b. Service Resilience in a Changing Climate Highways Management. Environment Group, Devon County Council.

Devon Live, 2018. It's Been Four Years Since the Dawlish Rail Disaster—What Has Happened Since? Retrieved from: https://www.devonlive.com/news/its-been-four-years-dawlish-1152802. (Accessed June 11, 2018).

Devon Maritime Forum, 2014. Holding the line? Reviewing the Impacts, Responses and Resilience of People and Places in Devon to the Winter Storms of 2013/2014. Retrieved from: http://www.devonmaritimeforum.org.uk/images/stories/DMFdocuments/DMFmeetingArchives/2014Autumn/DMF%20Storms%2013-14%20Summary%20Report.pdf. (Accessed June 11, 2018).

Environmental Agency, 2008. Thames Estuary 2100 Safeguarding Transport Phase 3 Studies—Work Element 6.2.

Environmental Agency, 2014. The Thames Barrier: How the Thames Barrier Works, and When It Is Scheduled to Close. Retrieved from: https://www.gov.uk/guidance/the-thames-barrier. (Accessed June 4, 2018).

Environmental Agency, 2016. TE2100 5 Year Review, Non-Technical Summary. July 2016.

Environmental Agency, 2017. Policy Paper: Thames Estuary 2100 (TE2100). Updated 2 March 2017. Retrieved from: https://www.gov.uk/government/publications/thames-estuary-2100-te2100/thames-estuary-2100-te2100. (Accessed June 5, 2018).

Greater London Authority, 2011. Managing Risks and Increasing Resilience: The Mayor's Climate Change Adaptation Strategy.

Highways Agency, 2009. Climate Change Adaptation Strategy and Framework. Revision B—issued in November , p.2009.

Highways Agency, 2011. Climate Change Risk Assessment August 2011. Retrieved from: http://assets.highways.gov.uk/about-us/climate-change/HA_Climate_Change_Risk_Assessment_August_2011_v2.pdf. (Accessed May 22, 2018).

Highways England, 2015. Highways England Delivery Plan 2015–2020.

Highways England, 2016. Climate Adaptation Risk Assessment Progress Update 2016.

Highways England, 2018a. Retrieved from: https://www.gov.uk/government/organisations/highways-england/about. (Accessed May 20, 2018).

Highways England, 2018b. Retrieved from: https://highwaysengland.co.uk/highways-england-about-us/. (Accessed May 22, 2018).

HM Treasury, 2016. Policy Paper: Autumn Statement 2016 Transport Projects. Retrieved from: https://www.gov.uk/government/publications/autumn-statement-2016-transport-announcements/autumn-statement-2016-transport-projects. (Accessed May 30, 2018).

Hooper, E., Chapman, L., 2012. Chapter 5. The impacts of climate change on national road and rail networks. In: Transport and Climate Change. Emerald Group Publishing Limited, pp. 105–136.

Institution of Civil Engineering, 2017. Thames Estuary Asset Management 2100 Programme (TEAM2100). Retrieved from: https://www.ice.org.uk/getattachment/events/thames.../TEAM2100-flyer.pdf.aspx. (Accessed 14 June 2018.)

Jaroszweski, D., 2015. Chapter 6. The impacts of climate change on the National Freight Sector. In: Transport and Climate Change. Emerald Group Publishing Limited, pp. 137–173.

Koetse, M.J., Rietveld, P., 2009. The impact of climate change and weather on transport: an overview of empirical findings. Transp. Res. Part D: Transp. Environ. 14 (3), 205–221.

Koetse, M.J., Rietveld, P., 2012. Adaptation to climate change in the transport sector. Transp. Rev. 32 (3), 267–286.

Love, G., Soares, A., Püempel, H., 2010. Climate change, climate variability and transportation. Procedia Environ. Sci. 1, 130–145.

McKenzie Hedger, M., Gawith, M., Brown, I., Connell, R., Downing, T.E., 2000. Climate change: assessing the impacts—identifying responses. In: The First Three Years of the UK Climate Impacts Programme. UKCIP and DETR, Oxford.

Miles, M.B., Huberman, A.M., 1984. Qualitative data analysis: a sourcebook of new methods. In: Qualitative Data Analysis: A Sourcebook of New Methods. Sage Publications.

Network Rail, 2015. Climate Change Adaptation Report 2015. Retrieved from: http://16cbgt3sbwr8204sf92da3xxc5m-wpengine.netdna-ssl.com/wp-content/uploads/2016/11/Climate-Change-Adaptation-Report-2015_FINAL.pdf. (Accessed April 7, 2017).

Network Rail, 2017a. Weather Resilience and Climate Change Adaptation Strategy 2017-2019.

Network Rail, 2017b. Weather Resilience & Climate Change Adaptation Policy.

Network Rail, 2018a. Retrieved from: https://www.networkrail.co.uk/who-we-are/. (Accessed May 25, 2018).

Network Rail, 2018b. Retrieved from: https://www.networkrail.co.uk/running-the-railway/our-routes/. (Accessed May 25, 2018).

Network Rail, 2018c. Retrieved from: https://www.networkrail.co.uk/communities/environment/climate-change-weather-resilience/weather-resilience/. (Accessed May 25, 2018).

Network Rail, 2018d. Retrieved from: https://www.networkrail.co.uk/communities/environment/climate-change-weather-resilience/climate-change/. (Accessed May 25, 2018).

Ng, A.K., Wang, T., Yang, Z., Li, K.X., Jiang, C., 2018. How is business adapting to climate change impacts appropriately? Insight from the Commercial Port Sector. J. Business Ethics 150 (4), 1029–1047.

Rail Safety and Standards Board, 2016. Tomorrow's Railway and Climate Change Adaptation: Final Report. Rail Safety and Standards Board Ltd.

Schweikert, A., Chinowsky, P., Espinet, X., Tarbert, M., 2014. Climate change and infrastructure impacts: comparing the impact on roads in ten countries through 2100. Proc. Eng. 78, 306–316.

The South West Peninsula Rail Task Force, 2016. 'Closing the Gap'—The South West Peninsula Strategic Rail Blueprint. Retrieved from: https://peninsularailtaskforce.co.uk/closing-the-gap-the-south-west-peninsula-strategic-rail-blueprint/. (Accessed June 11, 2018).

The Sun, 2017. Doris Pray as 50ft Waves Batter Britain's Coasts, Met Office Warns Brits to Brace Themselves as Worst of Storm Doris Will Hit TODAY. Retrieved from: https://www.thesun.co.uk/news/2765380/storm-doris-uk-weather-warning/. (Accessed May 31, 2018).

Transport Committee, 2014. Oral evidence: transport's winter resilience: rail flooding, HC 1087, Meeting on Tuesday 25 February 2014. Retrieved from: http://data.parliament.uk/writtenevidence/WrittenEvidence.svc/EvidenceHtml/6845. (Accessed June 12, 2018).

Transport for London, 2015. Providing Transport Service Resilience to Extreme Weather and Climate Change. Update Report following the last report to Government in 2011.

Transport for London, 2018a. Retrieved from: https://tfl.gov.uk/corporate/about-tfl/what-we-do?intcmp=2582. (Accessed May 31, 2018).

Transport for London, 2018b. Retrieved from: https://tfl.gov.uk/corporate/about-tfl/how-we-work/how-we-are-governed?intcmp=2724. (Accessed May 31, 2018).

UK Climate Projections, 2018. UKCP18 Science Overview report, November 2018. Retrieved from https://www.metoffice.gov.uk/pub/data/weather/uk/ukcp18/science-reports/UKCP18-Overview-report.pdf. (Accessed February 20, 2019).

Wang, T., Qu, Z., Yang, Z., Nichol, T., Dimitriu, D., Clarke, G., Bowden, D., 2018a. Impacts of climate change on rail systems: a new climate risk analysis model. In: Haugen, S., Barros, A., Gulijk, C.V., Kongsvik, T., Vinnem, J. (Eds.), Safety and Reliability—Safe Societies in a Changing World. CRC Press, London.

Wang, T., Qu, Z., Yang, Z., Nichol, T., Dimitriu, D., Clarke, G., Bowden, D., 2018b. How can the UK road system be adapted to the impacts posed by climate change? By creating a climate adaptation framework. In: Proceedings of the International Conference on Project Logistics (PROLOG), University of Hull, UK, 28-29 June 2018.

Wang, T., Qu, Z., Yang, Z., Nichol, T., Dimitriu, D., Clarke, G., Bowden, D., 2019. How can the UK road system be adapted to the impacts posed by climate change? By creating a climate adaptation framework. Transp. Res. D: Transp. Environ. Available from: https://doi.org/10.1016/j.trd.2019.02.007.

Wikinow (n.d.). British Railway System. 7 April 2017, Retrieved from: http://www.wikinow.co/topic/british-railway-system

Woolston, H. (2014). Managing Extreme Weather at Transport for London Climate Change. Transport for London. 30 May 2018, Retrieved from: https://www.arcc-network.org.uk/wp-content/pdfs/ARCC-2014-2b-TfL-Woolston.pdf.

Woolston, H. (n.d.). Climate Change—Impact on Transport Network User. LCCP, Transport for London. 30 May 2018, Retrieved from: http://sd-research.org.uk/sites/default/files/publications/Helen%20Woolston%20CC%20Adaptation.pdf

Yang, Z., Ng, A.K., Lee, P.T.W., Wang, T., Qu, Z., Rodrigues, V.S., … Lau, Y.Y., 2018. Risk and cost evaluation of port adaptation measures to climate change impacts. Trans. Res. D: Trans. Environ. 61, 444–458.

Yin, R.K., 2003. Case Study Research: Design and Methods. Sage, Thousand Oaks, CA.

Further reading

Getlink (n.d.). 20 May 2018, Retrieved from: https://www.getlinkgroup.com/uk/home/.

Network Rail, 2014. West of Exeter Route Resilience Study. Retrieved from: https://cdn.networkrail.co.uk/wp-content/uploads/2016/11/West-of-Exeter-Route-Resilience-Study.pdf. (Accessed June 11, 2018).

Network Rail, 2016. Great Britain National Rail Network Diagram. Retrieved from: http://www.nationalrail.co.uk/static/documents/content/routemaps/nationalrailnetworkmap.pdf. (Accessed April 7, 2017).

Peterson, T.C., McGuirk, M., Houston, T.G., Horvitz, A.H., Wehner, M.F., 2008. Climate Variability and Change With Implications for Transportation. Transportation Research Board.

UK Climate Projections, 2009. Retrieved from: http://ukclimateprojections.metoffice.gov.uk/21687. (Accessed June 1, 2018).