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Climate Change Adaptation and Transport Infrastructure

A Rapid Evidence Assessment

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Executive summary

Climate change is already creating risks for transport infrastructure. Extreme weather events – such as major storms, heavy precipitation, and heatwaves – can cause damage and disruption, and will only become more frequent (IPCC, 2022). There are also more gradual changes, such as sea level rise, which can push coastal transport infrastructure to the limits of its tolerance. Adapting transport infrastructure to these changes is increasingly a priority, but the costs of major works can be substantial, and there are many uncertainties to navigate. In this context, there is a clear need to robustly explore the costs and benefits of considering adaptation when planning and maintaining transport infrastructure. This report presents the results of a Rapid Evidence Assessment (REA). An REA is an attempt to find and summarise the available research on a topic as comprehensively as possible, within the constraints of a compressed timetable. REAs sit between literature reviews and systematic reviews, using rigorous search methods and prioritising the most relevant evidence for inclusion.

Key findings

A range of climate change impacts were discussed in the literature. **Heavy precipitation and floods** can close roads and railways, damage road and rail bridges, erode earthworks, cause landslides, damage drainage systems, and cause accidents. **Extreme heat** can damage roads and reduce road safety, cause bridges and railway tracks to buckle, and damage airport runways. Other threats include **storms** and **high winds**, which can cause damage directly, lead to debris blocking or damaging roads and railways, down power lines, and lead to tidal surges. **Sea level rise** will increase the erosion and damage of coastal infrastructure and increase the frequency of flooding. Most of the evidence reviewed related to **road** and **rail** infrastructure, but it is also important to note the extent to which the transport network is interconnected, meaning that disruption to a single mode can cascade to others.

There was a **consensus in the literature that the benefits of adaptation outweigh the costs**. This was true despite some cost-benefit analyses finding that individual adaptation actions were not good value for money. The literature identified a wide range of potential benefits – economic, social and environmental – which are, in general, harder to quantify than the costs of adaptation. The broader the view taken of the potential benefits of adaptation, the more clearly adaptation measures were found to be net beneficial. No single study in the review considered all, or even close to all, the full range of costs and benefits associated with adaptation measures. Any future attempts to do so will need to draw on literature and techniques from a broad range of fields and will be both conceptually and technically challenging.

Many *potential* benefits of adaptation were identified in the literature, but the evidence on whether these occurred, and their extent, was variable and some cases highly limited. These potential benefits included:

- Avoiding the immediate cost of **repairs**, **accidents**, **lost revenue** and **customer compensation**.
- Avoiding **wider economic costs**, including: the costs of passenger and freight delays; difficulties for staff getting to or from work, or travelling for work; impacts on local businesses and the tourism industry; negative impacts on employment levels; reduced spending power for transport users and transport operators; and the potential for sustained disruption to reduce future transport demand.
- **Indirect benefits**, including increased employment levels, lower levels of unemployment benefit payment, increased private investment, and increased transport efficiency.

In addition to the challenges involved in considering such a wide range of potential benefits, there are some distinct methodological challenges.

Firstly, most climate models operate at relatively large geographies, such as countries or regions, but transport infrastructure exists and operates at smaller geographies, and multiple studies in the review discussed lower levels. Furthermore, all models will have some significant degree of uncertainty, which reduces over time as the date of the projections gets closer: Cost-benefit analyses therefore need to be sensitive to the potential benefits of waiting for increased certainty before making decisions.

Secondly, there is a need to better understand the likely impacts of climate change on transport infrastructure, and, conversely, the extent of the damage and disruption that can be avoided by adaptation. There is more research on road and rail infrastructure than on aviation and maritime infrastructure, and more research on the effects of flooding and heavy precipitation than other climate change effects. There is relatively little research on the role of intermodal vulnerabilities – how extreme weather might affect multiple modes simultaneously, or how damage and disruption to one mode might affect another.

1 Introduction

This report presents the findings of a Rapid Evidence Assessment (REA) on Climate Change Adaptation (CCA) and transport infrastructure. The primary aim of the REA was to understand the costs and benefits associated with adapting transport infrastructure to the effects of climate change. A secondary aim was to summarise the existing evidence on how climate change is affecting and will affect transport infrastructure, and to provide an overview of what adaptation work is being done, has been planned, or has been recommended. The report highlights where there are key gaps in the evidence, and the primary methodological challenges involved in filling those gaps. The aim is for the review to inform an internal Department of Transport (DfT) strategy on incorporating directed CCA interventions in all forms of transportation policy making.

1.1 Background to the review

The United Nation's Intergovernmental Panel on Climate Change (IPCC) defines CCA as the adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities (IPCC, 2022). CCA is an area of growing importance, alongside ongoing efforts to mitigate climate change by reducing emissions. CCA works with an understanding that climate change is already happening and will continue to happen, and therefore transport infrastructure will need to be adapted to ensure it is resilient enough to cope with more extreme weather events over the next 30-50 years.

The Climate Change Act 2008 requires the Government to compile an assessment of the risks for the UK arising from climate change on a five-year basis, and to develop an adaptation programme to address those risks. The first assessment was published in 2012, and the third and most recent was published in 2021. The most recent National Adaptation Plan was published in 2018 and included a short section relating to transport. The 2008 Act also allows the Government to ask certain organisations to report on their climate risks and adaptation actions, under the 'Adaptation Reporting Power'. This includes National Highways, Network Rail, Transport for London, airport operators, and harbour authorities.

The winter of 2013/14 saw widespread transport disruption caused by a series of major storms. This prompted the DfT to undertake a Transport Resilience Review, which aimed to summarise the lessons learned for England to better anticipate the impact of future extreme weather events. The IPCC has concluded that climate change will increase the frequency of extreme weather events. The aim of this report is to fill a knowledge gap by exploring the evidence on the costs and benefits of considering adaptation when planning and maintaining transport infrastructure.

1.2 Research questions

The review attempts to answer the following questions:

1. What Climate Change Adaptation work has been and is being done in the transport sector in the UK?
    a. Which modes has work been done on?
    b. Does the work being done meet the level of need? Where are the key gaps?
    c. What has been and is being done in comparable countries?

    d. What can DfT learn in terms of incorporating CCA interventions to transport policy making?

2. What are the economic costs and benefits of considering Climate Change Adaptation when planning and developing transport infrastructure?
    a. What are the social costs and benefits?
    b. What are the environmental costs and benefits?

1.3 Methodology

This study used a Rapid Evidence Assessment (REA) methodology. An REA “is a tool for getting on top of the available research evidence on a policy issue, as comprehensively as possible, within the constraints of a given timetable” (National Archives, REA Toolkit). REAs sit between literature reviews and systematic reviews: they aim to follow rigorous and explicit methods for searching, screening, assessing and synthesising evidence, whilst making informed compromises on aspects of the systematic review process to deliver findings quickly.

The REA involved academic texts and grey literature; the former being located through complex search strings and the latter through extensive web-site searches. The relevance of literature identified in the search was assessed against detailed eligibility criteria. 158 papers were identified that met the inclusion criteria, and 34 were selected for inclusion in the review using prioritisation principles. A more detailed account of the methodology is in Chapter 2.

1.4 The structure of this report

The report structure is as follows:

- **Chapter 2** provides a detailed account of the methodology used to conduct the REA.
- **Chapter 3** outlines climate adaptation work being done in the transport sector in the UK (research question 1).
- **Chapter 4** addresses the costs and benefits of climate adaptation (research question 2).
- **Chapter 5** presents and discusses knowledge gaps and recommendations for future practice identified in the literature.

2 Methodology

This chapter provides a summary of the methodological approach taken in this Rapid Evidence Assessment (REA). An REA involves systematically searching, screening, assessing and synthesising evidence which helps to inform and address the research questions. The criteria and processes for the search strategy, screening, data extraction and synthesis are summarised below. Full methodological details can be found in Appendix A.

2.1 Search strategy

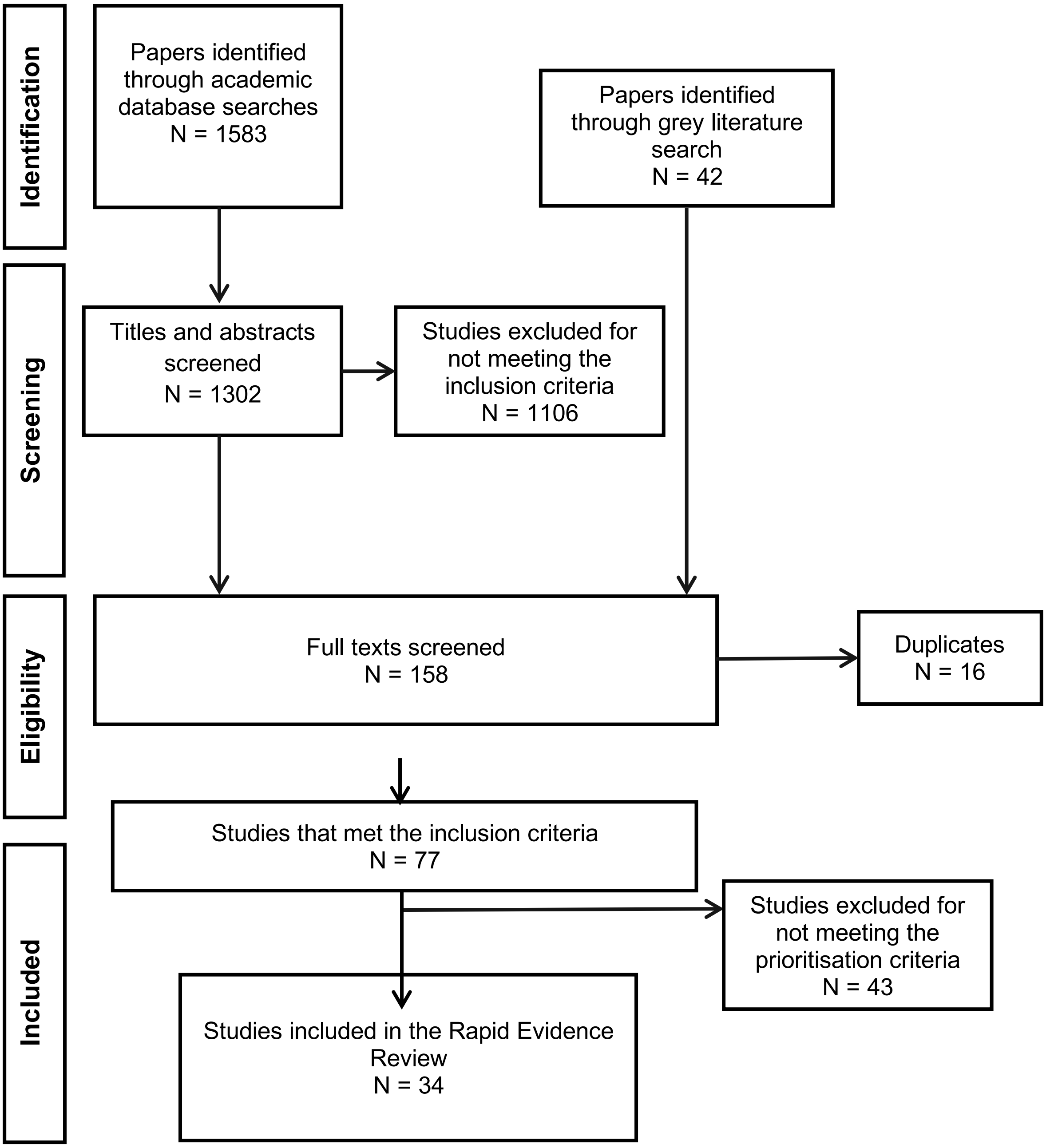
The study involved a systematic search for both academic and grey literature. Academic literature was located using complex search strings in academic databases, including Scopus, EconLit, Transport Research International Documentation (TRID), and ABI/Inform. The search strings were developed in relation to the inclusion criteria, and are set out in Appendix A. Where studies were found to be particularly relevant, citation tracking was conducted. This involved looking through the list of references in the chosen paper and/or viewing all the papers that cite the chosen paper.

Grey literature was searched for using a list of relevant websites, which were identified with input from the DfT. The research team used a set of core search terms to find documents on these websites. The list of websites is provided in Appendix A.

2.2 Screening

Academic literature was screened for inclusion at two stages: title and abstract, and full text. A total of 1302 academic studies were screened at title and abstract. 116 academic studies were then screened again at full-text, alongside 42 grey literature studies, totalling 158 items. Following full-text screening, 77 studies met the inclusion criteria. This was more evidence than could be included in the review, given time constraints. The studies were systematically prioritised based on relevance and other factors, and a total of 34 studies were included in the final review. Figure 1 illustrates the search and screening process undertaken, and Appendix A details the prioritisation criteria used.

Figure 1: PRISMA Flowchart



2.3 Data extraction and synthesis

Based on an initial read of a subset of the prioritised studies, a thematic framework was developed. Key themes included the impact of climate change on each mode of transport and its infrastructure, current and suggested adaptation measures, and the costs (economic, social, environmental) and benefits of adaptation. Members of the research team read the studies closely and extracted relevant information into the corresponding cells of the extraction framework in Covidence. Covidence is a web-based software platform for conducting systematic and other reviews.

Following data extraction, the evidence was narratively synthesised by research question. This was done by using a ‘framework method’, employing analytical matrices reflecting our primary and secondary research questions.

3 The impacts of climate change on transport infrastructure

This chapter provides an overview of the ways in which climate change is affecting, and will affect, transport infrastructure. For each of the four modes considered – road, rail, aviation and maritime – it first provides a brief background on infrastructure and governance, before outlining the evidence on climate change impacts, and examples of adaption works that have taken place or have been recommended. It concludes by discussing interactions between modes and sectors.

3.1 Roads

3.1.1 Road infrastructure and governance

The UK has a network of 422,100km of paved roads, divided between the Strategic Road Network (SRN) and the local road network.

The SRN comprises more than 4,300 miles of motorways and major A-class roads and is used by around 4 million vehicles each day (Wang, 2019). It is a significant national asset with a valuation of £109 billion as of 2014 (DfT, 2014). Responsibility for strategic roads is devolved and is overseen by National Highways (formerly the Highways Agency) in England, and by the Welsh Government, Transport Scotland, and Transport Northern Ireland in the other UK nations.

The local road network makes up 183,300 miles, and includes some motorways, dual carriageways, and busy urban distributor roads, in addition to minor roads. UK roads are used by 34 million vehicles annually (National Environment Research Council, 2015). Local roads are overseen by separate local highway authorities – typically Local Authorities. The UK Roads Liaison Group Code of Practice for Well Maintained Highways publishes frequently renewed guidance on how local authorities should be responding to climate change impacts on local roads (Climate Change Committee 2017).

In addition to the strategic and local road network, there is a large network of private roads used for servicing important infrastructure such as power lines, wind farms, communication facilities and water storage. These roads are often in remote locations and subject to the effects of weather and climate effects. However, there was no information or research into these private facilities in the included studies, although it is possible that service providers do have their own climate management and mitigation plans to deal with access to their facilities.

A report by the European Commission in 2012 provides estimates of the lifespan of road infrastructure across Europe. Typically, the lifespans of roads are 30-40 years, road pavements are 10-25 years, bridges are 100 years, causeways in low-lying coastal zones are 20-100 years, culverts are 20-100 years and surface drainage infrastructure are 20 years.

3.1.2 The impacts of climate change on road infrastructure

The primary threat to road infrastructure that was discussed in the literature came from flooding and heavy precipitation. Other threats included extreme heat and cold, landslides and high winds.

Flooding & Precipitation

The latest adaptation report from National Highways, in 2021, identified several ways in which flooding and precipitation can cause damage and disruption:

- Drainage systems can be overwhelmed, which can lead to roads being inundated, blocking traffic, and can lead to roads and underlying earthworks becoming waterlogged, leading to premature deterioration.
- When road surfaces are waterlogged for a prolonged time, asphalt can become weakened, leading to potholes and faults.
- Scour – the erosion of soil or rock at the foundation of a structure – is the main cause of bridge failure in the UK.
- Earthworks, such as slopes and embankments, can fail when the ground is saturated by water.

The UK Climate Change Risk Assessment (2017) reported that 6,600km of the UK road network is in areas that are vulnerable to flooding, claiming that this could increase by 53-160% by the 2080s. Multiple papers provide examples of the effects of flooding and precipitation on UK roads, or discussed their likely effects:

- Flooding in Cumbria in 2015, partly due to Storm Desmond, resulted in road closures and over 100 bridges being damaged or destroyed. Parts of roads had to be rebuilt and failure of traffic lights resulted in serious delays (Wang, 2019).
- A section of the M3 closed for two days in February 2014 due to a sinkhole caused by extreme rainfall (Dawson et al. 2016a).
- In June 2012, a series of storms hit Newcastle. Approximately 50mm of rainfall fell in less than two hours (a 1-in-100-year storm event), flooding 377 road links and leading to severe traffic congestion which lasted more than six hours (Pregnolato, 2017).
- Doll (2014) claimed that, because of intense precipitation, low-lying bridge and tunnel entrances for roads and rail will be more susceptible to flooding, and there will be erosion and subsidence of road bases and rail trackbeds, as well as erosion and scouring of bridge supports.

Extreme temperatures

Both extreme heat in the summer and extreme cold in the winter pose threats to road infrastructure. The UK Climate Change Risk Assessment (2021) discussed how high temperatures will result in expansion (which can lead to cracking), bleeding (when a thin film of asphalt appears on the road surface making it slippery) and rutting (when vehicles create depressions or grooves in the softer road surface). High temperatures will increase the frequency of droughts, which can cause drying of soil and plants, leading to earthwork problems. Cold weather can lead to ice and snow and accounted for 16% of all weather-related delays on the SRN in England between 2006 and 2014.

However, Doll (2014) pointed out that warming winter temperatures will lead to reduced snow and ice removal costs and will lessen the adverse environmental impacts from the use of salt and chemicals on roads and bridges. It will extend the construction season and improve the mobility and safety of passenger and freight travel through reduced winter hazards.

Landslides and high winds

Landslides and high winds have the capacity to cause immediate damage and danger. Postance (2017) discussed the impact of landslides in Scotland, which have caused repeated disruption to the major road network in Scotland. The author identified 152 road segments as susceptible to landslide activity, representing 34% of the road network in Scotland. High winds can topple high-sided vehicles, which is a clear safety threat, and can cause infrastructural damage, damage traffic signs, or cause debris and vegetation to fall onto the road (Dawson et al. (2016a). Storm Ali in September 2018 resulted in power cuts, vehicle damages and fallen debris, leading to traffic delays in Cumbria and closure of sections of the M6 and the Tay Road Bridge.

3.1.3 Adaptation for road infrastructure

The studies included did not provide extensive detail on specific adaptation measures for roads infrastructure. Given the significance of flooding on UK roads, several papers discussed the importance of increased drainage capacity, and the use of vegetation to improve water runoff. The papers also mentioned the need for early warning systems, and for increased road surface inspections for heat-related damage. Several papers discussed the importance of identifying ‘hotspots’ and critical routes that would cause disproportionate disruption if they were flooded or otherwise made impassable.

In 2009, Highways England published its adaptation strategy, which set out a model for assessing and understanding the risks posed to the SRN. Using this model, the agency identified 80 activities that may be affected by climate change, of which 60% were deemed high impact and time critical. These vulnerabilities were prioritised using a range of criteria, including the extent and severity of expected disruption. Options analysis was used to identify the preferred option for dealing with each risk, and “Adaptation Action Plans” were developed for each. This approach continues to guide activities. The last progress update was published in 2021 (National Highways, 2021).

The 2014 Transport Resilience Review recommended that local highway authorities identify roads that are a priority in terms of ensuring resilience to extreme weather events. These roads would constitute the “resilient network”. To create this network, key businesses, interest groups and the community should be engaged to help identify crucial routes. The proposed network would keep records of repeat events, such as flooding, to inform action and for future reference.

In Europe, there are multiple existing approaches to identifying and prioritising roads for adaptation work. The ROADAPT (Roads for Today, Adapted for Tomorrow) is a joint research project supported by the Netherlands, Germany, Denmark and Norway, which has developed a preliminary risk assessment methodology that can identify vulnerable locations in the road network, understand the consequences that climate change events could have on these locations, the probabilities of these outcomes, and provide options for adaptation options (Filosa, 2015).

3.2 Rail

3.2.1 Rail infrastructure and governance

The governance arrangements of the railway in the UK are complex. Network Rail owns, operates and maintains the railway network in Britain (responsibility is devolved to TransLink in Northern Ireland). In terms of infrastructure, this includes tracks, signalling systems, embankments, tunnels and bridges. Train operating companies (TOCs) run the passenger services, and lease and manage Network Rail’s stations. In London, the Overground and Underground services are managed by Transport for London (TfL).

Network Rail, the TOCs, and the Freight Operating Companies (FOCs) collaborate to manage disruption caused by extreme weather events. However, Network Rail must compensate train operators when the state of its infrastructure causes delays to or cancellations of services. This includes delays or disruption caused by extreme weather. These payments are in turn used by the train operators to compensate passengers for inconvenience, or to provide alternative arrangements such as rail replacement bus services (Dawson et al., 2016b).

As of 2020, the British railway network comprised around 19,000 miles of track across around 10,000 miles of routes, and over 2,500 stations (ORR, 2020), with 1.7 billion passenger journeys in 2019/20 (Network Rail, 2021a). In addition to the track, Network Rail oversees 30,000 bridges and viaducts, and many tunnels, signals and level crossings. Network Rail manage 190,000 earthworks assets, including 70,000 soil cuttings, 20,000 rock cuttings, and 100,000 embankments. Most of the network was built over 150 years ago, and in many ways is outdated. Much of the network is built on cuttings or embankments which do not meet modern standards and as such steep embankment slopes increase the risk of slips (Marsland, 2021).

3.2.2 The impacts of climate change on rail infrastructure

Network Rail's Third Adaptation Report provides a detailed overview the impacts of weather on the UK railway. The report identifies four 'key' risk areas, which were given a current risk rating of 'moderate' and/or a future risk rating for the 2050s as 'major' or 'severe'. These risk areas were precipitation; sea level rise and coastal erosion and flooding; temperature; and storm and wind events (Network Rail, 2021b).

The UK's third Climate Change Risk Assessment (2021) argued that rail infrastructure faces greater exposure to surface water flooding than river flooding: 596 railway stations and 3,544km of rail network are at risk from surface water flooding in the UK, compared to 81 stations and 1,144km of rail network at risk from river flooding. Flooding and heavy precipitation can cause scour, defined by Network Rail as "the removal of material from the bed and banks of a channel and from around structure foundations by the action of water, leading to structural damage or failure" (Network Rail, 2019). Multiple studies identified scour as the main cause of bridge collapse in the UK and elsewhere (Gavin et al., 2018; Prendergast et al., 2013). Bridges with shallow foundations are most at risk. Scour can cause significant delays and disruption: the Lamington Viaduct over the River Clyde was closed for over seven weeks in 2015-16 because of scour. In Ireland, in August 2009, a 20-metre section of the Malahide viaduct, which carried the main Dublin-Belfast rail line, collapsed due to the scour erosion of a single pier (Palin, 2021).

Earthworks are also at risk of failure because of heavy or prolonged precipitation, and from longer, drier summers. In 2020, heavy rain caused a landslip near Stonehaven, which was then hit by a passenger train, leading to loss of life (Climate Change Committee, 2021). The UK's third Climate Change Risk Assessment (2021) claimed that older, less well compacted assets such as those supporting the rail network are deteriorating at a faster rate than newer assets built to more modern standards. There were 67 earthwork failures a year across the rail network in England, Scotland and Wales between 2003 and 2014. The increased frequency of heavy rainfall combined with periods of dry weather will lead to greater fluctuations in soil moisture, which in turn causes cracking. This is expected to lead to an increase in earthwork failures on the rail network.

The primary effect of extreme heat on the rail network is because of track buckling. A buckle is any track misalignment serious enough to cause a derailment. Although railway track is pre-stressed to withstand a reasonable temperature range, extremes of temperatures can cause track to buckle due to the forces produced by the metal expanding. The August 2003 heatwave caused buckling across UK and Europe. In the

South-East region of the UK, 137 railway buckles were reported, compared to the long-term average of 30 (Doll, 2014). Buckling can lead to sections of track being closed, or to temporary speed restrictions being imposed (Palin, 2021).

High temperatures can also lead to point failures – the switching mechanisms used to move a train from one track to another fail due to excessive expansion. Conversely, low temperatures can clog the mechanism with snow and ice, and can cause cracks in rail tracks (Palin, 2021).

High winds can also cause disruption by blowing branches, trees and other debris onto lines. There are an estimated 2.5 million trees growing alongside the network. Of the 37,820 weather related incidents in England between 2006/07 and 2017/18, 31% were attributed to wind (Jaroszewski, 2021).

3.2.3 Adaptation for rail infrastructure

Under the Climate Change Act 2008, Network Rail are required to report every five years on how the railway is being prepared for the effects of climate change. Reports have been published in 2011, 2016 and 2021. In 2017, Network Rail published their Weather Resilience and Climate Change Adaptation Strategy (WRCCA), and each of the eight route areas that cover the network developed their own specific WRCCA plans in 2020. The extent of monitoring and planning for extreme weather and climate change on the railway is extensive. Network Rail have detailed strategies in place and methodologies for assessing risk. The 2021 UK Climate Change Risk Assessment concluded that Network Rail has “been proactive in implementing adaptation measures” but that “sustained action is still required”, with significant risks remaining particularly around flooding and heat, and around “single points of failure” such as bridges, earthworks, and subsidence.

Following the derailment at Stonehaven in 2020, Network Rail commissioned an independent Weather Advisory Task Force (WATF) to review Network Rail’s capability to manage adverse weather, with a focus on earthworks. The WATF made a range of recommendations, which focused on ways of improving monitoring, measuring and predicting earthwork failures (Network Rail, 2021c).

Network Rail have been exploring some more innovative approaches to ensuring resilience. For example, Lidar technology has been trialled to detect and monitor movements in earthwork slopes. This was found to be effective and allowed Network Rail to act before a landslip occurred (Marsland, 2021). In 2021, Network Rail published a review of earthwork management, which made several suggestions for using new technologies and approaches for monitoring earthworks in real time (Network Rail, 2021d).

A small number of more recent papers identified areas for improvement and development. Marsland (2021) argued that there needs to be better consideration of how different railway assets are interdependent and interact with one another. If one asset fails, this can cause disruption to others. But if one asset is upgraded, this can enhance the resilience of others. For example, Marsland discusses how improving drainage systems can reduce the likelihood of signal box and earthwork failures. Woodburn (2019) called for more consideration of diversionary routes as extreme weather becomes more frequent, and routes are more likely to be temporarily closed.

3.3 Aviation

3.3.1 Aviation infrastructure and governance

As of 2019, the Civil Aviation Authority (CAA) reported data on 52 airports, which were used by 296 million passengers in that year (CAA, 2019). Whilst the CAA is responsible for public safety at UK airports, the performance and resilience of airports is at the hands of operators themselves. From April 2014, Gatwick and Heathrow were required to publish operational resilience plans (Dawson et al., 2016a). Scotland has aviation infrastructure in remote and isolated communities which rely on air services. There are 13 airports which mainly serve the Scottish islands (Committee on Climate Change, 2019).

3.3.2 The impacts of climate change on aviation infrastructure

Most discussion in the literature of the effect of climate change on aviation focused on the effects that extreme weather can have on the operation of aeroplanes. There was relatively little discussion of the effect on infrastructure, such as runways, airports, monitoring and signalling systems, signage, buildings and access roads. Several papers mentioned that disruption to other transport modes (road and rail in particular) would have a knock-on impact on airports, since air travel is almost always part of a multimodal journey.

Perhaps more than any other major transport mode, aviation is highly reliant on computerised systems. Any extreme weather that has the potential to cause power disruptions is a significant threat. Doll et al. (2014) claimed that thunderstorms can create power failures, and that many airports lack backup systems for bridging long-lasting outages, although it should be noted that these airports may have since updated their power infrastructure.

Unlike for road and rail infrastructure, flooding was not cited as a major threat. However, Gatwick was subject to flooding in 2013, resulting in the failure of baggage reclaim facilities, check-in and flight information systems, telephone comms and screens. Flooding of the surrounding infrastructure such as the motorway and Gatwick train station also caused disruption (Dawson et al., 2016a).

Altvater et al. (2012) discussed the impact of extreme heat on airports. In addition to hastening the degradation of runways and runway foundations, extreme heat can reduce aircraft lift, and lead to a need for increased runway lengths.

3.3.3 Adaptation for aviation infrastructure

Given the limited discussion of aviation in the context of climate change adaptation, there was very little mention of aviation-specific adaptation measures. Potential options mentioned included:

- Building longer runways at airports which are at high-altitude or in places of high temperatures, due to the lower aircraft lift.
- Upgrading runway cooling systems.
- Installing or improving flood protections.
- Modifying the surface materials of runways to ensure they are better able to cope with extreme cases of temperature and precipitation (Altvater et al., 2012).

3.4 Maritime

3.4.1 Maritime infrastructure and governance

Maritime transport includes both coastal infrastructure – such as ports, harbours and marinas – and inland waterways. These are addressed in turn.

There are 52 major ports in the UK, defined as those that carry over 10 million tonnes of commercial cargo per year, and 110 active commercial ports in total. In 2014, 503.2 million tonnes of cargo passed through major ports. Ninety-five percent of the UK's imports and exports go through ports (Dawson et al., 2016a; Brooke, 2015). Goods of all kinds pass through UK ports, including critical fuels, industrial materials, and agriculture products. Other ports include ferry terminals, fishing harbours, and combine both commercial and recreational traffic. Ports are owned and operated by private companies, with five companies owning the majority of UK ports (Brooke, 2015). Port owners and operators are given rights and responsibilities as Statutory Harbour Authorities by the Marine Management Organisation. Although some marinas are located within harbour authority areas, governance and ownership arrangements are variable and depend on local circumstances (Brooke, 2015). Scotland, in particular, has port infrastructure in exposed coastal locations, and remote or isolated communities that rely on ferry services (Committee on Climate Change, 2019).

In general, "main rivers" are overseen in England by the Environment Agency, in Wales by Natural Resources Wales, in Scotland by the Scottish Environmental Protection Agency, and in Northern Ireland by the Rivers Agency. Main rivers are usually larger rivers or streams, and the respective agencies decide which waterways are given the designation. The agencies are responsible for maintenance, improvement and construction work on main rivers to manage flood risk. Canals in England and Wales are overseen by the Canal and Rivers Trust, whilst in Scotland they are the responsibility of Scottish Canals (Dawson et al., 2014). Other inland waterways are overseen by small organisations such as trusts and voluntary groups (Brook, 2015). The inland waterway network (IWN) has transitioned over time from commercial use to now being used heavily for leisure and recreation. Exceptions to this are the River Thames and the Manchester Ship Canal (Brooke, 2015).

Brooke (2015) claimed that infrastructure and equipment across maritime transport typically has a 20 to 100-year design life and will have considered potential sea-level rise in the design. However, some older sections of the maritime network will make use of older infrastructure which was not designed with climate change in mind.

3.4.2 The impacts of climate change on maritime infrastructure

The primary impacts discussed in the literature related to extreme highs and lows of water levels. For coastal infrastructure, this is primarily a consequence of sea-level rise, which is relatively predictable. Sea-level rise causes erosion and increases the risk of overtopping events and damage to defences. Brooke (2015) claimed that there is strong evidence for a link between sea level rise and an increased probability of extreme weather events in coastal regions. For rivers, estuaries, canals and other inland waterways, variation in water levels is a result of flooding, heavy precipitation or drought, and is less predictable.

There are several potential consequences from high water levels in rivers, estuaries and other inland waterways, including preventing ships from passing under bridges, and the uncontrolled opening of lock gates. There can also be consequences on other transport operators in flooding of road and rail access to port facilities. Low water levels caused by drought can reduce the amount of cargo ships can carry, and can lead to lower speeds, more fuel consumption, and congestion.

caused by drought can reduce the amount of cargo ships can carry, and can lead to lower speeds, more fuel consumption, and congestion.

Other extreme weather events with relevance to maritime infrastructure include storms, hurricanes, high wind speeds, and ice (Doll, 2014).

3.4.3 Adaptation for maritime infrastructure

Adaptation measures for coastal maritime infrastructure differ from adaptation measures for inland infrastructure. For coastal infrastructure, Becker (2018) identifies three main strategies: elevate, defend or retreat. Elevating a port would involve raising the port above the floodplain, rebuilding facilities at the new elevation, and designing systems to accommodate the difference in height between the water level and the new port infrastructure, including both port servicing and storage areas and access routes by road or rail. Defending a port involves construction of coastal protections, such as breakwaters, floodgates or locks. Retreating would be the option of last resort, because land adjacent to ports is typically not available: most ports for which neither elevation nor defence are possible would likely be abandoned, perhaps in favour of consolidation in a larger regional “super-port”. Following the UK Climate Change Act 2008, Port Authorities responsible for major ports were required to develop reports on the current and future impacts of climate change on their ports, and proposals for adaptation.

Inland waterways face different challenges. The governance arrangements for inland waterways are more complex, and authorities are often smaller, with correspondingly smaller budgets. They will often need to liaise with other authorities, including highway and rail authorities. Broome (2015) claimed that adaptation is significantly less advanced for inland waterways than for coastal infrastructure and recommended the development of a national “toolbox” of different adaptation measures that different local and regional authorities can draw on. In the short term, Brooke recommended that the priorities are around awareness raising, capacity building, data management, and user education.

3.5 Interactions between modes and sectors

Several papers in the review stressed the importance of taking a holistic or systems review of the transport network when thinking about adaptation (Climate Change Committee, 2021; Doll et al., 2014; Chapman, 2014; European Environment Agency, 2014; Bachner, 2017; Marteaux, 2016). Vulnerabilities on one part of the transport network can cause problems on another, and disruption to other infrastructure, such as IT and communications systems, can interact with transport disruption. The latest UK Climate Change Risk Assessment (2021) claimed that the vulnerability of interconnected systems may be significantly underestimated and provides a useful summary of current academic approaches to identifying and understanding interdependencies.

Modes are interconnected and interdependent in multiple ways. Disruption to one mode can displace transport users to other modes, which needs to be able to handle the increased capacity safely and efficiently. Extreme weather events can affect multiple modes at once: a failed bridge over a river can close a railway line and the river at the same time. Conversely, adaptation measures to protect one mode can also be beneficial to another: roads and railways lines often run alongside each other, meaning that improved drainage or earthworks can be mutually beneficial. There are also key points, such as airports, larger railway stations, and ports, which connect multiple transport modes, meaning that failure at these points can have wide ranging effects. Transport modes can also be dependent on each other for operation: in icy conditions, airports require de-icing substances, and if roads are also blocked then there can be difficulties acquiring these. Given the variety of authorities with responsibility for transport infrastructure, there is a clear need for effective communication and collaboration.

In addition to interactions between modes, the transport network often depends on other sectors of the economy that are affected by climate impacts. Most obviously, the rail network is largely dependent on the electricity sector, meaning that significant disruption to the electricity sector because of climate change could impact the rail network (Chapman, 2014). In 2019, a lightning strike triggered a series of power outages in England and Wales, leading to stranded trains, which in turn caused knock-on delays across the network (Jaroszewski, 2021). The flooding of a substation in Lancashire following rainfall associated with Storm Desmond in 2015 left the city with no power, meaning that there were no traffic lights, no lighting at the rail station, and issues with refuelling (Jaroszewski, 2021). Flooding of electricity substations have disrupted air travel, and heatwave impacts on IT and communications systems have caused freight and travel delays (Climate Change Committee, 2021).

4 The costs and benefits of adaptation

This chapter covers the costs and benefits of adapting transport infrastructure to deal with the effects of climate change. It begins with the benefits, of which there are two main kinds: the avoidance of costs associated with damage and disruption; and indirect benefits, such as increased employment. It then discusses the costs of adaptation works.

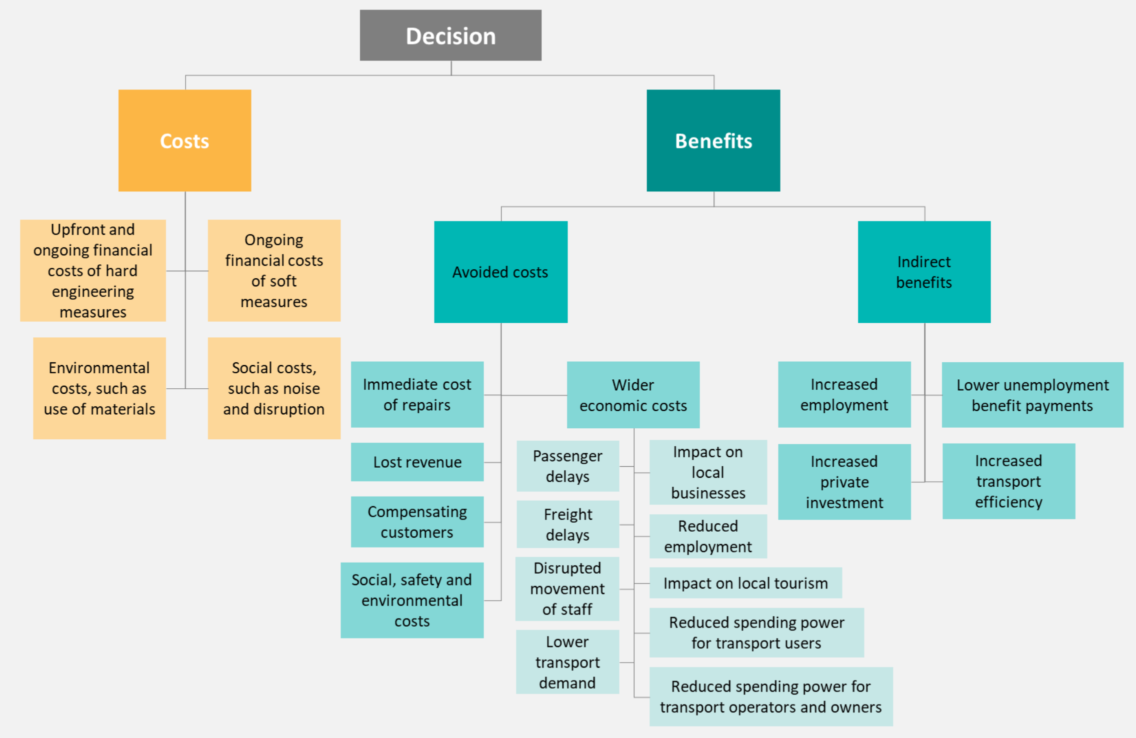


Figure 2: Categories of costs and benefits of adapting transport infrastructure to climate change.

In general, there was a consensus across the literature that the benefits of adaptation outweigh the costs. This was true despite some cost-benefit analyses finding that individual adaptation actions were not good value for money. In general, the costs are easier to quantify than the benefits, and the broader the view taken of the potential benefits of adaptation, the more clearly adaptation measures were found to have net benefits. No single study considered all, or even close to all, the full range of costs and benefits associated with adaptation measures.

4.1 The benefits of adaptation

This section discusses the benefits of adaptation measures. It begins by discussing avoided costs, including repairs, revenue, costs to customers, and wider economic costs. It then discusses indirect benefits, such as increased employment.

4.1.1 Avoiding the costs of damage and disruption

Immediate costs of repairs

Detailed breakdowns of the costs of repairs were limited in the literature included. Most studies provided headline figures, and it was typically unclear where these figures came from or how they were derived. Papers were often unclear about which geographies, time periods, climate change effects, and types of infrastructure they were referring to. Most figures related to flooding or heavy precipitation, with very few relating specifically to other types of climate change effects.

There were claims in the literature that the costs associated with emergency repairs were significantly higher than the costs of planned works, including resilience works. Nemry & Demirel (2012) reported that the costs associated with repairing damage to a bridge can be between two and ten times the actual cost of the bridge. The UK's 2017 Climate Change Risk Assessment similarly claimed that the cost of emergency repair on the railway is ten times greater than the cost of planned works.

Some studies provided general estimates of costs for whole countries, regions, or transport modes:

- Nemry & Demirel (2012) reported that, in Europe, weather stresses account for 30-50% of the current budget for road maintenance (between €8 and €13 billion). Extreme weather events account for 10% of this (€0.9 billion), most of which is a result of flooding and heavy precipitation.
- In the UK and Northern Ireland, United Nations (2020) reported that repair costs related to floods and heavy precipitation were estimated in 2010 at around £50 million per year, increasing to £500 million per year by the 2040s.
- Palin et al. (2021) provided estimated repair costs for railway flooding in Europe based on different global heating scenarios: the baseline cost (based on 1976-2005 data) of €581m per year would increase 255% under 1.5°C of global heating, 281% under 2°C, and 310% under 3°C.
- A study focussed on the road and rail sectors in Austria found annual costs of €39m and €16m respectively, and found that for roads, 67% of the damage was the result of flooding and heavy precipitation, 19% was due to snow and ice, 8% was due to storms, and 6% was due to heat (Bachner, 2017). These costs amounted to €300 per km in the road sector and €3300 per km in the rail sector. The authors estimated that these costs will double by 2050.

Other studies provided details of costs associated with specific damage events. These were almost all associated with flooding and heavy precipitation in the UK – Chapman (2014) cited the UK Climate Change Risk Assessment as identifying flooding as the risk incurring the most significant costs.

- Flooding in 2002 cost the UK road network around £73m (Chapman, 2014).
- Rainfall across the UK in July 2007 led to multiple motorways being closed (the M1, M4, M5, M18, M25, M40, M50, M54), and many local roads were also disrupted. The costs of repairs for all roads were estimated at £40-60m (Department for Transport, 2014).
- Total cost to return the English road network back to its prior condition following flooding in December 2009 and January 2010 was estimated at £3.7m, amounting to £5,700 per km of affected road (Doll et al., 2014).
- The winter floods of 2013-14 caused an estimated £1.8m in damage to ports (Becker et al., 2018).
- One paper reported that the 2003 heatwave in the UK cost the rail network £2.5m in repairs because of track buckling (Dawson et al., 2016a).

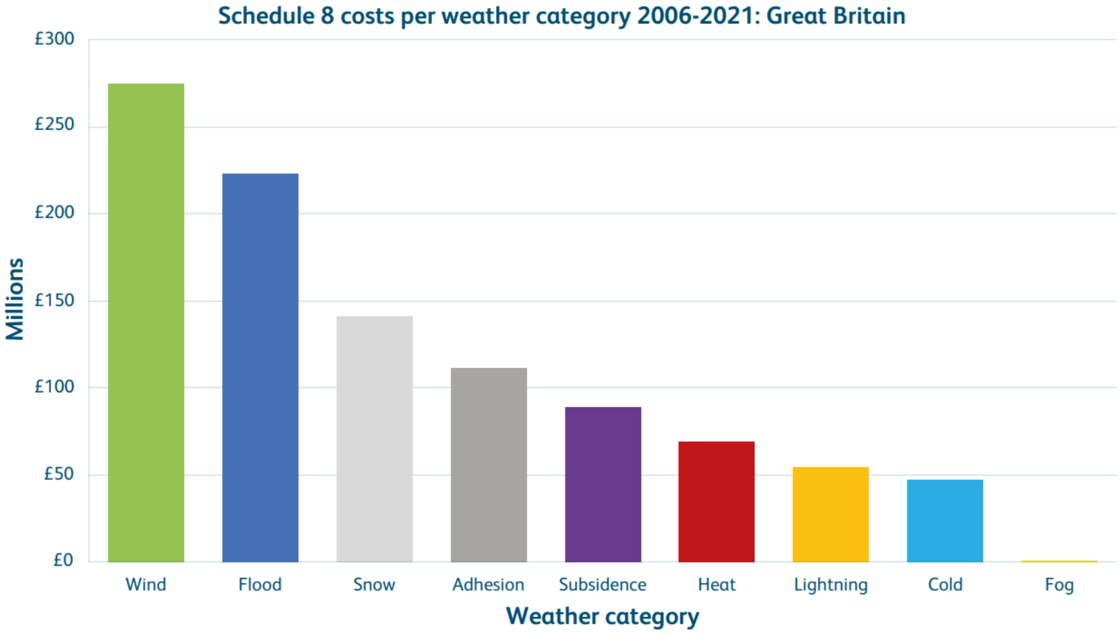
Lost revenue to transport operators and infrastructure owners

Information on the lost revenue to transport operators and infrastructure owners was limited in the included literature. Although it can be difficult to quantify – what would revenue have been in the absence of disruption? – it should at least be possible to compare revenue during disruption to revenue during typical operation. We are aware that some transport operators and infrastructure owners do hold this information, but it is not generally placed in the public domain. Examples from the literature fell into two categories: compensating customers for cancelled or delayed journeys, and disruption to freight transport.

Compensating operators and customers

Under the financial arrangements of the privatised railway in the UK, Network Rail must compensate train operators when the state of its infrastructure causes delays or cancellations to services. This includes weather-related delays and disruption. Extensive monitoring of network performance is used to support compensation payments, with detailed attribution of delays, including climate related factors (Network Rail, 2023a). These payments are in turn used by train operators to compensate passengers for inconvenience or provide alternative arrangements such as rail replacement buses (Dawson et al., 2016b). Network Rail have reported that between 2006/7 and 2020/21, weather related incidents caused over 322,000 delay events, around 26 million delay minutes, and over £1 billion in compensation payments. They note that not all incidents are correctly attributed to weather, and these figures are likely to be conservative, with the actual cost being much higher. The two biggest challenges are wind and flooding, costing £275 million and £223 million respectively, over the same period (Figure 3).

Figure 1: Cumulative Schedule 8 weather category costs 2006/07 to 2020/21 (Great Britain). Reproduced from Network Rail (2021b)



The National Audit Office estimates that each minute of delay on the UK rail network costs Network Rail around £70 (Ferranti et al., 2017). Based on this, Dawson et al. (2016b) estimated the costs associated with delays and cancellations due to disruption at Dawlish, as sea levels rise and increase the frequency of 'overtopping' events, in which the tracks are flooded and potentially damaged. These costs were estimated to rise from £270,000 per year between 1997 and 2009 to £1.1m per year by 2040. By comparison, passengers on the very busy Thameslink commuter network in the south east of England received £722,000 in compensation in 2012/13, and the operator (at the time, First Capital Connect) estimated that more than half of the delays that triggered compensation payments were the fault of Network Rail. There was no information in the included studies on the costs associated with compensating aviation and maritime passengers.

Disruption to freight transport

Damage and disruption can cause significant losses for the freight sector. Two examples were provided in the literature, both in Germany. Woodburn (2019) discussed the Rhine-Alpine rail freight corridor in Rastatt, which closed for 2 months in 2017 due to a tunnel collapsing. Only one third of scheduled trains ran during this time, at an estimated cost of €2 billion to the rail industry and wider supply chain. Jonkeren et al. (2014) reviewed multiple studies which showed that at extremely low water levels, the price per tonne for inland waterway transport in the river Rhine area will almost double. In 2003, a dry summer led to losses of up to €480m.

Costs to customers

Disruption can create costs for customers, including both financial costs and journey delays. There were no attempts in the included literature to explore the financial cost of delay and disruption to customers. Instead, all discussion of the impact of disruption on customers was focused on quantifying delays, and on road and rail disruption. It should be noted that there are established methodologies for pricing customer delays: for example, the QUADRO model (Queues and Delays at Roadworks) considers the value of road users' time, in addition to the increase in carbon emissions, and the cost of accidents (Milne et al., 2016).

Climate change effects can cause delays either by forcing service cancellations and closures, or by forcing vehicles to travel at reduced speed. This section first discusses delays for road users, followed by rail users, before discussing the importance of 'critical routes'.

Road

Flooding and heavy precipitation can cause roads to close – as already discussed. In more extreme cases, road users can become stranded: in the summer of 2007, around 10,000 motorways users were trapped on the M5 overnight due to heavy precipitation (Department for Transport, 2014). Even when not sufficient to cause road closures, precipitation can cause delays by reducing visibility, leading to cars slowing down (Chapman, 2014). There is evidence to suggest that most road users have experienced delays due to extreme weather. In a 2017 survey of Scottish road users, 67% of respondents said that at least one of their journeys had been affected by extreme weather over the last year, and almost half had experienced disruption due to heavy hail or rain. The survey findings also suggested room for improvement in providing early information and warnings to road users: 67% of respondents were satisfied with the accuracy of information and warning on likely conditions, 66% were satisfied with the availability of up-to-date information during extreme weather. Fewer were satisfied with measures to deal with disruptions (55%) and with the availability of diversions and alternative routes (50%).

Rail

Heavy precipitation and flooding can lead to earthwork failures, which in turn can lead to diversions, cancellations, or speed restrictions (Reeves et al., 2013). Woodburn (2019) estimated that the increased frequency of overtopping at Dawlish due to sea level rise could increase the number of days where the train service is disrupted by 1170% by 2100. Overtopping occurs when the height of sea defences is exceeded by a high sea level or waves.

European Environment Agency (2014) described in detail the delays caused by the short-duration heatwave in the UK from 30 June to 1 July 2015. Services were affected directly, because of asset failure or malfunction, and indirectly, by the need for emergency speed restrictions (ESRs) to reduce the likelihood of track buckling. Incidents caused by heat and lightning were recorded across the network, and knock-on delays affected rail travel in regions where extreme weather did not have any direct impact. There were 23,700 delay minutes due to the ESRs, 12,800 due to extreme heat and 4,000 due to lightning incidents. All regions experienced more than twice the daily average delay-minutes on one or both days.

Critical routes

Disruption on certain routes can have a much bigger impact on customer delays than disruption on others. During the 2015 short-duration heatwave, the majority of ESRs had a duration of just one day, but some had a far greater number of delay-minutes because they occurred along more critical sections of track, and therefore impacted a far greater number of trains and passengers. A lightning incident at Northallerton during the heatwave lasted only four minutes, but because it occurred on the London North Eastern mainline, which is a critical transport route, it impacted a total of 89 trains travelling between stations including London King's Cross, Glasgow, Manchester, Liverpool and Newcastle (Ferranti et al, 2018). Similarly, for road infrastructure, the failure of key links such as bridges can increase travel time significantly as network users are forced to re-route. Due to the failure of the Workington Bridge in 2009 during the Cumbria floods, residents had to take journeys of up to two hours for a trip that would usually take 15 minutes (Dawson et al., 2016a). Based on the modelling of the effect of a 1-in-200-year flood event in Newcastle, Dawson et al. (2016a) found that multiple route options would be simultaneously blocked, forcing travellers to take significant detours.

Wider economic costs

It is inherently difficult to quantify the wider economic costs of disruption to the transport network as a result of climate change. There are a wide range of potential costs to consider, which may or may not occur. An initial (but not exhaustive) list of factors is as follows:

- Disruption to the movement of goods, including materials for manufacturing and agriculture.
- Disruption to the movement of staff in both accessing their workplace and for any journeys while working.
- The knock-on effects of costs incurred by transport users, reducing their future spending power.
- The knock-on effects of costs incurred by transport operators and infrastructure owners, such as reductions in future investment in improvements.
- The effect of significant disruption on the future confidence in, and ongoing viability of, local businesses.
- The impact on tourist and other service economy businesses, and the longer-term effect on the reluctance of visitors to travel to and within affected areas (which may be a function of the degree of publicity disruption is given).
- The effect on employment levels (either directly because of reduced access to employment, or indirectly because of effects on employers in reducing access to their potential workforce), and the effect of reduced employment on the local economy and the extent of state benefit payments.
- The potential for feedback loops, in which reduced economic activity leads to reduced demand for transport services.

There are instances in which estimates of the wider economic cost have been made in haste, with unclear methodologies, and widely publicised. For example, following the 2014 incident at Dawlish, when a section of rail track collapsed into the sea, estimates appeared very quickly of the cost to the local economy. Dawson et al. (2016b) describes how Plymouth City Council estimated the daily impact on the city's economy in lost trade, tourism and potential investment to be up to £4-5m, with no credible methodology. The figure was later revised down to £600,000 per day.

Three papers in the included literature made a serious attempt to quantify the wider economic costs of disruption caused by climate change. Two of these (written by the same author) focussed on Austria (Bachner, 2017; and Bachner et al., 2019), and one focussed on Scotland (Milne et al., 2016). These are discussed in turn.

Bachner (2017)
This paper involved a macroeconomic assessment of climate change impacts in the road and rail sector in Austria, in addition to an assessment of possible adaptation measures. Austria has experienced relatively strong average temperature increases and severe flood events in recent decades. Up to 2050, Austria expects further warming and an intensification of heavy precipitation events, which is true of many other regions including the UK.

The modelling approach was based on a social accounting matrix (SAM). This is similar to an input-output table, which depicts the entire economy as monetary flows between agents (producers and consumers) on a yearly basis. An agent’s payments and income are shown as corresponding columns and rows, meaning that each cell of the matrix shows a transaction between two agents. The SAM was used to simulate the effects of extreme weather events in multiple ways:

- Damage to infrastructure was modelled as higher average annual depreciation in infrastructure-providing sectors, meaning higher capital demand, with various knock-on effects.
- Changes were made to the operating costs of different economic sectors.
- Changes were made to household consumption patterns.
- Time losses to private households were modelled, as were the costs of accidents.

The paper found that when the wider macroeconomic effects were included in the model, the total costs of climate change impacts were more than twice (a factor 2.2) as large as the direct costs of repairs only. This means that the wider macroeconomic costs were even larger than the direct cost of repairs.

The paper also modelled the extent to which these costs could be reduced by a range of adaptation measures. These included enlargements of drainage system capacities (to deal with flooding), vegetation management (to enhance water runoff and reduce flood damage), improving early warning systems, and increasing the frequency of road surface inspections. Key assumptions were made about the damage reduction potential of these measures. Specific estimates of costs and benefits were highly dependent on these assumptions. Despite this, the key finding of the paper was that these parameters would have to be set very low for the net macroeconomic effect of the adaptation measures to turn negative. In other words, because of the very significant wider macroeconomic costs of disruption to the transport network due to climate change, even modest improvements in resilience should have a net benefit.

Bachner et al. (2019)
This paper attempted to model the effect of climate change on GDP in Austria. It took a broader view than the 2017 paper, focussing not just on transport but on three main ‘impact fields’ with high budgetary importance: agriculture, forestry, and ‘catastrophe management’, which includes damage to public infrastructure, including buildings and transport infrastructure. The model assumed a range of changes to the composition and level of government expenditure as a result of climate change. These assumptions were largely based on existing macroeconomic models, rather than direct evidence:

- Reconstruction and relief payments increase due to higher damages.

- Due to negative effects on economic activity, there is a loss in tax revenues, reducing the means for expenditure and increasing the need for unemployment benefits.
- To ensure no increase of the public deficit as a result of the reduced available budget, government spending shifts towards disaster relief payments and away from other consumption.

The paper estimated that by 2050, the climate change-induced annual GDP losses will be -0.15% relative to the baseline. The authors did provide a breakdown of these losses by 'impact field'. However, information for transport infrastructure was not provided separately, but was included within a bigger group that additionally included water supply and sanitation, manufacturing and trade, cities and urban green spaces. Collectively, the impact of climate change on these sectors was modelled as leading to a -0.02% change in GDP by 2050. For context, the World Bank estimates that in 2020 the GDP of Austria was US$433 billion, meaning that a -0.02% change would equate to a loss of US$87m (World Bank, 2023).

It should be noted that this paper took a very high-level approach to estimating the impacts of climate change and did not consider any of the detailed mechanisms listed above by which transport disruption can have wider macroeconomic effects.

Milne et al. (2016)
This report aimed to assess the economic costs of a potential flood on a section of the A78, which runs along the west coast of Scotland between Skelmorlie and Largs and has frequently experienced flooding in the past and with very long diversionary routes. The authors cited previous research on road closures because of landslides, which suggested that the primary impacts of such events, in the absence of serious injuries and fatalities, are economic and social. These events can force road users to make extensive detours and can sever access to and from relatively remote communities for goods, services, employment, healthcare, education, and social activities. The authors noted that tourism makes a major contribution to the Scottish economy, meaning that the economic impacts of these events can be particularly severe in the summer, although floods and landslides are more common in the winter.

The authors distinguished between *direct* and *indirect* 'consequential economic impacts'. Direct impacts include the cost of journey delays, additional carbon costs and the cost of accidents. Indirect impacts include other factors listed at the start of this section, such as the effect on tourism, employment levels, and the viability of local businesses. The authors make no attempt to estimate the indirect impacts, due to the difficulty of doing so.

The study used information on a flooding event from January 2014 to model the direct economic impacts. The study uses the QUADRO model and considers the price of road users' time (to estimate the cost of delays), the change in carbon emissions because of re-routed traffic, and the cost of accidents (including property damage, police time, and insurance administration). Based on this, the total cost for the closure of the A78 was estimated at £135,000 (at 2012 prices). The majority of this was due to road user delay.

The authors compared these costs to estimates for five landslide events across Scotland, which ranged from £175,000 to £3.2m. Comparing these events, the authors note that costs are much higher on busier routes, due to the higher numbers of road users who are delayed, even when the duration of disruption is short. However, in more rural areas, where alternative routes are more likely to be limited, the authors note that impacts are borne by a much smaller number of people over an extended period, and the impacts on individuals and individual businesses are likely to be considerably greater.

Social and environmental costs

There was very little discussion in the literature of the wider social costs, such as effects on health and wellbeing and access to employment, as a result of damage and disruption to transport infrastructure. One study mentioned that between 1997 and 2002, earthwork failures on the railway had led to 10 cases of derailment, injuring 19 people, but it is not clear whether any of these were related to climate change (Reeves et al., 2013).

Similarly, there was very little discussion of environmental impacts. Disruption can lead to displacement to more carbon intensive modes, such as rail disruption leading to more car use (Woodburn, 2019), and heavy precipitation can reduce active travel (Chapman, 2014). Disruption can also lead to congestion, which can worsen air quality (Pregnolato et al., 2017). Earthwork failures can lead to soil erosion and damage to vegetation and habitats (Reeves et al., 2013).

4.1.2 Indirect benefits

There are a number of potential indirect benefits of adapting transport infrastructure to better deal with climate change. For example, modernising information and communication systems to improve preparedness and provide advance warning could, in addition, improve the reliability of services (Doll et al., 2014). Making infrastructure more resilient could also lead to competitive advantages: for example, shippers may be more comfortable investing in a 'climate-ready' port (Becker et al., 2018). However, examples of these effects actually occurring were not provided in the literature.

The two Bachner papers discussed above attempted to explicitly model the positive effects that adaptation measures can have on employment rates and levels of welfare spending. Bachner (2017) looked at a set of adaptation measures that are particularly labour intensive, on an ongoing basis, such as additional vegetation management alongside roads and rail tracks, and increased inspection of road surfaces. The paper modelled the wider macroeconomic effects of these measures and others. In the model, these so-called 'soft' adaptation measures reduced unemployment in Austria by 0.04 percentage points, leading to more consumption and higher tax revenues. The study found that these measures made a net positive contribution to GDP, and that the effect on employment played a significant role in this.

Similarly, Bachner et al. (2019) considers the increases in employment as a result of labour-intensive adaptation measures. The authors argue that higher employment leads to higher tax revenues and lower unemployment benefit payments. As discussed above, the authors consider a range of adaptation measures, and find that these have a net macroeconomic benefit. The extent of this benefit varies significantly with key assumptions around the effectiveness of different adaptation measures at reducing disruption. However, the authors conclude that "the direction of our results is highly robust with regard to different assumptions on the effectiveness of adaptation measures" (p.1337). In part, this is because the positive effects on employment and welfare spending are largely independent of the actual effectiveness of the adaptation measures. The authors conclude that the findings should be reasonably transferable to countries with (i) similar budgetary structures as well as (ii) similar patterns of climate change impacts.

4.2 The costs of adaptation

So far, this chapter has focussed on the benefits of adaptation. However, adaptation measures also come with costs. These costs are primarily financial, since many adaptation measures involve significant infrastructural works. There may be other – environmental and social – costs: environmental costs could include the use of carbon intensive building materials, and social costs could include the noise and disruption generated by building works. No studies explored these potential costs.

Future planning of transport infrastructure will need to involve an assessment of whether the costs of adaptation are higher or lower than the avoided costs of disruption and the indirect benefits of adaptation. In other words, there will be a need for robust cost-benefit analysis. There are multiple serious challenges to overcome in attempting these cost-benefit analyses, which are discussed in Chapter 5. A central challenge is uncertainty about future climate change projections: all climate projections have a degree of uncertainty, and the degree of uncertainty is higher at the smaller geographies necessary for transport infrastructure planning (Dawson et al., 2018). Some approaches to cost-benefit analysis make explicit attempts to account for this uncertainty. For example, Dawson et al. (2018) used an approach called 'Real Options Analysis' to understand the relative benefits of investing immediately in adaption measures to the rail track at Dawlish, as opposed to waiting for more precise climate projections to be developed. The study found that estimates of cost-benefit ratios change significantly based on different estimates of the degree of uncertainty over sea-level rise. It should be noted that traditional cost-benefit analysis has ways of accounting for uncertainty, including sensitivity testing. DfT's own Transport Analysis Guidance includes a dedicated Uncertainty Toolkit (Department for Transport, 2023).

Many of the studies included in the review provided some basic mention of the cost of a particular adaptation measure for a particular piece of infrastructure. There is limited value in enumerating these here, since they cover widely different measures, in different contexts, with different aims. Instead, we focus on three studies that provided estimates for a range of adaptation measures, or explicitly compared the cost effectiveness of different measures.

Altvater et al. (2012)
This extensive study aimed to determine the primary climate risks in Europe across four sectors: energy, transport infrastructure, urban areas and agriculture. Different techniques and assumptions were used to generate cost estimates for a small set of adaptation measures, across multiple European countries. The UK figures were as follows:

- The cost of adapting road drainage systems for increased drainage capacity was estimated at €29m for a 100% increase in capacity, €15m for a 50% increase, and €6m for a 20% increase.
- The cost of adapting drainage systems at airport runways for increased capacity was estimated at €36m for a 100% increase in capacity, €18m for a 50% increase, and €7m for a 20% increase.
- Additional costs for updating UK roads to use a type of asphalt that is better able to deal with increased temperatures were estimated at between €254m and €763m, per year. This assumes a 10-year update cycle on motorways and a 15-year cycle on other roads.
- Additional costs for updating UK airport runways to use a type of asphalt that is better able to deal with increased temperatures were estimated at between €22m and €65m per year, assuming a 10-year update cycle.

Wang et al. 2019
This study explored the costs and benefits of adaptation measures for UK roads. It involved a survey of 19 road experts, with a wide range of participants including CEOs, transport directors, transport planners, transport engineers, environmental managers, private operators, transport authorities, highway agencies, NGOs and academics.

Participants were asked to assess the likelihood of a given climate risk occurring, the timeframe in which it would be expected to occur, the severity of the consequences, and the current level of resilience. They were asked to make these assessments both with and without a set of adaptation measures in place. They were also asked to evaluate the cost of each adaptation measure. Participants' assessments were qualitative rather than quantitative: that is, they graded risks as 'high cost'/'high impact' or 'low cost'/'low impact', rather than estimating precise quantities. Based on this dataset, the authors ranked 21 adaptation measures by cost effectiveness. The top five were as follows:

Ranking	Environmental driver	Potential climate threat on UK roads	Adaptation measure
1	Intense rainfall / flooding	Rainfall events can cause rivers/watercourses to flood which damages bridges, culverts waterways and clearance, and scouring can ruin the foundation of bridges and culverts	Strengthen the foundation of bridges, river and bank protection, and corrosion protection
2	Intense rainfall / flooding	The road drainage cannot efficiently remove water due to heavy rains, which results in poor or dangerous driving conditions	Consider revised standards for drainage sewers (not the actual drain itself)
3	Intense rainfall / flooding	Rainfall events result in landslides and mudslides in hilling roads, and cause roadblocks	Consider slope and drain performance in landslide scenarios
4	Temperature increase	Traffic jams/alternative routing/accidents, increasing fuel consumption and CO_2 emissions, delivery delays and consequential costs	Provision of timely driver information to 'at risk' routes. Map the highway network and infrastructure asset base and identify at-risk locations/structures where there are issues as measured under different scenarios.

Dawson et al. (2018)
This paper examined the three potential adaptation options for the London-Penzance railway line in Devon, which connects South Devon and Cornwall to the rest of the country. The coastal section of this line between Dawlish and Teignmouth stretches 4.2 miles and is protected by extensive coastal defences. The line was closed for two months in 2014 when a stretch of track was destroyed in a coastal storm. The authors' primary aim was to understand how estimates of the cost effectiveness of adaptation measures vary with estimates of the degree of uncertainty over sea level rise.

The paper examined three potential adaptation options that were outlined by Network Rail in 2014:

- The **Baseline** option involved simply maintaining the current defences and repairing the line when events occur.
- The **Adaptation One** option involved maintaining and comprehensively reinforcing the existing route through a series of interventions including rock armour, heightening and reinforcement of critical structures. The total cost of this option was estimated at £528m.
- The **Adaptation Two** option involved building a new inland route, at a cost of £2.2bn.

The study finds that neither of the adaptation options have a net positive cost-benefit ratio, under any estimates of the degree of uncertainty over sea level rise. However, it should be noted that the authors take a narrow view of the 'benefit' side of the equation.

The original Network Rail assessment of the options also found that none of the assessed options were cost effective. The Network Rail Assessment used DfT’s standard Transport Analysis Guidance (TAG) to estimate the economic value of journey time savings and included the benefits to non-rail users through modal shift from car to rail e.g., road decongestion and environmental benefits (Network Rail, 2014). One option considered in the Network Rail assessment – “Further strengthening the existing railway” – was not assessed at the time, but a follow-up study did find a version of this to be cost effective, involving rock armour, heightening and reinforcing of critical structures, a rock galley and works on the cliffs behind the railway (Network Rail 2023b).

5 Evidence gaps and methodological challenges

This chapter provides a summary of the key evidence gaps that emerged during the review. Gaps were identified in two ways: by identifying topics for which little or no evidence was found during the literature search, and by recording what was said by studies included in the review about evidence gaps. Although the literature search conducted for this review was extensive, it should not be assumed that all the relevant literature was located. It is therefore possible that some of the evidence gaps listed in this chapter are, at least in part, filled by existing evidence. Given that this review only includes evidence from 2011 onwards, and evidence relating to certain countries, there may be older evidence or evidence relating to other countries that is relevant to the evidence gaps identified here.

In addition to identifying evidence gaps, this chapter also comments on some of the key methodological challenges that were discussed in the literature. The evidence gaps and methodological challenges identified fell into three broad categories: the uncertainty in climate change projections, and the difficulty of predicting the frequency of extreme weather events at smaller geographies; understanding in detail the effects of climate change on transport infrastructure, and in particular how inter-modal and inter-sectoral connections will be affected; and lastly, understanding the wider economic implications of damage and disruption, and integrating this into cost-benefit analyses. These are addressed in turn.

Climate change projections

Many of the included studies stressed the need for better projections of the future frequency of extreme weather events (Marteaux, 2016; Dora, 2015; Nemry & Demirel, 2012; European Environment Agency, 2014; Jonkeren et al.,2014). Most climate models operate at relatively large geographies, such as countries or regions. But transport infrastructure exists and operates at smaller geographies, and multiple studies discussed the need for models that predict the effects of climate change at these geographical levels (Dawson et al., 2018; Dora, 2015; Brooke, 2015; Becker et al., 2018).

Despite this, it should be noted that there has been and continues to be detailed work being undertaken by UK authorities, such as Network Rail and National Highways. Network Rail, for example, produce separate “Weather Resilience and Climate Change Adaptation” (WRCCA) plans for each of their eight routes – that is, at relatively small geographies. These make use of data from UK Climate Projections, from the Met Office, which projects climate change effects to 2080. Additionally, there have been some detailed business case assessments at small geographies that have considered climate change, such as the South West Rail Resilience Programme (Network Rail, 2023b). National Highways have standards for the development and design of local roads, which includes a methodology for conducting environmental assessments (National Highways, 2021).

Some studies claimed that some climate change effects are better understood than others. Dora (2015) claimed that there is a high level of agreement in predictions for rainfall and temperature change, a medium level of agreement for lightning and humidity, and a low level of agreement for wind speed and direction. Looking at coastal infrastructure, Brooke (2015) claimed that confidence in projections of sea level rise is relatively high (although Dawson et al. (2018) claimed otherwise), but that confidence in projections for wind, waves, storm surges and fog is low.

A level of uncertainty in climate change projections is inevitable, and several studies highlighted the need for approaches to risk assessment and cost-benefit analysis that were sensitive to this uncertainty. Both Wang et al. (2019) and Dawson et al. (2018) discussed the need to understand how this uncertainty is likely to change over time, and how this should inform decision making. Wang et al. (2019) used a 'Fuzzy Bayesian Reasoning' approach, which builds uncertainty into the decision-making process. Dawson et al. (2018) used 'Real Options Analysis', which allows decision makers to consider the merits and risks associated with delaying decision-making until uncertainty levels have reduced. As a case study, the authors applied this approach to options for adapting the train line through Dawlish, and claimed to show that Real Options Analysis is not as complex and labour intensive as assumed. European Environment Agency (2014) discussed the value of so-called 'low-regret' measures – that is, measures that have net benefits regardless of whether the projected negative impacts of climate change materialise.

The impacts of climate change on transport infrastructure

The literature search uncovered more research on road and rail infrastructure than on aviation and maritime infrastructure, and Jonkeren et al. (2014) also noted this difference. Evidence on the effects of climate change for inland waterways was particularly limited. There was also more evidence on some types of climate change effect than others: much of the evidence related to flooding and heavy precipitation. Marteaux (2016) noted that there is very little evidence on the effect of high winds on transport infrastructure. Milne et al. (2016) highlighted that there is no formal system for recording the impacts on transport infrastructure of extreme weather events, and no single database of past events, which can make it difficult to create robust models and projections.

Some papers noted a lack of evidence on the role of inter-modal vulnerabilities – how extreme weather might affect multiple modes simultaneously, or how damage and disruption to one mode might affect another (Palin et al., 2021; Department for Transport, 2014). There is also a need to understand the relationship between transport infrastructure and other types of infrastructure (Chapman, 2014): damage to buildings could lead to damage to transport infrastructure, for example. The Department for Transport (2014) stressed the importance of identifying 'single points of failure' that link together multiple parts of the transport network.

The wider economic impacts of damage and disruption

As discussed in Section 4.1.1, there are a wide range of factors to consider when thinking about the wider economic impacts of damage and disruption to transport infrastructure as a result of climate change. Only a small number of studies even attempted to estimate the wider economic impacts. Those that did so, tended to take a relatively narrow view of what should be included: for example, some papers simply used estimates of the cost of each delay-minute to customers (and two papers raised doubts about the quality of these estimates – Dawson et al., 2016b; and Chapman, 2014). No studies in the included literature took a broad view of the wider economic impacts and attempted to quantify these. Bachner (2017) was the most extensive attempt in the included literature, but aimed to generate estimates for both road and rail for the whole of Austria, rather than exploring in-depth the economic impacts of any particular damage or disruption. Multiple studies stressed the need for better evidence on the wider economic impacts of damage and disruption, and the wider economic benefits of adaptation (Marteaux, 2016; Bachner et al., 2019; Department for Transport, 2014).

Given the wide range of factors that would need to be considered, estimating wider economic impacts is highly challenging. Bachner (2017) argued that the primary tool for evaluating the macroeconomic costs of climate change has traditionally been Integrated Assessment Models (IAMs), which can capture the interaction between the economic and the climate system. However, the author argues that these models work on a highly aggregated level with only few sectors, or with no sectoral differentiation at all. The approach taken in this study was to use a Computable General Equilibrium model, which explicitly differentiates between multiple economic sectors, and captures the linkages between them. They are therefore able to simulate the ways in which ‘shocks’ can affect the wider economic system.

References

Altvater, et al. (2012) *Adaptation Measures in the EU: Policies, Costs, and Economic Assessment: “Climate Proofing” of key EU policies.* Available at: https://www.ecologic.eu/sites/default/files/publication/2021/altvater-12-climate-proofing-report-web.pdf (Accessed: 8th March 2022).

Bachner, G. (2017) ‘Assessing the economy-wide effects of climate change adaptation options of land transport systems in Austria’, *Regional Environmental Change*, 17 [online]. Available at: doi.org/10.1007/s10113-016-1089-x (Accessed: 2nd February 2022)

Bachner, et al. (2019) ‘How does climate change adaptation affect public budgets? Development of an assessment framework and a demonstration for Austria’, *Mitigation and Adaptation Strategies for Global Change*, 24 [online]. Available at: doi.org/10.1007/s11027-019-9842-3 (Accessed: 1st February 2022)

Becker, et al. (2018) ‘Implications of climate change for shipping: Ports and supply chains’, *WIREs Climate Change*, 9(2) e508 [online]. Available at: doi.org/10.1002/wcc.508 (Accessed: 2nd February 2022)

Bowyer, et al. (2020) *Climate Change Impacts and Adaptation for Transport Networks and Nodes*. Available at: https://unece.org/sites/default/files/2021-01/ECE-TRANS-283e_web.pdf (Accessed: 8th March 2022).

Brooke, J. (2015) *A Climate Change Report Card for Infrastructure, Working Technical Paper. Transport: Inland Waterways, Ports and Marine Infrastructure*. Available at: https://www.ukri.org/wp-content/uploads/2021/12/091221-NERC-LWEC-InfrastructureReport-TransportWaterways.pdf (Accessed: 8th March 2022).

CAA (2019) *Size of Reporting Airports 2019*. Available at: https://www.caa.co.uk/Documents/Download/3951/e925ed1f-e4b5-4d12-ad1c-e95e0b5b3307/1321

Chapman, L. (2014) *A Climate Change Report Card for Infrastructure, Working Technical Paper. Transport: Road transport (inc. cycling and walking)*. Available at: https://www.ukri.org/wp-content/uploads/2021/12/091221-NERC-LWEC-InfrastructureReport-TransportRoad.pdf (Accessed: 8th March 2022).

Climate Change Committee (2021) *Findings from the third UK Climate Change Risk Assessment (CCRA3) Evidence Report 2021: Transport Briefing.* Available at: https://www.ukclimaterisk.org/wp-content/uploads/2021/06/CCRA3-Briefing-Transport.pdf

Committee on Climate Change (2019) *Final Assessment: The first Scottish Climate Change Adaptation Assessment*. Available at: https://www.theccc.org.uk/wp-content/uploads/2019/03/Final-Assessment-of-the-first-SCCAP-CCC-2019.pdf (Accessed: 8th March 2022).

Dawson, et al. (2016a) *UK Climate Change Risk Assessment 2017: Evidence Report (Chapter 4: Infrastructure)*. Available at: https://www.theccc.org.uk/wp-content/uploads/2016/07/UK-CCRA-2017-Chapter-4-Infrastructure.pdf (Accessed: 8th March 2022).

Dawson, et al. (2016b) ‘Sea-level rise impacts on transport infrastructure: The notorious case of the coastal railway line at Dawlish, England’, *Journal of Transport Geography*, 51 [online]. Available at: doi.org/10.1016/j.jtrangeo.2015.11.009 (Accessed: 3rd February 2022)

Dawson, et al. (2018) ‘The Economic Value of Climate Information in Adaptation Decisions: Learning in the Sea-Level Rise and Coastal Infrastructure Context’, *Ecological Economics*, 150 [online]. Available at: doi.org/10.1016/j.ecolecon.2018.03.027 (Accessed: 3rd February 2022)

Department for Transport (2014) *Transport Resilience Review: A review of the resilience of the transport network to extreme weather events* (Cm 8874). Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/335115/transport-resilience-review-web.pdf (Accessed: 2nd February 2022).

Department for Transport (2023) TAG uncertainty toolkit. Available at: https://www.gov.uk/government/publications/tag-uncertainty-toolkit

Doll, et al. (2014) 'Large and small numbers: options for quantifying the costs of extremes on transport now and in 40 years', *Natural Hazards*, 72 [online]. Available at: doi.org/10.1007/s11069-013-0821-9 (Accessed: 3rd February 2022)

Dora, J. (2015) *A Climate Change Report Card for Infrastructure, Working Technical Paper. Transport: Rail*. Available at: https://www.ukri.org/wp-content/uploads/2021/12/091221-NERC-LWEC-InfrastructureReport-TransportRail.pdf (Accessed: 8th March 2022).

European Environment Agency (2014) *Adaptation of transport to climate change in Europe: Challenges and options across transport modes and stakeholders*. No. 8 2014. Available at: https://www.eea.europa.eu/publications/adaptation-of-transport-to-climate (Accessed: 11th February 2022).

Ferranti, et al. (2018) 'The hottest July day on the railway network: insights and thoughts for the future', *Meteorological Applications*, 25(2) [online]. Available at: doi.org/10.1002/met.1681 (Accessed: 3rd February 2022)

Filosa, G. and Oster, A. (2015) *International Practices on Climate Adaptation in Transportation: Findings from a Virtual Review*. Available at: https://rosap.ntl.bts.gov/view/dot/12152 (Accessed: 4th March 2022).

Hackl, J. and Adey, B.T. (2019) 'The effect of restoration on the resilience of transportation infrastructure', *13th International Conference on Applications of Statistics and Probability in Civil Engineering, ICASP13*. Seoul, South Korea, May 26-30, pp.1-8. Available at: https://s-space.snu.ac.kr/bitstream/10371/153257/1/24.pdf (Accessed: 9th February 2022)

Highways England (2016) *Highways England: Climate Adaptation Risk Assessment Progress Update*. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/596812/climate-adrep-highways-england.pdf (Accessed: 9th February 2022).

IPCC (2022) Climate Change 2022: *Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* Available at: https://report.ipcc.ch/ar6/wg2/IPCC_AR6_WGII_FullReport.pdf

Jaroszewski, D., Wood, R., and Chapman, L. (2021) Infrastructure. In: *The Third UK Climate Change Risk Assessment Technical Report.* [Betts, R.A., Haward, A.B., Pearson, K.V. (eds)] Prepared for the Climate Change Committee, London

Jonkeren, et al. (2014) 'Climate change and economic consequences for inland waterway transport in Europe', *Regional Environmental Change*, 14 [online]. Available at: doi.org/10.1007/s10113-013-0441-7 (Accessed: 3rd February 2022)

Marsland, et al. (2021) 'Regulating the effects of climate change on weather resilience: a spectrum of practice', *Proceedings of the Institution of Civil Engineers – Engineering Sustainability,* [online]. Available at: doi.org/10.1680/jensu.21.00007 (Accessed: 3rd February 2022)

Marteaux (2016) *Tomorrow's Railway and Climate Change Adaptation: Final Report*. Available at: https://www.yumpu.com/da/document/read/55618641/tomorrows-railway-and-climate-change-adaptation-final-report (Accessed: 15th February 2022).

Milne, et al. (2016) *Assessing the Risks to Infrastructure from Coastal Storms in a Changing Climate*. PPR800. Available at: https://trl.co.uk/uploads/trl/documents/PPR800%20-%20Assessing%20the%20Risks%20to%20Infrastructure%20from%20Coastal%20Storms%20in%20a%20Changing%20Climate_.pdf (Accessed: 8th March 2022).

National Archives, *Rapid Evidence Assessment Toolkit Index.* Available at https://webarchive.nationalarchives.gov.uk/ukgwa/20140402164155/http:/www.civilservice.gov.uk/networks/gsr/resources-and-guidance/rapid-evidence-assessment

National Highways (2021) *Preparing for climate change on the strategic road network – third adaptation report under the Climate Change Act.* Accessed at: https://nationalhighways.co.uk/media/z1ndodqx/preparing-for-climate-change-on-the-strategic-road-network.pdf

Nemry, F. and Demirel, H. (2012) *Impacts of Climate Change on transport: A focus on road and rail transport infrastructures*. Available at: https://op.europa.eu/en/publication-detail/-/publication/18b356c6-0d64-4bd1-8302-f8a128ca9416/language-en (Accessed: 8th March 2022).

Network Rail (2014) *West of Exeter Route Resilience Study*. Available at: https://www.networkrail.co.uk/wp-content/uploads/2019/05/West-of-Exeter-Route-Resilience-Study-1.pdf

Network Rail (2017) *Weather Resilience and Climate Change Adaptation Strategy 2017-2019*. Available at: https://safety.networkrail.co.uk/wp-content/uploads/2017/02/NR-WRCCA-Strategy-2017-2019.pdf (Accessed: 8th March 2022).

Network Rail (2019) Scour prevention and management. Available at: https://www.networkrail.co.uk/wp-content/uploads/2019/06/Challenge-Statement-Bridges-Scour-prevention-and-management.pdf

Network Rail (2021a) *Annual Report and Accounts 2021*. Available at: https://www.networkrail.co.uk/wp-content/uploads/2021/07/Annual-report-and-accounts-2021-Strategic-Report.pdf

Network Rail (2021b) *Network Rail Third Adaptation Report*. Available at: https://www.networkrail.co.uk/wp-content/uploads/2022/01/Network-Rail-Third-Adaptation-Report-December-2021.pdf

Network Rail (2021c) *Weather Advisory Task Force*. Available at: https://www.networkrail.co.uk/wp-content/uploads/2021/03/Network-Rail-Weather-Advisory-Task-Force-Final-Report.pdf

Network Rail (2021d) *A Review of Earthworks Management*. Available at: https://www.networkrail.co.uk/wp-content/uploads/2021/03/Network-Rail-Earthworks-Review-Final-Report.pdf

Network Rail (2023a) *Public performance measure and delay responsibility*. Available at: https://www.networkrail.co.uk/who-we-are/how-we-work/performance/railway-performance/public-performance-measure-and-delay-responsibility/

Network Rail (2023b) *South West Rail Resilience Programme*. Available at: https://www.networkrail.co.uk/running-the-railway/our-routes/western/south-west-rail-resilience-programme/

O'Keeffe, et al. (2020) 'Stakeholder awareness of climate adaptation in the commercial seaport sector: A case study from Ireland', *Marine Policy*, 111 [online]. Available at: doi.org/10.1016/j.marpol.2016.04.044 (Accessed: 3rd February 2022)

ORR (2020) Rail Infrastructure and Assets 2019-20. Available at: https://dataportal.orr.gov.uk/media/1842/rail-infrastructure-assets-2019-20.pdf

Palin, et al. (2021) 'Implications of climate change for railway infrastructure', *WIREs Climate Change*, 12(5) [online]. Available at: doi.org/10.1002/wcc.728 (Accessed: 3rd February 2022)

Postance, et al. (2017) 'Extending natural hazard impacts: an assessment of landslide disruptions on a national road transportation network', *Environmental Research Letters*, 12(1) [online]. Available at: doi.org/10.1088/1748-9326/aa5555 (Accessed: 3rd February 2022)

Pregnolato, et al. (2017) 'Impact of Climate Change on Disruption to Urban Transport Networks from Pluvial Flooding', *Journal of Infrastructure Systems,* 23(4) [online]. Available at: doi.org/10.1061/(ASCE)IS.1943-555X.0000372 (Accessed: 14th February 2022)

Reeves, et al. (2013) *The costs and benefits of increasing the resilience of rail geotechnical assets to climate change*. PPR672. Available at: https://trl.co.uk/uploads/trl/documents/PPR672.pdf (Accessed: 8th March 2022).

United Nations (2020) *Climate Change Impacts and Adaptation for Coastal Transport Infrastructure: A Compilation of Policies and Practices*. Series No 12. Available at: https://unctad.org/system/files/official-document/dtltlb2019d1_en.pdf (Accessed: 8th March 2022).

Wang, et al. (2019) 'How can the UK road system be adapted to the impacts posed by climate change? By creating a climate adaptation framework', *Transportation Research Part D: Transport and Environment*, 77 [online]. Available at: doi.org/10.1016/j.trd.2019.02.007 (Accessed: 3rd February 2022)

Wang, et al. (2020) 'How does the UK transport system respond to the risks posed by climate change? An analysis from the perspective of adaptation planning', in Ng, A.K.Y. and Jiang, C. and Monios, J. (eds.) *Maritime Transport and Regional Sustainability*. Netherlands: Elsevier, pp. 85-106.

Woodburn, A. (2019) 'Rail network resilience and operational responsiveness during unplanned disruption: A rail freight case study', *Journal of Transport Geography*, 77 [online]. Available at: doi.org/10.1016/j.jtrangeo.2019.04.006 (Accessed: 14th February 2022)

World Bank (2023) *Austria*. Available at: https://data.worldbank.org/country/austria?view=chart

Appendix A: Search Strategy

This section provides a detailed methodological overview of the literature search, including the databases and websites searched and the search strings used.

Databases

The following databases were used in the search for academic literature:

- Scopus
- EconLit
- TRID (Transport Research International Documentation)
- ABI/Inform
- Environmental Science Index (including Environmental Engineering Abstracts)

Websites

The following websites were used in the search for grey literature:

- The Department for Transport
- Defra
- Climate Change Committee
- National Environment Research Council
- TRL
- Climate Exchange
- National Infrastructure Commission
- Climate-ADAPT
- Climate Adaptation Platform
- Prevention Web
- weADAPT
- SYSTRA
- McKinsey
- Maritime UK
- Office for Rail and Road
- Civil Aviation Authority
- Network Rail
- National Highways
- OECD
- UNFCCC
- UN Economic Commission for Europe
- UN Conference on Trade and Development
- European Road Transport Research Advisory Council

- Paris Process on Mobility and Transport
- IPCC

Inclusion criteria

The detailed eligibility criteria for the studies were as follows:

1. **Language.** Studies must be written in English only. The search terms were in English only.
2. **Publication status.** Published academic and grey literature were included.
3. **Date of publication.** Studies included were published from 2012 onwards.
4. **Countries.** Includes evidence relating to both the UK and Northern Europe, to ensure that the evidence relates to countries with similar climates, economies and transport infrastructure.
5. **Topic.** Includes evidence relating to CCA and transport infrastructure. This includes evidence looking at the need for CCA work, and the costs and benefits of that work. It also includes evidence that attempts to assess the effectiveness of individual initiatives or groups of initiatives. It may include studies that set out conceptual approaches to categorising or thinking about CCA in the context of transport infrastructure. It is likely that some of the included evidence may be descriptive, and simply provide an overview of one or more initiatives.
6. **Transport mode.** Includes evidence that relates to one or more aviation, maritime, road or rail.
7. **Study design.** Includes both primary and secondary research studies. We took a broad view on appropriate methodologies given the relatively open nature of the research questions. Some of the evidence will simply be descriptive, but other evidence may be evaluative. Simulation and modelling evidence may also be included.

Search Strings

The search strings and results for each database are as follows:

Scopus
Platform: Elsevier

Date searched: January 25, 2022

Number of results: 640

1	TITLE-ABS-KEY(adapt* OR resilien*) AND TITLE-ABS-KEY(climate OR "extreme weather" OR "global warming" OR "global heating" OR drought OR megadrought OR flood* OR "heat wave" OR "extreme precipitation" OR "sea level rise" OR "weather extremes" OR emissions OR carbon OR "greenhouse gas" OR GHGs OR CO2 OR destablisation OR destabilization OR scour OR "cascad* failure")	**180,374**
2	TITLE-ABS-KEY("climate-smart" OR "climate risk" OR "climate change ready" OR "climate readiness" OR "climate change readiness")	**4,141**

3	#1 OR #2	**182,317**
4	TITLE-ABS-KEY(roads OR rail* OR trains OR "train tracks" OR ports OR airports OR bridges OR tunnels OR motorway* OR highway*)	**1,699,813**
5	TITLE-ABS-KEY(Infrastructure OR "built environment" OR "land-use") AND TITLE-ABS-KEY(freight OR "air travel" OR "air traffic" OR maritime OR aviation OR transport*)	**79,455**
6	#4 OR #5	**1,746,083**
7	TITLE-ABS-KEY("united kingdom" OR UK OR England OR London OR Britain OR British OR Scotland OR Ireland OR Wales OR Norway OR Denmark OR Sweden OR Finland OR Irish OR Scottish OR Welsh OR Norwegian OR Danish OR Swedish Or Finnish OR Iceland* OR Estonia* OR Faroe OR Aland OR "isle of man" OR Latvia* OR Lithuania* OR Svalbard OR "channel islands" OR Austria* OR Belgium OR France OR German* OR Liechtenstein OR Luxembourg OR Monaco OR Netherlands OR Switzerland OR Swiss OR Dutch OR French OR Scandinavia OR "northern Europe*" OR "western Europe*")	**4,358,181**
8	#3 AND #6 AND #7	**876**
9	Limit to 2012 to present	**661**
8	Limit to English	**640**

EconLit
Platform: EBSCOhost

Date searched: January 25, 2022

Number of results: 87

1	TX(adapt* OR resilien*) AND TX (climate OR "extreme weather" OR "global warming" OR "global heating" OR drought OR megadrought OR flood* OR "heat wave" OR "extreme precipitation" OR "sea level rise" OR "weather extremes" OR emissions OR carbon OR "greenhouse gas" OR GHGs OR CO2 OR destablisation OR destabilization OR scour OR "cascad* failure")	**4672**
2	TX("climate-smart" OR "climate risk" OR "climate change ready" OR "climate readiness" OR "climate change readiness")	**321**
3	S1 OR S2	**4825**
4	TX(roads OR rail* OR trains OR "train tracks" OR ports OR airports OR bridges OR tunnels OR motorway* OR highway*)	**36,217**

5	TX(Infrastructure OR "built environment" OR "land-use") AND TX(freight OR "air travel" OR "air traffic" OR maritime OR aviation OR transport*)	**42,785**
6	S4 OR S5	**72,096**
7	TX("united kingdom" OR UK OR England OR London OR Britain OR British OR Scotland OR Ireland OR Wales OR Norway OR Denmark OR Sweden OR Finland OR Irish OR Scottish OR Welsh OR Norwegian OR Danish OR Swedish Or Finnish OR Iceland* OR Estonia* OR Faroe OR Aland OR "isle of man" OR Latvia* OR Lithuania* OR Svalbard OR "channel islands" OR Austria* OR Belgium OR France OR German* OR Liechtenstein OR Luxembourg OR Monaco OR Netherlands OR Switzerland OR Swiss OR Dutch OR French OR Scandinavia OR "northern Europe*" OR "western Europe*") OR GE("united kingdom" OR UK OR England OR London OR Britain OR British OR Scotland OR Ireland OR Wales OR Norway OR Denmark OR Sweden OR Finland OR Irish OR Scottish OR Welsh OR Norwegian OR Danish OR Swedish Or Finnish OR Iceland* OR Estonia* OR Faroe OR Aland OR "isle of man" OR Latvia* OR Lithuania* OR Svalbard OR "channel islands" OR Austria* OR Belgium OR France OR German* OR Liechtenstein OR Luxembourg OR Monaco OR Netherlands OR Switzerland OR Swiss OR Dutch OR French OR Scandinavia OR "northern Europe*" OR "western Europe*")	**379,604**
8	S3 AND S6 AND S7	**140**
9	Limit to 2012 to present	**96**
8	Limit to English	**87**

TRID (Transport Research International Documentation)
Platform: Transportation Research Board

Date searched: January 25, 2022

Number of results: 319

"climate adaptation" OR "climate change adaptation" OR "climate change resilience" OR "climate resilience" OR climate-smart" OR "climate risk" OR "climate change ready" OR "climate readiness" OR "climate change readiness"

ABI/Inform
Platform: ProQuest

Date searched: January 25, 2022

Number of results: 506

1	noft(adapt* OR resilien*) AND noft(climate OR "extreme weather" OR "global warming" OR "global heating" OR drought	**142,350**

	OR megadrought OR flood* OR "heat wave" OR "extreme precipitation" OR "sea level rise" OR "weather extremes" OR emissions OR carbon OR "greenhouse gas" OR GHGs OR CO2 OR destablisation OR destabilization OR scour OR "cascad* failure")	
2	noft("climate-smart" OR "climate risk" OR "climate change ready" OR "climate readiness" OR "climate change readiness")	**4957**
3	1 OR 2	**145,880**
4	noft(roads OR rail* OR trains OR "train tracks" OR ports OR airports OR bridges OR tunnels OR motorway* OR highway*)	**5,043,505**
5	noft(Infrastructure OR "built environment" OR "land-use") AND noft(freight OR "air travel" OR "air traffic" OR maritime OR aviation OR transport*)	**206,710**
6	S4 OR S5	**5,152,154**
7	TI,AB("united kingdom" OR UK OR England OR London OR Britain OR British OR Scotland OR Ireland OR Wales OR Norway OR Denmark OR Sweden OR Finland OR Irish OR Scottish OR Welsh OR Norwegian OR Danish OR Swedish Or Finnish OR Iceland* OR Estonia* OR Faroe OR Aland OR "isle of man" OR Latvia* OR Lithuania* OR Svalbard OR "channel islands" OR Austria* OR Belgium OR France OR German* OR Liechtenstein OR Luxembourg OR Monaco OR Netherlands OR Switzerland OR Swiss OR Dutch OR French OR Scandinavia OR "northern Europe*" OR "western Europe*") OR LOC("united kingdom" OR UK OR England OR London OR Britain OR British OR Scotland OR Ireland OR Wales OR Norway OR Denmark OR Sweden OR Finland OR Irish OR Scottish OR Welsh OR Norwegian OR Danish OR Swedish Or Finnish OR Iceland* OR Estonia* OR Faroe OR Aland OR "isle of man" OR Latvia* OR Lithuania* OR Svalbard OR "channel islands" OR Austria* OR Belgium OR France OR German* OR Liechtenstein OR Luxembourg OR Monaco OR Netherlands OR Switzerland OR Swiss OR Dutch OR French OR Scandinavia OR "northern Europe*" OR "western Europe*")	**13,538,670**
8	S3 AND S6 AND S7	**849**
9	Limit to 2012 to present	**835**
10	Exclude Wire Feeds, Trade Journals, Newspapers, Magazines	**509**
11	Limit to English	**506**

Prioritisation

To determine the relevance of studies, the following criteria were applied in descending order (criterion 1 being the most important):

1. Studies that draw on multiple evidence sources such as systematic or evidence reviews will be prioritised.
2. Studies that answer more than one REA research question will be prioritised.
3. Studies that address multiple transport modes will be prioritised.
4. More recent studies will be prioritised.
5. Studies that address research questions, modes, or climate change impacts for which there is a comparatively small evidence base will be prioritised.
6. Real world evidence will be prioritised (over simulation and modelling, for example).
7. UK evidence will be prioritised over European evidence.