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Climate Change Risk Assessment for the Transport Sector

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Statement of Use

This report presents the research completed as part of the UK Climate Change Risk Assessment (CCRA) for a selected group of risks in the Transport sector. Whilst some broader context is provided, it is not intended to be a definitive or comprehensive analysis of the sector.

Before reading this report it is important to understand the process of evidence gathering for the CCRA.

The CCRA methodology is novel in that it has compared over 100 risks (prioritised from an initial list of over 700) from a number of disparate sectors based on the magnitude of the consequences and confidence in the evidence base. A key strength of the analysis is the use of a consistent method and set of climate projections to look at current and future threats and opportunities.

The CCRA methodology has been developed through a number of stages involving expert peer review. The approach developed is a tractable, repeatable methodology that is not dependent on changes in long term plans between the 5 year cycles of the CCRA.

The results, **with the exception of population growth where this is relevant, do not include societal change in assessing future risks, either from non-climate related change, for example economic growth, or developments in new technologies; or future responses to climate risks such as future Government policies or private adaptation investment plans**.

Excluding these factors from the analysis provides a more robust 'baseline' against which the effects of different plans and policies can be more easily assessed. However, when utilising the outputs of the CCRA, it is essential to consider that Government and key organisations are already taking action in many areas to minimise climate change risks and these interventions need to be considered when assessing where further action may be best directed or needed.

Initially, eleven 'sectors' were chosen from which to **gather** evidence: Agriculture; Biodiversity & Ecosystem Services; Built Environment; Business, Industry & Services; Energy; Forestry; Floods & Coastal Erosion; Health; Marine & Fisheries; Transport; and Water.

A review was undertaken to identify the range of climate risks within each sector. The review was followed by a selection process that included sector workshops to identify **the most important** risks (threats or opportunities) within the sector. Approximately **10%** of the total number of risks across all sectors was selected for more detailed consideration and analysis.

The risk assessment used UKCP09 climate projections to assess future changes to sector risks. Impacts were normally analysed using single climate variables, for example temperature.

A final **Evidence Report** draws together information from the 11 sectors (as well as other evidence streams) to provide an overview of risk from climate change to the UK.

Neither this report nor the Evidence Report aims to provide an in depth, quantitative analysis of risk within any particular 'sector'. Where detailed analysis is presented using large national or regional datasets, the objective is solely to build a consistent picture of risk for the UK and allow for some comparison between disparate risks and regional/national differences.

This is a UK risk assessment with some national and regional comparisons. The results presented here should not be used by the reader for re-analysis or interpretation at a local or site-specific scale.

In addition, as most impacts were analysed using single climate variables, the analysis may be over-simplified in cases where the consequence of climate change is caused by more than one climate variable (for example, higher summer temperatures combined with reduced summer precipitation).

Sector Summary

Background

Currently, operation and maintenance of the UK's transport networks is strongly affected by the weather, with the greatest risks for all modes posed by 'extreme' weather events. Undoubtedly therefore the transport system in the UK is vulnerable to climate change as more extreme weather events are likely.

However transport systems in other parts of the world already cope with weather conditions similar to those likely to be encountered in the future in the UK and useful practical lessons can be learned from overseas. In the current UK climate, disruption due to cold, wind, rain, snow and ice is still more frequently experienced than disruption due to heat.

As the climate changes, disruption caused by cold, snow and ice are likely to occur less frequently, whereas there is likely to be an increased risk posed by both heat and by flooding. Because climate projections contain some inherent uncertainty, adaptation decisions in infrastructure will need to take due account of some uncertainty within the broad picture of a gradually warming climate with increased flood risk in the longer term.

Transport networks in the UK are closely linked - a disruption in one mode of transport can have knock on effects on other modes with impacts on both the public and on business, through disrupted supply chains. An assessment of risk needs to consider where weak links in the system as a whole increase risks for the wider network. However the wide mix of options provided by the UK's transport infrastructure potentially makes the transport network inherently resilient to weather most of the time.

This could be improved further by a sharing of knowledge across transport modes such as common standards for drainage, subsidence and emergency procedures. Much greater consideration of the inherent capacity within and between networks, to allow for switching between modes to take place, could increase overall resilience to severe weather. It will be for the adaptation assessment to determine such things as the appropriate level of resilience building.

The low carbon agenda could change the way people travel - and in doing so could present opportunities for adaptation and resilient infrastructure development. Technological innovation has the potential to dominate travelling habits so should be considered alongside other socio-economic factors in assessing adaptation options. Ongoing research will be a first step in shedding light on some of these issues[1].

Much of the research in the transport sector to date has focussed on reducing greenhouse gas emissions. Transport is responsible for about one quarter of green house gas emissions worldwide (Chapman, 2007). Far less is known about climate impacts on the transport networks and adaptation options. Of the risks considered important by an initial assessment and by stakeholders and analysed in detail here, some do not appear to pose a significant threat at a UK level in the near term. This underlines the benefit further research could have on enhancing identification of the most significant climate risks - including how impacts interact and the scale of knock on consequences in the transport system.

[1] Current work includes the TRACCA project (Tomorrow's Railway and Climate Change Adaptation) to investigate the climate resilience of the West Coast Main line which feeds into the FUTURENET project and ongoing EU projects. The BIONICS project will investigate the effects of climate change on infrastructure slopes.

Overview

The UK transport network (comprising road, rail, air and water transport) is an essential enabling component of the economy. All modes of transport are affected by the weather, in particular extreme weather conditions and the variability from day-to-day. Extreme weather can cause serious disruption to the transport system. It may be possible to accommodate mitigation measures in new transport infrastructure but extreme weather is likely to remain a challenge for the maintenance and operation of existing infrastructure.

As the climate warms, weather patterns and the frequency of extreme events may also change. It also means (though outside the scope of this project) that a key component of the current resilience of all transport networks are current weather forecasts, as their accuracy and reliability has a significant influence on the ability of the operators to respond appropriately (Thornes and Chapman, 2008).

Gradual changes in climate may affect the criteria used for design and maintenance and will therefore be an important aspect of adaptation. This means that design, maintenance and operations may have to be able to cope with more extreme (higher) temperatures and more frequent flooding. However, there may also be reductions in the frequency of sub-zero temperatures and the problems caused by snow and ice. Conversely, the apparent benefit of warmer winters, when considered over several years or decades, may mean that operators become less well prepared for more extremely cold weather conditions when they do occur (such as heavy snowfalls experienced in 2009 and 2010). It may therefore be advisable to design and maintain transport infrastructure for a wider range of temperature in the future.

An initial scoping of the issues for the transport sector identified three broad areas of risk as follows:

- Direct damage to transport infrastructure and the associated disruption caused by extreme storm events (especially extreme rainfall and strong winds).
- Direct disruption to transport modes (vehicles, trains, aircraft and ships) caused by extreme storm events. This can range from precautionary closures of roads and rail/air/ship services through to potential catastrophic damage caused by a storm or power failure causing widespread disruption.
- Indirect disruption to transport caused by gradual changes in the climate, particularly increases in temperature causing heat stress to passengers, staff and goods.

These issues were therefore foremost in the initial list of 54 impacts that were identified at the outset of the project. By taking account of impacts that were similar or closely related, this list was reduced to some 27 generic impacts (most of which were applicable to all modes of transport) and these impacts were found to cluster around issues related to infrastructure, vehicles, staff, passengers and resources. These risks were discussed with a selection of transport stakeholders (mainly from road and rail transport) to get a sense of relative importance from different perspectives (economic, environmental and social).

Climate change typically represents a change to existing risks profiles – in other words they already represent familiar issues facing transport operators on a daily basis. Climate change simply represents a potential change in the magnitude, duration and/or frequency of occurrence of these impacts, and their subsequent effects on operations. As such, the key risks identified in this risk assessment include:

TR1: Flood disruption/delay to road traffic

TR2: Landslide impacting on the road network

TR4: Cost of road carriageway repairs

TR5: Rail buckling risk

TR6: Road and rail bridge failures due to scour.

The energy demand associated with cooling road vehicles[2] was also identified in the initial assessment of risks but was not considered in the analysis.

The selection of these impacts was the result of a methodological approach to individually score the identified generic risks. This selection process included assessment of the magnitude of consequence for economic, environmental and social categories, as well as the likelihood of the consequence occurring. Moreover, consideration was given to the urgency with which the decision to manage climate change needs to be made.

In the context of transport, the urgency criteria explains the dominant focus on road and to a lesser extent rail, where these two modes represent over 90% of present day needs[3]. Hence, these two modes are likely to dominate the adaptation agenda over the period to the next CCRA (up to 2017).

Furthermore, there may also be greater clarity on the dominant risk for air and waterborne transport systems, namely any changes to extreme storms and in particular winds. For the moment the UKCP09 projections for winds remain highly uncertain, albeit with a suggestion that there may be little change.

It is important to note that with the time and resources available it was not possible for the assessment to be comprehensive. The metrics analysed therefore illustrate the nature and indicative magnitude of the sort of risks that are likely to be experienced, rather than provide a comprehensive coverage. So, for example, landslides have been assessed for the road network and a similar analysis could be undertaken for the rail network.

Emerging Challenges and Opportunities

This section outlines some of the challenges and opportunities that may arise as a result of the way in which climate change could impact on transport in the future.

There are an increasing number of passengers using rail travel. If this trend continues, this may mean that any weather and climate related train delays have a greater impact, particularly as more services are provided on a fixed infrastructure.

This may also increase the pressure for greater integration of the various transport modes. The opportunities for adaptation of the various networks is likely to need a well researched mix of technological development and improved long-term spatial planning, where the integrated nature of the different transport networks is given greater recognition and importance in the planning and decision making process.

For ports and airports, the main climate change challenges are likely to arise from changes in wind strength, storm intensity and fog. Indeed in many respects conditions may improve for ports and airports with milder winters although perversely, as already noted, this may mean that operators may have greater problems dealing with extreme events when they do happen simply because of a lack of preparedness.

[2] This can be taken as a surrogate measure of the cost of ameliorating passenger discomfort

[3] Some 88 per cent of inland freight transport is carried by road transport in the UK, and 93 out of every 100 passenger kilometres are travelled by road.

A common concern is the potential for greater disruption due to storms and in particular high winds. For the moment this is not supported by the evidence presented in UKCP09, although the uncertainty that surrounds the wind projections is such that a watching brief should be maintained on this issue. A high level review of risks to ports and airports is included in this document.

The melting of the Arctic ice and the opening up of the north-west and north-east passages to the Pacific Ocean may lead to a shift in the importance of UK ports from the South to the North West or North East of the British Isles. The Far East is more than 3000 km shorter via the north-east passage than via the Suez Canal. The timing and extent of this change is examined in the Marine sector report and noted in relation to supply chains in the Business sector report.

Changes in technology could change the nature of climate risks in the future. If for example the proportion of transport that is electrified increases in the future, then this could change both the risks themselves (as different technologies might have different vulnerabilities) but also the nature and extent of links with other sectors. In this case the links with the energy sector and ICT (Information and Communications Technology) are likely to increase, making the transport system more vulnerable to climate change impacts in these areas.

Results of the analysis

The likely consequences of the risks analysed are briefly as follows.

TR1: Flood disruption/delay to road traffic: The widespread flooding of major and minor roads in 2007 gives a very useful guide to the scale and costs of the risks involved. It has been estimated that the cost of disruption was of the order of £100m and the probability of this type of event is likely to increase with climate change. The assessment suggests that the cost of disruption from floods is projected to remain relatively low to the 2050s with the potential to increase to an event similar to 2007 on an almost annual basis by the 2080s.

TR2: Landslide impacting on the road network: The length of roads currently under some kind of threat from landslides in the UK runs into thousands of kilometres. However, the length of road at risk is projected to remain similar to current levels over the next 40 years, with some increase in risk beyond this period.

TR4: Cost of road carriageway repairs: The deformation and rutting of road surfaces could increase as road surface temperatures increase due to warmer summers. Also road repairs might be postponed or delays could be caused as a result of the required cooling of the road surface after resurfacing before vehicles are allowed to reuse a road. The assessment indicates that this impact is likely to be less significant than those due to flood risk and the costs incurred as a result of increased thermal loading are likely to be relatively modest. However, it is noted that the costs incurred in the 2003 heatwave suggest a greater risk and that this may therefore be an underestimate of the level of change.

TR5: Rail buckling risk: As summer air temperatures are projected to rise, so are rail temperatures. This means that more rail buckles are likely to occur in future summers. The current average number of rail buckles in Great Britain is about 50 at a cost of nearly £1 million. In the hot summer of 2003 there were 137 rail buckles at a cost of about £2.5m for repairs and delays. By the 2080s this could more than double.

TR6: Bridge scour: Winter precipitation and river flood flows are projected to increase. This in turn could lead to an increase in the amount of scour at bridges across rivers and an increase in the potential number of bridge failures from this cause. Scour depths could increase by about 5% to over 50% depending on local conditions. Whilst it has not been possible to provide projections of future bridge failures due to scour, it is clear that number could increase from the present baseline of about one failure per year.

As stated above, the energy demand associated with cooling road vehicles (metric TR3) was only considered in the initial stages of the analysis but not taken through to the detailed stages.

Sensitivity

The various modes of transport each have their own sensitivities to weather and, as the climate changes, this is likely to affect each mode to a greater or lesser degree. These sensitivities are a key component of operations and so are generally as significant as other risks that have to be managed by the sector. The main sensitivities for each mode are as follows.

Air Transport

Today, aircraft and helicopters are designed to operate virtually anywhere in the world and, as such, the climatic design is advanced. Increasing air traffic is leading to worries about the amount of carbon dioxide and other greenhouse gases released into the atmosphere by aircraft, and this may lead to changes in the amount of air travel in the future. Impacts on aircraft including projected changes in air density as a result of climate change were included in the initial list of impacts but were not selected for analysis. Adaptation reports for a number of airports are available on the Defra website as required under the auspices of the Adaptation Reporting Power (ARP) derived from the Climate Change Act 2008:

Airports are designed to be kept open every day of the year in all weather conditions. All airports in the UK have provision for 'round the clock' snow and ice control, both for clearing runways and aircraft. The need for such services is intermittent and, as now, the challenge may be to provide good weather forecasts to operators, and for operators to maintain appropriate contingency plans. The Heathrow Winter Resilience Enquiry considered the heavy snow of December 2010, which severely disrupted operations at Heathrow Airport causing more than 4,000 flights to be cancelled (Begg Report, 2011), and concluded that there was:

'a low state of preparedness ahead of the snow and insufficient stock of critical supplies'. (p2)

Whilst the incidence of snow is projected to reduce as a result of climate change, precipitation (and, in particular, intense storms) is projected to increase. Not only might this cause an increase in disruption due to local flooding, but also visibility for aircraft take-off and landing could be affected.

Rail Transport

Heavy rain or snow can cause track blockages, particularly in cuttings, and cold weather affects many activities, particularly when accompanied by snow. Strong winds can also be a hazard and can bring down overhead cables, particularly if trees are blown onto them.

Railway engines are powered by either electricity or diesel and both are designed to operate in UK conditions. These can be sensitive to cold and hot weather conditions and under a changing climate there is likely to be a need to continue to refine designs and retrofit measures to cope with the changing conditions.

The effects of temperature extremes on the track range from buckling of rails in hot weather, at the one extreme, to freezing of points and broken rails in cold weather, at the other extreme. The track is also susceptible to landslides and flooding, which like the snow and ice hazard are all sensitive to the specific track alignment and local conditions.

Climate change is recognised as an important factor in future planning by Network Rail (Network Rail, 2011) and considerable work is underway to make the rail system more resilient to climate effects. To date this has been primarily addressed to the effects of extreme rainfall on drainage systems, embankment stability, extreme river flows on the stability of bridges and coastal defences.

Underground infrastructure is prone to rising water tables and pluvial flooding. The lack of heating and ventilation on the London Underground means temperatures can exceed thermal comfort thresholds (Mullins, 2011). All of these issues are likely to be exacerbated as the climate changes.

Road Transport

Most vehicles are expected to perform in all weather conditions but remain sensitive to extremes of heat and cold, damp, wet or icy road conditions and road blockages or closures due to snow or fog. Road design aims to minimise some of these problems, e.g. by alignments that avoid fog prone areas or limit the impact of snow drifts. As with runways, it only requires about a quarter of the amount of de-icing chemical to prevent ice formation than to melt ice, owing to the extra energy required to melt ice.

The hot weather of July 2003 caused asphalt roads to 'bleed' and stone dust had to be spread to prevent the surface breaking up, although warm and dry weather is very beneficial for construction activities owing to a lack of weather interference. However, as well as potential for increased damage to the road surface in high temperatures there is also the potential for an increase in disruption because, above 35°C, surface dressing of roads has to be suspended as the asphalt may not cool sufficiently quickly.

Heavy rainfall and flooding already cause disruption to road transport and this is projected to increase. This may affect the adequacy of existing road drainage systems and the design of new and improved systems in the future.

Water Transport

Vessels have varying abilities to cope with extremes of weather and this, in general, determines their range of use. For commercial vessels this is carefully controlled through vessel certification and so can be managed to take account of changes in climate (e.g. the distance offshore that a particular size of vessel is allowed to operate). Hence for vessels at sea the main changes are likely to be driven by requirements to reduce emissions, reduce energy usage and control discharges.

Ports are sensitive to wind, tide, sea level, fog and wave conditions, all of which influence the initial choice of port location to maximise the shelter they offer and hence the operational efficiency of the port. The present projections of climate change suggest minimal change to these conditions and so port sensitivity is relatively low. Sea level rise may be more critical in the long-term because quays are to a fixed elevation and, as water levels rise, there is a greater risk of flooding and for some ports lifting equipment may need to be modified. However the existing freeboard at most ports means that this is not of immediate concern and where issues such as flooding are a problem they are already being addressed (e.g. additional defences around the quays in the port of Hull). However, there may be some additional risk of damage to cargo and for those ports that choose not to protect the dock estate from flooding, there may be an increased risk to the surrounding neighbourhood.

The canal and inland waterway network is mainly used for leisure activities, although there has been an increase in commercial traffic in recent years and parts of the system are also used for the movement of grey water for industrial use. In winter parts of the system freeze over preventing vessel movement and increasing the damage to vessels and infrastructure and this may be reduced in a warmer climate. However the greater risk is the availability of water to maintain water depths in the network. As discussed in the Water sector report there is likely to be an increasing gap between water supply and demand, which is likely to put increasing pressure on the use of water storage and reservoirs that are currently maintained for the canal system.

Mutual dependence of transport systems

There is considerable overlap between the four transport modes discussed above, for instance road transport is fundamental to get the public and staff to airports, railway stations and ports. In difficult weather conditions, one form of transport may have to substitute for another, for example, in times of extreme flood, air transport may provide the only access into an area.

If transport is disrupted, then there is a considerable cascade effect for other industrial sectors including movement of labour and materials. For example, 'just-in-time' production, where stockpiles of material are kept to a minimum, reduces any margin of flexibility if transport is disrupted.

The majority of current climate effects on the UK transport sector are projected to occur with increasing frequency under future scenarios, particularly those related to increases in precipitation and high temperatures. Whilst extreme winter conditions are projected to reduce, there may be increases in problems caused by the freeze/thaw cycle in parts of the UK.

Extreme climate events caused by high precipitation or temperatures are likely to affect all modes of transport to some degree. Improved forecasting for transport providers and users together with contingency planning may form an important component of future adaptation of the transport system to climate change.

A reduction in petrol and diesel cars in urban areas may lead to a lessening of the Urban Heat Island effect but may also lead to a negative health impact due to increasing ozone levels in cities caused by a decrease in nitrogen oxides. However increased cycling and walking could raise physical activity thereby improving mental health, improving circulatory and heart health as well as helping to tackle obesity.

Current and future vulnerability

As already outlined, weather is a major consideration in the operation of the transport networks. Disruption is already caused by weather effects including high temperatures, low temperatures, extreme rainfall and storms. Recent events that demonstrate the current vulnerability of transport to extremes of climate include the July 2007 floods and cold weather during December 2010. A key requirement is to understand how the variability in weather is likely to change in the future and to continue to improve the accuracy and reliability of weather forecasts to underpin more responsive management.

Future changes in the climate may affect both the maintenance of existing infrastructure, and new transport investments. Maintenance operations cover a wide range of activities. Whilst there may be a need to increase some activities and reduce others in response to a changing climate, flexibility is likely to be needed. For example, although there may be an overall reduction in cold weather working, there is still likely to be a need to respond to extreme winter conditions from time to time.

The response to climate mitigation and the very long-term nature of transport infrastructure related investments mean that the transport sector may be vulnerable to the adequacy of planning and design decisions in the light of climate change.

The importance of the interaction of the individual networks and the need for better integration between networks (to improve both the supply chain and the mobility of the public) will be key aspects of adaptation and need to be better understood to inform the planning process.

The results of the analysis suggest that the greatest risk is in England due to the greater length of the transport networks and higher volumes of traffic. It is projected that disruption from some climate drivers (particularly increases in extreme temperature and flooding) could increase. A potential approach to adaptation of existing infrastructure is to identify and make more resilient the sections of road and rail, and infrastructure at ports and airports that are vulnerable to flooding, landslides, subsidence, buckling, etc.

Interdependencies

There are interdependencies between the transport sector and other sectors. For example, business relies heavily on the transport sector and may be affected by any disruption to transport. This section considers interdependencies between the sectors used in the CCRA analysis, and some of the other factors that could potentially affect transport in the future.

Key links to other CCRA sector risks

The systematic mapping undertaken as part of the CCRA analysis has identified the extensive nature of the cross-sectoral linkages. This is, perhaps, not surprising because of the importance of transport to society as a whole including people getting to and from work, the timely supply of materials and goods, and social and leisure activities.

The CCRA analysis covers ten sectors in addition to the transport sector, all of which have overlaps with transport. Metrics analysed in other sectors that are relevant to the transport sector include the following:

- Increased risk of flooding of road and rail infrastructure (Floods and Coastal Erosion sector).
- Water supply and demand, which may be relevant to the future management of inland waterways (Water sector).
- The opening up of navigation passages across the arctic and the potential impact on global shipping patterns (Marine sector).
- Movement of invasive non-native species that could affect ports and shipping (Marine sector).
- Overheating of buildings, airports, stations etc (Built environment sector).
- Building subsidence (Built environment sector).
- Changes in fire risk, that could affect road and rail travel (Forestry sector).
- Effects of transport disruption on business supply chains and consequent loss of output (Business sector).

In addition to the above, other cross-sectoral impacts that have not been analysed include:

- Flooding of other transport infrastructure.
- Effects of transport disruption on agriculture and food supply, particularly the transport of perishable goods.

- Health effects caused by increasing temperatures on people using transport systems.
- Insurability, premiums and claims resulting from damage to transport infrastructure, material, shipping, etc.
- Changes in demand for travel arising from changes in tourism and the potential for change in modal choices as a response to 'outdoor activity' such as walking and cycling.

This document contains results from the analysis of opening up of navigation passages across the arctic (Marine and Fisheries sector metric MA5) and the increased risk of flooding of road and rail infrastructure (Floods and Coastal Erosion sector metric FL8). The results are summarised below.

The projections for changes in arctic sea ice show more future navigable days for the north-east passage than the north-west passage. This is important for UK economies as this is the route most relevant for UK markets. The total number of days per year where navigation might be possible is projected to be of the order of 180 by the 2080s and possibly as many as 90 days by the 2020s.

The length of roads at significant likelihood (annual probability of 1.3% or 1 in 75 years on average) of flooding from rivers or the sea in England and Wales is projected to increase from the baseline of about 12,000km (including 3,400km of motorways and A roads) to between 14,000km and 19,000km by the 2080s (including 3,900km to 5,500km of motorways and A roads). The equivalent figures for rail are a projected increase from the baseline of about 2,000km to between 2,300km and 3,100km by the 2080s.

Other drivers of change

Climate risks should be considered in conjunction with other potential future changes to transport. These include the development of the low carbon agenda and changes to the balance between different modes of transport in the future.

The government agenda to promote a low carbon economy is likely to drive technological development for alternative or more efficient power sources and may well be accompanied by a shift in public preferences, although the sociological issues involved are complex and future societal preferences are difficult to anticipate.

With regard to future modes of transport, some futures work has looked at how the mix of Road/Rail/Air transport may change in the future, as shown in the table below. For all of the scenarios considered, road remains the dominant mode, although in some scenarios this is substantially reduced from the present day where it represents over 90% of the need.

Proportions of Air/Rail/Road transport by the 2050s for four projected socio-economic scenarios (UKCIP, 2000)[4]

Scenario **Today**	**Air** **1.5%**	**Rail** **6.5%**	**Road (Public transport)** **6%**	**Road (Private Transport)** **86%**
National Enterprise	1%	7%	7%	85%
Local Stewardship	0.5%	15%	14.5%	70%
World Markets	3%	10%	2%	85%
Global Sustainability	1.5%	15%	19.5%	64%

This suggests that the short to medium term is likely to be dominated by road transport, despite the influence of a range of other drivers. The analysis also indicates that all modes of transport will be important and major shifts from one mode of transport to another appear unlikely.

About the analysis

Data quality and modelling issues

For the transport sector the identification of metrics for direct biophysical impacts, such as flood risk to roads, was a relatively straightforward task but these on their own are insufficient to explain risk in the sector, as they do not provide enough information to measure the economic, social and environmental consequences of climate change. Within this sector, for many users it is the impact of the disruption caused by delay and diversion around flooded roads rather than the length of road at risk which is a more relevant metric and more work is needed to collect and collate suitable data on this aspect.

The availability of quantitative data (incidents and costs) was a problem for all the metrics. In general this provided baseline information to define the scale of the risk in the present climate but very little information on how this was changing over time and more importantly how it might be changing with respect to climate. For this reason the metrics were developed based on expert elicitation using the approach set out in the CCRA method. It is important for future versions of CCRA that databases are established to enable more rigorous and where possible quantitative analysis to be undertaken.

What is certain and what is uncertain

Modelling the future is full of uncertainties for both the climate and socio-economic aspects of the United Kingdom. Adaptation and mitigation are also linked. Whilst

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[4] The *National Enterprise* scenario sees people aspiring to personal independence and material wealth within a nationally-based cultural identity.

In the *Local Stewardship* scenario, people aspire to sustainable levels of welfare in federal and networked communities.

In the *World Markets* scenario, people aspire to personal independence, material wealth and mobility to the exclusion of wider social goals.

Under the *Global Sustainability* scenario, people aspire to high levels of welfare within communities with shared values, more equally distributed opportunities and a sound environment.

much of the analysis is based on the assumption that transport in the future will broadly be similar to the present, transport may change in the future in ways that cannot be foreseen.

For example, an additional pragmatic approach for the transport sector might involve asking the following questions:

- How might the current transport impacts/risks be affected by reducing transport emissions by 80% by 2050?
- Would vehicles/infrastructure and passengers be more or less vulnerable to climate change if fossil fuels were no longer in widespread use?
- Will electric and hybrid cars become the dominant form of transport in the UK? How would transport networks and infrastructure have to change to cope?
- How would such changes impact on human health and well-being?

Answering these questions requires careful consideration of likely technological changes, societal preferences and clear identification of the opportunities to enact infrastructure changes through more integrated planning of the combined modal transport system.

Key Term Glossary

The key terms are defined below.

Adaptation (IPCC AR4, 2007)

- **Autonomous adaptation** – Adaptation that does not constitute a conscious[5] response to climatic stimuli but is triggered by ecological changes in natural systems and by market or welfare changes in human systems. Also referred to as spontaneous adaptation.
- **Planned adaptation** – Adaptation that is the result of a deliberate policy decision, based on an awareness that conditions have changed or are about to change and that action is required to return to, maintain, or achieve a desired state.

Adaptive Capacity -The ability of a system to design or implement effective adaptation strategies to adjust to information about potential climate change (including climate variability and extremes), to moderate potential damages, to take advantage of opportunities, or to cope with the consequences (modified from the IPCC to support project focus on management of future risks). As such this does not include the adaptive capacity of biophysical systems.

Adaptation costs and benefits

- The costs of planning, preparing for, facilitating, and implementing adaptation measures, including transition costs.
- The avoided damage costs or the accrued benefits following the adoption and implementation of adaptation measures.

Consequence - The end result or effect on society, the economy or environment caused by some event or action (e.g. economic losses, loss of life). Consequences may be beneficial or detrimental. This may be expressed descriptively and/or semi-quantitatively (high, medium, low) or quantitatively (monetary value, number of people affected etc).

Impact - An effect of climate change on the socio-bio-physical system (e.g. flooding, rails buckling).

Response function - Defines how climate impacts or consequences vary with key climate variables; can be based on observations, sensitivity analysis, impacts modelling and/or expert elicitation.

Risk – Combines the likelihood an event will occur with the magnitude of its outcome.

Sensitivity - The degree to which a system is affected, either adversely or beneficially, by climate variability or change.

Uncertainty - A characteristic of a system or decision where the probabilities that certain states or outcomes have occurred or may occur is not precisely known.

Vulnerability - Climate vulnerability defines the extent to which a system is susceptible to, or unable to cope with, adverse effects of climate change including climate

[5] The inclusion of the word 'conscious' in this IPCC definition is a problem for the CCRA and we treat this as anticipated adaptation that is not part of a planned adaptation programme. It may include behavioural changes by people who are fully aware of climate change issues.

variability and extremes. It depends not only on a system's sensitivity but also on its adaptive capacity.

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1. Introduction

1.1 Background

It is widely accepted that the world's climate is being affected by the increasing anthropogenic emissions of greenhouse gases into the atmosphere. Even if efforts to mitigate these emissions are successful, the Earth is already committed to significant climatic change (IPCC, 2007).

Over the past century, the Earth has warmed by approximately 0.7°C[6]. Since the mid-1970s, global average temperature increased at an average of around 0.17°C per decade[7]. UK average temperature increased by 1°C since the mid-1970s (Jenkins *et al*., 2009), however recent years have been below the long-term trend highlighting the significant year-to-year variability. Due to the time lag between emissions and temperature rise, past emissions are expected to contribute an estimated further 0.2°C increase per decade in global temperatures for the next 2-3 decades (IPCC, 2007), irrespective of mitigation efforts during that time period.

The sorts of impacts expected later in the Century are already being felt in some cases, for example:

- Global sea levels rose by 3.3 mm per year (± 0.4 mm) between 1993 and 2007; approximately 30% was due to ocean thermal expansion due to ocean warming and 55% due to melting of land ice. The rise in sea level is slightly faster since the early 1990s than previous decades (Cazenave and Llovel, 2010).
- Acidification of the oceans caused by increasing atmospheric carbon dioxide (CO_2) concentrations is likely to have a negative impact on the many marine organisms and there are already signs that this is occurring, e.g. reported loss of shell weight of Antarctic plankton, and a decrease in growth of Great Barrier coral reefs (ISCCC, 2009).
- Sea ice is already reducing in extent and coverage. Annual average Arctic sea ice extent has decreased by 3.7% per decade since 1978 (Comiso *et al*., 2008).
- There is evidence that human activity has doubled the risk of a very hot summer occurring in Europe, akin to the 2003 heatwave (Stott *et al*., 2004).

The main greenhouse gas responsible for recent climate change is carbon dioxide (CO_2) and CO_2 emissions from burning fossil fuels have increased by 41% between 1990 and 2008. The rate of increase in emissions has increased between 2000 and 2007 (3.4% per year) compared to the 1990s (1.0% per year) (Le Quéré *et al*., 2009). At the end of 2009 the global atmospheric concentration of CO_2 was 387.2 ppm (Friedlingstein *et al*., 2010); this high level has not been experienced on earth for at least 650,000 years (IPCC, 2007).

The UK government is committed to action to both mitigate and adapt to climate change[8] and the Climate Change Act 2008[9] makes the UK the first country in the world

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[6] Global temperature trends 1911-2010 were: HadCRUT3 0.8°C/century, NCDC 0.7°C/century, GISS 0.7°C/century. Similar values are obtained if we difference the decadal averages 2000-2009 and 1910-1919, or 2000-2009 and 1920-1929.
[7] Global temperature trends 1975-2010 were: HadCRUT3 0.16°C/decade, NCDC 0.17°C/decade, GISS 0.18°C/decade.
[8] http://www.defra.gov.uk/environment/climate/government/

to have a legally binding long-term framework to cut carbon emissions, as well as setting a framework for building the nation's adaptive capacity.

The Act sets a clear and credible long term framework for the UK to reduce its greenhouse gas (GHG) emissions including:

- A legal requirement to reduce emissions by at least 80% below 1990 levels by 2050 and by at least 34% by 2020.
- Compliance with a system of five-year carbon budgets, set up to 15 years in advance, to deliver the emissions reductions required to achieve the 2020 and 2050 targets.

In addition it requires the Government to create a framework for building the UK's ability to adapt to climate change and requires Government to:

- Carry out a UK wide Climate Change Risk Assessment (CCRA) every five years.
- Put in place a National Adaptation Programme for England and reserved matters to address the most pressing climate change risks as soon as possible after every CCRA.

The purpose of this first CCRA is to provide underpinning evidence, assessing the key risks and opportunities to the UK from climate change, and so enable Government to prioritise climate adaptation policies for current and future policy development as part of the statutory National Adaptation Programme for England which will begin from 2012. The CCRA will also inform devolved Governments' policy on climate change mitigation and adaptation.

Climate Change Act: First 5 year Cycle

The Scope of the CCRA covers an assessment of the risks and opportunities to those things which have social, environmental and economic value in the UK, from the current climate and future climate change, in order to help the UK and devolved Governments identify priorities for action and implement necessary adaptation measures. The Government requires the CCRA to identify, assess, and where possible estimate economic costs of the key climate change risks and opportunities at UK and national (England, Wales, Scotland, Northern Ireland) level. The outputs from the CCRA will also be of value to other public and private sector organisations that have a stake in the sectors covered by the assessment.

The CCRA will be accompanied (in 2012) with a study on the Economics of Climate Resilience[10] (ECR) that will identify options for addressing some of the priority risks identified by the CCRA, and will analyse their costs and benefits. This analysis will provide an overall indication of the scale of the challenge and potential benefits from acting; and, given the wide-ranging nature of possible interventions, will help to identify priority areas for action by Government on a consistent basis.

This will be followed by the first National Adaptation Programme (NAP) for England and reserved matters. The NAP will set out:

- objectives in relation to adaptation
- proposals and policies for meeting those objectives
- timescales

[9] http://www.legislation.gov.uk/ukpga/2008/27/contents
[10] http://www.defra.gov.uk/environment/climate/government/

- an explanation about how those proposals and policies contribute to sustainable development.

The CCRA analysis has been split into eleven sectors to mirror the general sectoral split of climate impacts research; agriculture, biodiversity, business, built environment, energy, flooding and coastal erosion, forestry, health, marine, transport and water.

1.2 Scope of the Transport Sector Report

This Transport Sector Report is one of the 11 Sector reports commissioned as part of the CCRA, which provide the underpinning evidence used in the development of the UK CCRA to be delivered to Parliament, as required by the Climate Change Act, by January 2012. Sector Reports include the main risks and opportunities identified within each sector, drawing from the information in other sector reports where relevant.

The analysis presented in this report is based on CCRA methodology including the identification of risk metrics, systematic mapping, response functions, assessment of impacts and policy landscape mapping. It required consultation with Government departments, experts and practitioners in the transport sector to collect data and review and share the analysis.

The scope of this report only covers part of the transport sector as a whole – specifically cost and risk impacts of climate change on transport infrastructure and operations. Obviously the transport sector itself has a much wider scope and has a big impact on other sectors such as the built environment. The impact of climate change on all primary modes of transport (road, rail, air, water and marine) has been considered but it must be remembered that this is a first attempt to try and quantify the links between climate and transport. Most previous reports in this area are still at the qualitative inventory stage i.e. just grading possible impacts as low, medium or high in vulnerability matrices. This report attempts, for the first time, to quantify, where possible, the strength of the relationships between climate and transport.

1.3 Overview of the transport sector

The UK transport sector plays a major role in the UK and world economy. It is vital that the transport network is maintained to a high standard and is as resilient to climate change as possible. However sections of the network have been around for a considerable time and it is a delicate balancing act to optimise the cost benefit of improving transport infrastructure and services.

The Blue Book (2010) shows that the transport sector was worth just under £100 billion in 2008 (about 8%) which was 5th out of the 11 sectors considered (Figure 1.1). However transport is also very important to the performance of most of the other sectors in terms of journey to work and deliveries.

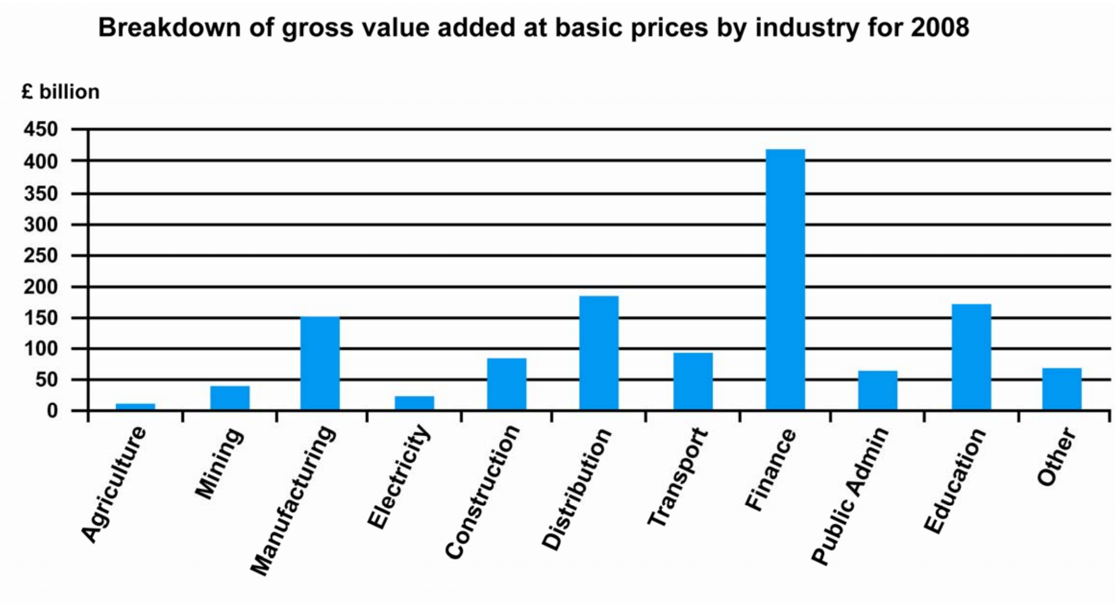

Figure 1.1 Value of the transport and other sectors
Source: Blue Book (2010)

The transport sector covers all modes of transport including road, rail, air and water transport. Pipelines are also important for the transport of resources such as oil and gas, but are not discussed in this report. The Office for National Statistics produces a chapter on Transport and the latest report for 2011 gives the following highlights (http://www.statistics.gov.uk/articles/social_trends/ST41Transport.pdf):

1. The number of journeys made on Great Britain's national railway network in 2009/10 was 1.3 billion, while there were 1.1 billion journeys on the London Underground.
2. A total distance of 504 billion motor vehicle kilometres was travelled on Great Britain's roads in 2009.
3. In 2009 around 1.9 billion tonnes of freight was lifted within Great Britain, over 80 per cent of which was by road. Between 2008 and 2009 total freight lifted decreased by 15 per cent.
4. UK ports handled 501 million tonnes of freight in 2009 of which 132 million tonnes was domestic freight. Between 2008 and 2009 overall freight decreased by 10.9 per cent.
5. In 2009 UK airports moved a total of 2.0 million tonnes of freight, a decrease of 10 per cent from 2008.

Transport Trends (DfT, 2009) gives an introduction to major trends in domestic transport in Great Britain with sections on Roads, Vehicles and Congestion; Personal Travel by Mode; Public Transport; Variation in Personal Travel and Access to Services; Freight and Logistics; Ports and Airports; Safety and Health and the Environment. Basic statistics for each mode include:

1. There are about 395 thousand kilometres of road. In 2008 motorways and main roads account for less than 13% of road length but about two thirds of traffic.
2. Rail travel has increased by nearly 70% since 1980 whereas bus usage has stayed much the same.

3. The number of passengers using UK airports more than quadrupled between 1980 and 2008. Spain is the most popular destination followed by the USA.

4. In 2008 81% of UK residents' trips abroad were by air, 12% by sea and 7% by the Channel Tunnel.

Transport Statistics Great Britain (DfT, 2010b) goes into more comprehensive detail for example giving some international comparisons such as Figure 1.2.

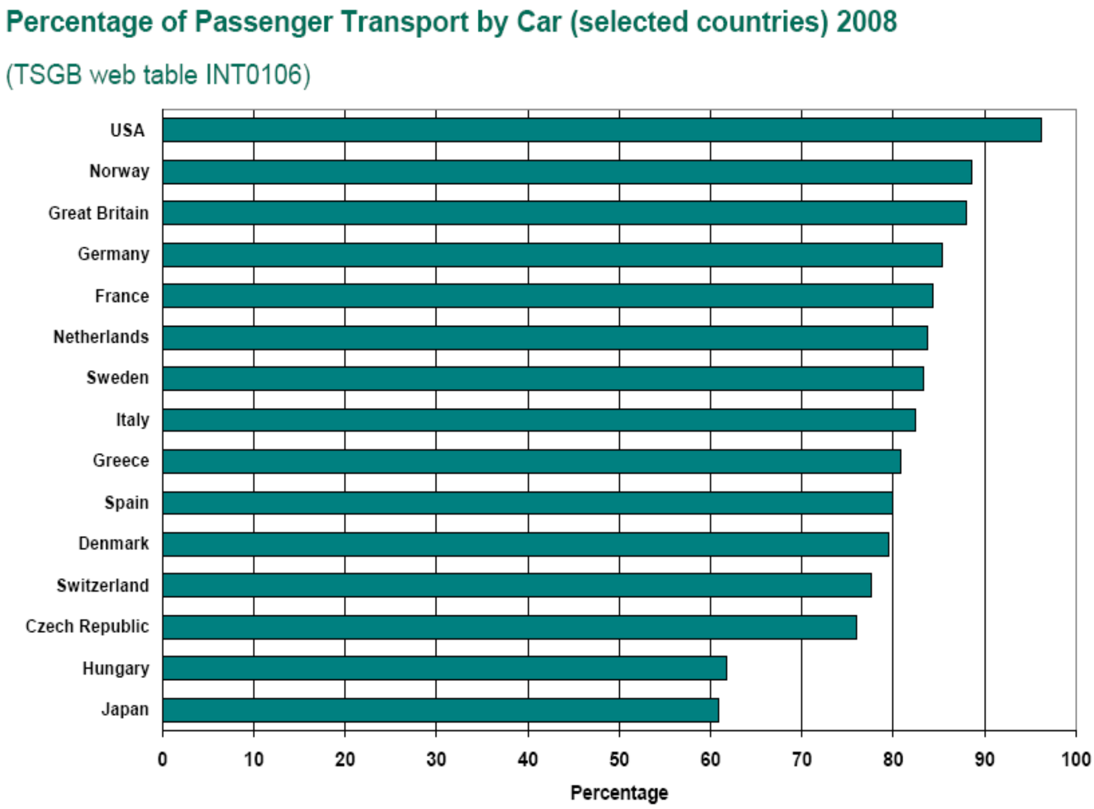

Figure 1.2 International comparison of car usage
Source: Transport Statistics Great Britain 2010

Having briefly established the size and importance of the different modes of the transport sector it is now important to review the impact of weather and climate on their operation and maintenance. An efficient, safe and cost-effective transport system is a vital goal for every country and region in the UK. Transport underpins all national economies as well as being an economic sector in its own right. All transport services are dependent upon weather and the current climate. As travel has become ubiquitous, so transport agencies have gained experience in all weather and climate types.

People normally expect to be able to travel to any part of the UK, on any day of the year, in the same elapsed time, regardless of the weather and climate. This has meant that transport agencies have had to try to become less weather sensitive in order to compete, at a time when the volume of traffic is still increasing. Weather and climate impact upon the means of transport (e.g. car or train) in a different way to the surface or space on or in which the vehicles operate.

Anticipated climate extremes such as 'dry' snow may immobilize a train engine whilst not affecting the track. On the other hand 'wet' snow might not affect the train engine but might bring down overhead electric cables. The climatic design and maintenance of roads and railway lines, therefore, present a very different problem to the climatic design of vehicles and trains.

Roads and railway lines need to be routed and airports located to avoid hazards such as frost hollows, preferential sites for fog formation and areas prone to flooding. Also they need to be designed to cope with extremes of temperature, for instance to avoid rail buckling and roads and runways 'bleeding' in hot weather. Knowledge of likely climatic extremes is vital therefore before any roads, runways or railway lines are built or upgraded.

Extremes of weather and climate are not always the most costly or dangerous. For example, zero degrees Celsius is a critical temperature because water freezes, and is most slippery at that temperature. Hence roads, rails and runways are likely to be more hazardous in climates where the zero degrees Celsius threshold is crossed most frequently. Where de-icing chemicals are applied then the critical thresholds are reduced to temperatures below zero. The reduced threshold temperatures depend upon which chemical is used (e.g. on roads salt is effective down to about minus ten degrees Celsius and urea down to about minus five degrees Celsius). In addition, more potholes are formed in roads and runways when temperatures oscillate around zero as a result of the freeze-thaw cycle. From an economic and safety point of view, it is often the variability of the climate from year to year, and the unpredictable nature of that variability, that is important.

Effective atmospheric resource management also has to bear in mind whether or not the decision to travel rests with the individual or the transport companies. The decision whether or not a train, bus, boat or aircraft will travel in severe weather depends upon the transport management. However, the individual driver can decide whether or not to use a road whatever the weather. It is unusual for roads to be closed in severe weather, although it is common for some mountain roads to be closed in winter. It is therefore potentially easier to control rail, bus, water and air transport as long as the public are kept well informed.

It is not easy to distinguish between the impact of weather and the impact of climate on transport, as most managers have to consider both. In general, the climate of a region should determine the design of infrastructure and the quantity of equipment required and labour resources that need to be allocated to maintain systems efficiently and safely, whereas the weather will determine day-to-day operational expenditure and safety.

The operational managers responsible for day-to-day activities may not have had the same level of training as the administrative managers who make the strategic decisions and plan for the future on an annual timescale. There may well be conflicts of interest concerning, for example, the introduction of new weather-related technology to decide when to salt roads or winter maintenance (e.g. the introduction of road/rail/runway/port weather information systems). New equipment may enable the performance of operational activities to be more carefully monitored by management and therefore consultation between administrative and operational staff is important to avoid resistance to the introduction of the new technology.

The management of the impact of weather and climate also depends upon whether or not the impact can be reduced. Snow and ice on a road or runway or aircraft can be treated cost-effectively and even prevented by using de-icing chemicals, whereas fog, heavy rain and high winds cannot be controlled directly. Thus fog on roads, for instance, can only be managed by reducing speed limits, which unfortunately many motorists are likely to ignore. Ultimately roads may have to be closed, which is preferable to a road having to be closed because of a weather-related accident. The sensitivity of air, rail, road and water transport to weather and climate will now be discussed in turn.

It is vital to understand the current impact of weather and climate on existing transport services before it is possible to assess the likely impact of climate change. The

Adaptation Sub-Committee, established by the Climate Change Act, state in their Progress Report (AS-C 2011, p11):

An assessment of current vulnerability is a good starting point for assessing future climate impacts, because it draws on what is already known, establishes a baseline against which changes in risk and vulnerability can be tracked over time, and helps to make the case for prompt action to reduce current risks.

1.3.1 Air transport

The UK has 20 airports which handle more than 1 million terminal passengers per year and many smaller airports particularly in the Scottish Islands. There were nearly 3 million aircraft movements across the UK in 2010 and 2.3 million tonnes of freight lifted according to the Civil Aviation Authority (http://www.caa.co.uk/docs/80/airport_data/2010Annual/Table_01_Size_of_UK_Airports_2010_Comp_2009.pdf).

Aircraft are designed to operate in all climates of the world and are therefore not likely to be directly affected by climate change in the UK. Airports are potentially likely to be more susceptible to climate change and will need to become more resilient to flooding, overheating of terminal buildings, changes in cross wind frequency, increases in severe weather and coping with delays (Pejovic *et al.,* 2009).

Modern aircraft use the atmosphere more than they suffer from it; hence the resource usage of the atmosphere far outweighs the hazard. Aircraft do still have problems in severe weather, mostly when taking off and landing and, because the aircraft use the atmosphere continually, virtually all weather parameters are important (Sasse & Hauf, 2003). In the USA 85 per cent of total delays to aircraft for periods of at least 30 minutes are weather related, and the weather is responsible for 36 per cent of the accidents. Thunderstorms account for 25.6 per cent of delays, snow/ice for 15.5 per cent, wind 18.9 per cent and poor visibility 18.7 per cent (Bromley, 1977). Most modern international airports attempt to operate every day of the year whatever the weather (Pejovic *et al.,* 2009).

Aircraft

Today, aircraft and helicopters are designed to operate virtually anywhere in the world and, as such, the climatic design is advanced. Also aircraft fly at a height through the atmosphere where the temperature may be as low as -65°C and the winds as strong as 400 knots. Most flights are 'above the weather' and although these conditions are more severe in absolute terms than at the earth's surface, the air density is much less and flying is safer. The climatic design is apparently good in so far as the airlines have an excellent safety record. Clear-air turbulence is still a problem, but quick reporting allows rerouting to avoid the problem.

Helicopters are designed to fly at low levels and therefore they are more vulnerable to severe weather. Nevertheless, they are capable of operation in severe conditions and have a reasonable safety record. Standards of vehicle maintenance are high. Most of the stress on the vehicle is encountered during take-off and landing and severe weather adds to the high 'wear and tear'. The cost of maintenance is high, but it is difficult to estimate the added cost of severe weather.

Airports and runways

Airports are designed to be kept open every day of the year in all weather conditions. International airports are huge complexes with problems in severe weather of access by road as well as keeping the runways open. At many airports, drainage can be an issue due to large expanses of concrete and tarmac, although flooding is often more of a problem on access roads (DfT, 2005). The main runway is normally orientated in the direction of the prevailing wind to assist take-off and landing. Obviously the climate will determine the frequency of wind direction, and some locations will have difficulty if there is no identifiable prevailing wind. Cross-winds are always a problem on take-off and landing.

All airports in the UK have provision for 'round the clock' snow and ice control, both for clearing runways and aircraft. De-icing chemicals, applied in advance of snow or ice formation if possible, are expensive and can cause corrosion of the runway surface. If snow is allowed to bond to the surface, damage to the runway can be caused by snow ploughs, and hence brushes are preferred. Access roads will still be ploughed and damage may be caused. There is evidence that the impact of the snow forecasts for Heathrow Airport in December 2010 were not fully appreciated until it was too late (Begg, 2011). Some airports have experimented with the use of helicopters or jet engines to try and disperse warm fogs. Some success may be achieved with thin layers of fog, but the method is rather costly and unreliable.

Weather Sensitivity and Thresholds

Aircraft

1. Temperature: Aircraft are likely to have to operate in temperatures ranging from ~ -70°C up to about 50°C. At least four thresholds are present:
    a. below ~ -52°C fuel can freeze
    b. below -30°C de-icing chemicals will not be able to keep the aircraft free of ice for take off
    c. below 0°C de-icing chemicals may have to be used to prevent ice building up on the aircraft which may hinder take-off
    d. above 25°C payloads may have to be reduced for take-off owing to the lower air density. Thus these problems mostly relate to take off.
2. Snow: Any falling snow during take-off and landing reduces visibility.
3. Wind: A lack of wind can be a problem for take-off and landing as some wind resistance is useful. Light aircraft are affected by crosswinds as low as 15 knots and, at 25 knots, even heavy aircraft can be troubled and alternative runways may have to be used. Above about 35 knots, an aircraft will have problems with any runway orientation (Beckwith, 1985).
4. Rain: Heavy rain can cause flooding and reduce visibility which may be a problem for take-off and landing.
5. Visibility: Any visibility below 800 m is a problem for take-off and landing.
6. Low cloud: A low cloud base below 60 m is a hazard to take-off and landing.
7. Humidity: High humidity above about 98 per cent is a problem if condensation or sublimation takes place, leading to possible engine-starting problems or wing icing.

Airports and runways

1. Temperature: If the runway temperature falls below 0°C and there is moisture around, then ice is a possibility on the runway. For temperatures down to ~ -5°C, urea can be used to lower the eutectic point of the moisture but below that temperature, then CMA (Calcium

Magnesium Acetate), Konsin or some other glycol-based chemical has to be used. Less chemical application (about a quarter) is needed to prevent ice formation than to melt ice and hence accurate predictions are essential. If the chemical is spread too soon, it may be washed off the runway by rain. If the runway surface temperature gets too warm, above 45°C, then the melting of asphalt may be a problem.

2. Snow: Normally anything more than a light covering of snow will be brushed off the runways but continuous brushing may be required if snow persists.
3. Wind: Strong cross-winds of greater than 30 knots may put emergency services on alert.
4. Rain: More than 50 mm an hour is likely to flood runways at Heathrow but each Airport will have a different threshold according to drainage and topography. Heavy rain can be brushed off to avoid aquaplaning on landings.
5. Visibility: Maintenance is affected below about 200m.
6. Humidity: If de-icing chemicals are hygroscopic then runways or approach roads may be made wet rather than dry, which will reduce friction on the runways or approach roads.

1.3.2 Rail transport

The rail network in the United Kingdom consists of two independent parts, that of Northern Ireland and that of Great Britain. Since 1994, the latter has been connected to mainland Europe via the Channel Tunnel. The network of Northern Ireland is connected to that of the Republic of Ireland. The National Rail network of 16,209 km in Great Britain and 303 route km in Northern Ireland carries over 18,000 passenger trains and 1,000 freight trains daily. Urban rail networks are also well developed in London and several other cities.

Climate change is likely to affect both the trains and the track and railway companies will have to become more resilient to rail buckling, rail flooding, embankment and bridge failures, carriage overheating and increased delays (Dobney, 2010).

Railways, in having their own dedicated corridor (i.e. track), could be thought to be less weather sensitive than other modes of transport. Fog, for instance, should not be a hazard if signalling systems do their job properly. However, heavy rain or snow can cause track blockages, particularly in cuttings, and cold weather affects many activities, particularly when accompanied by snow.

Although major disruptions to rail services are normally confined to a few days per year, mid-winter on-time punctuality is 6-7 per cent below that achieved for the rest of the year. The presence of snow on the ground is the most important single factor in creating delays.

Punctuality starts to deteriorate at screen minimum temperatures around +2°C, a threshold which occurs on average every other day during the winter. Overall, for about 15 per cent of the year, the weather is responsible for about half of the delay and disruption experienced (Dobney *et al.*, 2010).

Strong winds are a hazard and can bring down overhead cables, particularly if trees are blown onto them.

Rail Vehicles

Railway engines are powered primarily by either electricity or diesel. Both are designed in the UK to operate in UK conditions, and exports are no longer significant. Hence it could be argued that trains designed in more severe climates might have more climatic design features. The recent cold winters caused significant revenue losses and several design faults have been identified, such as air-cooled engines freezing, diesel fuel waxing, sliding doors freezing, passenger heating failing; suspension freezing and brakes locking. The air intake of locomotive engines caused considerable problems as discussed below.

Track

There are reduced opportunities on the rail network for diversionary routes and hence any significant climatic event can be the cause of major disruption on the network. Climatic design should ensure that the track will not buckle in hot weather, at the one extreme, and that points will not freeze or rails crack at the other (Thornes and Chapman, 2008). Considerable investment in point heaters has been made in recent years, but problems are still rife in severe winter weather. The effective design of cuttings to limit drifting snow is important, along with the use of snow fences to reduce drifting across the track. However, snow fences are expensive, and it is unfeasible to fence the entire network.

Flooding (Estuarine, coastal and pluvial) can be a major problem. Heavy rain also brings scouring problems with earthworks and bridges (DfT, 2005). Much of this infrastructure is old and the condition of hidden elements including foundations is difficult to establish. In particular, assessments of bridges are difficult with a swollen river beneath. For example, the rail bridge collapsed at Glanrhyd in October 1987 resulting in the death of four people.

Underground railways bring together a new set of problems. There is a lack of heating and ventilation on the London Underground which can exceed thermal comfort thresholds (LCCP, 2005; Mullins, 2011). In July 2003, 4000 people became trapped on the London Underground in temperatures exceeding 40°C and 637 people required treatment. Underground infrastructure is also prone to rising water tables. The London Underground is pumped daily at 630 locations (DfT, 2005). Pluvial flooding can also be a problem as seen in July 2009.

Weather Sensitivity and Thresholds

For train and track

1. Temperature: At low temperatures (below -20°C), electric trains may suffer power loss due to icing of overhead cables, or the third rail. Diesel oil may wax at temperatures below ~ -18°C. Below -3°C, it is dangerous to load coal and below 0°C, points may freeze. Rails will buckle if they get too hot, and above 50°C, speed restrictions may apply (Thornes and Chapman, 2008).

2. Snow: Above a depth of 5 cm, problems may be encountered and the effective limit of operation is 15 cm above track height.

3. Wind: If the mean wind exceeds 34 knots or gusts in excess of 60 knots are experienced, then overhead cables may be disrupted if trees or other objects are blown onto them, or directly onto the line. However, the thresholds are not clear and the DfT (2005) recommends further research into this aspect.

4. Rain: Normal movement of all rail traction should cease when the water level reaches a point 0.05 m below the top of the running rail. However,

locomotives may run on flooded sections at walking pace, provided the level of water is no more than 0.1 m above rail level.

Heavy rain, as well as causing flooding of the track and underground systems, rain may also cause landslips, or bridge damage. The thresholds depend upon previous rainfall as well as local geography.

5. Visibility: This is not really a problem unless people are unable to get to the stations, or signals cannot be seen (SPADS: Signals Passed At Danger).
6. Humidity: Problems are associated with starting engines affected by condensation or sublimation in cold weather.

1.3.3 Road transport

Some 88 per cent of inland freight is carried by road transport in the UK, and 93 out of every 100 passenger kilometres are travelled by road. Hence, road transport is the most important form of transport for the UK economy and weather and climate interference is of great consequence. Climate change may lead to significant problems such as flooding, infrastructure damage, road melting, more severe weather and an inevitable increase in delays (Chapman, 2007; Thornes and Chapman, 2008).

Vehicles

Cars, vans, lorries and buses are expected to perform in all weather conditions with a minimum of fuss. The main areas of concern for drivers relate to the starting of the vehicle on a cold damp morning, and the grip that the tyres have on the road surface. Automatic chokes and fuel injection to give instant starting are now common, but certainly not universal, and of course vehicle maintenance responsibility of individual drivers. Radial tyres and advanced braking systems offer a considerable improvement to road safety, by reducing stopping distances on wet roads.

Icy roads are still a problem though despite winter maintenance since not all roads are treated and weather forecasts are never going to be 100 per cent accurate. Studded tyres and snow chains are still used in snowier climates but have been banned by many countries owing to the damage caused to the road surface. It is also important that engines do not overheat in warm summer weather, and that batteries do not go flat in winter.

Roads and Bridges

Roads and bridges are treated together in this section as the conditions suffered are similar. Climatic design is already incorporated in roads. For example, motorways are built to avoid fog-prone areas and cuttings are topographically designed to avoid snow drifts. Similarly, the M62 across the Pennines has a special design of crash barriers to avoid trapping snow.

The hot weather of July 2003 caused asphalt roads to 'bleed' and stone dust had to be spread to prevent the surface breaking up, although warm and dry weather is very beneficial for construction activities owing to a lack of weather interference. However, there are issues here with respect to working conditions for maintenance personnel.

The winter maintenance of roads is carried out by the Highways Agency, county councils and district authorities. The recent run of severe UK winters makes it difficult for winter maintenance planning. Should engineers gear up for another winter as severe as 2009/10, 1980/81, 1978/9 or 1962/3, or should they plan for an average winter with reserve resources when required?

Owing to problems related to the corrosion of structures, the elevated section of the M6 in the Midlands is treated with urea, but there were problems in the cold weather of January 2010 as urea is only effective in preventing ice formation down to about -5°C. Steel-deck bridges like the Severn Bridge in England and the Kessock Bridge in Scotland use Konsin which is non-corrosive.

As with runways, it only requires about a quarter of the amount of de-icing chemical to prevent ice formation than to melt ice, owing to the extra energy required to melt ice. Hence an accurate forecast of the likely formation and timing of ice may enable pre-salting to be carried out (i.e. application of de-icing chemical before ice formation). There are several other thresholds that the engineer is interested in apart from 0°C and their probability can also be relayed to the engineer. It has been shown that there can be considerable differences between air and road temperatures (Thornes and Chapman, 2008).

For roads, the critical thresholds are as follows:

1. Air/Road temperature: Diesel waxing might be a problem below -15°C. The British Standard is -15°C but a recent survey found that of 11 oil companies whose diesel fuel was tested, all functioned down to -16°C and three operated below -20°C. Until the cold weather of the winter of 1982/3, legislation only required diesel fuel to be operative down to -9°C.

   Below about -10°C, rock salt is not very effective and below about -5°C urea is no longer an effective de-icer, whereas at 0°C ice is at its slipperiest. Below 10°C asphalting and concreting are a problem if there is also a wind above about 25 knots. The wind-chill cools the surface too quickly and the surface may well have a short lifespan. Above 35°C, surface dressing of roads must be suspended as the asphalt will not cool sufficiently quickly.

2. Snow: More than 6 cm of snow will require snow ploughs to be engaged. Lesser quantities will normally be dispersed by traffic, or a pre-salt will be sufficient to melt it.

3. Wind: Gusts above 30 knots cause problems for suspension bridges, high-sided vehicles, construction cranes, signs and falling trees may block roads. Bridges may be closed if wind speeds exceed 35 knots.

4. Rain: Flooding is the main issue causing blocking of roads and often requires expensive cleaning up operations afterwards. Rainfall also prevents road repairs.

5. Visibility: All road repairs have to stop in poor visibility. It is always argued that drivers should reduce speed in poor visibility but evidence suggests that this is rarely the case unless visibility gets down below about 100 m.

6. Humidity: The salt used on roads is hygroscopic above 80 percent humidity. In the UK, the average humidity in winter is usually above 80 per cent, and therefore salt often remains in solution making the roads wet and more slippery than if they were dry. Hoar frost and condensation on the inside and outside of vehicles can considerably reduce visibility for a time, and rock salt splashed onto windscreens can be problem. Visibility can also be reduced by low sun angles around dawn and sunset if there is little cloud around.

1.3.4 Water transport

Approximately 95% of freight enters the UK by sea (75% by value). The UK merchant fleet has about 700 ships with a total of about 17 million metric tons deadweight (DfT, 2009). Passenger ferries operate internationally to nearby countries such as France, the Republic of Ireland, Belgium, the Netherlands, Denmark, Spain. Cruise ships depart from the UK for destinations worldwide. The Solent is a world centre for yachting and home to largest number of private yachts in the world. There are currently just over 3,000 km of waterways in the United Kingdom, and the primary use is recreational.

Any work at sea is extremely weather-sensitive, ranging from the most common activity - the operation of a ship going as efficiently as possible from one point to another - to the most esoteric - such as underwater construction and the operation of oil drilling, production, and transportation. Weather forecasts, as well as including normal projections of wind, temperature and precipitation, also have to include forecasts of the routine and violent action of waves, tides and currents.

Large vessels

These are normally designed to operate globally and must be designed to withstand most conditions, including periods of violent weather. For this reason, a large percentage of ships tend to be over-engineered with beneficial safety margins offset by sometimes undesirable weight penalties and maintenance problems. The safety and life expectancy of a vessel is very much dependent on the initial design. This has a fundamental bearing on both the capacity to withstand severe weather and the 'ongoing' maintenance procedures. Maintenance schedules may depend to a certain extent on the climatologic regime under which a vessel normally operates.

The effect of significant anomalies is likely to be proportional to any non-routine cumulative weather stress. In any environment where competition is fierce and profit margins traditionally slender, there may be pressure to produce more cost-effective designs in the future. A good understanding of the dynamics and variations of weather-related stress will therefore be essential in producing effective and safe designs.

Ultimately severe weather can (possibly in combination with other circumstances) produce catastrophic loss of a vessel no matter how large or well equipped it may be. Thankfully, such occasions are relatively rare and, in conjunction with improvements in weather forecasting technology, can usually be avoided (Weather Routing). Apart from the obvious sensitivity to violent events, even large vessels are sensitive to normal weather variations. There can be a profound effect on stability, journey time, safety of cargo and fuel efficiency. Prior knowledge of the weather along a route can therefore become a powerful management tool, contributing towards a safer, more efficient and cost-effective operation.

Smaller vessels

These normally operate in a restricted environment and therefore their design can be influenced by a number of factors. These include:

1. Climatologic domain
2. Usage
3. Capacity
4. Speed
5. Endurance.

Small vessels, including a number of specialized craft, may only operate under certain conditions but also include some which may have to withstand extreme conditions that are taken for granted by larger vessels.

Limitations of size and price mean that the majority of small vessels are more weather sensitive than their larger cousins. Winds as low as 22 knots can cause problems for certain crafts and therefore weather information is very important. Around the UK, competition from the Channel Tunnel has created a resurgence of interest in fast, large-capacity craft. These offer minimal time penalties over the tunnel traffic, potentially lower cost and more point-to-point flexibility. The quest for speed does, however, make such craft weather sensitive, with limits depending on the size of the type of craft.

Examples of vessels which normally operate in a restricted environment are:

1. Hovercraft
2. Jetfoils
3. Catamarans
4. Small charter vessels.

The design of hovercraft, jetfoils and catamarans is usually the best possible compromise between speed, capacity and weather tolerance. The fact that such vessels are designed for speed tends to make them more weather sensitive than the larger and more traditional mono-hull versions.

Apart from the well-accepted hovercraft and jetfoils, effort continues into perfecting the more recent wave-piercing catamaran concept. Generally such vessels become inoperative with wind speeds in the range of 35-45 knots and significant sea heights in the range 2.5-4 metres. The likely conditions in a particular area can also have a very important influence on the exacting design technology used on these highly specialized craft. Subtleties such as wave period and direction become just as important as the more obvious wind speed and wave height parameters.

Ports/Harbours

There are about 120 commercial ports in the UK including all purpose ports like London and Liverpool, ferry ports like Dover and specialised container ports such as Felixstowe. The UK ports industry is one of the largest in Europe handling around 500 million tonnes of freight per year and about 23 million international passengers. The top 16 ports handle about 80% of the tonnage.

Land-based infrastructure will provide an initial logical basis for choosing potential harbour sites, with exposure and related climatology also having an important influence. Strong winds, whilst possibly favouring certain directions, can come from any direction. The controlling factor (when designing the harbour itself) therefore tends to be providing shelter from the predominantly worst sea conditions and, in particular, heavy swells when relevant.

The weather can affect the day-to-day running of a harbour with wind and rain critical to loading and docking strategy. On certain occasions severe weather can close a port completely with high seas making it dangerous for vessels to negotiate the harbour entrance. Although rare, advance notice of the likely onset and cessation of these events can facilitate beneficial operational decisions from both the operator and client points of view.

There is insufficient information to list individual weather thresholds but certainly all sea-going vessels are weather sensitive, with a large variation of capability across the spectrum of vessels.

1.3.5 Overlap between modes

There is considerable overlap between the four transport modes discussed above, for instance road transport is fundamental to get the public and staff to airports, railway stations and ports. In difficult weather conditions, one form of transport may have to substitute for another, for example, in deep snow, air transport may provide the only access into an area. If transport is disrupted, then there is a considerable cascade effect for other industrial sectors. There are clear cascade effects with those industrial sectors that rely on transport for the movement of labour and materials, and some recent innovations in this area may increase weather sensitivity in manufacturing industry. For example, 'just-in-time' production, where stockpiles of material are kept to a minimum, reduces any margin of flexibility if transport is disrupted.

The cost of delays is enormous. Delays due to road works have been estimated by the Confederation of British Industries (CBI) to cost UK industry up to £20 billion per annum. Delays due to severe weather might also be measured in billions of pounds in a severe winter. There is therefore a need to get weather information to the transport users as well as the transport managers. Today in-car information systems mean that drivers can obtain 'real-time' weather routing information for roads around the UK.

Most transport services require daily weather forecast information but 2 to 5 day planning forecasts are important to aid planning for emergencies. However, agencies should be prepared for false alarms as the new technology is not infallible. New technology may push back thresholds but changes may make the transport system vulnerable in different ways if, for example, a new system relies on computer systems that may occasionally fail. Staff training is vital for emergency procedures in the use of new technology.

Contingency plans are also very important and need to be continuously updated. The spatial variability of extreme weather events needs to be carefully monitored and the information passed effectively to the public so that they know which transport services are operable, and how timetables have been affected. The use of the internet, local radio and television is to be encouraged, so that the public are effectively informed at home before they commence a journey, during a journey if possible and at the transport nodes.

It is accepted that adverse weather conditions result in a reduction in performance of transport systems (Mills & Andrey, 2003; Arkell & Darch, 2006; Peterson *et al.,* 2008; Koetse & Rietveld, 2009). Peterson *et al.* (2008) highlight the range of impacts that projected climate change may have on all modes of transportation.

Indeed, the majority of current climate effects on the UK transport sector may occur with increasing frequency under future scenarios. For example, extreme high temperatures will increase buckling on railways and may result in a need for air conditioning for signalling (DfT, 2005). There may also be increasing problems with thermal comfort on underground rail. High temperatures will cause increased rutting on roads, although the higher quality materials used on airport runways should prevent this from becoming an issue for aviation. However, there are possible issues with runway length as the reduced density of air in higher temperatures may mean older planes may struggle to take off in time, although new aircraft should not have any problems (DfT, 2005).

For all sectors, climate change may provide an opportunity to reduce winter maintenance costs, however there is a need to protect against complacency. As the winters of 2009/10 and 2010/11 have shown, road and airport closures due to snow can still be a cause of major disruption as at Heathrow in December 2010 (Quarmby *et al.,* 2010, Begg, 2011).

An increased intensity of storms would mean an increased risk of flooding from rivers and the sea. Problems in urban areas would be particularly acute where drains may be old and badly maintained. Road and rail embankments may also be at increased risk of subsidence (DfT, 2005). Railways face the added problem of leaves on the line. The timing of autumn storms and frosts may change the nature of leaf-fall, but the exact nature of this is unknown (Eddowes *et al.,* 2003).

In summary, climate change is likely to ensure that impacts on transport will happen more frequently. Infrastructure will need to be adapted to new standards and improved contingency planning is likely to be required to mitigate against the impacts of catastrophic extreme events.

1.4 Policy context

The UK Government is committed to adapting transport infrastructure to a changing climate and the report *Climate Resilient Infrastructure: Preparing for a Changing Climate* (DEFRA, 2011b) sets out the required recommendations. An effective and reliable transport network is vital for the growth of the economy.

The main responsibility for transport policy at a national level is with the Department for Transport (DfT) which includes the UK's roads, rail, aviation and ports. Elements of transport infrastructure management are devolved to country level including Transport Scotland, the Welsh Government and the Northern Ireland Executive, who operate and manage the main road networks in those countries, setting their own policy for each devolved administration.

The UK transport sectors for road, rail, ports and airports are managed by a mixture of public and private sector organisations, with most regulations focusing on safety and security. Strategic decisions are made by governments and local authorities, some of which are in response to European directives. Local authorities have a legal duty to maintain local roads (98% of the road network) whilst the Highways Agency manages the strategic network of motorways and trunk roads, As road transport is a devolved matter, Scotland, Wales and Northern Ireland largely plan their own road networks. Rail is also devolved to Scotland (other than rail security) and Northern Ireland.

Much of the regulation pertaining to aviation and shipping is developed – through a process of negotiation in which the UK and other states actively engage – in the relevant United Nations bodies, the International Civil Aviation Organization (ICAO) and the International Maritime Organization (IMO). These international regulations have effect in the UK when they are implemented in national legislation. The local consequences for airports and ports are agreed at a national level. Maritime transport is a reserved matter, for which the UK Government is responsible. Transport emergency planning remains almost unregulated, as the majority of sector regulators focus on internal safety and security. The Government has limited powers over management of transport services, which are mostly managed by the private sector.

The main stakeholders in the transport sector in England and Wales are the DfT, its executive agencies (notably the Highways Agency and the Maritime and Coastguard Agency), Network Rail, the Civil Aviation Authority, local authorities and transport users, recognising that transport infrastructure and operation of services supports activity across a range of other sectors and underpins the running of an efficient national economy. Transport for London (TfL) is the local government body responsible for most aspects of the transport system in Greater London. Its role is to implement the transport strategy and to manage transport services across London.

In addition, the Transport Security and Strategy Division manage the DfT's relationship with the Cabinet Office regarding the Government's work on civil contingency planning. The aim is to ensure that the DfT and transport industry are effectively prepared to respond to and recover from emergencies such as those resulting from extreme weather events and other natural hazards. As highlighted in the DfT *Climate Change Adaptation Plan for Transport* (DfT, 2010a and 2011), adapting the UK's transport system to climate change is an important part of delivering transport infrastructure that works both now and in the future and continues to support national economic competitiveness and growth.

The Highways Agency, an Executive Agency of DfT, has produced its own adaptation strategy (Highways Agency, 2009) but the DfT does not prescribe how local authorities manage their highways although it has influence through working with stakeholders to produce guidance. Current DfT guidance relevant to adaptation includes *The effects of climate change on highway pavements and how to minimise them* (DfT, 2008) and *Maintaining Pavements in a Changing Climate* (Willway *et al.*, 2008).

The Government announced its intention in March 2011 to develop a new sustainable framework for UK aviation which would take into account changes to the sector – both in the UK and globally – since the 2003 *Future of Air Transport* White Paper was published, and incorporates the latest evidence on key issues such as air passenger demand and climate change impacts. The draft aviation policy framework will be published for consultation in spring 2012, with adoption of the framework in spring 2013.

In 2007, DfT announced a new framework for planning of transport called *Towards a Sustainable Transport System* (DfT, 2007) which highlights that it is vital that the transport systems adapt to climate change which cannot be avoided in order to both minimise disruption and to ensure safety.

The DfT is working to embed adaptation in decision making through use of processes such as National Policy Statements. National Policy Statements (NPS) are an important part of reforms to the planning system for major infrastructure introduced by the Planning Act 2008. The Act includes a duty on Ministers to ensure that the statements are drawn up with the objective of contributing to adaptation to climate change (amongst other things).

- The Ports National Policy Statement[11] (NPS) which was laid before Parliament in October 2011 expects port developers to fulfil adaptation requirements. It is expected that the impacts identified will affect the safe operation of UK ports and their susceptibility to flooding.

- The National Networks NPS will set out policy in relation to nationally significant infrastructure on the strategic road network, rail network and rail freight interchanges over a certain size. The NPS will set out the DfT objectives for sustainable development, mitigation and adaptation to climate change. The inclusion of adaptation will ensure that developments on national networks address, avoid, mitigate or compensate for the adverse impacts of climate change.

[11] http://assets.dft.gov.uk/publications/national-policy-statement-for-ports/111018-ports-nps-for-das.pdf

- The *Major Infrastructure Planning Reform Work Plan*[12], published by the Department for Communities and Local Government in December 2010, made clear the Government's priority to create a sustainable framework for UK aviation, rather than to produce a national policy statement on aviation.

The DfT DAP published in 2010 for 2010-2012 sets out adaptation actions for the department, including current or planned research to underpin policy development. At the same time, the DfT is working with a range of organisations and also provides funding to bodies such as the Rail Safety Standards Board (RSSB) to develop research which can help with the development of adaptation and build future resilience to climate change impacts. The topics of this research therefore have the potential to be the focus of future policy and include:

- The impact of temperature change on the railway with the aim of stimulating development of adaptation measures to build future resilience.
- Foresight studies on sustainable development which identifies long term planning and provides tools and techniques for the rail industry to determine potential future strategies.
- Quantifying the costs and benefits of climate change and identifying appropriate adaptation measures for the rail network.
- Assessing how passenger comfort and safety (compared to other safety risks) may be increasingly threatened on trains during hot weather in the event of train failure.

Scotland's *Climate Change Adaptation Framework - Transport Sector Action Plan* has recently been published[13] and contains a series of action points to be implemented at three levels:

1 - Understanding the consequences of a changing climate.

2 - Equip decision makers with skills and tools.

3 - Integrate adaptation into public policy and regulation.

Legislative powers in relation to "Highways and Transport" are devolved to the Welsh Government. However, there are a number of notable exceptions including: policing; road signs; vehicle construction and use regulations; vehicle testing and licensing; and driver testing and licensing, which remain reserved to the UK Government. The *Highways Act 1980* (as amended) establishes that the Welsh Government is the highway authority for trunk roads (motorways and some A roads), while the 22 County and County Borough Councils are the highway authority for all other roads.

With regard to rail, the Welsh Government shares responsibility for the Wales and Borders franchise with the Secretary of State for Transport, and is able to develop and fund rail infrastructure enhancement schemes and new rail passenger services.

The Transport (Wales) Act 2006 required the Welsh Government to publish a strategy, setting out policies for the "safe, integrated, sustainable, efficient and economic transport facilities to, from and within Wales". The objectives of the Wales Transport Strategy *One Wales: Connecting the Nation* (2008) are delivered at a national level through the *National Transport Plan* (NTP) (2010), and at a regional level through the Regional Transport Plans prepared by the Regional Transport Consortia. A transport system that is adapting to the impacts of climate change is a key long-term outcome of the Wales Transport Strategy.

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[12] http://www.communities.gov.uk/documents/planningandbuilding/pdf/1803122.pdf
[13] http://www.scotland.gov.uk/Resource/Doc/175776/0114931.pdf

A recent report *Preparing for a changing climate in Northern Ireland* includes a section on adaptation measures for transport which emphasises the need to monitor and improve infrastructure and emergency planning[14].

In its *Corporate & Business Plan 2010 -2011* the Department for Regional Development in Northern Ireland recognises the need to continue to work to ensure that the transportation services which it delivers and the ways in which it delivers them promote sustainability, achieving a proper balance between economic, environmental and social needs.

The *Regional Transportation Strategy for Northern Ireland 2002-2012* sought to address the years of underinvestment in transportation and at the same time initiated programmes to promote sustainable transport and to encourage modes of travel other that the private car for appropriate journeys. A revised Regional Transportation Strategy now being developed seeks to build on what has been achieved so far. It proposes a range of high level aims and strategic objectives that will support the economy in an integrated, equitable and environmentally sensitive manner.

The intention behind the revised Strategy is to rebalance transportation priorities and provide greater emphasis on sustainability in the travel choices NI citizens make. Transport users must be able to make better informed choices in how they travel and see value in a seamless interchange between services, an effective supporting infrastructure and a greater awareness of the environmental consequences of their choices. The new strategic approach will be published in autumn 2011[15].

Finally, the *Climate Change Act 2008* established the 'Adaptation Reporting Power' for the UK and Welsh Governments. As a result, a number of transport organisations across the sector are developing their adaptation reports, setting out how climate may impact their business and what actions they have identified to manage or mitigate the identified risks and opportunities. These reports were submitted and reviewed during 2011 and will contribute to the development of the National Adaptation Programme for England only and non-devolved matters alongside the results of the national Climate Change Risk Assessment. The organisations that have produced ARP adaptation reports are:

Table 1.1 List of the transport organisations producing adaptation reports

The reports are published on the Defra website:
http://www.defra.gov.uk/environment/climate/sectors/reporting-authorities/reporting-authorities-reports/

Rail
Eurotunnel
Network Rail Infrastructure Ltd
Office of Rail Regulation
TfL
Aviation
Civil Aviation Authority
NATS Holdings Ltd
Strategic Airport Operators (Scotland, England & Wales)
Birmingham International Airport
Cardiff International Airport

[14] http://www.doeni.gov.uk/preparing_for_a_climate_change_in_northern_ireland.pdf
[15] http://www.drdni.gov.uk/rts

East Midlands Airport
Edinburgh Airport
Glasgow International Airport
London Gatwick Airport
London Heathrow Airport
London Luton Airport
London Stansted Airport
Manchester International Airport
Harbour Authorities (England and Wales)
ABP Harbour Authority Hull
ABP Harbour Authority Humber
ABP Harbour Authority Immingham
ABP Harbour Authority Southampton
Dover Harbour Board
Harwich Haven Authority
Mersey Docks and Harbour Company
Milford Haven Port Authority
PD Teesport Ltd
Port of London Authority
Port of Sheerness Ltd
The Felixstowe Dock and Railway Company
Lighthouse Authorities (England, Scotland and Wales)
Corporation of Trinity House of Deptford Strond
Northern Lighthouse Board
Volunteer Reports
Highways Agency
Maritime & Coastguard Agency

1.5 The structure of this report

This report describes the methodological steps taken in the transport sector analysis. These steps include:

- An overview of the methods used for impact selection and analysis in the CCRA (Chapter 2).
- A list of impacts in the transport sector, referred to as the 'Tier 1' list (Section 3.1 and Appendix 1).
- The Tier 2 list of impacts and consequences, which are the impacts selected for analysis (Section 3.3 and Appendix 4).

- Identification of ‘risk metrics’ used for the analysis (Section 3.4). These are measures for the consequences associated with the impacts of climate change.
- Relevant risk metrics covered in other reports (Section 3.6).
- Development of response functions, which show how the metric values are affected by climate change variables (Chapter 4).
- Calculation of the consequences of climate change for the selected risks and climate change scenarios (Chapter 5).
- Discussion of socio-economic dimensions that could affect the sector risks covered by the analysis (Chapter 6).
- Estimation of the economic impacts of climate change for the selected consequences (Chapter 7).
- Consideration of adaptive capacity within the sector (Chapter 8).
- Discussion of the findings (Chapter 9).
- Conclusions (Chapter 10).

The report structure broadly follows the risk assessment steps in Figure 2.2 as described in detail in the CCRA Method Report (Defra, 2010b).

Each section provides a summary of the work undertaken for each step and ‘sign posts’ additional information that includes stand-alone reports and the additional information contained in Appendices to this report.

2. Methods

2.1 Introduction: CCRA Framework

The overall aim of the CCRA is to inform UK adaptation policy, by assessing the main current and future risks (threats and opportunities) posed by the current climate and future climate change for the UK to the year 2100. The overall approach to the risk assessment and subsequent adaptation plan is based on the UK Climate Impacts Programme (UKCIP) Risk and Uncertainty Framework (UKCIP, 2003). The framework comprises eight stages as shown in Figure 2.1. The CCRA has undertaken the Stages 1, 2 and 3 as outlined below. Stages 4 and 5 will be addressed as part of a separate economic assessment, entitled the 'Economics of Climate Resilience', and the remaining stages will be implemented by the UK Government and Devolved Administrations. The framework presents a continual process that can adapt as new evidence and policy emerges; in the case of the CCRA the process will be revisited every five years.

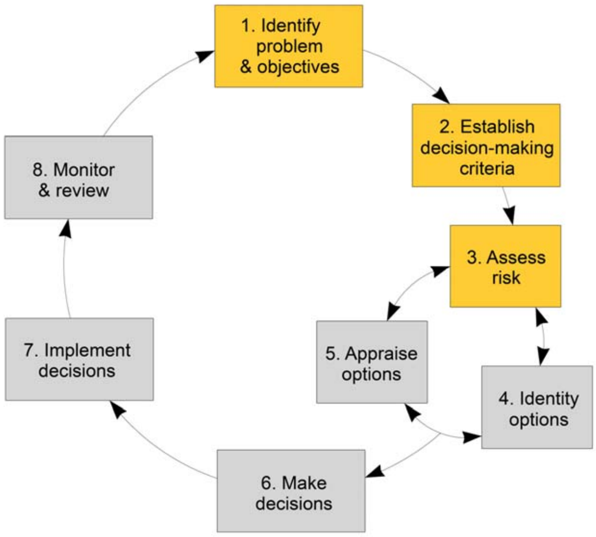

Figure 2.1 Stages of the CCRA (yellow) and other actions for Government (grey)
Adapted from UKCIP (2003)

- Stage 1 is defined by the aim of the CCRA project, to undertake an assessment of the main risks (including both threats and opportunities) posed by climate change that will have social, environmental and economic consequences for the UK.
- Stage 2 established decision-making criteria for the study, which were used to inform the selection of impacts for analysis in Stage 3. These criteria are the social, environmental and economic magnitude of consequences and the urgency of taking adaptation action for UK society as a whole.
- Stage 3 covers the risk assessment process. This involved a tiered assessment of risks with Tier 1 (broad level) identifying a broad range of potential impacts and Tier 2 (detailed level) providing a more detailed analysis including quantification and monetisation of some impacts. A list of climate change impacts was developed based on eleven sectors with further impacts added to cover cross-cutting issues and impacts which fell between sectors. This list of climate change impacts is referred to as the

'Tier 1' list of impacts. This list contained over 700 impacts – too many to analyse in detail as part of this first CCRA. A consolidated list of the highest priority climate change impacts for analysis was developed and referred to as the **'Tier 2 list of impacts'**. This report presents the risk assessment for Tier 2 impacts.

The background to the framework and the approach used for each of the first three stages is set out in more detail in the CCRA Method Report (Defra, 2010a). This chapter aims to summarise the CCRA method for the risk assessment stage (Stage 3 in the framework above) because this includes the specific steps for which results are presented in this report.

2.2 Outline of the method used to assess impacts, consequences and risks

The risk assessment presented in this report is the focus of Stage 3 in the CCRA Framework (see Figure 2.1). This was done through a series of steps as set out in Figure 2.2. These steps are explained in Sections 2.3 - 2.7 below and are discussed in more detail in the CCRA Method report (Defra, 2010b).

The components of the assessment sought to:

- **Identify and characterise the impacts** of climate change

  This was achieved by developing the Tier 1 list of impacts, which included impacts across eleven sectors as well as impacts not covered by the sectors and arising from cross sector links (see Section 3.1 of this report).

- **Identify the main risks** for closer analysis

  This involved the selection of Tier 2 impacts for further analysis from the long list of impacts in Tier 1. Higher priority impacts were selected by stakeholder groups based on the social, environmental and economic magnitude of impacts and the urgency of taking action (see Section 3.2 of this report and Section 2.5 below).

- **Assess current and future risk**, using climate projections and considering socio-economic factors

  The risk assessment was done by developing 'response functions' that provide a relationship between changes in climate with specific consequences based on analysis of historic data, the use of models or expert elicitation. In some cases this was not possible, and a narrative approach was taken instead. The UKCP09 climate projections and other climate models were then applied to assess future risks. The potential impact of changes in future society and the economy was also considered to understand the combined effects for future scenarios. (See Chapters 4 to 6 of this report and Section 2.6 below.)

- **Assess vulnerability** of the UK as a whole

  This involved:

  i. a high level review of Government policy on climate change in the eleven sectors (see Chapter 1 of this report)

  ii. a high level assessment of social vulnerability to the climate change impacts (see Appendix 2 of this report)

iii. a high level assessment of the adaptive capacity of the sectors (see Chapter 8 of this report and Section 2.4 for an overview of the approach, below).

- **Report on risks** to inform action

  This report presents the results of the risk assessment for the transport sector. The results for the other ten sectors are presented in similar reports and the CCRA Evidence Report (CCRA, 2012) draws together the main findings from the whole project, including consideration of cross-linkages, and outlines the risks to the UK as a whole.

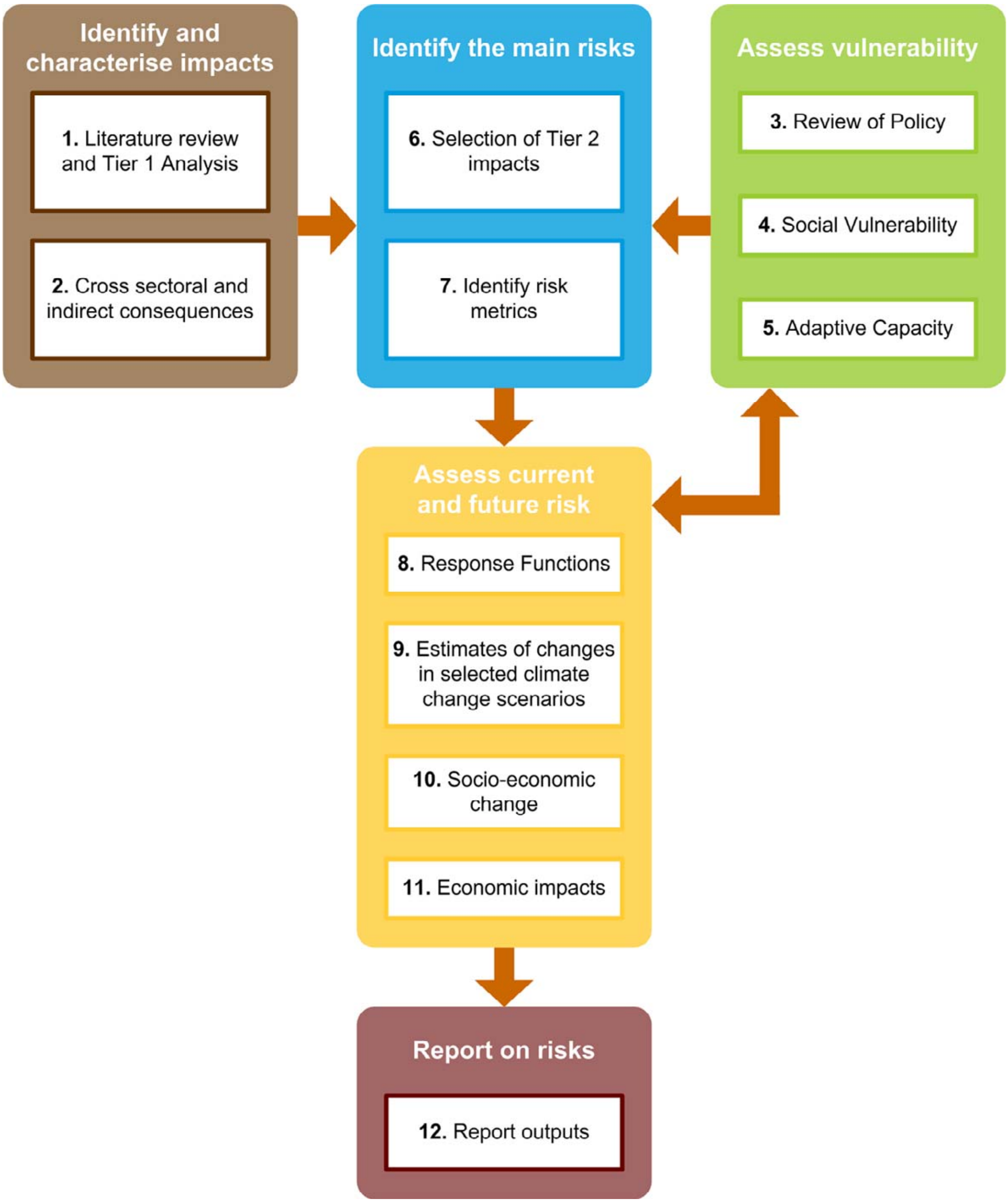

Figure 2.2 Steps of the CCRA Method (that cover Stage 3 of the CCRA Framework: Assess risks)

2.3 Identify and characterise the impacts

Step 1 – Literature review and Tier 1 analysis

This step scoped the potential impacts of climate change on the UK based on existing evidence and collating the findings from literature reviews, stakeholder participation through workshops, correspondence with wider stakeholders and soliciting expert opinion. This work developed the Tier 1 list of impacts (see Appendix 1). The Tier 1 impacts have not been analysed in detail; high level discussion of these impacts is provided in Chapter 3 of this report.

Step 2 – Cross sectoral and indirect impacts

The Tier 1 lists for the eleven sectors in CCRA were compared and developed further to include cross-sectoral and indirect impacts. This was done by 'Systematic Mapping', which sets out a flow chart to link causes and effects in a logical process. The impacts that were identified in this step were added to the Tier 1 list of impacts.

2.4 Assess vulnerability

Step 3 – Review of Policy

Government policy on climate change develops and changes rapidly to keep pace with emerging science and understanding of how to respond through mitigation and adaptation. This report includes an overview of selected relevant policy in Chapter 1 as this provides important context for understanding how risks that are influenced by climate relate to existing policies. This information will be expanded in the Economics of Climate Resilience project and the National Adaptation Programme.

Step 4 – Social Vulnerability

The vulnerability of different groups in society to the climate change risks for each sector was considered at a high level through a check list. The completed check list for the transport sector is provided in Appendix 2. This information is provided for context; it is not a detailed assessment of social vulnerability to specific risks. Note that this step is different from Step 10, which considers how future changes in society may affect the risks.

Step 5 – Adaptive Capacity

The adaptive capacity of a sector is the ability of the sector as a whole, including the organisations involved in working in the sector, to devise and implement effective adaptation strategies in response to information about potential future climate impacts. A summary of the adaptive capacity assessment is provided for context in Chapter 8.

2.5 Identify the main risks

Step 6 – Selection of Tier 2 impacts

The Tier 1 list of impacts for each sector that resulted from Step 2 (see above) was consolidated to select the higher priority impacts for analysis in Tier 2. Firstly, similar or overlapping impacts were grouped where possible in a simple cluster analysis, which is provided in Chapter 3. Secondly, the Tier 2 impacts were selected using a simple multi-criteria assessment based on the following criteria:

- the social, economic and environmental magnitude of impacts
- overall confidence in the available evidence

- the urgency with which adaptation decisions needs to be taken.

Each of these criteria were allocated a score of 1 (low), 2 (medium) or 3 (high) and the impacts with highest scores over all criteria were selected for Tier 2 analysis. The scoring for each sector was carried out based on expert judgement and feedback from expert consultation workshops (or telephone interviews). Checks were carried out to ensure that a consistent approach was taken across all the sectors. The results of the scoring process are provided in Appendix 3.

Step 7 – Identifying risk metrics

For each impact in the Tier 2 list, one or more risk metrics were identified. Risk metrics provide a measure of the impacts or consequences of climate change, related to specific climate variables or biophysical impacts. For example, in the transport sector, one of the impacts identified is 'flood disruption/delay to road traffic'. The risk metric identified to measure the consequences of this impact included the costs of disruption and delay using data from literature. The risk metrics were developed to provide a spread of information about economic, environmental and social consequences. The metrics have been referenced using the sector acronym and a number; the transport sector metrics are referenced as TR1 to TR6.

2.6 Assess current and future risk

Step 8 – Response functions

This step established how each risk metric varied with one or more climate variables using available data or previous modelling work. This step was only possible where evidence existed to relate metrics to specific climate drivers, and has not been possible for all of the tier 2 impacts. This step was carried out by developing a 'response function', which is a relationship to show how the risk metric varies with change in climate variables. Some of the response functions were qualitative, based on expert elicitation, whereas others were quantitative.

Step 9 – Estimates of changes in selected climate change scenarios

The response functions were used to assess the magnitude of consequences the UK could face due to climate change by making use of the UKCP09 climate projections. This step used the response functions to provide estimates of future risk under three different emissions scenarios (high carbon emissions, A1FI; medium emissions, A1B; low emissions, B1; see http://ukclimateprojections.defra.gov.uk/content/view/1367/687/ for further details) and for three probability levels (10, 50 and 90 percent, see http://ukclimateprojections.defra.gov.uk/content/view/1277/500/ for further details).

All of the changes given in the UKCP09 projections are from a 1961-1990 baseline.

The purpose of this step is to provide the estimates for the level of future risk (threat or opportunity), as measured by each risk metric.

Step 10 – Socio-economic change

It is recognised that many of the risk metrics in the CCRA are influenced by a wide range of drivers, not just by climate change. The way in which the social and economic future of the UK develops will influence the risk metrics. Growth in population is one of the major drivers in influencing risk metrics and may result in much larger changes than if the present day population is assumed. For some of the sectors where this driver is particularly important, future projections for change in population have been considered to adjust the magnitude of the estimated risks derived in Step 9.

For all of the sectors, a broad consideration has been made of how different changes in our society and economy may influence future risks and opportunities. The dimensions of socio-economic change that were considered are:

- Population needs/demands (high/low)
- Global stability (high/low)
- Distribution of wealth (even/uneven)
- Consumer driven values and wealth (sustainable/unsustainable)
- Level of Government decision making (local/national)
- Land use change/management (high/low Government input).

The full details of these dimensions and the assessment of the influence they have on the transport sector is provided in Chapter 6. Note that this step is different from Step 4, which considers how the risks may affect society; whereas this step considers how changes in society may affect the risks.

Step 11 – Economic impacts

Based on standard investment appraisal approaches (HM Treasury, 2003) and existing evidence, some of the risks were expressed as monetary values. This provides a broad estimate of the costs associated with the risks and is presented in Chapter 7 of this report. A more detailed analysis of the costs of climate change will be carried out in a study on the Economics of Climate Resilience[16].

2.7 Report on risks

Step 12 – Report outputs

The main report outputs from the work carried out for the CCRA are:

- The eleven sector reports (this is the sector report for the transport sector), which present the overview of impacts developed from Tier 1 and the detailed risk analysis carried out in Tier 2.
- The Evidence Report, which draws together the main findings from all the sectors into a smaller number of overarching themes.
- Reports for the Devolved Administrations for Scotland, Wales and Northern Ireland to provide conclusions that are relevant to their country.

[16] http://www.defra.gov.uk/environment/climate/government/

3. Impacts and Risk Metrics

3.1 Scoping of impacts

A preliminary overview of the potential impacts of climate change on the transport sector was provided in the CCRA Phase 1 report (University of Birmingham, 2010). The report recognised the diversity of the sector given the variety of modes of transport in common use in the UK and the range of challenges the sector faces in relation to the impacts of climate change.

A long list of the impacts of climate change on transport was developed and reviewed at a sector workshop on 25th May 2010. The Tier 1 list of impacts is provided in Appendix 1.

The ubiquitous nature of transport systems and the established expectation that travel to all parts of the country in any weather conditions should be possible, has meant that travel service providers have developed experience in reducing their sensitivity to weather. Indeed, an efficient, safe and cost-effective transport system underpins a healthy national economy.

However, some of the trigger mechanisms and thresholds are not so well understood, such as urban, pluvial flooding (as distinct from river flooding) which arises from high intensity ‘extreme’ rainfall events. Transport as a sector has received little attention for research into climate change impacts, even though some impacts, such as urban pluvial flooding, can have the greatest cost impacts on road infrastructure and disruption to transport requirements.

Different climatic changes, such as the difference between ‘dry’ and ‘wet’ snow, have disparate impacts on different elements of the national transport system – for example, the former may immobilise a train engine while not affecting the track, whereas the latter may damage overhead cables. The thresholds and trigger points vary greatly between design of road and rail infrastructure.

Furthermore, extreme weather and climate conditions are not the only climate concerns. For example, zero degrees Celsius is a critical temperature because water freezes and is most slippery at that temperature. Hence roads are likely to be more hazardous in climates where the zero degrees Celsius threshold is crossed most frequently. In addition, the freeze/thaw cycle that occurs under these conditions causes rapid damage to paved surfaces.

To calculate the scale of climate change risks on transportation, a number of assumptions need to be made to take into account socio-economic scenarios and technological change. It would be advantageous to develop a holistic framework to take these non-physical elements into account instead of just purely looking at the climate response of the sector. However, this remains a significant gap in current research.

Extreme weather can cause serious disruption to the transport system. It may be possible to accommodate mitigation measures in new transport infrastructure but extreme weather is likely to remain a challenge for existing infrastructure. Transport is also affected by the variability of the climate from year to year and the unpredictable nature of that variability.

Gradual changes in the climate affect the criteria that should be applied for the design and maintenance of transport elements and infrastructure. Infrastructure that has been designed in the past may not have the capability to accommodate present and future changes.

Increases in temperature (and the associated heat waves) for example may lead to conditions that exceed the design limits of existing infrastructure. Consequences could include, for example, buckling of rails or bridges (in the absence of effective bridge expansion joints)[17].

The effects of changes in storminess on transport are particularly severe. The UKCP09 projections include future increases in rainfall intensity but show little change in wind conditions and storm frequency. Transport infrastructure is generally constructed to have a long design life, but changes in storm intensity can lead to an increasing number of failures and the consequent disruption to the transport network.

Thus the key impacts on transport can be classified as:

- Direct damage to transport infrastructure and the associated disruption caused by extreme storm events (especially extreme rainfall and strong winds).
- Direct disruption to transport modes (vehicles, trains, aircraft and ships) caused by extreme storm events. This can range from precautionary closures of roads and rail/air/ship services through to potential catastrophic damage caused by a storm, for example, an air crash caused by severe weather, or a train derailment caused by rail buckling during a heat wave.
- Indirect disruption to transport caused by gradual changes in the climate, particularly increases in temperature causing heat stress to passengers, staff and goods.

Climate change also presents opportunities for transport, particularly in the reduction in the likelihood of sub-zero temperatures and the problems caused by ice and snow. However, because of the variability of the climate, there is a risk that resources may not be available for these conditions when needed, as it is not cost effective to keep such resources in readiness for infrequent events. More winter precipitation can mean more snow and, as seen in the winters of 2009/10 and 2010/11, resources to clear snow and keep roads ice free can become stretched (Quarmby *et al.,* 2010).

The impacts and consequences identified generally refer to specific modes of transport. However, there are important linkages in the transport network between the different modes, for example the need for road and rail transport to get personnel and passengers to and from airports. In view of the importance of extreme events on transport, weather forecasting has a vital role in transport planning.

The need for contingency planning is also likely to increase and may change as climate changes. For example, increased storminess could lead to different responses and also an increase in the incidence of false alarms. Different responses might include the closure of an airport or seaport based on forecasts of extreme weather.

Figure 3.1 shows a cognitive map of 'clusters' of the initial Tier 1 list of impacts and consequences for the transport sector. The interactions between impacts and consequences are explored in more detail in the systematic mapping (see Section 3.5).

[17] "During the heatwave of 2005, the Swing Bridge across the River Tyne in Newcastle experienced problems when beams expanded and the bridge was unable to close, causing disruption to some journeys" (Source: **North East Climate Change Adaptation** study, http://www.neccap.org/NE%20Adapt/home.htm)

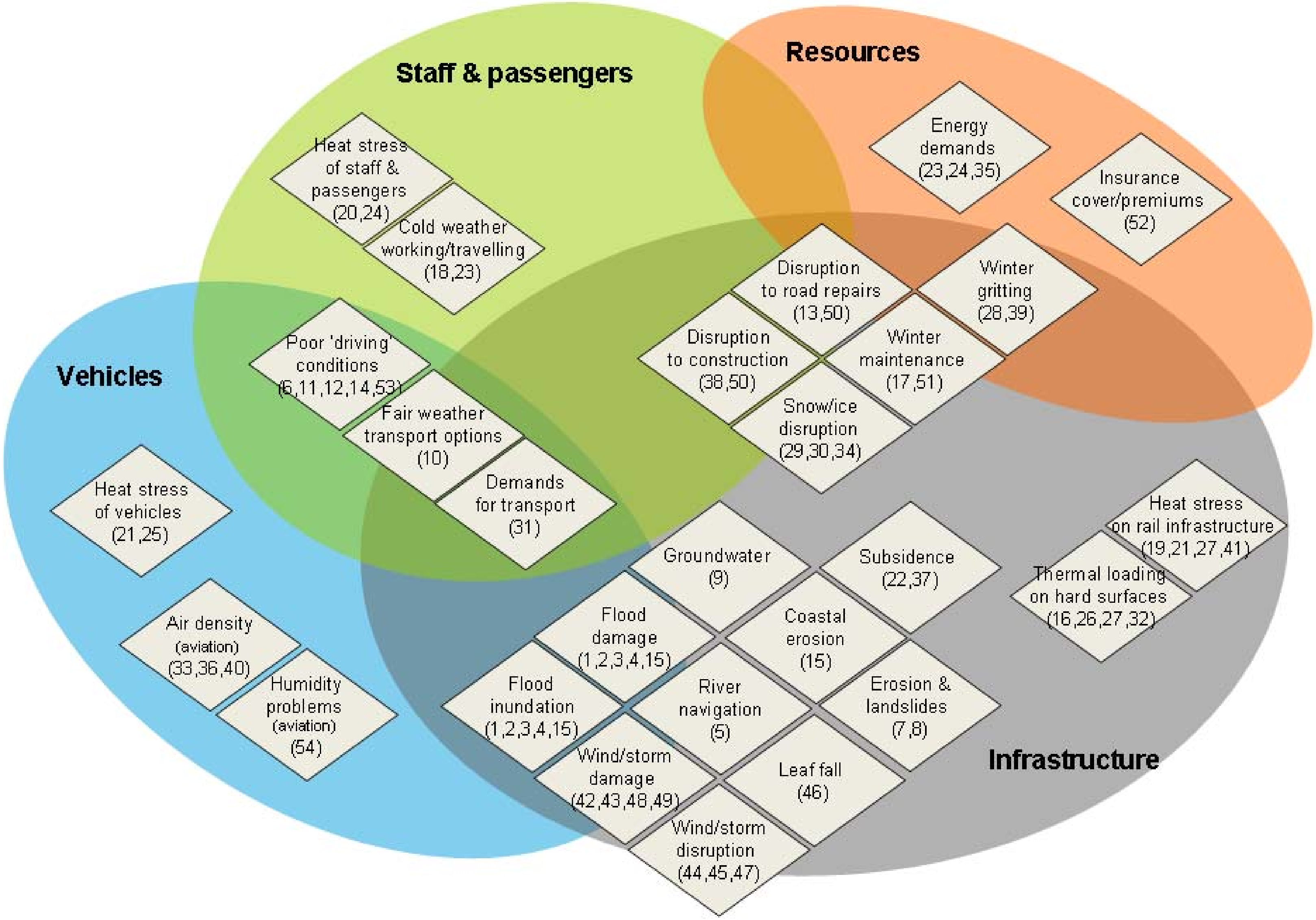

Figure 3.1 Clusters of impacts in the initial Tier 1 transport sector impacts

The numbers in brackets refer to a reference number in the initial Tier 1 impacts list which is provided in Appendix 1.

Social Vulnerability

The effects of climate change impacts on people will depend on their vulnerability. For example the elderly or those dependent on social services are likely to be more vulnerable to the effects of transport disruption.

A simple social vulnerability checklist was used to flag any social equity issues related to analysis of transport sector impacts and consequences. The checklist is included in Appendix 2.

Practically all elements of society are reliant on the transport sector, for supply of goods to homes and communities, for travel to work or socially and to distribute products and services. Many in society are reliant on public transport and have limited capacity for alternative transport options. Others rely upon transport as a necessity to connect rural or isolated communities.

The cost of transport can have a disproportionate consequence for those with a lower income or who rely upon cheap transportation costs to make their business effective. As the costs of transport increase then charges to customers are like to increase as a consequence, again having potential to disproportionately impact those on lower incomes.

It should be noted that the spread of social vulnerability impacts varies across the UK. For example, some isolated communities in Scotland can be highly reliant on a single road and/or a ferry for access to their homes, workplaces and facilities.

Workshop feedback

Attendees at a CCRA transport sector workshop, held in Reading on 25th May 2010, reviewed the list of Tier 1 transport sector impacts. Specifically they were asked to:

- Review and comment on the impacts and consequences identified for the transport sector, identifying any important omissions to the list, any concerns or disagreement with the list and to give views on how they have been scored.
- Provide guidance as to what impacts should be considered in the Tier 2 list.
- Identify potential ‘response metrics’ for key impact areas.

A full write-up of the workshop is available at hhtp://ccra.defra.gov.uk/. Key points arising from the feedback provided are given below:

- The composition of the stakeholder group itself meant that some impacts may not have been identified.
- For the transport sector, it is not always possible to combine more than one issue in a single impact and caution should be exercised when combining issues which have both negative and positive consequences.
- The adaptive capacity of the national transport system must be considered (especially as transport managers must consider both weather and climate impacts in planning and operation).
- The impact of hot/cold weather will be complex and may result in a change in the working day to safe guard work force health and safety, but equally if there is a national shift to working different patterns of hours then transport infrastructure must be available for more hours in the day thereby limiting windows of opportunity for maintenance.

3.2 Selection of Tier 2 impacts

3.2.1 Overview

There are over 700 impacts identified in the Tier 1 assessment for all eleven sectors and more than fifty in the transport sector (including additions identified during or subsequent to the workshop). With the time and resources available for the CCRA, it simply would not have been possible to have undertaken a detailed analysis of all of the Tier 1 risks, and so a selection process was carried out.

3.2.2 Comments from workshops

Judgement on the relative priority of the Tier 1 impacts list was made at the transport sector workshop, although undertaken in a subjective way without a formal scoring process. Attendees were asked whether they regarded each risk as high or low priority, thereby providing some insight into the perceived relative importance of each identified impact. The outcome of this informal voting process ranked Flooding highest (11 votes), Subsidence/Landslides and Energy Demand equal second (8 votes) and Demand for Transport and Thermal Loading as equal fourth (6 votes). In addition, further comments and feedback from the workshop indicated:

- A potential difficulty in forming robust quantitative metrics as there are many diverse users and operators of transport infrastructure in the UK.
- Risk to airports (including on site functions, safety, facilities and access routes) from flooding was perceived as a gap in the Tier 1 list.
- Suggestion to use publicly available data for number of complaints about road conditions mapped against the temperature and precipitation for the area.
- Caution is required if using data from existing road condition datasets which may contain variations due to differing departmental approaches to data collection, and storage. Further variation issues may arise, e.g. maintenance regimes, materials and traffic levels could ‘skew’ results.
- Further skews may become apparent as the typical network land survey is in the region of a 25% sample.

3.2.3 Scoring of impacts

As explained in Section 2 of this report, the list of Tier 1 impacts was consolidated to a shorter list of impacts for analysis in Tier 2. This was done by selecting those impacts with highest scores for social, economic and environmental impact and greatest urgency to take action. The scoring process was informed by the workshop outcome presented in Section 3.3.2. The scores are included in Appendix 3. These scores were also informed by consideration of social vulnerability (see Appendix 2).

The overall outcomes of the scoring are shown in Table 3.1[18]. This shows the impacts which scored above the threshold for inclusion in Tier 2. Figure 3.2 shows how the same impacts relate to levels of urgency and risk. It should be noted that Figure 3.2 indicates that there is a relatively low level of urgency assigned to many of the impacts in this sector primarily because there is a limited need for major policy or infrastructure

[18] Note: the numbers indicate the identifying number given to each impact in the full Tier 1 list

decisions to address these impacts to be taken before 2020 and that decisions could have a high degree of flexibility with potential for incremental adaptation over time.

Table 3.1 Outcomes of the scoring for the transport sector

Selected (threshold > 30)	Marginal (threshold = 17)	Excluded (below score of 17)
Flooding and inundation (1,2,3,4,15) Subsidence and landslides (22,37) Energy Demands (23,24,35) Thermal Loading on Hard Surfaces (16,26,27,32) Heat Stress on Rail Infrastructure (19,21,27,41)	Coastal erosion (15) Cold Weather Working/Travelling (18,23) Heat Stress of Staff & Passengers (20,24) Demands for Transport (31) Insurance Cover/Premiums (52)* Erosion & Landslides (7,8)* Poor 'driving' Conditions (6,11,12,14,53)* * Score <17 but included in this category following consultation	Wind/storm damage (42,43,48,49) Leaf fall (46) Snow/Ice Disruption (29,30,34) Winter Maintenance (17,51) Winter Gritting (28,39) Wind/storm disruption (44,45,47) Heat Stress of Vehicles (21,25) Air Density (aviation) (33,36,40) Fair Weather Transport Options (10) Disruption to Road Repairs (13,50) Disruption to Construction (38,50) Sea level rise in ports River navigation (5) Groundwater (9) Humidity Problems (aviation) (54) High winds at Ports increased storminess (55)

The impacts which scored above the threshold value are as follows:

- Flooding and inundation
- Land movements – subsidence and landslides
- Energy demands
- Thermal Loading on Hard Surfaces
- Heat Stress on Rail Infrastructure.

These were selected for analysis together with scour at bridges, which was added following review of the draft sector report.

Risk (qualitative estimate)	Low	Medium	High
High	Heat Stress of Staff & Passengers (20,24) Insurance Cover/Premiums (52) Erosion & Landslides (7,8) Poor 'driving' Conditions (6,11,12,14,53)	Subsidence and landslides (22,37) Energy Demands (23,24,35) Thermal Loading on Hard Surfaces (16,26,27,32) Heat Stress on Rail Infrastructure (19,21,27,41) Coastal erosion (15)	Flooding and inundation (1,2,3,4,15)
Medium	Demands for Transport (31) Wind/storm damage (42,43,48,49) Leaf fall (46) Snow/Ice Disruption (29,30,34) Winter Maintenance (17,51) Winter Gritting (28,39) Wind/storm disruption (44,45,47) Heat Stress of Vehicles (21,25) Air Density (aviation) (33,36,40) Fair Weather Transport Options (10) Disruption to Road Repairs (13,50) Disruption to Construction (38,50)	Cold Weather Working/Travelling (18,23)	
Low	River navigation (5) Groundwater (9) Humidity Problems (aviation) (54) High winds at Ports increased storminess (55)		
	Urgency of decisions		

Figure 3.2 Alternative scoring rule based on risk AND urgency

Note: scores provided from a transport resources perspective

It should also be noted that some of the impacts which scored highly in this sector are addressed by other sectors. These include for example flooding and inundation (routes affected), which is covered in the Floods and Coastal Erosion sector. There are other links across sectors, including the Health sector analysis of the potential impact of heat on health and changing levels of incident of skin cancer, a key risk in this sector given the outdoor nature of the vast majority of maintenance work (see the Health sector report).

Subsidence from a property perspective is considered in the Built Environment report while shipping is discussed in the Marine sector report. The Energy sector report also discussed some of the challenges faced by the sector in relation to maintaining energy supply as temperatures increase.

3.3 Risk Metrics allocated to the impacts

3.3.1 Introduction

In order to undertake the analysis it is first necessary to identify ‘risk metrics’, which are measures of the consequences of climate change. Estimates of the magnitude of the consequences of climate change are expressed in terms of the risk metrics.

For national risk assessment, ‘good’ metrics are likely to have a number of criteria, i.e. they:

- Are sensitive to climate but also allow the disaggregation of climate and socio-economic effects.
- Provide a measure of changing probability or consequences relevant to a baseline, so historical data are required to establish the current situation.
- Can be presented at the national and regional scales, based on high quality data that are collected and held by Government departments, agencies or research institutes. The use of Government data should provide consistency between sectors and allow the metrics to be repeatable in subsequent CCRA cycles.
- Reflect economic, environmental and social consequences of climate change; some metrics may be monetised but others may simply indicate the areas affected or consequences for vulnerable groups of society.
- Are relevant/have legitimacy to the relevant Government policy.

For the transport sector the identification of metrics for direct biophysical impacts, such as flood risk to roads, is a relatively straightforward task but these on their own are insufficient to explain risk in the sector, as they do not provide enough information to measure the economic, social and environmental consequences of climate change. Within this sector, for many users it is the impact of the disruption caused by delay and diversion around flooded roads rather than the length of road at risk which is a more relevant metric.

3.3.2 Impacts

Some parts of the transport sector are relatively data rich, particularly those elements within the remit of a Government Agency or regulated body but many of the Tier 2 impacts identified focused upon elements of risk which are harder to quantify than the routinely reported figures.

Reporting also varies depending upon mode of transport, with road and rail figures (and risks) being considered separately for instance. As noted during the stakeholder workshop, not all datasets are directly comparable and so could not easily used within the CCRA.

For these reasons, five metrics have been developed which between them consider a range of impacts across road and rail drawing upon a range of information sources. Impacts on others modes of transport were identified in the Tier 1 list but none scored highly enough in the assessment of all impacts to be included in the Tier 2 list, hence the focus upon road and rail in this first CCRA.

Following review, and liaison with data providers, the agreed metrics to be analysed, each exploring a key aspect of a shortlisted Tier 2 impact, were:

- TR1 - Disruption and delay associated with flooding on the road network. A similar metric could have been formulated for rail, airport and port flooding.
- TR2 - Subsidence/landslip associated with roadside slopes. A similar metric could have been formulated for railways and ports.
- TR4 - Cost of carriageway repairs (a similar metric could have been formulated for rail tracks).
- TR5 - Rail buckling risk and costs of delays (a similar metric could have been formulated for the melting of roads and runways).
- TR6 - Road and rail bridge failures due to scour.

Other metrics relevant to the transport sector were analysed in other sectors. These are discussed in Section 3.5.2.

The rail buckling risk can lead to associated delay costs due to imposed speed restrictions being introduced when rail temperatures increase towards 50°C (Thornes and Chapman, 2008) even though a rail buckling incident does not occur. These costs have not been analysed in this study nor the cost of delays caused by speed restrictions due other causes such as cracked rails in cold weather.

In addition, the energy demand associated with cooling road vehicles[19] was also considered (metric TR3) but at the detailed stages of the analysis it was not taken through.

It has to be noted that each metric is selected to explore just one consequence of a risk or impact. For example, although the impact is flooding and inundation, the specific consequence considered by metric TR1 is delay and disruption on the road network. A similar metric could have been developed to consider the same consequences for the rail network, or for airports, etc. The choice of metric is however shaped by a number of factors including data availability and the potential to undertake a national assessment.

The metrics are mostly a qualitative or semi-quantitative assessment of the consequences of climate change on the transport sector, seeking to explore some of the key risks identified by this analysis where data is currently more limited. The exception to this is the rail buckling metric which is quantified.

3.4 Impacts for future consideration

A number of the Tier 1 impacts that have not been selected for detailed Tier 2 analysis are discussed at a high level in this section, to provide context on some of the wider impacts that may potentially arise as a result of climate change. Each of these impacts may be considered for more detailed analysis if appropriate in future. The impacts discussed in this section are:

- Disruption to ports and shipping
- Disruption to airports and air travel
- Technological innovation
- Social and economic changes: demands for transport
- Landslide impacts on the rail network

[19] This can be taken as a surrogate measure of the cost of ameliorating passenger discomfort

- Cooling in vehicles
- Coastal erosion
- Heat stress of staff and passengers
- Cold weather working/travelling
- Poor 'driving' conditions
- Insurance cover/premiums
- Key workers unable to get to work due to extreme events or infrastructure failure.

3.4.1 Disruption to ports and shipping

The potential consequences of climate change on port operations (PIANC, 2008) include:

- Delays, closure of ports and prevention of port activities arising from severe weather including surface water flooding and the combined effect of sea level rise and wave action, that could increase wave heights at ports.
- Damage to infrastructure and cargo from flooding and severe weather.
- Changes to sedimentation and tidal patterns leading to increases in the costs of maintaining navigation channels.
- Changes in shipping routes as a result of ice melt.
- Changes in water availability for the inland waterway system.
- Reduction in cold weather disruption including ice formation on inland waters.

There have been occasions when port activities have been disrupted by severe weather including wind and wave action. This has affected the many ferry terminals around the UK including the major passenger and freight services to the continent. On rare occasions it has also affected deep sea container terminals including damage to container cranes.

Water depths in the approaches to ports may increase as a result of sea level rise leading to higher inshore waves in port areas, although this effect may be small. For these reasons, impacts of climate change caused by wind and wave action were not considered sufficiently important for detailed analysis.

Sea level rise could potentially have a direct impact on ports by increasing the frequency of tidal flooding. These impacts include potential overtopping of tidal quays and an increased risk of tidal water levels exceeding water levels in enclosed docks. Some dock entrances are designed to prevent high tidal water levels entering the docks, for example at the King George Dock, Hull.

The risk of tidal flooding at ports was not considered sufficiently important for detailed analysis within a national assessment. New port facilities take sea level rise into account, for example the new Thames Gateway port where the quays have been designed for a very low probability of overtopping. It is however important for individual ports to assess the present and projected future risks of tidal flooding and take appropriate measures to manage the risk.

Surface water flooding is projected to increase as a result of increases in rainfall intensity. This could affect ports, particularly container and ferry terminals as they have extensive paved areas. Drainage requirements are likely to increase if damage to cargo and facilities from intense rainfall is to be avoided. Whilst increases in surface water flooding are recognised as a potentially serious problem, it was not analysed in the CCRA owing to a lack of suitable data.

A major potential opportunity resulting from climate change is the opening up of arctic shipping routes. This could reduce passage times to the Far East and could lead to changes in the future locations of deep sea cargo terminals, as there would be benefits in more northerly locations (see metric MA5, discussed in Section 3.5.2).

3.4.2 Disruption to airports and air travel

Severe weather is a problem for air travel, mostly when aircraft take off and land at airports. Data from the USA indicates that 85% of total delays to aircraft for periods of at least 30 minutes are weather related, and the weather is responsible for 36 per cent of accidents. Thunderstorms account for about 25% of delays, snow/ice for 15%, wind for about 20% and poor visibility about 20% (Sasse & Hauf, 2003).

Airports are designed to be kept open every day of the year in all weather conditions. International airports are huge complexes with problems in severe weather of access by road as well as keeping the runways open. At many airports, drainage can be an issue because of the large expanses of concrete and tarmac, although flooding is often more of a problem on access roads (DfT, 2005). It should be noted that parts of some airports lie within flood risk areas shown on national flood maps, indicating that flooding is a direct risk in these cases.

The main runway is normally orientated in the direction of the prevailing wind to assist take-off and landing. Obviously the climate will determine the frequency of wind direction, and some locations may have difficulty if there is no identifiable prevailing wind. Cross-winds are always a problem on take-off and landing.

Changes in wind direction due to climate change would affect airport operations. Light aircraft are affected by crosswinds as low as 15 knots and, at 25 knots, even heavy aircraft can be troubled. Above about 35 knots, an aircraft will have problems with any runway orientation.

All airports in the UK have provision for 'round the clock' snow and ice control, both for clearing runways and aircraft. However, these operations can lead to damage to surfaces and pollution from de-icing chemicals. Whilst winters are projected to become milder, extreme snow and ice events are likely to continue as at Heathrow in the winter of 2009/10 and in December 2010 (Quarmby *et al.*, 2010, Begg, 2011).

Impacts associated with increases in temperature include the potential need to reduce payloads above about 25°C, and potential melting of runways and other surfaces at very high temperatures.

Heavy rainfall can cause flooding and reduce visibility which may be a problem for take-off and landing. More than 50 mm an hour of rain is likely to flood runways at Heathrow but each airport will have a different threshold according to drainage and topography.

3.4.3 Technological innovation

In much the same way as technological change is considered to deliver the solution to the reduction of greenhouse gases in the transport sector (e.g. alternative fuels;

Chapman, 2007), technology will have a role in shaping how the future transport network will look and function. The electrification of transport networks is perhaps the main example of how a major change in technology that could change the nature of climate risks to transport in the future. If a large proportion of transport is electrified in the future, then this would change both the risks themselves (as new technologies might have different vulnerabilities) but also the nature and extent of links with other sectors. In this case the links with the Energy sector and possibly ICT (Information and Communications Technology) would also be affected. For a fuller discussion, see Section 3.5.3.

3.4.4 Social and economic changes / transport demand

Other factors that could change the way in which the climate affects transport are changes in social behaviour, economic conditions and policies. Social and economic changes are a significant control on transport demand and therefore the nature of infrastructure required to satisfy the demand. Improvements in technology may reduce the need for transport – for example if more people work from home or local centres, taking advantage of potential improvements in ICT systems. Demand would also be reduced from various 'carrot or stick' approaches aimed at changing the propensity to travel or incentivising modal shift from private to public transport, particularly in urban areas as a broader measure of sustainable development (Chapman, 2007).

Travel demand has increased significantly over the last few decades (see Section 1.3 for a detailed breakdown). Road traffic has increased by 85% since 1980 whereas air travel between, or from, UK airports have quadrupled in the same period (DfT, 2009). Much of this growth is linked with disposable income and despite the onset of recession in the last 5 years, both mid and long term trends indicate that demand will continue to rise. However, the exact impact on travel costs and associated demands with respect to peak oil and the impact of new technologies on the sector is an inexact science. This requires scenario development (discussed in detail in Section 6) and the wider issues should be kept under review in successive CCRAs.

The proposed High Speed 2 (HS2) rail link between London and Birmingham and beyond is currently under review. If approved, work will begin in 2017 with the first operational trains in 2025. Links to Heathrow Airport are also being considered. Currently the only high speed rail link in the UK is HS1, the Channel Tunnel rail link.

3.4.5 Landslides impacts on the rail network

Whilst the selected risks for analysis include the effects of landslides on the road network, there is also a risk to the rail network. This not only includes railways in cuttings or on hillsides but also railways on embankments. It is estimated that there are about 5,000km of rail lines on embankments and a further 5,000km in cuttings. Work is in progress to evaluate the potential risks from climate change, which may be suitable for use in the next CCRA (Loveridge *et al*., 2010). Academic research is ongoing in this area, with both the CLIFFS[20] and BIONICS[21] projects particularly worthy of mention.

3.4.6 Cooling in vehicles

There is no clear consensus view on how energy demand associated with the summer cooling of cars, trains, tube trains, buses, lorries etc. may change in relation to

[20] http://cliffs.lboro.ac.uk/

[21] http://research.ncl.ac.uk/bionics/

temperature. Many factors are relevant including the size, age, design and efficiency of the vehicle. There is widespread agreement that when used during high speed travel, the increase in fuel consumption attributable to use of air conditioning in vehicles is relatively small – in the region of one per cent or so. The frequency of usage of air conditioning will increase with a warming climate.

3.4.7 Coastal erosion

There is a danger of increased coastal erosion due to a combination of sea level change and higher frequency extreme events leading to flooding and increasingly damaging wave action. In affected areas there are two options:

1. Protection (e.g. reinforced defences)
2. Planned Retreat (i.e. re-route affected roads and railways).

For example, the railway line at Dawlish in Devon is subjected to frequent closure as a result of high tides and storms. A feasibility study rejected re-routing the track inland in favour of the less expensive option (in this case) of reinforcing sea walls[22]. There are many other examples of transport infrastructure subjected to similar problems around the UK and site specific assessments will be required in each case.

Problems may also be encountered at ports and harbours (see 3.4.1) but there is not considered to be a significant problem at UK airport locations. Indeed, the biggest impact of coastal impacts on the UK is perceived to be impacts elsewhere in the globe upon which the country is increasingly dependent for trade (Nichols & Kebede, 2010).

3.4.8 Heat stress of staff and passengers

Heat stress (thermal comfort) is likely to become an increasingly important issue under the changing climate, particularly during times of heatwave. For much of the transport infrastructure, the impact on passengers should be minimal as air conditioning units become increasingly standard across modes. However, one notable exception is the London Underground system. During the summer months, the underground is often subjected to high temperatures from equipment and rolling stock. These problems may worsen with climate change and a solution to cool the network is now much needed. Traditional air conditioning will exacerbate the problem and hence other solutions utilising groundwater is under trial (LCCP, 2005).

All staff working outside may also be at increased risk of heat stress, with the problem being particularly acute for rail and road maintenance workers. Both roads and rails may be subjected to increasing heat related problems which would need urgent attention. The result is that maintenance personnel may be subjected to increased heat stress during heatwave events. There will be an increasing need for employers to review risk assessments in light of climate change and implement subtle changes to improve working conditions (e.g. provision of cold drinks and portable air conditioning units, relaxed dress codes, frequent breaks, etc.)

3.4.9 Cold weather working/travelling

Whilst a general trend of warming winter temperatures is to be expected, the problems involving cold weather will not be eliminated. Indeed as the winters 2009/10 and 2010/2011 have shown, it is essential to remain prepared for severe winter weather.

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22 http://www.rssb.co.uk/PressReleases/Pages/RSSBresearchsupportsNetworkRailonclimatechangechallenge.aspx

However, such events may decline in frequency, very low freezing temperatures may be less common and the winter season may be shorter (Andersson & Chapman, 2011). As a result, winter disruption across all modes should be reduced.

The road network is very sensitive to severe winter weather and although the UK is well prepared to deal with icy roads, it is underprepared for snow-related problems (Thornes, 2005) due to their infrequency. This, coupled with general driver complacency caused by a lack of experience of driving in such conditions, may cause an increase in accidents and subsequent disruption on the road network. However the two consecutive cold winters of 2009/10 and 2010/11 have refocused attention on winter resilience (Quarmby *et al.*, 2010).

3.4.10 Poor 'driving' conditions

A large number of studies have been undertaken into the impact of weather conditions on traffic accidents (e.g. Edwards, 1996). Of all the weather types, it is precipitation and associated reduced visibility which appears to be the main factor for the majority of weather related road accidents (Keay & Simmonds, 2006; Koetse & Rietveld, 2009).

Problems appear to be most acute in winter with reduced hours of daylight. Hence, the projected increase in winter precipitation in the UK may well be problematic and lead to an increased number of accidents during the winter season. However, this may be offset to some extent by a reduction in snow and ice which is a frequent cause of accidents (Andersson & Chapman, 2010). Also increased usage of winter tyres (and tyre 'socks') could make winter driving safer.

Those regions of the UK that are projected to have reduced summer precipitation might therefore benefit from improved driving conditions. However, much of the summer precipitation may be increasingly heavy and as such could cause sudden, significant reductions in visibility, increased spray and flash flooding. Also precipitation after long dry periods can cause particularly slippery conditions due to dirty/oil deposits on the road surface.

The exact impact of poor driving conditions is difficult to ascertain over an extended timeframe because of technological change (e.g. developments such as ABS). The impact of driver behaviour is also very variable as there is a tendency for motorists to slow significantly (or even restrict travel) if conditions are bad. Overall, it is presently unclear whether there will be a net increase or decrease in road traffic accidents as a result of climate change.

3.4.11 Insurance cover/premiums

The impacts of weather related events can often result in a large number of insurance claims and insurers are now attempting to take this into account in their pricing. For example, flood insurance rate maps are often used for land use planning including new transport corridors (TRB, 2008). As is indicated by the uncertainty surrounding future driving conditions, the potential impact of climate change on the insurance industry is still very unclear with many providers uncertain of the climate-related risks on their valuations.

3.4.12 Key workers unable to get to work due to extreme events or infrastructure failure

Several definitions of critical infrastructure exist in the literature, but the term is generally used as a collective term for assets essential to the functioning of society and where prolonged disruption would result in a negative economic impact (Moteff *et al.*, 2003). Other than transport, examples of critical infrastructure include power supplies and communications. The Cabinet Office (2010) definition of Critical National Infrastructure (CNI) is: "those facilities, systems, sites and networks necessary for the functioning of the country and the delivery of the essential services upon which daily life in the UK depends."

A large scale weather event has the potential to simultaneously incapacitate many components of critical infrastructure. For example, the summer floods of 2007 in Gloucestershire affected the Mythe water treatment works (supplying 350,000 people) and also threatened the Walham electricity substation (supplying 500,000 people). Many roads were impassable which resulted in key workers being unable to get into work; numerous stories were reported of the use of boats and 4x4 vehicles in order to get key workers such as nurses to hospitals (see Environment Agency, 2010). The impact of extreme events affecting multiple sectors is an example of a cascade failure which is discussed in Section 3.5.3.

3.5 Cross-sectoral and indirect consequences

3.5.1 Systematic mapping

To supplement the initial identification of risks (Tier 1 list), a more formal process was undertaken, to identify direct, indirect and 'cross-sectoral' impacts and consequences. This is referred to as 'Systematic Mapping'. This starts with changes in climate variables as the cause of direct impacts, which were largely bio-physical. These changes were then used as the causes for the next iteration to capture indirect consequences and links between sectoral sub-systems. The process was then repeated in a series of iterations as illustrated in Figure 3.3.

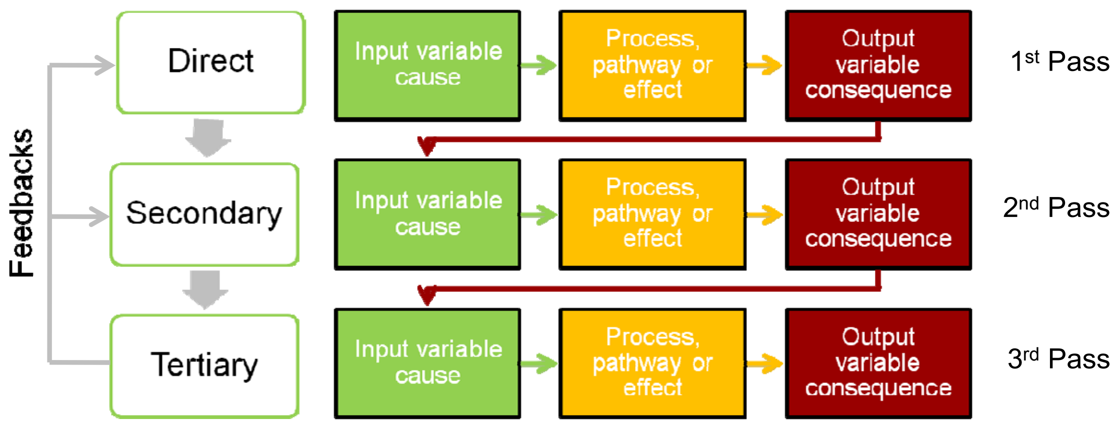

Figure 3.3 Systematic mapping of cause-consequence linkages

Outputs from the systematic mapping include diagrams showing links between climate drivers (e.g. increased precipitation), bio-physical impacts (e.g. flooding), direct consequences (e.g. property damage) and indirect consequences (e.g. health effects on people). The examples cited reveal the cross-sectoral links between Flooding, the Built Environment and Health sectors.

The systematic mapping identified a network with around 2400 consequences, of which some 1300 are unique sector based consequences (once identical consequences with different attributes have been removed). Many consequences identified within individual sectors were essentially similar to those in other sectors. For example, damage to buildings was identified in relation to hospitals under Health, commercial property under Business and all types of building under Built Environment. These were consolidated into single common consequences, with narratives that reflect the interest in the different sectors. After consolidation, the total number of impacts identified by the systematic mapping was reduced to about 240 generic consequences. These are of course much more general than the largely sector specific impacts identified in the individual sector scoping reports and this explains why there are only 240, as compared to over 700 in the Tier 1 list of impacts.

The systematic mapping identified a wide range of potential links. Many of these were identified in the Tier 1 impacts list, but others emerged from the mapping, including:

- Health impacts such as heat stress and wind chill.
- Insurability, premiums and claims results from damage to infrastructure, material, shipping, etc.
- Demand for travel arising from tourism and potential for change in modal choices as a response to 'outdoor activity' such as walking and cycling.

3.5.2 Risks addressed in other Sector Reports

Some of the metrics considered in other reports are also relevant to the transport sector and these include:

- Impact of flooding on road and rail infrastructure (Floods sector Metric FL8; this impact is also presented in Chapters 4 to 7 of this report).
- The opening up of navigation passages across the arctic and the potential impact on global shipping patterns (Marine sector Metric MA5; this impact is also presented in Chapters 4 to 7 of this report).
- Water supply and demand, which may be of relevance to the future management of inland waterways (Water sector Metric WA5).

  Water availability could potentially affect inland waterways, particularly during summer when precipitation is projected to reduce. The Water sector assessed the supply demand balance and concluded that there is little significant risk to the supply demand balance in the near term (by the 2020s) but there could be large potential risks faced by some river basin regions in the longer term (by the 2080s).
- Northward spread of invasive non-native species (Marine sector Metric MA6).

  An assessment of the potential spread of marine invasive non-native species indicates that the habitable range of all the invasive non-native species considered in the analysis could encompass the entire UK by the 2080s. Whilst the potential impacts of these species have not been assessed, there is considerable potential for them to have significant economic and environmental implications. One example relevant to the transport sector is fouling of structures in ports.
- Overheating of buildings (Built Environment sector Metric BE3).

  Overheating of buildings (including transport terminals) is projected to increase as temperatures rise. The analysis in the Built Environment sector provides projections of the number of days per year when critical temperature thresholds will be exceeded. For example, the number of days per year when overheating could occur in London is projected to rise from a baseline of 18 days to between 22 and 51 days by the 2020s (central estimate 33 days), and to between 27 and 121 days per year by the 2080s (central estimate 69 days).

- Building subsidence (Built Environment sector Metric BE2).

  Changes to the present shrink swell pattern of clay soils may occur due to wetter winters and hotter drier summers, leading to changes in incidents of building subsidence. Although soil moisture projections are not provided within UKCP09, estimates of soil dryness have been made using UKCP09 summer rainfall projections. An increase of around 7% in the number of subsidence incidents is projected by the 2020s rising to about 17% by the 2050s and 20% by the 2080s (central estimate).

- Wildfire risk (Biodiversity sector Metric BD12).

  An increased prevalence of hotter, drier conditions is likely to lead to an increase in the risk of fire in both rural and urban environments. Some ecosystems, such as woodlands, semi-natural grasslands, heathlands, and those on peat soils (e.g. bogs) are particularly sensitive to fire. Potential implications for transport include increased disruption if services are delayed because of fires, and damage to infrastructure.

- A decrease in output for UK businesses due to an increase in supply chain disruption as a result of extreme events. (Business sector Metric BU9).

  Increase in supply chain disruption, has many interrelated components including disruption to transport. Supply chain disruption has the potential to disrupt UK businesses by affecting availability of natural resources and raw materials, or by causing distribution delays.

  The effects of flooding on supply chains were considered in the Business sector. In recent years, lean supply chains have become the standard. Businesses have invested considerable effort in maximizing efficiency by delivering products to the customer with minimal waste. This is achieved by streamlining operations across all links in the supply chain, from procurement and manufacturing to warehousing and transportation.

  Transport is a critical element in this approach. Streamlining has brought efficiency and cost savings, but it has also resulted in increased risk of disruption. A survey from the Business Continuity Institute, which analysed responses from businesses in 35 countries, showed that over 70% of respondents recorded at least one supply chain disruption in 2010 (BCI, 2010). Adverse weather was the main cause of disruption, with 53% of businesses citing this as contributing to recent supply chain disruption.

  Because retail supply chains are complex and dependent on a network of interconnected, yet independent, elements, it was not possible to develop a clear and direct causal link between climate change and supply chain disruption. Therefore supply chain disruption (Metric BU9) is not covered in Chapters 4 and 5 but the implications of socio-economic change is briefly discussed in Chapter 6 and an indication of potential costs is given in Chapter 7.

3.5.3 Interdependencies between the transport sector and other sectors

A further complication when considering the resilience of the transport sector is the growing interdependency of the network on other national networks. Indeed, the whole of UK infrastructure is essentially an interconnected network of assets (Defra, 2011b), belonging to the energy, ICT, water, waste and transport sectors. Whilst these are often treated as independent sectors (as per the CCRA exercise for example), the reality is all networks are heavily reliant on each other.

Whilst interdependencies can often increase resilience, dependencies also give rise to vulnerabilities (Royal Academy of Engineering, 2011). In the case of transport, there is a growing dependency upon energy and ICT.

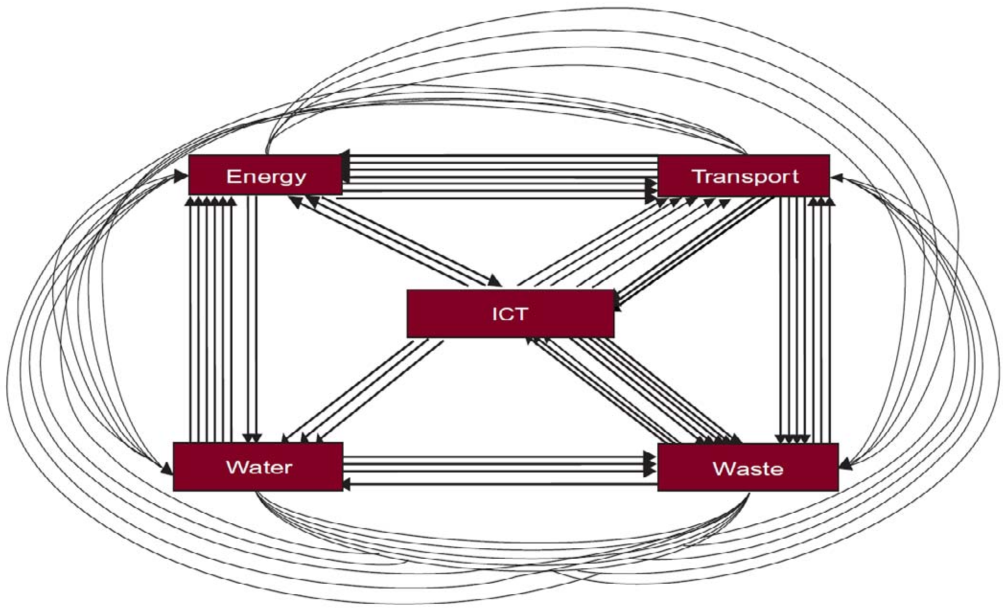

Figure 3.4 System interdependencies
Source: AEA, 2009

The electrification of transport networks (e.g. rail and electric vehicles) is frequently cited as one approach towards meeting climate change mitigation targets in the transport sector (Chapman, 2007). However, in this scenario, a significant failure on the electricity network could ultimately cascade onto the transport network with far reaching consequences (Royal Academy of Engineering, 2011).

Similarly, a widespread failure in the transport sector could prevent key-workers in the energy sector from getting to where they are needed. An example of this is provided by the snow event in December 2010 where multi-modal disruption on the transport network was estimated to have cost the UK economy £600m per day (Defra, 2011b).

The November 2009 floods in Cumbria provide another clear example where the Workington bridge collapse severed transport communications. Bridges are often used as conduits for other infrastructure such as water and communications. In this case, important ICT links were also severed.

Hence, a problem on one network can quickly cascade across all infrastructure leading to a total failure. As the impacts of climate change and extreme events are increasingly felt across individual networks, interdependencies will become progressively more apparent (Royal Academy of Engineering, 2011). For this reason, increased research is needed to study the risk of cascade failure across infrastructure networks. To this end, EPSRC are presently funding the Infrastructure Transitions

Research Consortium[23] (ITRC) to fully highlight system interdependencies at the national scale.

Research projects such as the ITRC will allow vulnerabilities to be identified and prioritised across all sectors. However, this also brings a new set of adaptation challenges as there is then a need to consider and incorporate adaptive capacity simultaneously across all sectors. Adaptations can often be readily implemented on a single network (particularly on new assets); however, further cost savings can be made by implementing ‘dual-use’ infrastructure. A commonly cited case study is the SMART[24] motorway tunnel in Kuala Lumpur which doubles as a stormwater management system during tropical storms.

Overall, there is a need to promote systems resilience as opposed to just sector resilience (Royal Academy of Engineering, 2011).

[23] http://www.itrc.org.uk/
[24] http://www.smarttunnel.com.my/

4. Consequences Response Functions

4.1 Introduction

The purpose of this step is to understand the sensitivity (according to the available evidence) of the selected risk metrics to changing climate conditions. It was based on review and synthesis of existing research outputs and Government analyses and is presented within the context of key assumptions and uncertainties related to the assessment of each metric.

As already noted, the transport sector is inherently sensitive to weather and climate patterns. The national systems of transportation (air, rail, road and sea) are sensitive to extreme weather events, but do well to rise to the expectation that travel to all parts of the country should be possible in more or less any weather conditions.

This is in part because parts of the sector have completed a lot of work to date regarding climate risks and potential adaptation requirements in the face of extreme or more frequent extreme events, for example the *Scottish Road Network Climate Change Study* commissioned by the Scottish Executive in 2005 or the DfT commissioned research on *Maintaining Pavements in a Changing Climate* (Willway *et al.*, 2008). Further, the sector is currently working to identify the risks and changes relevant to the expected impacts of climate change, for example in the current RSSB study, *Adapting to Climate Change*. Many in the sector are also developing their responses to the Adaptation Reporting Power[25].

The following sections describe 'response functions' developed for each metric, seeking to link the climate driver for the risk, i.e. rainfall, increasing temperature, etc, with the potential outcome or consequence. The ranges of change used are all plausible and derived from the UKCP09 scenarios (see Chapter 5).

4.2 TR1 – Flood disruption/delay to road traffic

An assessment of the length of road and rail which is at risk of flood has been undertaken within the Flood and Coastal Erosion sector assessment (see Ramsbottom *et al.*, 2012). The focus here is instead the implications of flood events on transport users. Given the nature of this impact and the supporting data available, the scope of the 'cost of disruption/delay' used in this analysis refers to the total traffic disruption costs[26]. This metric has been assessed for England where suitable data were available.

There have been a number of flood events in recent years which have been investigated to provide estimates of the costs arising from delay or disruption. For example, the economic costs of the autumn 2000 floods including delays have been estimated at approximately £50 million for the rail sector and £13 million (economic) / £73 million (financial) for the road sector (Penning Rowsell *et al.*, 2002).

The cost of disruption to road transport from flooding in 2007 has been estimated in an Environment Agency (EA) report *The cost of the 2007 Summer Floods* (Environment

[25] See http://www.defra.gov.uk/environment/climate/legislation/reporting.htm
[26] A similar analysis could be undertaken for other forms of transport but given that the majority of journeys undertaken in the UK are by road, this metric focuses upon road users.

Agency, 2010), based on the number of roads inundated, congestion, additional journey length due to delays, etc. It does not specifically cover damage to vehicles or roads but none the less, estimated total costs relating to delays and disruption to road users during the 2007 floods was approximately £100m. Accompanying notes to the report (Environment Agency, 2010) state that there is much uncertainty in these cost estimates. Although the mean estimated cost of disruption is £98m, the overall range of estimates was £22m to £174m, depending on the methods used.

The challenge in understanding costs and how they may vary is that each of these floods, which have been investigated in this way, were significant events. For instance, the 2007 floods were record breaking and highly unusual in their severity. The severity of the autumn 2000 floods is confirmed in a statement by the Met Office[27]: "*The flooding that occurred across much of England and Wales in the autumn and early winter of 2000 was the most extensive since the snowmelt-generated floods of March 1947.*"

A study at the time showed that although the rainfall conditions associated with the flooding in 2000 were unusual it was similar to the kind of pattern of change given by climate projections, implying that autumn flooding events like those in the year 2000 may become more common (MAFF, 2001). No estimate has been identified of an annual average cost of delay and disruption from flooding in the UK.

There is a framework for estimating the cost of disruption associated with flooding which is employed as a tool when undertaking a flood risk assessment. The *Multi-Coloured Handbook* (Middlesex University, 2010) uses a combination of the number of vehicles delayed, additional cost per vehicle and the number of hours that the flood disruption lasts. Given the level of data available to undertake this CCRA assessment and the degree of uncertainty associated with it, it is not possible to adopt such a framework here and hence a qualitative approach has been taken to this metric[28].

The metric is based upon the potential increase in risk of flooding in a year as a result of increases in average winter rainfall projected by UKCP09. This does not account for summer flood events such as those which occurred in 2007. However given the overall trend in the UKCP09 projections towards wetter winters and drier summers, it is considered to be a satisfactory basis for estimating the increase in flood risk (from either a pluvial or fluvial source) based on current evidence and guidance. For this reason, the climate driver used in this response function is the projected increase in winter precipitation. The range of values used within the response function was thus determined as plausible based on the changes projected by the UKCP09 scenarios.

Given the uncertainty in determining cost estimates, a response function was developed combining published figures concerning the 2007 flooding events in England with the Low, Medium and High risk magnitude guidance employed during the impact scoring. This approach places the 2007 in the Medium to High risk category. Given the severity of the event this appears a reasonable assessment and provides a context against which to interpret the rest of the analysis.

It is noted that this estimation relates to England only (based on the available data) – and that the relative costs of disruption in each administration may vary due to regional variation in road networks, travel statistics and flood characteristics. Additional work would be required to estimate similar consequences associated with other modes of transport. It is noted however that in the example of the autumn 2000 floods discussed above, estimated costs of delay and disruption to rail were estimated to be of a similar magnitude to that from road disruption (Penning Rowsell *et al.*, 2002).

[27] http://www.metoffice.gov.uk/climate/uk/interesting/autumn2000.html

[28] The flood and Coastal Erosion sector analysis includes consideration of the number of kilometres of road and rail in England and Wales which are at risk of flooding.

Table 4.1 below shows the resulting response function, incorporating inputs gained through a process of engagement with sector representatives (such as the Highways Agency). Each column represents an estimated consequence associated with a given change in winter rainfall for England. Given the uncertainty, this is estimated through use of probabilities (based on expert opinion such that each column adds up to 100%).

It can be seen that for moderate increases in rainfall there is a high degree of uncertainty in the estimated outcome and hence a spread in the probability assigned. This uncertainty arises from both a lack of confidence in the way winter rainfall may translate to the severity and frequency of flooding and to the costs which may be incurred as a result of flood. The fact that the spread of probabilities assigned is broad underlines the uncertainty associated with this metric.

Table 4.1 Metric TR1 response function

(Costs of delay and disruption (road) associated with flooding – England)

Magnitude class	**Estimated change in metric** Numbers in boxes are the percentage probability of each class being realised						**Estimated cost of disruption for each magnitude class (£m)**
Very High	0	0	0	30	60	80	400
High	0	10	40	50	30	20	100
Medium	0	60	50	20	10	0	10
Low	20	30	10	0	0	0	1
Very Low	80	0	0	0	0	0	-10
	-10%	10%	30%	50%	70%	90%	
	Change in winter precipitation from present day (%) - UK average[29]						

4.3 TR2 – Landslide impacting the road network

This metric has been assessed for England, Scotland and Northern Ireland. Suitable data were not available for Wales.

When it was assessed at the Tier 2 selection stage this impact was described as relating to land movement from either subsidence or land slip. On further investigation of the data available (via discussion with Highways Agency), the analysis has been focused predominantly on landslip/landslide. The evidence base showed that for road maintenance, subsidence is not considered to be a significant issue, as it is generally managed effectively as part of existing road maintenance programmes. Therefore subsidence or low level ground movement is not quantified or reported separately from general road condition.

However landslip adjacent to roads presents a higher level of risk and requires more specific monitoring and management; hence the evidence base presented more readily available data on the proportion of road networks which are adjacent to slopes at risk of failure. This risk is actively monitored and managed throughout Scotland, and while the evidence base offers less detailed data for the other administrations, the evidence base for slope failure risk was considered to be sufficiently robust to achieve a reasonable analysis of this metric.

It should be noted that subsidence is one of the risks considered within the CCRA Built Environment assessment.

[29] This range of change values was developed using the minimum and maximum values from all emission scenarios and all probability values for all regions in the UKCP09 output.

Several factors contribute to slope stability including soil type, soil moisture/rate of saturation, and the intensity, frequency and quantity of precipitation. Each of these factors vary spatially, for example see Figure 4.1 for a map of landslide hazard based upon soil type. Other factors can influence slope stability such as periods of dryness between storm events, where dry periods can cause cracks and fissures in the soil which can form failure lines. When dry periods are followed by storm or intense rainfall events, chances of slope failure can increase.

The landslide potential shown on Figure 4.1 is based on a susceptibility score that takes account of a range of factors including ground slope and hydrogeology. Whilst specific probabilities are not attached to the 'significant' and 'moderate' potential bands, there is a strong correlation between these areas and observed landslides.

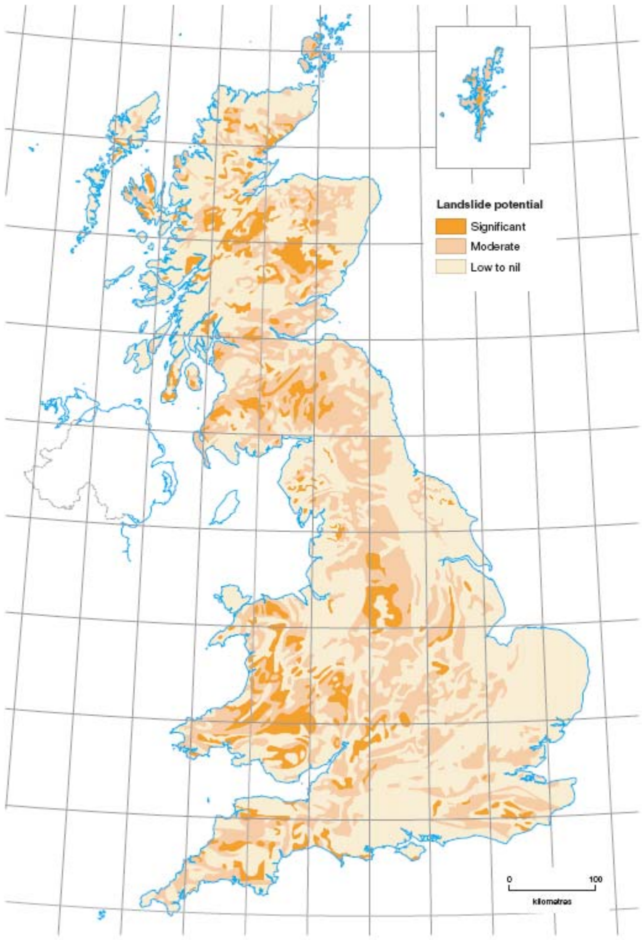

Figure 4.1 Map of landslide hazard in the UK

Source: IPR/129-70C British Geological Survey © NERC.

To put into context what a landslide can mean, there were a number of events across Scotland in August 2004 following unusually high rainfall. The most dramatic of these occurred at Glen Ogle on the A85, where 57 people had to be airlifted to safety when they became trapped between two major debris flows. Although nobody was seriously hurt there were both economic and social consequences, in particular through isolation of some relatively remote communities. In September 2010, the A83 near Rest and Be Thankful in Argyll suffered its third significant landslide in three years. As a known high risk route, this road is already subject to a £470,000 drainage project funded by Transport Scotland which aims to minimize this risk.

There have been a number of in-depth studies of slope stability and landslide. For example, the BIONICS[30] project investigated the impact though use of controlled experiments. Following a number of significant events the Scottish Executive commissioned the *Scottish Road Network Landslide Study* (Winter *et al.*, 2005). Each underlined the complexity of determining landslide risk. Further, no dataset has been identified which gives a robust estimate of the number or scale of events per year across the UK. For this reason a simple 'indicator of risk' is used as the climatic driver for this metric.

The climate driver used for the response function of this metric is the 'increase in winter precipitation' only. This is considered reasonable within the context of the level of assessment undertaken within this first phase of the CCRA given that a) increase in precipitation can be interpreted as an *indicator* of increasing climate risk such as increasing risk of soil saturation and average rainfall amounts; and b) while slope failures and weather impacts are complex to model, it can be said that where there is a significant increase in precipitation, the likelihood of slope failures may increase.

It is recognised that this approach will underestimate slope failures as it neglects events caused by the drying and storm combination most likely to be seen during summer months. It also omits the impact of storm events and considers only the condition likely to increase level of risk of a slope failure.

Areas at risk are a function of slope characteristics. For this reason, a response function matrix is developed for each of the four devolved administrations. In this way the road, slope stability and climate model data for each administration can be considered accordingly.

England

Qualitative information formed the basis of the approach for this metric (see Appendix 4), taking estimates of the proportion of the road network in England which can be considered to be at risk due to slope stability concerns. These estimates were derived through expert elicitation with the Highways Agency (HA) and a representative of the UK Roads Board from a County Council. While the HA have a good understanding of the road lengths at risk, categorising length of road considered to be at Severe risk, Medium risk, etc , information on the network is much less detailed at local authority level, which constitutes the majority (98%) of England's roads.

However, it has been assumed that the estimates generated based on the proportions of HA roads identified as being at risk for slope failure can be considered as a reasonable approximation of the average slope failure risk areas across the country. This is because many roads through the most hilly/undulating areas tend to be B, C or unclassified roads and have a tendency towards following and flowing *with* the lie of the land, thereby reducing the likelihood that slopes adjacent to roads are inherently less stable.

While these assumptions are very generic and high-level, this approach is considered to be consistent with the overall level of detail available for the analysis. Given this uncertainty, a qualitative response function has been developed based on these assumptions and expert elicitation, see Table 4.2. As with TR1, each column shows an estimated likelihood of an outcome for a given change in winter precipitation. The matrix shows that the uncertainty over slope failure increases as the climate change driver moves further from the current baseline climate. This reflects the complexity of estimating slope failure from this climate change driver.

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30 BIOlogical and eNgineering Impacts of Climate change on Slopes, part of the 'Building Knowledge for a Changing Climate' initiative, led by EPSRC and UKCIP

Table 4.2 TR2 response function – England

(Length of road impacted by landslip in England)

Magnitude class	Estimated change in metric Numbers in boxes are the percentage probability of each class being realised						Estimated Increase in length of at risk road impacted for each magnitude class (km)	% of *all* roads
Very High	0	0	0	0	10	10	5,000	1.7%
High	0	0	20	30	30	30	3,000	1%
Medium	0	30	60	60	50	60	1,500	0.5%
Low	40	70	20	10	10	0	630	0.21%
Very Low	60	0	0	0	0	0	150	0.05%
	-10%	10%	30%	50%	70%	90%		
	Change in winter precipitation from present day (%)							

It should also be noted that the 1.7% of England's roads that constitute the 'Very High' risk category is equivalent to the entire estimated length of roads in the country which currently fall into a known 'medium-high' or 'severe' risk categories. That is to say, an estimated 1.7% of all roads in England are currently can be considered as being at risk from landslide.

Scotland

In 2005 the Scottish Executive published a Climate Change Study[31] to identify issues which may face Scotland's road network as a result of changing climate. The overall conclusion, based on the projected consequences for the 2020s, was that the projected changes for Scotland were relatively small. One specific area of concern was increases rainfall, with respect to drainage systems and influencing slope stability.

Values for the length of trunk road in a 'severe' risk category were published in the Transport Scotland *Scottish Road Network Landslides Study* (part 2)[32]. These concern the trunk road network only, which constitutes around 3,400km of roads, 6% of the Scottish road network. As for the remainder of the road network, around 40,830km, there is a of priority risk classification, with the vast majority of the high priority roads (approximately 90%) being within Scotland's north west. However, sufficient data to estimate risks to all roads (in addition to trunk roads) was not identified and hence this metric covers the increase in risk areas for Scotland's trunk road network only.

The geotechnical conditions in Scotland tend to have different characteristics from those in England. As a result, it was felt that winter precipitation, unless projected to be exceedingly high, may not be an adequate climate change driver against which to analyse the increase of slope failure risk areas on road networks with a more pertinent driver being summer drying/storm patterns. Advice from Transport Scotland is that landslides are most prevalent in the periods July to August and October to January. However, for consistency, the same approach as taken for the England metric was maintained.

Table 4.3 shows the response function for slope failure in Scotland. As previously, the uncertainty in the function reflects the uncertainty in the climate change driver and response. A further uncertainty is reflected in the road kilometre ranges used.

[31] *Scottish Road Network Climate Change Study*, Scottish Executive, 2005. See http://www.scotland.gov.uk/Publications/2005/07/08131510/15117 Date accessed October 2010
[32] *Scottish Road Network Landslides Study*, Transport Scotland, 2005. See http://www.scotland.gov.uk/Publications/2005/07/08131738/17395 Date accessed October 2010

Table 4.3 TR2 response function – Scotland

(Length of road impacted by landslip in Scotland)

Magnitude class	Estimated change in metric Numbers in boxes are the percentage probability of each class being realised					Estimated Increase in length of at risk road impacted for each magnitude class (km)	Increase in length of at risk trunk road impacted (%)
Very High	0	0	0	0	10	750 to 1650 km	46% to 100%
High	0	10	20	20	30	330 to 750 km	21% to 45%
Medium	30	30	60	70	50	200 to 330 km	13% to 20%
Low	40	60	20	10	10	50 to 200 km	4% to 12%
Very Low	30	0	0	0	0	16 to 50 km	<1% to 3%
	-10%	10%	30%	50%	70%		
	Change in winter precipitation from present day (%)						

Northern Ireland

The information used in this analysis was provided as a best estimate based on the rates of risk provided for England's road network as equivalent data for Northern Ireland could not be identified. However, qualitative information on the extent of risk slopes adjacent to Northern Ireland's road network was provided by the Department for Regional Development (DRDNI). This was taken into the analysis but the TR2 response function for Northern Ireland should be interpreted with this limitation in mind. As for England, a similar approach to categorisation of length of roads at risk is used.

Table 4.4 TR2 response function – Northern Ireland

(Length of road impacted by landslip in Northern Ireland)

Magnitude class	Estimated change in metric Numbers in boxes are the percentage probability of each class being realised						Estimated Increase in length of at risk road impacted for each magnitude class (km)	% of *all* roads
Very High	0	0	0	0	0	0	1000	4%
High	0	0	0	30	30	30	500	2%
Medium	0	20	40	50	50	50	250	1%
Low	20	60	60	20	20	20	125	0.50%
Very Low	80	20	0	0	0	0	60	0.25%
	-10%	0%	10%	20%	30%	40%		
	Change in winter precipitation from present day (%)							

Wales

While the Welsh Government publishes road condition data on the transport statistics area of the website, the information relates to surface condition surveys rather than stability and/or risk of the slopes adjacent to the road network. The Welsh Government is currently in the process of initiating surveys and data collection relating to the country's geotechnical assets and hence is not able to provide a meaningful estimate of the risk areas at this time. For this reason, given the very different characteristics of the geography of Wales compared to the other administration, a response function has not been developed.

Summary

Response functions have been developed for the lengths of road potentially affected by landslide. Whilst this information can be used to assess repair costs it does not cover the number or locations of roads affected. The main consequence of landslides on roads is likely to be the associated disruption to transport, which is not specifically covered by this metric.

4.4 TR4 – Cost of carriageway repairs

The sector scoping report and the workshop each identified the risk that higher temperatures will contribute to higher rates of heat damage to road surfaces as being important within this sector. This manifests itself in two ways: first, the physical damage and deformation of roads due to the impact of high road surface temperatures, and second, that the road surface must be sufficiently cool before repair work can commence. The latter is an indirect increase in cost, as it concerns increased delays and/or damage or the necessity to carry out repair works at night. This metric has been assessed for England and Northern Ireland as suitable data for Scotland and Wales were not identified.

The cost baseline for repairs to roads due to heat damage was derived from a) the actual annual spend from an example County Council (Leicestershire) and b) the estimated expenditure on Highways Agency assets, which is based on the same spend/km for heat damage. The baseline of current expenditure is approximately £34m, based on £115 spend per km of network in Leicestershire.[33] These low values contribute to the shallow risk profile depicted on the response matrix which shows the cost decrease/increase in £m above the current estimated baseline costs of £34m.

It should be noted that the response function fails to capture the stark difference in consequences between the impact on England's highways and principal trunk roads network and the cost of repairs to other A, B, C and unclassified roads and. Background research for this metric highlighted that the burden of cost increases is likely to fall on local authorities rather than the Highways Agency. This is due to the inherent difference in physical vulnerability of local and unclassified roads as opposed to the Highways Agency roads, the latter currently being designed and constructed to a greater heat-resilient specification than is standard for other roads in the UK.

[33] These figures were provided by a representative of the UK Roads Board and hence are taken as a reasonable estimate of costs. However, it should be noted that analysis of this qualitative type does have limitations and a more robust figure could potentially be developed from a wider pool of consultees across local authorities although successfully obtaining quantitative data in the correct format may be problematic as there is variation in the available data between authorities.

Table 4.5 TR4 Response function – England

(Cost of carriageway repairs in England)

Magnitude class	Estimated change in metric Numbers in boxes are the percentage probability of each class being realised						Estimated increase in cost of repairs for each magnitude class (£m)
Very High	0	0	0	0	0	0	100
High	0	0	0	0	0	20	50
Medium	10	10	50	50	50	50	10
Low	10	20	50	50	50	30	1
Very Low	80	70	0	0	0	0	-10
	0	2	4	6	8	10	
	Increase in mean summer temperatures from present day - °C						

Data to support the development of the matrices was sourced for England and for Northern Ireland but at the time of the analysis, equivalent data for Scotland or for Wales was not identified. Table 4.6 is the response function matrix for Northern Ireland. The spread of probabilities assigned underlines the uncertainty associated with this risk.

Table 4.6 TR4 Response function –Northern Ireland

(Cost of carriageway repairs in Northern Ireland)

Magnitude class	Estimated change in metric Numbers in boxes are the percentage probability of each class being realised					Estimated increase in cost of repairs for each magnitude class (£m)
Very High						100
High						50
Medium	0	0	10	10	10	10
Low	20	20	20	30	40	1
Very Low	80	80	70	60	50	0
	0	2	4	6	8	
	Increase in mean summer temperatures from present day - °C					

Summary

Response functions have been developed for the costs of road repairs arising from heat damage to roads. Whilst this information can be used to assess repair costs it does not cover the number or locations of roads affected. The main impact is likely to be the associated disruption to transport, which is not specifically covered by this metric.

4.5 TR5 – Rail buckling risk

Monthly frequency of rail buckling data for Great Britain has been calculated from a database of 575 rail buckling incidents[34] for the years 1997-2009. Monthly data for 1995-1996 for 200 rail buckling incidents has also been obtained (Thornes, 1997) to give a total of 755 rail buckling incidents. This metric has therefore been assessed for England, Scotland and Wales. Unfortunately, similar data for Northern Ireland has not been identified.

[34] Supplied by Network Rail (John Dora and Nathan Sharp)

Table 4.7 shows the monthly rail buckling data together with the mean summer Central England air Temperature (CETsummer).

Table 4.7 Rail buckling frequency and temperature

Year	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Total	CETsummer
1995			1	14	60	23	37		135	17.4
1996			2	1	24	14	4		45	15.8
1997				6	2	10	19		37	16.6
1998				9	1	3	5		18	15.2
1999				5	9	38	5	2	59	15.9
2000				1	22	3	3		29	15.7
2001			1	15	12	19	1		48	16.1
2002	1		3	1	6	7	4		22	15.8
2003			4	10	15	56	51	1	137	17.3
2004			2	6	7	4	13		32	16.2
2005			1	2	29	22	1		55	16.2
2006			1	6	18	66			91	17.2
2007					3				3	15.2
2008				4	7	4	1		16	15.4
2009		1	1	4	15	7			28	15.8
Mean									**50.3**	**16.1**
Total									**755**	

For the initial analysis, the annual totals have been plotted against the mean summer Central England Temperature (CET) as shown in Figure 4.2. As can be seen there is an excellent agreement with a high degree of correlation, suggesting that up to 82% of the variations in annual rail buckling in Great Britain are due to variations in summer temperature.

Obviously the actual track temperature that causes a rail to buckle will be much higher (40 to 50+ degrees Celsius) but there is no data available on rail temperatures. For a discussion of the relationship between air and rail temperatures see Chapman *et al.*, 2008.

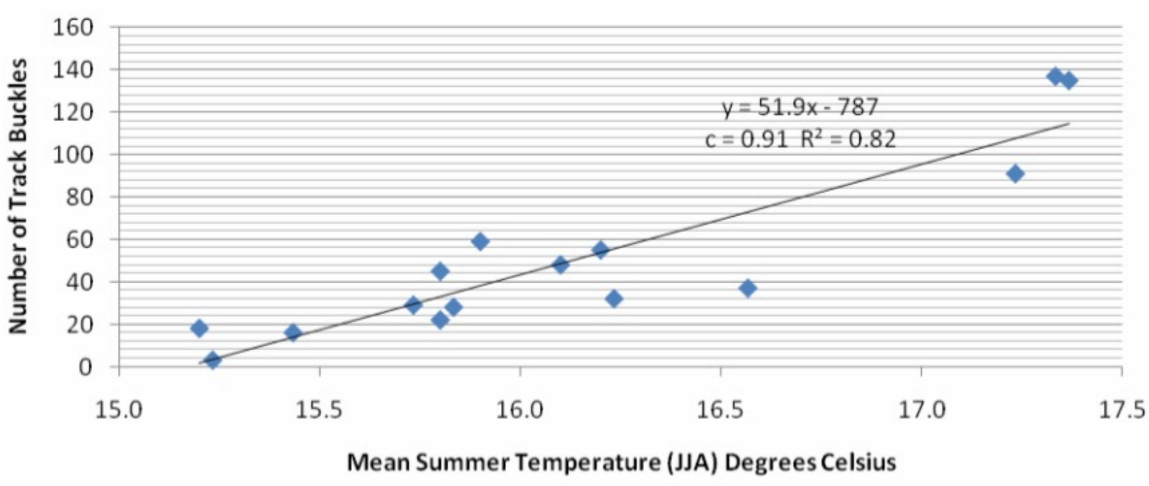


Figure 4.2 Correlation between rail buckling and temperature
(Based on 1995 to 2009 data)

The database supplied by Network Rail also provides the location for each of the rail buckling incidents for 1997-2009 (although location data is not available for 1995 and 1996 data). Where possible, incidents since 1997 have been classified as by UKCP09 administrative region. Table 4.8 shows the distribution of rail buckles for 11 regions for which data was available. From this short period of data the impact of heat wave is clear with more rail buckling events recorded in 2003 than in any other year. From this data alone it is not possible to infer any regional bias (although one would be presumed based on regional variation in UK temperature). To understand this, further data would be required on the kilometres of track in each region so that a measure of exposure to risk can be developed.

Table 4.8 Regional variation in observed rail buckling frequency

	EM	EE	SC	LO	NE	NW	SE	SW	WA	WM	YH	Total
1997	5	5	0	5	2	5	3	2	0	4	6	37
1998	1	1	0	4	1	2	2	1	1	3	2	18
1999	2	3	2	9	0	10	11	3	5	6	8	59
2000	2	3	1	6	1	1	3	3	0	4	5	29
2001	2	3	3	8	0	5	7	1	1	6	12	48
2002	1	1	0	7	0	2	1	1	0	7	2	22
2003	6	8	8	31	5	15	19	12	2	21	10	137
2004	3	3	0	8	1	4	4	1	0	4	4	32
2005	5	6	2	5	3	3	7	8	2	5	9	55
2006	4	11	0	13	5	18	6	8	6	10	10	91
2007	0	0	0	0	0	3	0	0	0	0	0	3
2008	0	0	2	0	1	1	3	1	1	1	6	16
2009	1	2	2	1	7	4	1	1	1	0	8	28
Total	**32**	**46**	**20**	**97**	**26**	**73**	**67**	**42**	**19**	**71**	**82**	**575**

Regions – EM: East Midlands; EE: East of England; SC: Scotland; LO: London; NE: North East; NW: North West; SE: South East; SW: South West; WA: Wales; WM: West Midlands; YH: Yorkshire & Humber

4.6 TR6 – Road and rail bridge failures due to scour

This metric has been considered for the UK although suitable data for quantification of the impact were not available.

Bridges built with footings in rivers or estuaries are at risk of scour occurring around these foundations. If the development of scour at these foundations becomes significant, then the stability of the foundations may be threatened and there is associated danger of structural damage or failure.

Scour is a term used to describe the movement of the riverbed sediment as a response to the shear forces associated with flowing water in the presence of a hydraulic structure such as a bridge. It should be noted that in the case where sediment is moved irrespective of the presence of any anthropogenic-imposed structure (in this instance a bridge), this is often termed erosion.

Bridges are of varying characteristics and age and scour may have been taken into account in the design of the bridge for the specific design and specific location using results from detailed analysis and engineering experience available at the time. More recently scour in design has been considered more systematically as scientific knowledge has improved.

A scour assessment has been carried out of potential increases in scour that could occur with projected increases in river flood flows identified in the Floods and Coastal Erosion Sector Report. The projected increases in flows compared with a 1961-90 baseline are between 0% and 20% by the 2020s, 0% and 40% by the 2050s, and 0% and 60% by the 2080s. Further details of the assessment are given in the Floods and Coastal Erosion sector report.

Bridge vulnerability

The principal issue relating to estimating the vulnerability of a bridge to failure is the inherent uncertainty about its performance during infrequent events or subject to unobserved hazards and this introduces the concept of probability and risk.

Assessing the vulnerability to scouring of bridges with unknown foundations is made difficult by the lack of information about the construction (i.e. form, depth, or geotechnical setting) of piers, footings, or abutments, and determining the substructure of an unknown foundation may be expensive. Therefore, for bridges with unknown foundations it may be useful to relate what is known about the bridge and its setting to similar bridges in order to help determine scour risk.

It is estimated that there are over 9,000 major railway structures that cross watercourses (Table 4.9). A database of 131 rail structure failures due to scour and/or flood in the UK and Ireland has also been constructed and used to review the causes of failure (JBA Consulting, 2004). This includes the bridge collapse over the River Towy, Wales (Glanrhyd) in October 1987 which resulted in 4 deaths.

Table 4.9 Estimated number of major railway structures over water

Network Rail Region	Number of structures
Southern	1,171
Great Western	1,820
London North Eastern	1,366
Midland	1,152
Scotland	2,144
North West	830
Anglia	545
Total	9,028

The range of bridge types within the UK and their vulnerability to scour is very wide. The UK has a small number of medieval road bridges. The foundation depths for most of these bridges are unknown and so the vulnerability to scour is unknown. Where foundation depths have been determined they are generally small and such bridges are often potentially vulnerable to scour. An increasing number of bridges have been constructed through time but the prediction and analysis of scour was only a significant design issue from the mid to late 19th Century and bridges constructed before then may be vulnerable to scour.

The railway bridges in the UK date predominantly from the railway boom in the second half of the 19th Century. Work has been carried out to identify scour critical structures and improve resistance to scour where necessary. Major modern road bridges, such as most motorway bridges, have deep foundations for structural reasons. As a result it is unusual for them to be vulnerable to scour. Bridge failures in the UK in the last 10 years include:

Year	Location
2002	Rawtenstall (Railway bridge)
2003	Beighton (Railway bridge)
2004	Boscastle
2005	Helmsley
2006	Shropshire
2009	Workington (Three bridges failed and one life lost)
2009	River Crane (Railway bridge).

The continued occurrence of bridge failures show that there are significant numbers of bridges in the UK which are currently vulnerable to scour under present conditions. Many of the bridges that are currently not vulnerable to scour have foundation depths that are not significantly greater than estimated scour depths. Thus a small increase in scour depths may lead to a significant increase in the numbers of bridges vulnerable to scour.

Scour Assessment

The metric used in this analysis is number of bridge failures due to scour. However data do not exist for this metric, and response functions have been developed for scour depth against river flow.

Example calculations of scour estimates have been made to demonstrate likely increases in scour depth with increases in flow for a sample bridge with (a) a gravel bed, (b) a sand bed and (c) a gravel bed with natural bed armouring. The abutments project into the river and there is a 20% width reduction. In practice there could be a more severe flow contraction at bridges during floods as floodplain and river channel flow is required to contract into the bridge opening.

The results are shown in Figures 4.3, 4.4 and 4.5 respectively. The analysis provided projection for local scour at piers and abutments, and contraction scour caused by the removal of material from the bed and the banks of a channel.

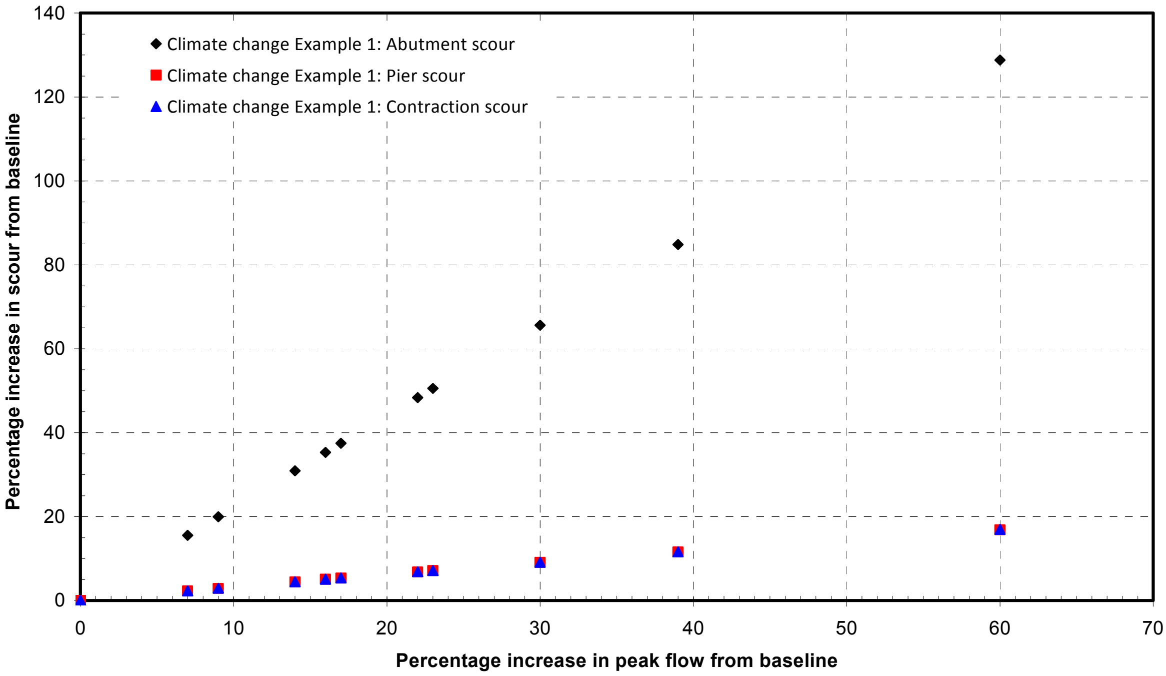


Figure 4.3 Increase in scour depth against flow for a gravel bed river

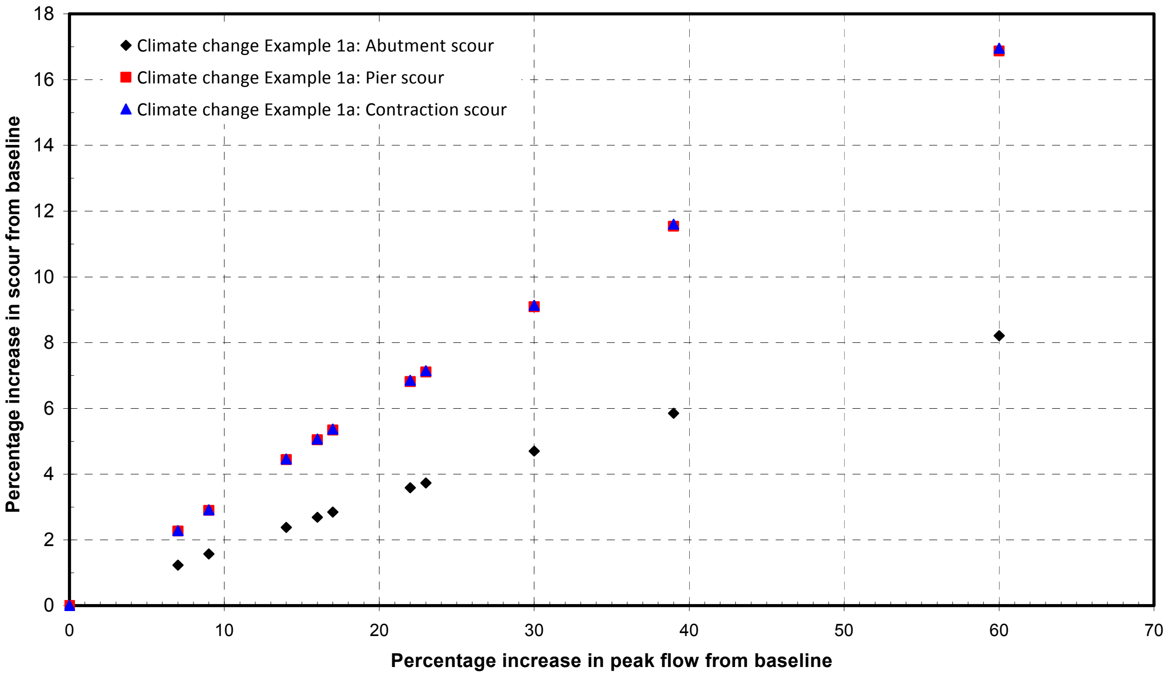


Figure 4.4 Increase in scour depth against flow for a sand bed river

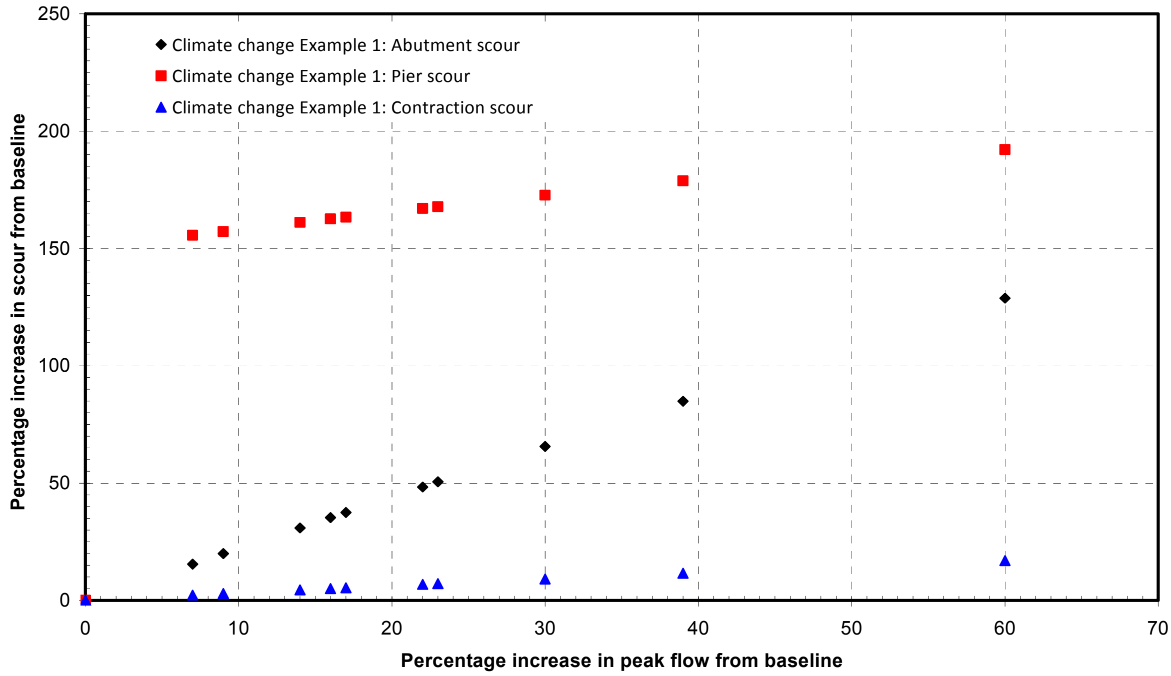


Figure 4.5 Increase in scour depth against flow for a gravel bed river with natural bed armouring

Note: The effect of natural bed armouring is included in the pier scour calculations

The results show greater local scour depths for the gravel bed river example compared with the sand bed river example. For a 60% increase in flow the increase in local scour depth for the gravel bed is over 100% compared with less than 20% for sand.

Bed armouring is the term used to describe what happens when the surface sediments are coarser than the underlying sediments and occurs as a result of selective transport of different sediment sizes. The results in Figure 4.5 show a potential sensitivity of scour depths to changes in peak flow. Once scour has removed the armour layer, there is a rapid increase in scour.

This impact of natural bed armouring demonstrates the sensitivity of the calculations to the site specific characteristics which will also include the geotechnical properties of the riverbed soils. In this example there is a potential rapid increase in scour projected for only a 7% increase in peak flow. The actual combination of river flow and bed sediment conditions will control the point at which this projected change in scour response takes place.

The overall conclusion is that the response to climate change is sensitive to the river bed sediment type. For sand bed rivers and gravel bed rivers with no natural sediment armouring or peak flows below the velocity that initiates scour, the scour depth is projected to increase linearly in proportion to the percentage increase in peak flow. In gravel bed rivers with natural sediment armouring the potential for increased flows to break up the armour layer can lead to a large increase in scour response.

4.7 FL8 – Roads and rail at significant likelihood of flooding

The length of road and rail at significant likelihood of flooding was assessed in the Floods and Coastal Erosion Sector (Metric FL8, Ramsbottom *et al.*, 2012). This metric was assessed for England and Wales but not Scotland and Northern Ireland owing to a lack of suitable data. This metric links closely with Metric TR1 (Flood disruption/delay to road traffic) discussed above.

The consequences were calculated directly using flood frequency data. As the frequency of flooding increases with climate change, the length of road (by type) and rail inundated more frequently than the threshold specified in the analysis ('significant' likelihood, which is 1.3% annual probability of flooding or 1 in 75 years on average) may increase. Separate response functions were not calculated.

The data used for the analysis was regional flood frequency data, which provides information on the expected increase in the frequency of flooding based on sea level rise and the change in river flows.

For example, a coastal flood with an annual probability of occurrence of 0.5% (1:200) today may have an annual probability of occurrence of 2% (1:50) in 50 years time. This means that a flood of this magnitude is projected to occur four times more frequently in 50 years time (in this example).

Detailed flood frequency data were prepared using UKCP09 projections for river and tidal flooding. Some specific examples from the data are as follows:

- A 1% (1:100) river flood in Northumberland could occur 3.2 to 5 times more frequently by the 2080s compared with a 1961-90 baseline.
- A 1% (1:100) river flood in the South-East could occur 1.8 to 3.1 times more frequently by the 2080s compared with a 1961-90 baseline.
- A 0.01% (1:1000) tidal flood in the East of England could occur about 2.4 to 14 times more frequently by the 2080s compared with the present day frequency.
- A 0.01% (1:1000) tidal flood in Wales could occur about 3 to 40 times more frequently by the 2080s compared with the present day frequency.

These examples indicate the magnitude of increases in the frequency of flooding of transport infrastructure that could occur as a result of climate change. The data were used to estimate the lengths at significant likelihood of flooding (Section 5.9).

4.8 MA5 – Shipping routes: navigable days for the north-west and north-east passages per annum

4.8.1 Overview

One of the main potential impacts on the transport sector that was identified in other sector reports is related to changes in Arctic sea ice and the consequences for navigation. This was assessed in the Marine Sector Report (Metric MA5, Pinnegar *et al.*, 2012). This metric is a UK-wide issue and has therefore been assessed in the context of the UK rather than any particular country.

Arctic sea ice is an important part of the global climate system. The natural variability of ice extent affects the reflection of radiation and heat exchange between the ocean and the atmosphere and modifies ocean stratification influencing thermohaline circulation systems, such as the North Atlantic Current (commonly but incorrectly known as the 'Gulf Stream'). Sea ice extent is also key to socioeconomic activities in the Arctic and its surroundings and any changes to sea ice will have huge environmental and socioeconomic consequences (EEA, 2004). Shrinking sea ice endangers habitats for indigenous people and animals that rely on the frozen environment to survive.

Reductions in sea ice and increased shipping opportunities may serve to increase the risk of oil spills and the opening up of these previously unused routes and also provide a new mechanism for transport of new invasive non-native species to other parts of the world. However a reduction in sea ice also presents opportunities by facilitating trade in the opening of the Arctic passages for shipping and transportation.

Although the environmental consequences of sea ice reduction in the Arctic will undoubtedly be severe, the risk metric identified focuses upon the economic advantages of trade and transportation, taking a measure of the potential opportunities of 'navigable days' through the Arctic. This is because this metric was selected to assess the implications of an ice free Arctic from a socio-economic perspective. The opening of new trade routes was identified as a key consequence of melting sea ice causing this metric to be scored very highly for socio-economic magnitude. This high score and further comments from the consultation exercise resulted in this metric being taken forwards for assessment under Tier 2 rather than the environmental consequences. The environmental consequences of such changes are therefore not discussed here.

The Polar Regions are very sensitive indicators of climate change and the United Nations Intergovernmental Panel on Climate Change (IPPC) demonstrated that these regions are highly vulnerable to rising temperatures. The past decade was the warmest in the Arctic for the last 2,000 years and four of the five warmest decades in the past 2,000 years occurred during 1950 - 2000, despite the fact that summertime solar radiation in the Arctic has been steadily declining over this period (Kaufman *et al.*, 2009). If not for the increase in human-produced greenhouse gases, it is thought that summer temperatures would have actually gradually cooled in the Arctic over the last century due to the increasing distance between the earth's surface and the sun (Kaufman *et al.*, 2009).

In line with the changing climatic conditions, Arctic sea ice is known to be declining and has been observed to be decreasing in extent and thickness during the second half of the 20th century and the early 21st century (AMSA, 2009). Arctic sea ice naturally extends surface coverage each northern winter and recedes each northern summer, but the rate of overall loss since 1978 when satellite records began has accelerated. Observed sea ice extent for the years 1979 - 2006 indicates a decrease or annual loss of around 45,000 km^2 of ice (3.7%) per decade. The summer of 2007 saw a record low when sea ice extent shrank to around 3 million km^2, its lowest level since satellite measurements began nearly 30 years ago, and approximately 1 million km^2 less than the previous minima of 2005 and 2006. A reduction of 1 million km^2 in just one year was extreme and loss of this magnitude indicates that reductions in ice due to climate change may occur faster than previously believed. The IPPC project that the Arctic may be virtually ice free by the summer of 2070, while more recent research (2006-2008) indicates that the ice free state could occur as early as 2040 (AMSA, 2009).

For more than three centuries, explorers and entrepreneurs have envisioned a direct route across the top of the world between the Pacific and Atlantic oceans but Arctic sea ice has always presented a significant barrier to developing such a global trade route. However in recent years, owing to the extreme reductions in ice extent during the Arctic summer, both the north-west and the north-east (northern sea route) passages have been open to shipping. In 2007 the most direct route of the north-west passage across northern Canada was fully navigable, while the north-east passage along the Siberian coast remained only partially blocked and in subsequent years (2008/2009) the north-east passage was also considered navigable. The north-west passage provides a shortcut between the Atlantic and Pacific Oceans through the Canadian Arctic, which offers huge savings in both time and fuel for ships that currently travel through the Suez Canal in Egypt or the Panama Canal in Central America (and incur passage fees). The north-east passage (the northern sea route) provides the fastest direct route for vessels travelling from the UK to the Asiatic markets and vice versa. The opening up of these passages for commercial vessels represents huge advantages for the shipping industry in saving valuable time, thousands of kilometres and tonnes of fuel. The most relevant to UK markets and economies is the north-east passage through the Russian Arctic (AMSA, 2009).

4.8.2 Analysis

One of the impacts identified to the Marine sector as a result of climate change, was that of Arctic sea ice extent and the number of navigable days through the Arctic passages. This was identified as an opportunity rather than a risk and was taken through for further assessment due to the considerable socio-economic implications of such an impact.

In calculating the number of navigable days through the Arctic passages it was not possible to use navigation records directly due to the sporadic nature of the history of transport through these routes, combined with a lack of data to catalogue such transport. Case histories are sparse; the Arctic Marine Shipping Assessment (AMSA, 2009) report provides a history of the transport through these routes along with descriptions of the type of vessels operating in the Arctic waters. The overview of the distribution of vessel activities demonstrate that nearly all voyages take place on the periphery of the Arctic ocean with only between 1 – 10 trips operating around the northern passages.

The complications in using these data combined with the lack of commercial shipping data against a meaningful climatic variable meant that measuring ‘navigable days’ presented some problems, as histories did not exist to provide a baseline to project from. Instead it was considered that navigable days could be derived from projections of sea ice extent for the Arctic, using the known navigation routes (north-west and north-east passages) to identify ‘ice free days’ and therefore ‘navigable’ days.

The north-west passage (NWP), although well known throughout history, is complex in definition and is the name given to the various marine routes that are possible between the Atlantic and the Pacific oceans, along the northern coast of North America and through the Canadian Archipelago. The north-east passage (NEP) is less defined and it is sometimes referred to as the ‘northern sea route’ (NSR) when it is actually a combination of the two. The Northern sea route is defined in Russian Federation law as a set of marine routes from Kara Gate in the west to the Bering Strait in the east, while the north-east passage runs from north west Europe (the UK) around the north cape (Norway) and along the north coast of Eurasia and Siberia through the Bering Strait to the Pacific. The most relevant of these routes for the UK shipping industry is therefore the north-east passage. The different combinations of these routes are demonstrated in Figure 4.6.

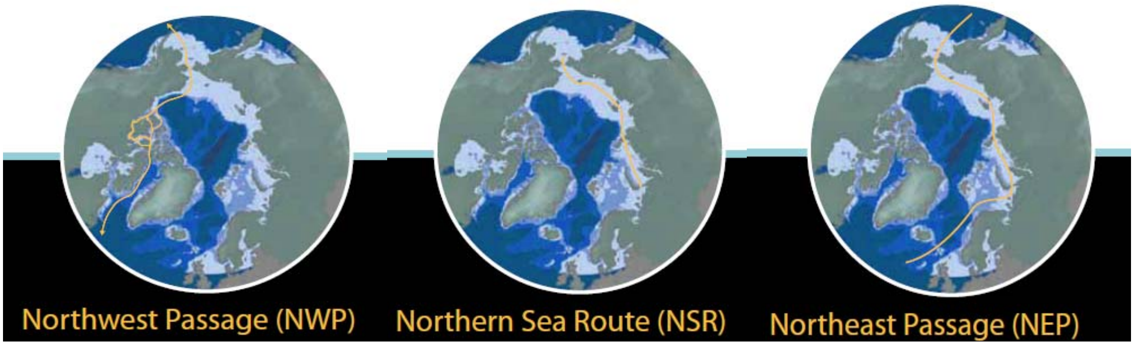


Figure 4.6 Routes of the northern passages
Source: Arctic Marine Shipping Assessment (AMSA), 2009

Although different potential routes exist for the northern passages, for the purposes of this assessment it was considered that if any of the potential routes were free of ice to provide one continuous route through either the north-west or north-east passages then this would be considered as ‘navigable’. The routes observed may therefore shift to either the east or west of the central Arctic to provide a clear ice free route for vessels.

It is acknowledged that identifying the north-west and north-east transport routes is complicated particularly with regard to the north-west passage due to the complexity of the land-sea mix that exists. However in order to make an assessment of navigable days it has been necessary to make some assumptions about ‘navigable routes’. For this assessment it was considered that if an available continuous route could be identified as ice free then this provided a potential ‘navigable route’ for vessels through the Arctic passages.

4.8.3 Metric

The ice extent projections used were supplied by the Met Office from their HADCM3 model which is able to provide projections for the three UKCP09 scenarios and for 12 months of the year. It should be highlighted that the Met Office is currently developing a new generation of climate models knows as the HADGEM series (Hadley Global Environment Model).The key difference between these models and the HADCM3 model is the greater level of detail and resolution able to be provided. However the new generation models are currently under development and following discussions with the Met Office it was considered practical to use the established HADCM3 model for the purposes of this assessment, particularly because of its relevance to the UKCP09 projections.

HADCM3 data sets are used as the Met Office advised that this model provided the baseline for UKCP09 in simulating the 17 transient projections of climate change. The projections are therefore key to the underlying emission scenarios for UKCP09 and can be directly applied for analysis.

Projections were provided for three different ice cut off scenarios, 30%, 15% and 5% in line with the Met Office’s own assessments of ice extent. These cut offs relate to ice extent in percentage cover of each grid cell and therefore ice breaker capability. For example, under the 30% cut off it is assumed that vessels are able to navigate through ice conditions of up to 30% coverage per grid cell due to ice breaker capability and therefore vessels will be able to navigate through these conditions more frequently. In terms of commercial transport the most relevant ice cut off is 5% as this requires the least ice breaking capability and therefore has the lowest costs associated with transit.

Use of the HADCM3 projections has enabled the assessment of both seasonality and navigable days as a function of navigable months throughout the year. It was also possible to measure total ice extent in km^2 both historically and for future projections. Ice extent data was also graphed to demonstrate patterns of seasonality and the declining trend.

To provide a baseline from which to assess the future projections, the Met Offices HadOBS marine dataset HadISST projections were used. The Met Office Hadley Centre produces and maintains a range of gridded datasets of meteorological variables for use in climate monitoring and climate modelling. One of the marine outputs for use is HadISST, which provides a unique combination of monthly globally-complete fields of sea surface temperature and sea ice concentration on 1 degree latitude-longitude grid from 1870 to date. The sea ice data are taken from a variety of sources including digitised sea ice charts and passive microwave retrievals (Met Office 2010[35]).

Some example projections of sea ice extent for present day and the 2080s from HADOBS and HADCM3 are provided in Figure 4.7. It should be noted that there is an anomaly in the minimum winter sea extent (September 2009), which was corrected for estimations of future changes to sea ice extent.

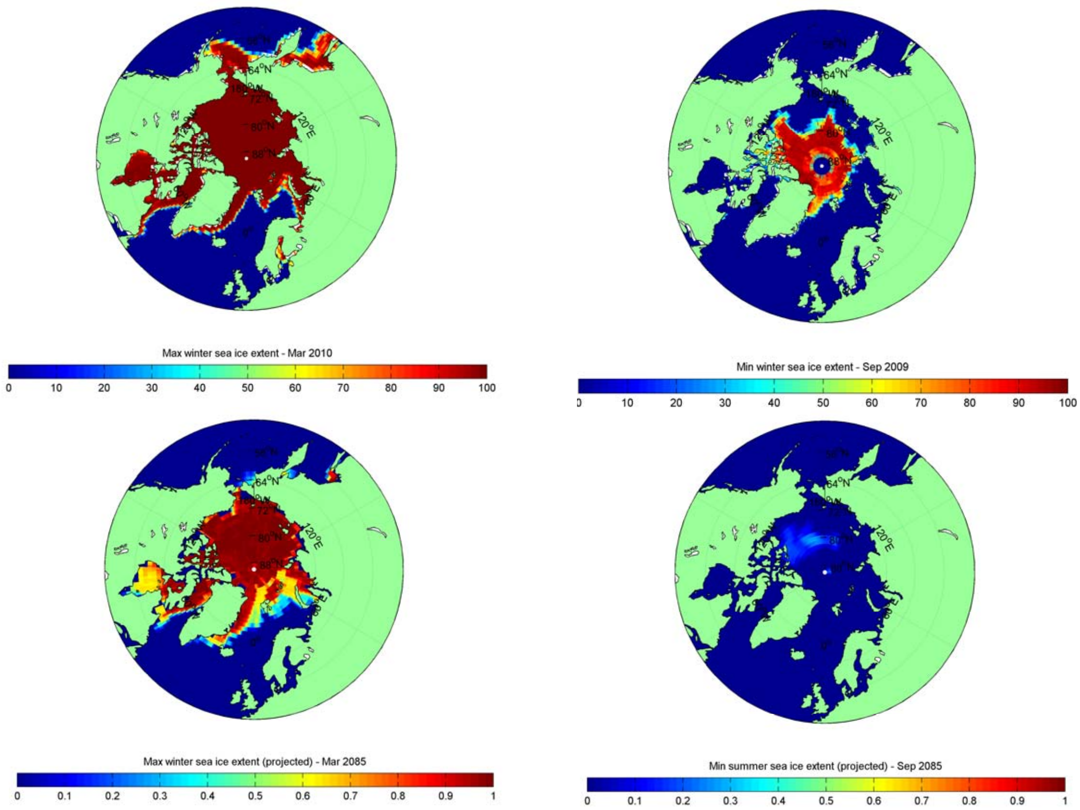


Figure 4.7 Examples of sea ice projections used both present day (2009/2010) and projected (2080s)

[35] http://hadobs.metoffice.com/hadisst/

5. Changes with Climate

5.1 Introduction

The purpose of this step is to apply the UKCP09 projections to the response functions developed in Section 4 (which establish the potential relationship between a climate driver and the consequence) to estimate consequences under different future scenarios. It is based on scaling using the relevant climate variable(s) and/or expert opinion and provides consistent assessment in the context of the UKCP09 projections.

The results presented in this section are for climate change impacts only, i.e. they consider the impacts of climate change on the current socio-economic baseline. Where a metric considers costs, the application of the scenarios only indicates how the current transport network may be impacted in terms of current costs. Social and economic drivers are only introduced in Section 6.

For each metric a scorecard is given at the start of each section to indicate the confidence in the estimates given and the level of risk or opportunity. Confidence is assessed as high (H), medium (M) or low (L). Risks and opportunities are scored either high (3) medium (2) or low (1) (shown to the right). These are given for the lower (l), central (c) and upper (u) estimates for the 2020s, 2050s and 2080s. Further information is provided in Appendix 3. Where estimates are uncertain, or no data is available, this is stated in the scorecard.

M	Confidence assessment from high (H) to low (L)
3	High opportunity (positive)
2	Medium opportunity (positive)
1	Low opportunity (positive)
1	Low risk (negative)
2	Medium risk (negative)
3	High risk (negative)

5.2 Data used

The following data were used to estimate the impact of climate change with selected climate scenarios:

- Total petroleum consumption by road transport in Great Britain and Northern Ireland (DfT and the DRDNI).
- Road maintenance cost data (qualitatively estimated from the HA and Leicestershire CC).
- Road length and classification statistics for the UK (DfT and DRDNI).
- Cost of traffic disruption from flooding (EA, Foresight).
- Cooling degree day data (derived from the UKCP09 observations dataset).

5.3 Use of UKCP09

The full UKCP09 data set was downloaded[36], for averages of three thirty year periods centred on the 2020s, 2050s and 2080s, for the Low, Medium and High emission scenarios. The following variables were used:

- Change in mean summer temperature (degrees Celsius) (change in future 30-year average of annual average air temperature at 1.5m from the baseline climate (1961-90) long term average).
- Change in winter average precipitation (%) (change in future winter average precipitation from the baseline climate (1961-90) long term average).

5.4 TR1 – Flood disruption/delay to road traffic

Metric code	Metric name	Confidence	Summary Class								
			2020s			2050s			2080s		
			l	c	u	l	c	u	l	c	u
TR1	Flood disruption/delay to road traffic	M	1	1	1	1	1	2	1	2	3

The qualitative response function developed for this metric was presented in Section 4.2. As noted, there is not a direct link between increase in winter precipitation and the number or severity of flooding events although arguably increased average winter precipitation could mean an elevated risk.

Bearing this in mind, a qualitative estimate (based on existing literature and expert elicitation) of the level of costs associated with the impact on road users arising from flood related delay and disruption was developed. Based upon this qualitative response function an estimate of potential future risk has been derived though application of the UKCP09 scenarios (see Table 5.1).

The outcome of the assessment shows that cost of disruption from flood is projected to remain relatively low until the 2050s when there may be more significant consequences (at the p90 level, Medium and High emissions scenarios). By the 2080s, this qualitative estimate indicates a potential for Medium to High risk, equating to an event each year of comparable cost to the summer 2007 flood, or multiple events like the 2000 floods. This risk is calculated at today's costs but it must be underlined that this estimate is highly uncertain.

[36] http://ukclimateprojections-ui.defra.gov.uk

Table 5.1 Metric TR1 assessment - England

(Qualitative assessment of the impact of delays and disruption arising from flooding)

	Low Emissions			Medium Emissions			High Emissions		
	p10 (dry)	P50 (mid)	p90 (wet)	p10 (dry)	p50 (mid)	p90 (wet)	p10 (dry)	p50 (mid)	p90 (wet)
2020s	0	1	1	0	1	1	0	1	1
2050s	0	1	1	0	1	2	0	1	2
2080s	1	1	2	1	2	3	1	2	3

0	Very low – less than £1m cost of disruption per year
1	Low – £1m to £10m per year
2	Medium – £10 to £100m per year
3	High – £100 to £400m per year
4	Very high – >£400m per year

It is noted that this metric is focused upon risk of flood arising from a wet winter and therefore is likely to underestimate total costs, given the potential for summer flooding such as that experienced in 2007. Coastal impacts associated with sea level rise are also excluded from this estimate.

It is also noted that this metric is focused upon delay and disruption to road users but that this is only one element of the cost of a significant flooding event, including delays and disruption to rail users and to users of other forms of transport, or arising from impacts to other infrastructure.

The potential for autonomous adaptation via change in driver behaviours is also excluded from this analysis. However with improved communications networks and the ability to adapt travel routes in response to real time information provided direct to drivers, there is potential for delay costs to be minimised in any one event.

5.5 TR2 – Landslide impacting the road network

Metric code	Metric name	Confidence	Summary Class								
			2020s			2050s			2080s		
			l	c	u	l	c	u	l	c	u
TR2	Landslide impacting the road network	M	1	1	1	1	1	2	1	2	2

As with TR1, the qualitative response function developed for this metric was presented in Section 4.3. Again, there is not a direct link between increase in winter precipitation with the risk of landslide but it is assumed that an increase in average winter precipitation will mean an elevated level of risk.

It should however be noted that the total distance of road at risk cannot increase indefinitely as there has to be a susceptible slope adjacent or above a road for there to be risk of land slide. Applying the future projections for winter rainfall to the response functions, qualitative assessments of the risk have been developed.

Table 5.2 Metric TR2 assessment - England

(Qualitative assessment of the length of roads (km) impacted by landslide)

	Low Emissions			Medium Emissions			High Emissions		
	p10 (dry)	p50 (mid)	p90 (wet)	p10 (dry)	p50 (mid)	p90 (wet)	p10 (dry)	p50 (mid)	p90 (wet)
2020s	0	1	1	0	1	1	0	1	1
2050s	0	1	2	1	1	2	1	1	2
2080s	1	2	2	1	2	2	1	2	2

0	Very low – 150km
1	Low – 630km (current extent)
2	Medium – 1,505km
3	High – 3,000km
4	Very high – 5,000km (occurrences at maximum frequency and magnitude in all identified risk areas)

For England (see Table 5.2) the length of road at risk is projected to remain roughly at current levels until the 2050s when the degree of risk may increase (at the p90 level). Based on this estimate it is considered unlikely that the length of roads in England impacted by landslide may increase significantly.

Table 5.3 and Table 5.4 show the assessment results for Scotland and Northern Ireland respectively. It should be noted that while the overall length of road affected is greater for England, the percentage changes are much greater for Scotland as the analysis is restricted to trunk roads.

Table 5.3 Metric TR2 assessment - Scotland

(Qualitative assessment of the length of roads (km) impacted by landslide)

	Low Emissions			Medium Emissions			High Emissions		
	p10 (dry)	p50 (mid)	p90 (wet)	p10 (dry)	p50 (mid)	p90 (wet)	p10 (dry)	p50 (mid)	p90 (wet)
2020s	1	1	1	1	1	1	1	1	1
2050s	1	1	1	1	1	2	1	1	2
2080s	1	1	2	1	1	2	1	1	2

0	Very low – 16 to 50km per year
1	Low – 50 to 200km per year (current extent)
2	Medium – 200 to 330km per year
3	High – 330 to 750km per year
4	Very high – 750 to 1,650km per year (occurrences at maximum frequency and magnitude in all identified risk areas)

Table 5.4 Metric TR2 assessment - Northern Ireland

(Qualitative assessment of the length of roads (km) impacted by landslide)

	Low Emissions			Medium Emissions			High Emissions		
	p10 (dry)	p50 (mid)	p90 (wet)	p10 (dry)	p50 (mid)	p90 (wet)	p10 (dry)	p50 (mid)	p90 (wet)
2020s	0	0	1	0	0	1	0	0	1
2050s	0	1	1	0	1	2	0	1	2
2080s	0	1	2	0	1	2	1	2	2

0	Very low – 60km per year
1	Low – 125km per year (current extent)
2	Medium – 250km per year
3	High – 500km per year
4	Very high – 1000km per year (occurrences at maximum frequency and magnitude in all identified risk areas)

This qualitative projection of future risk is based upon the detrimental effect increased rainfall is likely to have on slope stability but it has to be recognised that appropriate land management practice can significantly reduce this risk in many locations. The analysis is qualitative and uncertain and therefore should only be considered as indicative of the level of risk.

The following have not been considered:

- The impact climate change may have on the frequency of failure of slopes, an impact which has the potential to be more costly than the potential consequences discussed here. This can arise from the combined effects on slopes of drier summers and wetter winters.
- The disruption to transport that would be caused by landslides.

5.6 TR4 – Cost of carriageway repairs

Metric code	Metric name	Confidence	Summary Class								
			2020s			2050s			2080s		
			l	c	u	l	c	u	l	c	u
TR4	Cost of carriageway repairs	M	1	1	1	1	1	1	1	1	1

The response functions for metric TR4 are available for England and Northern Ireland only due to the availability of background data. Tables 5.5 and 5.6 show the outcome of applying the UKCP09 scenarios to the response functions for England and Northern Ireland respectively. It is clear, based on the assumptions used to form these metrics, that the projected costs that could be incurred as a result of thermal loading on roads is relatively modest when compared to the costs associated with flood for example.

It is also worth noting that the reported costs for road resurfacing as a result of the 2003 heat wave would fall into the Medium risk category, indicating that this assessment may be an underestimate of the risk as it is based on national average temperature figures. A better estimate is likely to be derived by considering extreme temperatures rather than seasonal averages.

Table 5.5 Metric TR4 assessment– England

(Cost of carriageway repairs in England)

	Low Emissions			Medium Emissions			High Emissions		
	p10 (dry)	P50 (mid)	p90 (wet)	p10 (dry)	p50 (mid)	p90 (wet)	p10 (dry)	p50 (mid)	p90 (wet)
2020s	0	0	0	0	0	0	0	0	0
2050s	0	0	1	0	0	1	0	0	1
2080s	0	0	1	0	1	1	0	1	2

0	Very low – less than £1m cost of disruption
1	Low – £1m to £10m per year
2	Medium – £10 to £100m per year
3	High – £100 to £400m per year
4	Very high – >£400m per year

Table 5.6 Metric TR4 assessment – Northern Ireland

(Cost of carriageway repairs in Northern Ireland)

	Low Emissions			Medium Emissions			High Emissions		
	p10 (dry)	p50 (mid)	p90 (wet)	p10 (dry)	p50 (mid)	p90 (wet)	p10 (dry)	p50 (mid)	p90 (wet)
2020s	0	0	0	0	0	0	0	0	0
2050s	0	0	0	0	0	0	0	0	0
2080s	0	0	0	0	0	1	0	0	1

0	Very low – less than £1m cost of disruption
1	Low – £1m to £10m per year
2	Medium – £10 to £100m per year
3	High – £100 to £400m per year
4	Very high – >£400m per year

It is also worth observing that the risk to the trunk road network is projected to be low given current design standards. There is also anecdotal evidence (from the sector workshop) that local authorities are looking to road surfacing and design in other parts of the world as a way of improving resilience of existing road surfaces.

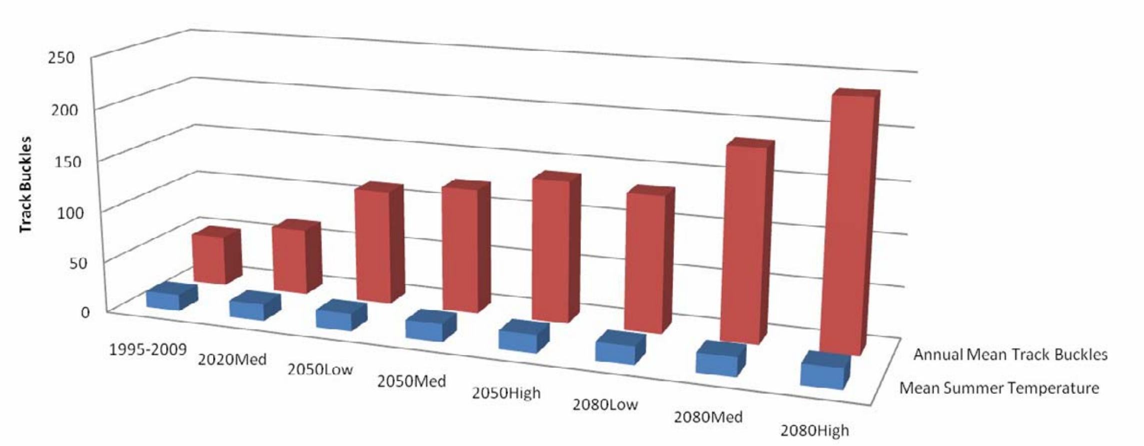
This metric does not cover the associated disruption to transport arising from road damage and repairs.

5.7 TR5 – Rail buckling risk

Metric code	Metric name	Confidence	Summary Class 2020s l	Summary Class 2020s c	Summary Class 2020s u	2050s l	2050s c	2050s u	2080s l	2080s c	2080s u
TR5	Rail buckling	H	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**

Given the identified correlation between summer temperatures and rail buckling events it is possible to project the number of rail buckles that might take place in the future using the UKCP09 scenarios. The mean summer temperatures for each region have also been calculated for 1997-2009 to provide base line temperatures and best fit equations for each region as shown in Table 4.8.

The relationships are not as strong as for the CET summer temperatures discussed in Section 4.5 but the correlation is still high for most regions (see Appendix 4). As might be expected, correlations are lowest in Scotland where fewer events occur. Using these response functions projected numbers of rail buckling events for Great Britain as a whole and by region have been estimated for UKCP09 scenarios, see Figures 5.1 to 5.4.



	1995-2009	2020Med	2050Low	2050Med	2050High	2080Low	2080Med	2080High
Mean Summer Temperature	16.1	16.4	17.3	17.5	17.8	17.7	18.7	19.7
Annual Mean Track Buckles	50	66	113	123	139	133	185	237

Figure 5.1 Projected mean annual number of rail buckles in Great Britain

(50% probability level climate change projections, or 'p50')

The cost of each rail buckle can be split into two parts, repair and delay costs per minute. Network Rail estimate repair costs to be on average approximately £10,000 and current delay costs can be estimated to be on average about £9,000 (2hours = 120 minutes times £76 per minute). This gives a total cost on average for each rail buckle to be about £19,000. The value of passenger delay costs have been estimated to be £73.47 per minute (2007 prices) by the National Audit Office (NAO, 2008). This figure has been raised to £76 for 2010 prices (4% increase). Estimated costs for the future UKCP09 scenarios are shown in Figure 5.5.

Figure 5.2 Regional projections of rail buckling - low

(10% probability level climate change projections, or ‘p10’)
The numbers in the legend are the numbers of individual buckles per country/region

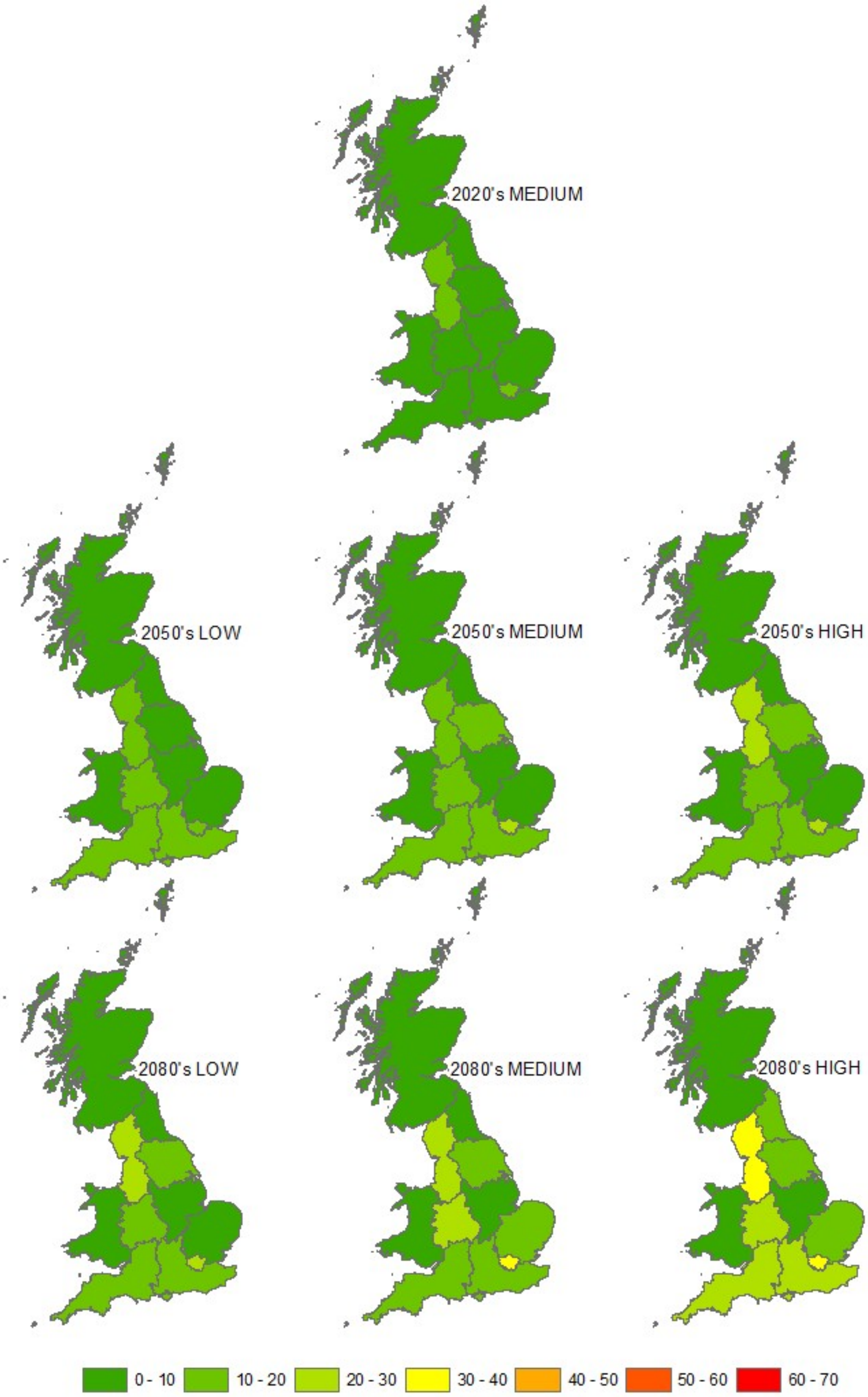


Figure 5.3 Regional projections of rail buckling - medium

(50% probability level climate change projections, or 'p50')
The numbers in the legend are the numbers of individual buckles per country/region

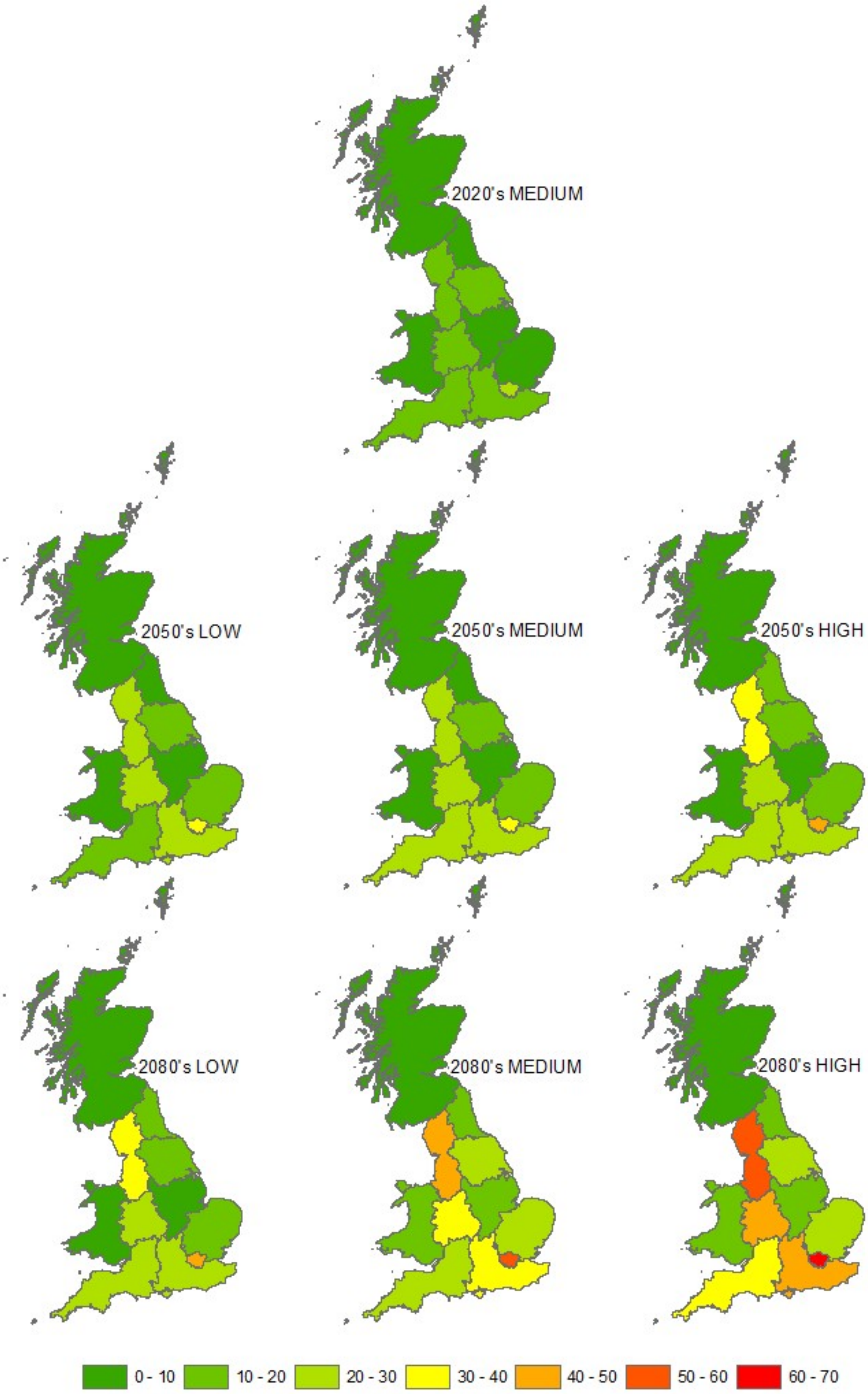
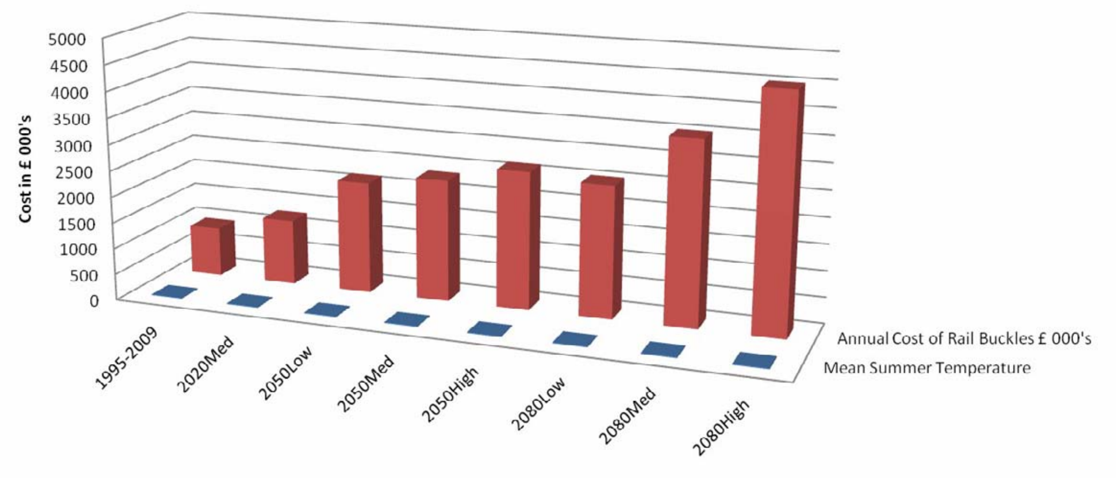


Figure 5.4 Regional projections of rail buckling - high

(90% probability level climate change projections, or ‘p90’)
The numbers in the legend are the numbers of individual buckles per country/region



	1995-2009	2020Med	2050Low	2050Med	2050High	2080Low	2080Med	2080High
Mean Summer Temperature	16.1	16.4	17.3	17.5	17.8	17.7	18.7	19.7
Annual Cost of Rail Buckles £ 000's	950	1254	2147	2337	2641	2527	3515	4503

Figure 5.5 Projected mean annual cost of Track Buckles (£ 000s), p50

(50% probability level climate change projections, or 'p50')

It is clear from this analysis that the potential future costs associated with rails buckling could be significant (although not large compared with some other climate change impacts). To put this into the context of the other impacts considered in this sector and across the CCRA, this scale of financial impact would be classed as a Low to Medium risk.

5.8 TR6 – Road and rail bridge failures due to scour

Metric code	Metric name	Confidence	Summary Class								
			2020s			2050s			2080s		
			l	c	u	l	c	u	l	c	u
TR6	Scouring of road and rail bridges	M	1	1	2	1	2	3	1	2	3

There are approximately 155,000 bridges in the UK (Bridle and Sim, 2009). These bridges vary widely in size, type and date with a few dating back to the Middle Ages. With advances in structural design and the understanding of scour, major modern bridges are rarely vulnerable to scour.

In general, it is likely to be pre-20th Century bridges that are most at risk as it is more likely that these structures have shallow foundations and be of variable (and often unknown) construction. For example, old masonry arch bridges may have soil fill behind the abutments, which when exposed to flowing water is easily washed away.

The continuing failure of bridges shows that under existing conditions there are still a number of bridges that are vulnerable to scour. In the last 10 years there have been at least 9 bridge failures in the UK. This corresponds to a current rate of bridge failures due to scour of about one failure per year. The projected increases in peak flood flow as a result of climate change could increase the scour at bridges and the potential risk of failure.

There is no national bridge register and for many bridges the nature and depth of the foundations are unknown. This means that the data is not available with which to assess the current scour risk at UK bridges. It also implies that data is not available with which to assess the potential increase in risk of scour as a result of climate change. At this stage it is therefore not possible to provide projections of future numbers of bridge failures.

Many bridges that are currently not at significant risk from scour have foundation depths that are only just greater than the projected scour. This means that any increase in projected scour could significantly increase the number of bridges that are vulnerable to scour.

However it should also be noted that scour is one of several mechanisms that can lead to bridge failure due to flooding. Flooding events can result in a range of different forcing mechanisms including impact loading on bridges due to floating debris (including vehicles), wash-out of masonry and fill material due to poor maintenance, or through a combination of scour and structural failure.

Many of the pre 20th Century bridges are likely to be masonry arch bridges, although an actual number is not possible to determine currently. Bridle and Sim (2009) categorise UK bridge stock into three types of structure: masonry, metal and concrete. Based on data for 1980 and a sample of 48,879 UK bridges out of an estimated 155,000 bridges, about 45% of these structures were brick or masonry arches. These are the bridge type most at risk from scour, suggesting that 45% of bridges are most at risk.

The scour estimates in Section 4.6 have demonstrated the sensitivity of scouring at bridges both to the hydrodynamic forcing from peak flow and also the sediment properties of the site. Scour has been shown to increase linearly with the percentage increase in peak flow from the baseline for gravel and sand bed rivers. The sensitivity of the response of gravel bed rivers with natural bed armouring has been demonstrated for one example, where a potentially rapid increase in scour is projected for only a 7% increase in peak flow. The actual combination of river flow and bed sediment conditions will control this sensitivity.

The results show a steady increase in scour with flow for gravel and sand beds. For an armoured bed, the increase in scour can be dramatic once the armour layer is eroded. Scour in gravel beds is of particular concern as the effects of bed armouring is still an uncertain science. Unlike sand beds, where scouring increases steadily as the flood flows increase, in the case of an armoured riverbed the flood flow may increase for a while without significant scour. However, once the sediment armouring threshold is overcome, scour can be rapid and deep.

Evaluation of the potential number bridge failures due to climate change will require information on the bridge assets including foundation depth, hydraulic conditions at each bridge and river channel bed sediment properties. The systematic collection of this information could provide the basis of an improved analysis for the next CCRA.

Climate change is likely to result in bridges which are currently classed as being adequately protected against scour risk being moved into the scour critical category. This in turn would lead to adaptation measures ranging from local scour countermeasures to bridge replacement.

5.9 FL8 – Roads and rail at significant likelihood of flooding

Metric code	Metric name	Confidence	Summary Class								
			2020s			2050s			2080s		
			l	c	u	l	c	u	l	c	u
FL8a	Roads at significant likelihood of flooding (tidal and river)	H	2	2	2	2	2	3	2	3	3
FL8b	Rail at significant likelihood of flooding (tidal and river)	H	2	2	2	2	2	3	2	3	3

The lengths of road and railway at significant likelihood of flooding in England and Wales for different climate change scenarios was assessed for the selected climate change scenarios.

The results show that the projected length of road at significant likelihood of flooding is between 13,000 and 16,000km by the 2020s, compared with a baseline of about 12,000km. The length is projected to rise to between 14,000 and 19,000km by the 2080s.

The corresponding lengths for rail are between 2,000 and 2,600km by the 2020s compared with a baseline of about 2,000km, rising to between 2,300 and 3,100km by the 2080s.

In addition to an increase in the overall length of transport infrastructure that could be affected by flooding, the frequency of flooding of infrastructure that is already in the floodplains is projected to increase.

Major roads and railways in floodplains are often raised above the ground surface on embankments. These embankments are sometimes, but not always, identified in the flood modelling and mapping. There is therefore an added uncertainty in the lengths of road and rail at risk from flooding and it is possible that the length of road and rail at significant likelihood of flooding is overestimated. This uncertainty is likely to reduce with climate change as some raised roads and railways may be overtopped more frequently.

The data are based upon regional growth curves which are used to uplift the present day flood probabilities, which in turn are based on modelled baseline flood probabilities. The present day flood probabilities are aggregated from the base 50m grid to a mean probability in 100m grid cells.

Road and rail data are based on the Environment Agency's National Receptor Database which has been converted to a hectare grid coincident with the 100m probability grid. Roads and rail lengths are based on a count of the hectare grid cells where the annual flood probability exceeds 0.0133 (1:75 year).

This has been converted to a length by assuming a mean length through each cell of 85.25m. This assumes that within each 100m x 100m cell, the road or railway line is a straight line. Each 100x100m grid cell is counted once for railways and per road class (motorway, A-road, B-Road, minor road) and thus the method does not count multiple railway lines or roads of the same class that run through the same 100m x 100m grid cell.

5.10 MA5 – Shipping routes: navigable days for the north-west and north-east passages per annum

Metric code	Metric name	Confidence	Summary Class								
			2020s			2050s			2080s		
			l	c	u	l	c	u	l	c	u
MA5	Shipping routes: navigable days for north-west and north-east passage per annum	M	1	2	2	2	2	3	2	3	3

Navigable Days

Data supplied by the Met Office from the HADCM3 model were processed and assessed against both the north-west and north-east transport routes as described in Section 4.8. The number of occurrences when these routes were observed to be 'ice free' and therefore 'navigable' was noted for each month of the year against the three ice cut-off scenarios and these are presented in Tables 5.7 to 5.9. In deriving the number of 'navigable days' it was assumed that for each month the routes were navigable the routes were open every day in that month.

Table 5.7 Navigable days calculated for the north-east passage (for different ice cut-off thresholds)

Sea Ice Extent	North-east Passage							
2020s			2050s			2080s		
0.05	0.15	0.3	0.05	0.15	0.3	0.05	0.15	0.3
30	60	90	90	90	120	120	150	180

Table 5.8 Navigable days calculated for the north-west passage (for different ice cut-off thresholds)

Sea Ice Extent	North-west Passage							
2020s			2050s			2080s		
0.05	0.15	0.3	0.05	0.15	0.3	0.05	0.15	0.3
0	0	30	0	60	90	0	90	120

Table 5.9 Navigable days calculated for the central Arctic passage (for different ice cut-off thresholds)

Sea Ice Extent	Central Arctic							
2020s			2050s			2080s		
0.05	0.15	0.3	0.05	0.15	0.3	0.05	0.15	0.3
0	0	0	0	0	0	0	0	60

The projections show more future navigable days for the north-east passage than the north-west passage. This is important for UK economies as this is the route most relevant for UK markets. The total number of days assuming 30% ice extent cut-off is 180 by the 2080s and as many as 90 days by the 2020s.

This is in line with estimates from the Met Office and the Arctic Climate Impact Assessment (ACIA, 2005). In comparison, the north-west passage is projected to be open up to 120 days of the year by the 2080s and only 30 days per year (one month) by the 2020s under the same ice cut-off scenario.

Under the lowest ice cut-off scenario of 5%, the north-east passage is still projected to be navigable up to 120 days by the 2080s and 30 days by the 2020s. This is relevant when considering commercial benefits as this will require the lowest ice breaker capability or support, therefore lowering costs associated with safe transit.

Of note is that the central Arctic is considered to be 'open to navigation' for 60 days by the 2080s under the 30% cut-off scenario. In effect this suggests that the Arctic could be ice free during the summer months by the 2080s. Such projections have huge environmental and socio-economic consequences.

Sea Ice extent

By interrogating the Met Office data it was possible to calculate the area of Arctic sea ice projected by the HADCM3 model. This is shown in Figures 5.6 and 5.7 below.

Figure 5.6 demonstrates that from approximately the 1900's through to the present day a clear decline in sea ice extent is established despite natural variability. Of note is the accelerated decline from approximately the 1970's and the very steep decline observed in 2007 to the lowest on record at approximately 9.5 million km^2.

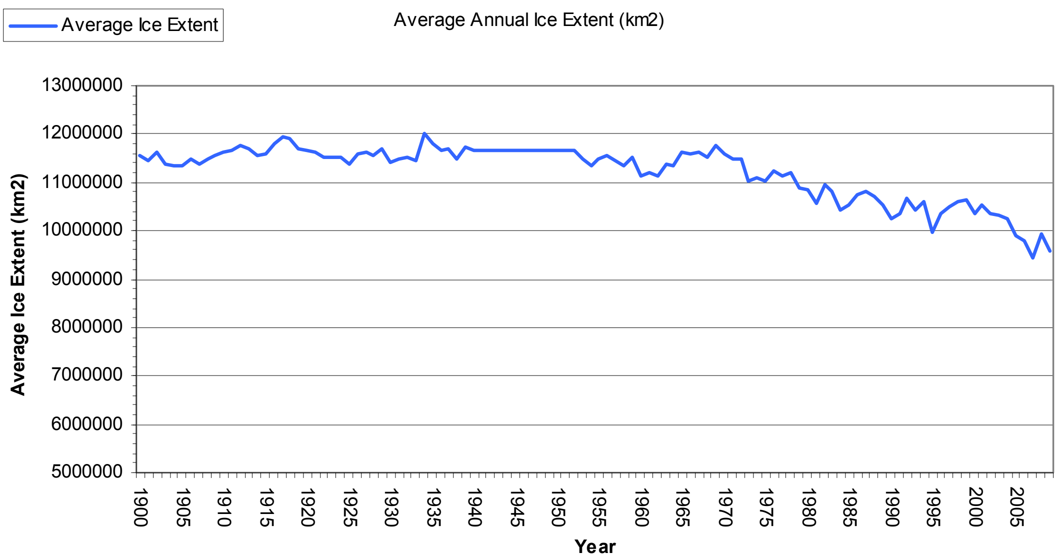


Figure 5.6 Average annual ice extent (km^2) from 1900 to 2009.

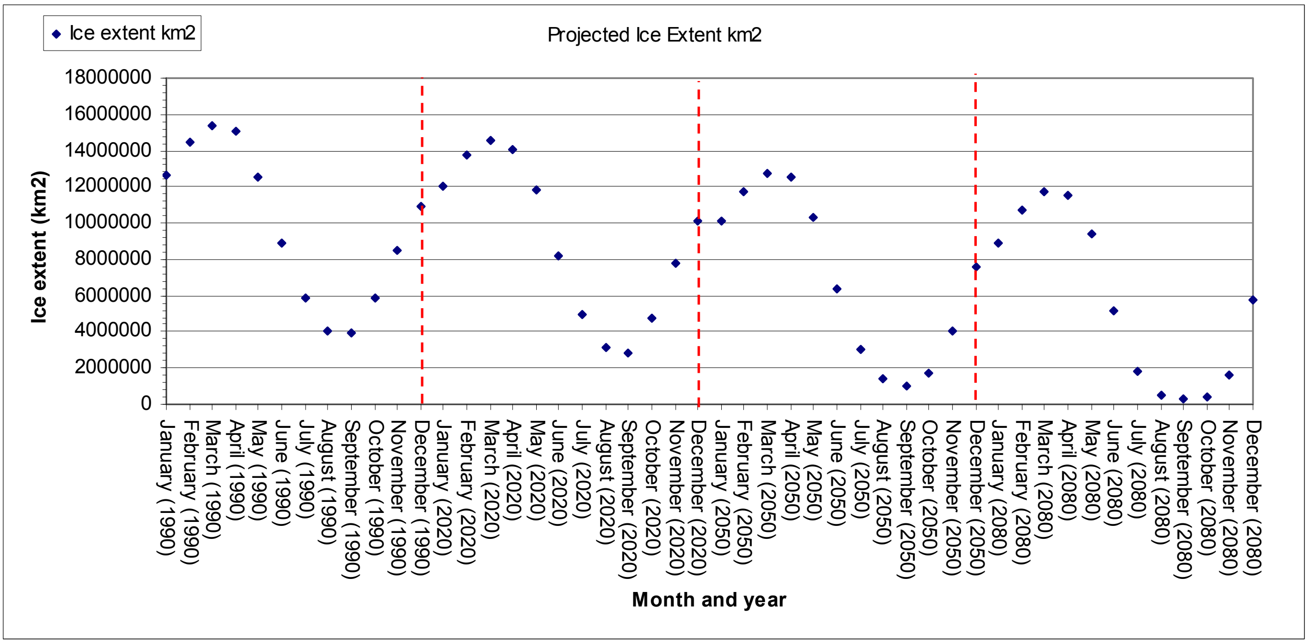


Figure 5.7 Projected annual ice extent (km^2)

Month and year for 1990, 2020, 2050 and 2080

6. Socioeconomic Changes

6.1 Introduction

Each of the metrics identified in this analysis have been determined at a level which makes the formal application of quantified socio-economic scenarios challenging, i.e. population projections, etc. Although it is assumed that an increase in the UK's population has the potential to increase exposure to each of these risks as there will be more people reliant upon transport infrastructure, it is not clear how to relate population figures with individual transport choices. Many factors will influence behavioural change as well travel choices. For this reason, quantified socio-economic scenarios have not been applied to the metrics.

In trying to quantify potential socio-economic factors for the 2080s which may influence the metrics identified in this study, six sets of socio-economic dimensions have been devised following consultation with sector analysts and project team members. These dimensions represent socio-economic factors that may have the potential to make a significant impact on the sector risks identified but also contain a high degree of uncertainty making them unsuitable to model as a forecast.

A commentary is provided for each risk metric, showing the relevance of each socio-economic dimension and a brief discussion of what the effects of the extremes of each dimension occurring might be, see Table 6.1.

This shows that the primary sensitivities for most of the risks considered in this analysis are:

- Population needs/demands and consumer driven values: It is not simply the number of people and their corresponding demands that could put pressure on transport infrastructure but also their personal choices in terms of behaviour and modal selection.
- The level of government decision making: The transport system crosses local authority, devolved administration and national borders. The level of integration of the transport system, its resilience and its effectiveness is thus sensitive to the level of decision making.

Since 2006 DfT has been developing a research programme to further understand how individual's attitudes to climate change relate to their transport behaviour. A recent survey of public attitudes to climate change and transport choices (DfT, 2010c) found a wide variety of challenges to be addressed in order to enable and encourage more sustainable transport behaviour. These challenges varied for different groups of people and different types of locations.

The findings suggested that people tend to travel by car out of habit, particularly if aged 40-69 or living in rural areas. Those living in rural areas tended to show particularly high levels of car travel, more positive attitudes about cars and less positive attitudes about alternative modes. Frequent (at least every 15 minutes) bus services were associated with regular bus travel. A lack of suitable routes and slow, infrequent services were the key barriers to travelling by bus.

Lack of suitable routes and a lack of infrastructure emerged as the key barriers to travelling by train for regular journeys such as travelling to work. Safety concerns / 'too much traffic' were a key barrier to cycling. For many regular cyclists, three miles tended to be the maximum distance cycled. Only 14% of those who could cycle did so regularly. Older age groups and women cycled less and tended to hold greater concerns about cycling. Lack of time, inconvenience, the weather and having to carry things emerged as key barriers to walking journeys of less than two miles.

This survey shows that there is a long way to go to persuade people to change their transport habits. Part of the adaptation challenge is to get the public 'on-board'.

In addition to changes to the market for transport, the industry itself will change. For example, 50 years ago the UK had only just started building motorways. By 2060 the role of high speed rail may be much more dominant than it is today. The government agenda to promote a low carbon economy is also likely to lead to technological changes, which would result in changes to the relative costs and convenience of different modes of transport.

6.2 Impacts assessed in other sectors

The implications of socio-economic on impacts assessed in other sectors are briefly discussed in this section.

Supply chain disruption

Climate change impacts on UK business supply chains depend on the rate and magnitude of climate change, but also on changes in technology, economics, lifestyles, policy and trade that will affect the capacity both for restricting and adapting to climate change.

This is particularly relevant to a discussion of supply chains, as climate risks on the other side of the globe can have significant repercussions for UK businesses. Analyses of climate risks depend heavily on assumptions about underlying socio-economic developments, which can be explored through the use of socio-economic scenarios describing possible future states of the world.

Within the UK, socio-economic change including increasing population may lead to additional disruption, for example in terms of increased congestions on road networks.

Shipping routes: navigable days for the north-west and north-east passages per annum

The socio-economic consequences of navigation through the Arctic will be large but complex to measure due to a lack of data for vessels related to UK shipping and the use of the north-east passage. It is clear that using the Arctic routes over current routes through the Suez or Panama Canals would provide large savings in terms of time and fuel (also passage fees) and therefore money but there are implications in terms of ice breaker support, safety and insurance to consider.

Container traffic to the Far East is most likely to benefit from the potential Arctic shipping routes to/from Asiatic markets. The principal ports for container shipping in the UK include Felixstowe, Southampton and Thamesport. These currently handle the largest container flows from Asia that could use the Arctic as an alternative route. Currently there are approximately 27 calls per week from these ports for the largest container vessels to Asia.

At present crude oil, which makes up a large proportion of shipping traffic, is currently sourced from the Black sea, north and West Africa and the middle east. However, with the opening of Arctic shipping routes, there could be new traffic in bulk cargoes including crude oil and coal from new Arctic sources.

By using the Arctic shipping routes it is considered that there could be as much as a 40% reduction in shipping transportation required to service current flow demand.

There is also the possibility of the development of new port terminals further north in the UK.

Roads and rail at significant likelihood of flooding

Future socio economic scenarios were not applied to the future projections for roads and railways at risk of flooding. This is because the future scenarios do not include assessment of the increases in transport links.

It may however be speculated that the number of links is likely to increase as the population increases and the need for mass transit systems in particular increases. Conversely, an increase in home working and community based economies could reduce the need for transport.

Table 6.1 Socio-economic dimensions summary

Dimension	Category	Flood	Landslip	Thermal Loading	Rail Buckling	Bridge scour
Population Needs / Demands	High	Assuming no change to availability of choices made in terms of modes of transport, the risk is likely to become greater as reliance on road transport also increases.	There is no direct population link to this metric apart from the likelihood that the number of people affected by any one event could increase.	There is no direct link to population growth although any increase in road traffic could increase deformation of road surfaces during periods of hot weather, thereby increasing cost or frequency of repair.	Assuming that more people travel by train as population increases, the cost of this impact will increase as greater passenger delay costs are incurred.	There is no direct population link to this metric apart from the likelihood that the number of people affected by any one event could increase.
	Low	Conversely, with low population growth, exposure to this risk may be reduced.	Conversely, with lower population growth exposure to this risk may be reduced.	Conversely, with lower population growth exposure to this risk may be reduced.	Conversely, with lower population growth exposure to this risk may be reduced.	Conversely, with lower population growth exposure to this risk may be reduced.
Global Stability	High	National and local economies may recover from disruption more rapidly.	Local issue - Not applicable	Local issue - Not applicable	Local issue - Not applicable	Local issue - Not applicable
	Low	National and local economies may take longer to recover with as links to global markets/economies are affected by instability.				
Distribution of Wealth	Even	Even cost burden to those people and businesses affected by disruption/delay.	Not applicable	Not applicable	Not applicable	Not applicable
	Uneven	Potentially greater risk and impact of cost burden to people and businesses at the lower end.	Not applicable	Not applicable	Not applicable	Not applicable
Consumer Driven Values and Wealth	Unsustainable	Risk may increase if consumer trends increase road transport and freight.	Risk may increase if consumer trends increase road transport and freight.	Risk may increase if consumer trends increase road transport and freight.	Risk may increase if consumer trends increase rail transport and freight.	Risk may increase if consumer trends increase transport and freight.

Dimension	Category	Flood	Landslip	Thermal Loading	Rail Buckling	Bridge scour
	Sustainable	Risk may be reduced if there is a reduction in road transport/freight due to more sustainable travel choices and dampened consumer markets.	Risk may be reduced if there is a reduction in road transport/freight due to more sustainable travel choices and dampened consumer markets.	Risk may be reduced if there is a reduction in road transport/freight due to more sustainable travel choices and dampened consumer markets.	Risk may be reduced if there is a reduction in rail transport/freight due to dampened consumer markets.	Risk may be reduced if there is a reduction in transport/freight due to more sustainable travel choices and dampened consumer markets.
Level of Government Decision Making	National	Risk reduced if centralised decision-making leads to greater investment in flood risk management and defences.	Risk reduced if more centralised decision-making leads to more effective mitigation against landslip.	Exposure to risk depends on availability of funds – if national governance leads to sufficient availability of funds for local road repairs, impact is reduced.	Not applicable	Risk reduced if more centralised decision-making leads to more effective mitigation against landslip.
	Local	Equally, risk reduced if more local decision making leads to effective flood risk management and defences. Increases if the converse is true.	Risk increased if local decision making does not equate to adequate investment and mitigation against landslip risks.	If the converse is true, local authorities bear the weight of the cost burden without support from central government.	Not applicable	Risk increased if local decision making does not equate to adequate investment and mitigation against scour risks.
Land Use Change / Management	High Government input	Unclear which extreme would lead to greater need for travel by road – both extremes may increase exposure to risk.	Unclear which extreme would lead to greater need for travel by road – both extremes may increase exposure to risk.	Unclear which extreme would lead to greater need for travel by road – both extremes may increase exposure to risk.	Unclear which extreme would lead to greater need for travel by rail – both extremes may increase exposure to risk.	Unclear which extreme would lead to greater need for travel by road – both extremes may increase exposure to risk.
	Low Government Input					

7. Economic Impacts

7.1 Summary

Climate change adaptation decisions that are designed to reduce climate change risks inevitably involved making trade-offs concerning the use of scarce economic resources. To the extent that economic efficiency is an important criterion in informing such decision-making, it is useful to express climate change risks in monetary terms, so that they can be:

- Assessed and compared directly (using £ as a common metric) and
- Compared against the costs of reducing such risks by adaptation.

For the CCRA, a monetisation exercise has been undertaken to allow an initial comparison of the relative importance of different risks within and between sectors. Since money is a metric with which people are familiar, it may also serve as an effective way of communicating the possible extent of climate change risks in the UK and help raise awareness.

Where possible, an attempt has been made to express the size of individual risks (as described in this report) in monetary terms (cost per year) however, due to a lack of available data it has sometimes been necessary to use alternative costs (repair or adaption) to provide an estimate. A summary of the results is provided in Table 7.1.

A variety of methods have been used to determine the costs with the approach used. In broad terms, these methods can be categorised according to whether they are based on:

- Market prices (MP)
- Non-market values (NMV) or
- Informed judgement (IJ).

Informed judgement has been used where there is no quantitative evidence and was based on extrapolation and/or interpretation of existing data.

In general terms, these three categories of method have differing degrees of uncertainty attached to them, with market prices being the most certain and informed judgement being the least certain. It is important to stress that the confidence and uncertainty of consequences differs. Therefore, care must be taken in directly comparing the results. Whilst an attempt has been made to use the best monetary valuation data available, the matching-up of physical and monetary data is to be understood as an approximation only.

Further, it is important to highlight that some results are presented for a scenario of future climate change only, whilst others include climate change under assumptions of future socio-economic change. The approach used, and the relative baseline, is stated in Table 7.1. There are also some important cross-sectoral links, or areas where there is the risk of double counting impacts: these are highlighted on the table.

Table 7.1 shows that one risk metric, TR1 (flood disruption), has potentially medium rankings (annual costs £10-99 million/year) in later time periods. Other metrics have a low ranking attached to them.

Table 7.1 Economic impacts: summary of results

2010 prices, no uplift or discounting; climate change signal only (current socio-economics); relative change from baseline period; p50 Medium emissions scenario

Risk metrics	2020s	2050s	2080s	Estimation Method	Confidence ranking	Notes
TR1 Road disruption and delay caused by flooding/ inundation*	-L	-L	-M	Informed judgement. Market Price Value of Time	L	Climate change only (no future socio-economics). Road sector only.
TR2 Landslide Risk areas; qualitative increase*	-L	-L	-L	Informed judgement.	L	Climate change only (no future socio-economics). Road sector only.
Cooling - ancillary impacts (GHG / Air Pollution)	-L	See notes	See Notes	Non market values Reduced GHG and air pollution	L	Additional ancillary impacts of fuel increases. Only assessed for short term (2020s), as later time periods assume low carbon.
*Note that additional costs would arise for TR1, TR2 for other transport modes, notably rail.						
TR4 Cost of carriageway repairs from heat stress	- VL	-VL	-L	Informed judgement Repair costs (adaptation cost)	L	Climate change only (no future socio-economics). Road sector only. Excludes additional costs of delay and disruption.
TR5 Rail buckling risk; financial cost of delays	-L	-L	-L	Market Price time delay + repair cost	L	Climate change only (no future socio-economics).
TR6 Bridge scour	-L?	-L?	-L?	Informed judgement	L	Climate change only (no future socio-economics). No data for assessment.
BU9 A decrease in output for UK businesses due to an increase in supply chain disruption as a result of extreme events	-M?	-M?	-H?	Informed judgement	L	Qualitative risk assessment.
FL8 Road and rail at significant likelihood of flooding	-L	-L	-L	Informed judgement	L	Links with Transport and overlaps with TR1. Double-counting if summed.
MA5: Shipping routes: Navigable days for north-west and north-east passage per annum	+M/H	+H	+H	Informed judgement	L	Positive effects from opening of N-E and N-W passages. Also potential disruption to shipping and ferry services associated with changes in storminess.

Note: - signifies a negative impact or loss; + signifies benefits or cost reductions.

Impact Cost Ranking: L = £1-9m/pa M = £10-99m, H = £100-999m, VH= £1000m+, ? = Not assessed

Monetisation Confidence Ranking:

Ranking	Description	Colour code
High	Indicates significant confidence in the data, models and assumptions used in monetisation and their applicability to the current assessment.	
Medium	Implies that there are some limitations regarding consistency and completeness of the data, models and assumptions used in monetisation.	
Low	Indicates that the knowledge base used for monetisation is extremely limited.	

7.2 Introduction to Monetisation

The overall aim of the monetisation is to advance knowledge of the costs of climate change in the UK, by generating initial estimates of the welfare effects.

The basic approach to the costing analysis is, for each impact category considered, to multiply relevant unit values (market prices or non-market prices) by the physical impacts identified in earlier sections of this sector report. The total value to society of any risk is taken to be the sum of the values of the different individuals affected. This distinguishes this system of values from one based on 'expert' preferences, or on the preferences of political leaders. However, due to the availability of data, it has sometimes been necessary to use alternative approaches (e.g. repair or adaptation costs) to provide indicative estimates.

There are a number of methodological issues that have to be addressed in making this conversion including the compatibility between physical units and monetary units and the selection of unit values that address market and non-market impacts. As far as possible, physical and monetary units have been reconciled. The selection of unit values is justified in the explanation of the method used to monetise each risk metric. The aim is to express the risk in terms of its effects on social welfare, as measured by the preferences of individuals in the affected population. Individual preferences are expressed in two, theoretically equivalent, ways. These are:

- The minimum payment an individual is willing to accept (WTA) for bearing the risk or
- The maximum amount an individual is willing to pay (WTP) to avoid the risk.

There are also other issues (beyond this scoping analysis) in terms of impacts that have non-marginal effects on the UK economy, the treatment of distributional variations in impacts, and the aggregation of impact cost estimates over sectors and time.

Only TR2 and TR6 have not been monetised. TR2 is a qualitative assessment and TR6 is lacking suitable data. As indicated in the table, the Transport report in the CCRA has undertaken the monetisation process within the quantification process. However, further analysis is needed to make sure that the valuation assessment is consistent with UK government appraisal, and to factor in other aspects of economic appraisal.

7.2.1 Presentation of results, uplifts and discounting

Consistent with other sectors, the results below are presented in terms of constant (2010) prices for the three time periods considered in the CCRA i.e. the 2020s, 2050s and 2080s. The results are presented in this way to facilitate direct comparison.

At this stage, the values below are not presented as a present value or equivalent annual cost. However, the use of the values in subsequent analysis, for example in looking at the costs and benefits of adaptation options to reduce these impacts, would need to work with present values. For this, the values below would need to be adjusted and discounted.

The existing Government transport appraisal provides guidance on how to adjust values over time, for example, the value of non-working time is assumed to increase with income, and thus values are increased over time in line with GDP per head (adjusting for relevant elasticity for work and non-work time).

For discounting, the Green Book recommends 3.5% discount rates/factors noting that for longer time periods as assessed here, this requires the use of the declining discount rate scheme.

7.3 TR1 Disruption and delay caused by flooding/inundation

7.3.1 Outputs from the risk assessment

This metric looks at the disruption and delay (associated with flooding on the road network). As highlighted earlier, these economic costs can be important: the costs of the autumn 2000 floods including delays were estimated at £13 million (economic) and £73 (financial) for the road sector (Penning Rowsell *et al.*, 2002), while the estimated total costs relating to delays and disruption to road users during the 2007 floods was approximately £100 million (Environment Agency, 2010) and also led to an estimated £25.6 million in rail user delays and a further £10.5 million for rail infrastructure costs.

The analysis reported in Section 4 uses a qualitative response function that links the projected increase in winter precipitation (as an indicator of the likely increase in flood risks) to published figures for the cost of disruption/delay from the 2007 flooding events in England.

The analysis of future risks was presented in Section 5. This earlier section attributes a medium level of confidence to these estimates.

7.3.2 Methodology and unit values to be adopted

Ideally this analysis would use the traditional transport appraisal guidance (in the DfT Transport Appraisal Guidance and webtag[37]) to look at the costs of time delays (using the value of time, VOT), and combine this with estimated impacts of future flood risk and levels of disruption to road users. Consistent with the guidance, the analysis would also include higher vehicle operating costs (VOC) where there are diversions, i.e. extended trips. It would also include the additional repair and restoration costs where these were additional to the costs of time delays. However, undertaking such assessment would require an extremely detailed quantitative analysis, which is not possible given the current level of evidence.

Therefore, a simplified version of such an approach has been adopted in the earlier section, using previous estimates of the value of lost time from 2007 floods to build up a semi-quantitative analysis. It uses the Environment Agency (2010) estimates of the 2007 floods of £98 million (with a range from £22 to £174 million depending on assumptions) from the extra time and distances travelled due to blockage at given 'nodes' on the road network, plus an additional £85 million cost of road damage to roads and related infrastructure such as bridges and culverts. The underlying work on

[37] http://www.dft.gov.uk/webtag/

VOT/VOC for these estimates was undertaken by Highways Agency and used the DfT appraisal approach. These estimates are used here, but represent current values with no adjustments for future time periods.

7.3.3 Results and discussion

The resulting cost estimates were reported in Section 5.4, thus are not repeated here except in summary.

For England, the outcome of the assessment shows that cost of disruption from flood is expected to remain relatively low in economic terms in the 2020s (£1 – 9 million per year) for the p50 and p90 projections (but effectively zero for the low p10 projection).

It also remains low in economic terms in the 2050s (£1 – 9 million per year) for the medium emissions projection (p50) in the 2050s, but increases to a medium cost (£10 – 99 million/year) for the medium and high emissions projections for the p90 (although zero for the p10 projections)[38].

Finally, the costs are estimated to rise to a medium level (£10 – 99 million/year) for the medium emissions projection in the 2080s and are estimated to rise to a high level (£100 – 1000 million/year) under the p90 projection for the medium and high emissions projections.

It is highlighted that these estimates are indicative only. They are presented in current prices, with no adjustments or discounting. They would also rise further with future projections of increases in transport demand. They would also rise if other transport modes, such as rail, were included, and if other flood hazards, such as coastal and intra-urban flooding, were included. Note that the estimates do not include any planned adaptation, including as part of on-going future maintenance.

7.4 TR2 Landslide risk areas; qualitative increase

7.4.1 Outputs from the risk assessment

This metric is the subsidence/landslip associated with roadside slopes. Owing to the complexity of determining landslide risk, and the very site specific nature, no dataset was identified that allowed a robust estimate of the number or scale of events per year across the UK. Instead an indicator of risk was used. This reports the length of road considered to be at severe risk. The results are reported in Section 5.5.

7.4.2 Methodology and unit values to be adopted

As for TR1, ideally this analysis would follow the approach for transport disruption and delays using Government appraisal methods, following the identification of the impacts (the number of landslides/landslips and their average effect on road users). It would also include the additional repair and restoration costs where these were additional to the costs of time delays. However, undertaking such assessment would require an extremely detailed quantitative analysis, which is not possible given the current level of evidence.

[38] As explained in Section 2.6, estimates of future risk are provided for three different emissions scenarios (high carbon emissions, A1FI; medium emissions, A1B; low emissions, B1; see http://ukclimateprojections.defra.gov.uk/content/view/1367/687/ for further details) and for three probability levels (10, 50 and 90 percent, see http://ukclimateprojections.defra.gov.uk/content/view/1277/500/ for further details).

The earlier results provide an indicator of the potential exposure (the road distance at risk) rather than an indication of impacts, due to the lack of data on hazards and impacts (consequences) of individual events. This makes valuation very challenging.

However, it is possible to provide an informed judgement, based on the estimates of the costs of these events in Europe. Analysis in Sweden (SCCV, 2007) reports the repair costs from landslips on the road network. It provides historical costs of £0.5 to 2 million per case (involving road embankments washed away), with a much larger incident (major road damage) involving costs in excess of £10 million. Note that these only involve the repair costs (a form of adaptation costs) and not the direct costs of disruption and lost time, although the study reports that the indirect costs (in terms of distance and thus presumably travel and vehicle operating costs) are of the same order of magnitude. The report estimates the total costs (damage costs and indirect costs) from landslides over the past decade were £2 to 5 million, and the costs of adaptation measures to prevent future landslide (including climate change) will be £20 million. These provide some context for the informed judgement of possible UK estimates. Note that these represent current values and that there are no adjustments for future time periods.

7.4.3 Results and discussion

In the absence of quantitative information, an indicative estimate has been made for this risk, based on the information above. Given the relatively low costs, even in a country with higher reported observed rates, and the relatively low increase in relative risks reported in Section 5.5, future risks are considered to be low in monetary terms (£1 – 10 million/year). This can only be considered a very approximate estimate. It is highlighted that these estimates only apply to the road network, and would rise further if other transport modes such as rail was included.

7.5 TR4 Cost of carriageway repairs from heat stress

7.5.1 Outputs from the risk assessment

This metric considers heat damage to road surfaces and the cost of carriageway repairs. This involves the physical damage and deformation of roads due to the impact of high road surface temperatures.

These effects can be significant in economic terms. For example, the 1995 hot year led to and road deformation repairs of £10 million (Thornes, 1997) and the 2003 extreme heat wave was reported (Metroeconomica *et al.*, 2006) to have led to repair costs of £23 million from road deformation. There is also a related consequence of lost travel time and delays, which extends over time due to the need for the road surface to cool before repair work can commence.

The earlier analysis in Section 4.4 developed a semi-quantitative function to assess this metric. The response function developed uses historical analogues of road damage and expert judgement. It is stressed that these estimates are therefore only indicative. The results are presented in Section 5.6.

7.5.2 Methodology and unit values to be adopted

Ideally this analysis would follow Government transport appraisal guidance, estimating the transport delays (the value of time) above, and the additional costs of repair (repairs are undertaken after the initial delays, as a minimum after the road surface has cooled). However, undertaking such assessment would require an extremely detailed quantitative analysis, which is not possible given the current level of evidence.

Therefore, a simplified version of such an approach has been adopted. This has used the available information, which only provides costs of repairs (and thus excludes additional disruption).

7.5.3 Results and discussion

The results were presented in Section 5.6. In summary, the results reported for the 2020s are extremely low (below £1 million/year). They are also very low in the 2050s, with the exception of the p90 projections (which are possibly above £1 million/year). Only the high emission projection p90 scenario has estimated values that exceed £10 million/year, but this is still only a medium ranking.

A number of issues are highlighted. The most important is that these only consider the repair cost: a consideration of the full welfare costs, expressed in terms of lost time, could be much higher. Further, these only apply to the road sector only (although rail buckling is assessed separately in TR5) and are based on current demand levels for transport.

7.6 TR5 Buckling risk; financial cost of delays

7.6.1 Outputs from the risk assessment

This metric considers the rail buckling risk and the costs of delays.

Previous warm years have been associated with major impacts, mostly associated with the costs of delay (either due to rail buckling or due to lower rail speeds to avoid buckling during hot weather). The 1995 hot summer led to estimated passenger delay costs of £1 million and a similar cost for repair (Thornes, 1997), whilst the 2003 hot summer led to estimate passenger delay costs of £2.2 million as well as additional maintenance costs of a further £1.3 million (Metroeconomica *et al.*, 2006).

This metric was quantified using a quantitative analysis. The results are presented in Section 5.7.

7.6.2 Methodology and unit values to be adopted

The analysis of rail delay requires analysis of the valuation of lost time for rail users, consistent with the DfT Appraisal guidance. This requires detailed information on the location and impact of any events. As outlined above, the cost of rail buckling has been estimated based on repair and delay costs per minute. The analysis uses average Network Rail repair costs of approximately £10,000 and delay costs of £9,000, i.e. a total cost for each rail buckle of £19,000. These represent current values and no adjustments are made for future time periods.

7.6.3 Results and discussion

The results were presented in Section 5.7 and are reproduced below.

Table 7.2 Marginal Change for Rail Buckling

Metric TR5 (£ Million/year) due to climate change in the 2020s, 2050s and 2080s (no socio-economic change). Constant prices (2009), no discounting.

	1995-2009	2020 Med	2050 Low	2050 Med	2050 High	2080 Low	2080 Med	2080 High
Annual cost	0.9	1.2	2.2	2.3	2.6	2.5	3.5	4.5

These are therefore considered low in terms of monetisation (£1-10 million/year), across all future time periods.

Note that the values assume current rail demand. Future socio-economic projections for rail demand would increase demand significantly, which would increase the relative costs of delay for any event. However, no planned adaptation is considered, even as part of upgrade and replacement programmes.

7.7 TR6 Road and rail bridge failures due to scour

7.7.1 Outputs from the risk assessment

This metric considers the potential for road and rail bridge failures due to scour.

Section 4.6 discusses the a response function for scour depth against river flow, but as reported in Section 5.8, it was not possible to estimate the potential number of bridge failures and a qualitative discussion is presented on this risk.

7.7.2 Methodology and unit values to be adopted

Ideally this analysis would follow the approach for road and rail transport disruption and delays (the value of time) above, along with the additional costs of repair. However, undertaking such assessment would require an extremely detailed quantitative analysis, which is not possible given the current level of evidence, and at present even a semi-qualitative assessment is not possible. This makes it extremely difficult to provide any valuation context because, while there are estimated costs of repair and costs of disruption could possibly be estimated, there is no qualitative or quantitative estimate of the potential level of future risks.

7.7.3 Results and discussion

In the absence of quantitative or qualitative information, it is very difficult to provide even an indicative estimate for this risk.

The information in Section 4.6 indicates historical failures over the past decade, but it has not been possible to translate these into estimates of future risks (see Section 5.8). Assuming a relatively modest increase in relative risks from climate change, it is possible that future risks will be low in monetary terms (£1 – 10 million/year) but this can only be considered an extremely approximate estimate.

7.8 BU9 - Supply chain disruption as a result of extreme events

This metric is concerned with a potential decrease in output for UK businesses due to an increase in supply chain disruption as a result of extreme events. Supply chain disruption can cause significant harm to business operations. Retail supply chains are complex and dependent on a network of interconnected, yet independent, elements. As a consequence, the risk assessment above judges that it is not possible to develop a clear and direct causal link between climate change and supply chain disruption across the whole of the Business sector. The risk assessment provides no quantitative assessment of the potential supply side disruption caused by extreme events and therefore it is difficult to attach an economic estimate to such events.

There are a number of studies that derive estimates of the economic impacts of extreme events on UK business. For example, the summer 2007 floods in England were estimated to cause £740 million of damage (Environment Agency, 2010). On an international level, climate change presents a number of risks to the UK food and drink sector, through the sourcing of raw materials and foodstuffs. It is suggested that climate change impacts may affect agricultural yields and their subsequent supply price.

This possibility is explored in Hunt *et al.* (2009), suggesting that the production and preserving of meat and poultry meat, operation of dairies and cheese making, and the manufacture of prepared feeds for farm animals are the most vulnerable sub-sectors, with the potential to suffer profitability losses of 10-20% in the 2020s and 20-40% by the 2080s. On the basis of this and similar evidence, an informed judgement is that this impact may justify an indicative medium or high cost ranking, although with a high degree of uncertainty.

7.9 FL8 – Roads and rail at significant likelihood of flooding

7.9.1 Outputs from the risk assessment

The metric used in the risk assessment is kilometres at significant likelihood of flooding. This metric closely relates to the transport sector risk metric, TR1, which assesses transport disruption caused by flooding.

7.9.2 Methodology and unit values to be adopted

The TE2100 flood risk analysis (TE2100, 2009) makes some initial estimates of the welfare cost of the disruption that might result from such flood risks. Specifically, it generates the following unit values:

- Motorway disruption - £200,000/day/km
- “A” Class Road disruption - £77,000/day/km
- Rail disruption - £115,000/day/km.

It is assumed that a flood disrupts each kilometre impacted by one day once in 75 years. The unit values are then multiplied through to give total damage costs.

7.9.3 Results and discussion

The annualised results, attributable to climate change alone, for the p50 Medium Emissions climate change scenario and current transport socio-economics, are presented in Table 7.3 for the three transport modes considered. As can be seen, the costs are low although these totals will be higher if more frequent flood events are included in the analysis.

The results overall are below the levels estimated by TR1 since the analysis considers a 1 in 75 year flood risk only whereas the TR1 considers all flood frequencies. Moreover, it is comforting to see the consistency in scale of the estimates given the different methods utilised to generate the estimates.

Table 7.3 Flood costs to transport

EAD, £m/year, no uplift or discounting; Climate change only (p50 Medium Emissions scenario); no socio-economic change.

	2020s		2050s		2080s	
	River	Tidal	River	Tidal	River	Tidal
Rail	0.37	0.09	0.54	0.21	0.69	0.32
Motorway	0.13	0.04	0.20	0.10	0.26	0.14
A Road	0.43	0.09	0.60	0.23	0.75	0.35
Total	0.93	0.22	1.34	0.54	1.7	0.81

7.10 MA5 – Shipping routes: navigable days for the north-west and north-east passages per annum

7.10.1 Outputs from the risk assessment

This metric assesses the number of navigable days for shipping through the north-west and north-east passage, a potential benefit (opportunity) arising from climate change. Section 4.8 developed a response function to assess the number of navigable days for difference ice cut-off thresholds. The results reported 30 to 90 days per year in the 2020s for the north-east passage (the route most relevant for UK markets) and 0 to 30 days per year for the north-west passage, increasing to 90 to 120 days and 0 to 90 days in the 2050s respectively and rising further by the 2080s.

These results present potential economic benefits by increasing the number of navigable days, and providing significant saving in fuel costs and journey times, for transportation of goods to and from Asia – particularly for container ships. They also reduce CO_2 emissions.

Potential fuel and journey time savings that this opportunity would offer are discussed in the Marine Sector Report (Pinnegar *el al.*, 2012), citing a study from Beluga Shipping (2009). In this example, journey times were reduced by approximately 3000 miles, and for the two vessels studied, this led to reduced bunker fuel consumption of approximately 200 tonnes per vessel, or around approximately $100,000 per vessel. When combined with savings of approximately $20,000 per day from the shorter voyage time, this led to potential cost savings per voyage of up to $300,000.

In shortening voyage time and bunker consumption, CO_2 emissions are also reduced. Using the Defra GHG reporting guidelines and emission factors for fuel/marine oil (Defra, 2010c), a saving of 200 tonnes of fuel would be equivalent to 644 tonnes of CO_2.

However, the analysis did not estimate the total cumulative benefits of these changes, which makes informed judgement necessary to provide a valuation.

7.10.2 Methodology and Unit Values

There is supplementary HMT / DECC guidance on valuing energy use and GHG emissions[39] (DECC, 2010), which provides the unit values for assessing any changes in marine oil and CO_2 emissions. This is accompanied by a spread-sheet calculation toolkit which provides carbon values, the long run variable energy supply costs, emission factors and air quality damage costs over the 2008-2050 periods. There is also guidance on how to extend the analysis post-2050. The guidance recommends that changes in energy use, for the purpose of economic appraisal, should be valued at the long-run variable cost of energy supply. However, the guidance does not include marine fuel oil projections (only burning oil).

The CO_2 and air pollution valuation numbers are for UK emissions, whereas most of the emissions from these journeys will not be from the UK but instead from international waters (and thus not allocated to the UK under emission inventory guidance). In the case of air pollution, releasing emissions would not increase air pollution in the UK. Nonetheless, using the current (2009) value for the cost of carbon, the estimated benefits per voyage (from saving 200 tonnes of fuel), would have a value of £33,000, (assuming £52/tCO_2 for a non-traded sector), i.e. around a further 10% on top of existing fuel and time savings. These would rise very significantly in future years because of rising prices indicated in the Defra guidance per tonne of CO_2.

These reduced costs could also feed through to the price of goods in the UK, or the costs of exports, with potentially important supply chain consequences as well.

In order to estimate the total benefits, some indication is needed of future shipping volumes. Total savings could be very large, with potentially a 40% reduction in container shipping transport requirements to service current flow demand (noting that future demand flows could be very different, because of socio-economic growth). However, as well as these direct effects, there could also be complex secondary effects, for example through re-routing. This is because the economic benefits of shorter sailing distances may be offset by losses in efficiency of container shipping because of the changed route, as at present container ships calling into the UK call at other hub ports in Northern Europe, the Mediterranean and the Middle East.

7.10.3 Results and discussion

It is has proved very difficult to provide a value for the impact that increased navigable days would have in terms of international marine transportation savings, let alone on the UK economy. However, as a crude first approximation, the data referred to above was used to make an order of magnitude estimate. Each voyage is assumed to result in benefits of £330,000. At present, the three ports that receive the majority of the large container shipping from Asia – Felixstowe, Thamesport and Southampton - receive a total of 27 of these vessels per week.

If it is assumed that these vessels are able to use the north-east passage for eight weeks each year (a mid-point figure projected for the 2020s) then a total of 216 vessels accrue the benefits of £330,000. This results in a total benefit of about £70 million per year. Since this calculation only includes the largest vessels this is likely to be an under-estimate. It also does not include any benefits from the north-west passage being ice-free. An indicative informed judgment here suggests that the benefit could be Medium/High for the 2020s and High for the 2050s and 2080s.

[39] http://www.decc.gov.uk/en/content/cms/statistics/analysts_group/analysts_group.aspx

8. Adaptive Capacity

8.1 Overview

Adaptive capacity considers the ability of a system to design or implement effective adaptation strategies to adjust to information about potential climate change, to moderate potential damages, to take advantage of opportunities, or to cope with the consequences (Ballard, 2009, after IPCC, 2007). This can be considered as having two components; the inherent biological and ecological adaptive capacity of ecosystems and the socio-economic factors determining the ability to implement planned adaptation measures (Lindner *et al.*, 2010). Considering adaptive capacity is essential for adaptation planning and the CCRA project has included work in this area that will contribute to the ongoing Economics of Climate Resilience study and the National Adaptation Programme. The CCRA work on adaptive capacity focuses on structural and organisational adaptive capacity and this chapter provides an overview of the assessment approach. The subsequent sections of this chapter provide an overview of the findings from other work on adaptive capacity in the transport sector that has been carried out.

The climate change risks for any sector can only be fully understood by taking into account that sector's level of adaptive capacity. Climate change risks can be reduced or worsened depending on how well we recognise and prepare for them. The consequences of climate change are not limited to its direct impacts. Social and physical infrastructure, the backdrop against which climate change occurs, must also be considered. If such infrastructure is maladapted, the economic, social or environmental cost of climate impacts may be much greater; other consequences could also be considerably more detrimental than they otherwise might have been. Avoiding maladaptation is one outcome of high adaptive capacity; high adaptive capacity lowers the negative consequence of climate impacts. Conversely, low adaptive capacity increases the negative consequences.

8.2 Assessing structural and organisational adaptive capacity

The methods used for assessing structural and organisational adaptive capacity in the
The methods used for assessing structural and organisational adaptive capacity in the
CCRA are based on the PACT framework[40]. The work included a preliminary literature- and expert interview-based assessment of all eleven sectors in the CCRA. This was followed by more detailed analysis for the following sectors:

- **Business, Industry and Services** (focusing on the finance sector)
- **Transport** (focusing on road and rail)
- **Built Environment** (focusing on house building)
- **Health**
- **Biodiversity and Ecosystem Services**
- **Water**

[40] PACT was developed in the UK as one of the outcomes of the ESPACE Project (European Spatial Planning: Adapting to Climate Events) http://www.pact.co/home.

Structural adaptive capacity

The extent to which a system is free of structural barriers to change that makes it hard to devise and implement effective adaptation strategies to prepare for future impacts. This covers issues such as:

> ***Decision timescales***: This considers the lifetimes of decisions, from their conception to the point when their effects are no longer felt. The longer this period is, the greater the uncertainty as to the effects of climate change impacts. Cost-effective adaptation becomes harder. Potential climate impacts also become more extreme over longer timescales. This means that a greater scale of adaptation may need to be considered, and that the barriers to adaptation resulting from 'lock-in' to maladapted processes become more pronounced (Stafford-Smith *et al.*, 2011). Adaptive capacity is therefore lower, and maladaptation more likely, when long-lasting decisions are taken.
>
> ***Activity levels***: This considers what opportunities are there for adaptation, and on what scale. The frequency with which assets are replaced or created determines how many opportunities there will be to take action which increases adaptive capacity.[41] In addition, when a lot of asset replacement and/or new investment is expected, there will be more chances to learn from experience, which increases adaptive capacity.
>
> ***Maladaptation***: This evaluates the effect of decisions already made on adaptive capacity. Long-term previous decisions which have reduced adaptive capacity are often difficult or expensive to reverse. Such decisions were made either before climate change was recognised as an issue, or more recently as a result of poor organisational capacity. Such maladaptation makes implementing effective strategies much harder.
>
> ***Sector (or industry) complexity***: This refers to the level of interaction between stakeholders within an industry, or with outside industries and groups, that is required to facilitate effective decision-making. Complexity is higher (and adaptive capacity lower) when many stakeholders are involved in decision-making and when their agendas (e.g. their financial interests) differ substantially.

Organisational adaptive capacity

Organisational adaptive capacity is the extent to which human capacity has developed to enable organisations to devise and implement effective adaptation strategies. Effective adaptation requires decision-making that takes account of an uncertain future and avoids locking-out future options that might be more cost-effective if climate impacts become more severe, or arrive more rapidly, than expected. The PACT framework used to assess this recognises different levels of adaptation. This framework is arranged in a hierarchy of ‘Response Levels’ (‘RLs’), as set out below, of increasing capacity[42]. These levels do not supersede one another; instead, each one builds on the experiences and practices built up in the previous response level. Organisations may need to be active on all levels for an effective adaptation programme. An RL4 organisation focused on breakthrough projects still needs to be stakeholder-responsive, for example.

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[41]This differs from ‘Decision timescales’ because investment in a sector is not continuous but varies over time, with periods of high investment being followed by periods of little or no investment.

[42] The PACT framework contains six response levels: those cited are the most relevant to the adaptation field.

RL1: Core Business Focused: At this level, organisations see no benefit from adapting; if change is required of them, it should both be very straightforward to implement and also incentivised, e.g. through 'carrots' and 'sticks'.

RL2: Stakeholder Responsive: At early stages of adaptation, organisations lack basic skills, information, processes and also skilled people; they need very clear advice and information plus regulations that are straightforward enough to help them get started.

RL3: Efficient Management: As organisations begin to professionalise adaptation, they become more self-directing, able to handle short term impacts up to 10 years (Stafford-Smith *et al.*, 2011). They need professional networks, best practice guidelines, management standards, etc.

RL4: Breakthrough projects: When impacts beyond 10 years need to be considered, organisations may need to consider more radical adaptation options. As well as high quality support from scientists, they may need support with the costs of innovation.

RL5: Strategic Resilience: Adapting a whole region or industry for long-term climate impacts of 30 years or more requires lead organisations to develop very advanced capacity that is able to co-ordinate and support action by a wide range of actors over programmes that are likely to last for many years.

8.3 The effect of ARPs on adaptive capacity

Some insights into the state of adaptation in this sector are provided by a review by Defra of Adaptation Reporting Power reports (which are required from organisations that are responsible for climate-sensitive infrastructure under the Climate Change Act 2008)[43]. Three transport authorities (Highways Agency, 2010, Network Rail, 2010 and Trinity House, 2010) were selected to submit their reports early as 'Benchmark Reports'. The review of the preliminary Benchmark findings (Defra, 2011a) suggests that the reports are still focussing on risk analysis rather than risk management and adaptation planning (p9), that further work on interdependencies is still required, and that more training is needed for authorities to fully understand climate risk assessment methodologies.

A preliminary comparison of the climate-related risks for transport identified in this report as part of the CCRA and those cited in the ARP reports has been carried out by UKCIP (UKCIP, 2011). This report showed that the CCRA approach is more concerned with identifying risks at a national, strategic level whereas most of the ARP reports are more focussed at a local or corporate level (e.g. ports and airports). UKCIP also point out that as the ARP reports will be made public, private companies are aware that the 'information will be used by, for example, shareholders, journalists and competitors and are likely to be cautious in their use of language and description of risks' (p4).

[43] http://www.defra.gov.uk/environment/climate/sectors/reporting-authorities/reporting-authorities-reports/

9. Discussion

9.1 Overview of methodology

Travel and transport underpin the national economy. This CCRA forms a core part of the framework stipulated by the Climate Change Act 2008 in order to improve the ability of the UK to adapt to climate change, including the transport sector.

The impact of climate change on all modes has been considered and a methodology designed to provide a first attempt at quantifying climate impacts on the transport network. The overall aim is to inform UK adaptation policy in 2012 as current design codes will need to be amended to take into account future climate variability in order to improve adaptive capacity.

A range of impacts and thresholds (including both threats and opportunities) were identified during an initial scoping exercise which consisted of literature reviews and stakeholder workshops. The result was a tiered assessment of over 50 potential impacts covering a broad range of climate impacts on transport. The list could generally be subdivided into:

- Damage to infrastructure
- Damage and disruption to transport modes (vehicles, trains, aircraft and ships).

Whilst each of the impacts is potentially important, there was a need to streamline the list into the most pressing impacts for further analysis in terms of quantification and monetisation (Tier 2). This was achieved by expert consultation workshops which grouped the impacts into broad areas of similarity, before subsequently ranking the impacts in terms of urgency and importance (many impacts were considered to be non-urgent). Consideration was also given at this stage to the availability of evidence for each of the impacts. The result was 5 impacts selected for further analysis:

- Flooding - TR1: Disruption and delay due to flooding
- Land movements - TR2: Subsidence & landslip
- Thermal Loading - TR4: Cost of carriageway repairs
- Heat stress on rail - TR5: Rail buckling risk
- Bridge scour - TR6: Scour at bridges

The energy demand associated with cooling road vehicles[44], metric TR3, was considered during the initial stages of the analysis but was not taken through at the detailed stage.

Impacts related to transport were also assessed in other CCRA sectors, and the results for the following are included in this report:

- Shipping Routes - MA5: Navigable days for the north-west and north-east passages
- Flooding - FL8: Roads and rail at risk of flooding

Also retail supply chains were analysed, but as they are complex and dependent on a network of interconnected, yet independent, elements, it was not possible to develop a

[44] This can be taken as a surrogate measure of the cost of ameliorating passenger discomfort

clear and direct causal link between climate change and supply chain disruption. Therefore supply chain disruption (Metric BU9) is not covered in Chapters 4 and 5 but the implications of socio-economic change is briefly discussed in Chapter 6 and an indication of potential costs is given in Chapter 7.

For each of the selected impacts, risk metrics (a measure of the consequences) were calculated. This was followed by the development of response functions (how the risk metric varies with changes in climate variables, mostly via simple relationships). A broad estimate of the total impact was then quantified via monetisation after socio-economic dimensions had been taken into account.

9.2 Gaps in evidence

The high number of Tier 1 impacts identified during the scoping exercise is testimony to the strength of expertise assembled at the various workshops. Whilst the initial scoping exercise was straightforward resulting in a number of potential impacts for investigation, it quickly became apparent that in order to promote an impact to Tier 2 for detailed analysis, there was a need for sufficient quantitative data in order to produce robust metrics.

This is perhaps the biggest downfall of the assessment approach as even though impacts were chosen where it was known that suitable datasets existed, subsequent analyses still suffered from a lack of coherent data availability. It is clear that improved record keeping is required across all modes of the transport network, for example delay times, if such analyses are to be improved in due course.

Further problems can be encountered by workshop attendance. The success of such an exercise is dependent on the participation of stakeholders and the absence of one or two key players can be problematic. This can be seen during this assessment when vehicle cooling was elevated to a Tier 2 impact, where perhaps impacts on airports and ports should have featured more heavily. There also appears to be a bias towards recent high profile events in the media, for example bridge scour and flooding.

Analyses are difficult for many impacts in the sector as there is a gap in knowledge with respect to trigger mechanisms and thresholds. Whilst some thresholds are clear, for example, 0°C for ice formation, 36°C for blanket speed restrictions on the railway (Dobney *et al.*, 2010), such simple thresholds cannot be applied universally across all impacts and modes. Impacts such as flooding and bridge scour are location specific and the trigger mechanism will vary from location to location. A detailed inventory of all hard infrastructure and past climate events is required to complete a detailed analysis of such impacts.

Throughout this assessment, there is a general lack of quantitative data sufficient to produce robust metrics. Examples of this are evident for many of the Tier 2 impacts. For example, no qualitative landslip information in TR2; no data available for Northern Ireland in TR5; no national bridge register and no data on bridge foundations in TR6. The result of a lack of data is ultimately the reason behind the low-medium confidence rating in the results of this report.

However, one exception to this is TR5 which provides an example of the improved level of analysis that can be achieved if adequate datasets are available. The availability of data here is a combination of diligent record keeping by stakeholders as well as a substantial record of academic research in the field (e.g. Dobney *et al.*, 2010) which has enabled datasets to be managed and analysed over an extended time period. The result is that the impact of buckling risk can be explored in this report at a greater level than other impacts and is indicative of what could be achieved for all other climate impacts if resources are available.

Data availability is the key issue leading to reduced confidence in analyses. However, further uncertainty in the response functions reflects the uncertainties in climate change drivers. The majority of analyses in this report have used the UKCP09 temperature and precipitation data. Other impacts would need additional datasets and these are not readily available (e.g. wind and visibility projections).

Similarly, analysis of some impacts (e.g. landslides) needs to consider antecedence, which can be achieved in UKCP09 by using a weather generator, but is ultimately a difficult exercise. Indeed, the majority of the analysis conducted on the Tier 2 impacts in this report is completely dependent on the accuracy of UKCP09 scenarios and therefore its limitations (for example, non-inclusion of urban areas which are major hubs of the UK transport network).

Many of the impacts of climate on the transport sector are caused by extreme short lived events. In this analysis seasonal mean changes in mean temperature and rainfall from UKCP09 have been used as the basis for assessing future climate change projections. Consideration should be given to developing better projections of daily and extreme climate variables and using these for future CCRAs.

Finally, there are uncertainties surrounding the application of socio-economic scenarios in the analysis. It is accepted that the application of these is challenging and an attempt has been made to incorporate these based on the assumption of increasing population and travel demand. Whilst this is a useful first attempt, more work is needed to fully test this assumption and fully integrate potential scenarios into the analysis.

9.3 Limitations and strengths of the current methodology

Whilst a number of gaps in the evidence have been highlighted in the previous section, it is worth noting that these gaps have been prohibitive to completing an exercise on such a scale previously. The CCRA is ultimately a first attempt at quantification of impacts as other projects have been broadly qualitative. Evidently, a number of barriers and gaps were going to be identified during the process.

The identification of over 700 Tier 1 impacts across eleven sectors (both opportunities as well as negative impacts) is a particular strength of the risk assessment and is a level of detail which far exceeds the number of impacts detailed in existing reports and papers on the subject (e.g. Koetse & Rietveld, 2009; TRB, 2008). Indeed, many of the Tier 1 impacts are worthy of further investigation and a light-touch analysis would be appropriate (see Section 3.4).

At this level of analysis, no formalised impact assessment method really exists, but the general approach used by others is the dose-response approach which has also been utilised in this exercise (Jaroszweski *et al.*, 2009). Considerations of socio-economic change are a crucial component (Füssel & Klein, 2006) and, until recently, have been noticeable absent in climate change impact assessments (Berkhout *et al.*, 2002). Hence, the inclusion of socio-economic scenarios and social vulnerability, albeit qualitatively, is a strength of the approach.

A further strength is the attempt to monetise the findings in this assessment. Clearly, this is a difficult given the uncertainties involved. Here, detailed socio-economic scenarios are particularly useful in terms of travel demand and infrastructure supply. It is exceptionally difficult to calculate future costs when there is little knowledge of what exactly the nature of the transport system will be in 50 years.

50 years ago, the UK barely had a motorway network – what will the situation be in 2060? Certainly, there is the potential that high speed rail may be a more dominant mode than it is today. Difficulties in monetisation are highlighted by the difficulties in costing events today. For example, disruption from the 2007 floods was estimated to be between £22m and £174m and this is just a single event (Environment Agency, 2010). The techniques used in this assessment are considered sensible and simplifications using 'cost rankings' are a useful approach.

Overall, the main limitation of the methodology is the lack of robust data. At each stage of the analysis, for the majority of impacts investigated, there has been a need to round numbers for the response functions, subsequently leading to cost rankings for the calculation of economic impacts and reducing overall confidence in the projections. Until improved data becomes available, there is little more that can be achieved for many of the impacts identified at Tier 1.

Risk assessments for other sectors face similar issues and whilst a national assessment needs to also take into account interdependencies across sectors in the analysis, there is a need for each sector to urgently improve relevant data collection and sector adaptation issues. Improving adaptive capacity across all sectors is a desirable goal but inherently complicated.

10. Conclusions

The analysis presented here provides an early insight into some potential consequences for the transport sector and the challenge of linking the climate drivers to the potential impacts and scale of risk at a national level.

The analysis has identified some sensitivities to climate drivers such as increasing mean summer temperatures, which translate into increasing numbers of cooling degree days, and increasing winter precipitation, which is correlated to more frequent or severe flooding events and landslides.

Future changes in the climate may affect both the maintenance of existing infrastructure, and new transport investments. Whilst there may be a need to increase some maintenance activities and reduce others in response to a changing climate, flexibility is likely to be needed. For example, whilst there may be an overall reduction in cold weather working, there is likely to still be a need to respond to extreme winter conditions from time to time.

The response to climate mitigation and the very long-term nature of transport infrastructure related investments mean that the transport sector will be vulnerable to the adequacy of planning and design decisions in the light of climate change.

This study has also found that several of the impacts identified here are either a) being actively addressed by the transport sector, such as risk of landslide and thermal loading on some road surfaces, or b) are not considered to be a significant issue, such as increase in fuel use for cooling. The latter metric has highlighted however that while the relative consequence per road users is small, the overall costs to the UK could be significant.

Where impacts are being well managed, it can be taken as evidence that there is a degree of adaptive capacity demonstrated in the sector and that adaptation is well supported by good governance (for example through design standards for trunk roads). Further supporting this observation, some adaptive measures have already been introduced; major infrastructure is being managed with future risks and extreme weather pressures in mind.

Conclusions in relation to each metric are:

- TR1 – Flood disruption and delay. The costs of disruption and delay can often be borne by transport users rather than the transport sector as a whole. Risk management and adaptive measures for this metric are already underway as part of flood risk planning and prevention. Although the costs associated with flood events is relatively well known in general, there remains limited evidence on the costs of disruption and delay associated with an event. Also, the events which have been analysed to date are typically significant, such as the 2007 floods. This lack of information, particularly for the consequences of more typical events, means that there is a great deal of uncertainty in the projected increases, as shown by the broad range of potential consequences.
- TR2 – Landslides impacting on the roads network. Of the three administrations which were analysed, England and Northern Ireland have very low areas of risk on their road networks. Scotland has a higher percentage of road network at risk, however there is good working knowledge in place regarding the extent of the threat and adaptation measures are being well managed. Overall, increases in precipitation quantity and intensity as a result of climate change could increase

occurrences of landslide and subsidence in risk areas. At a UK level, further data gathering and research is underway to understand this risk better.

- TR4 – Carriageway repairs. The analysis of this metric fell into two aspects: costs of repairs to highways/trunk roads and to B, C and unclassified roads. This analysis shows that the cost burden of increasing heat damage surface repairs is likely to be borne by local authorities, seeing as the issue relates to predominantly local roads. The UK's highways and trunk roads (maintained by the Highways Agency) are currently specified to a high heat resistance and receive regular surface maintenance. Thus heat damage to surfaces is not as big an issue for HA as for LAs, but is still important. Given the current cost of repairs the overall risk is in the Low to Medium category of the CCRA.
- TR5 – Rail bucking. The likelihood of delays arising from rail buckling is projected to increase with the largest increase in numbers in London and the North West of England. Of all of the impacts considered in the transport sector, rail buckling is one area where there are limited options available to users in an event to minimise delay.
- TR6 – Bridge scour. Damage and delay caused by bridge failures due to scour is likely to increase. However it was not possible to estimate the magnitude of the future risk owing to a lack of suitable data on bridge foundations.

The energy demand associated with cooling road vehicles[45], metric TR3, was considered during the initial stages of the analysis but was not taken through at the detailed stage.

Landslip is also a problem for the rail network that could increase as a result of climate change. Studies on this impact are in progress and may be suitable for use in the next CCRA. Impacts on seaports and airports were not scored highly enough to be included in the assessment. However in view of the importance of sea and air travel, these should be considered in more detail in future cycles of the CCRA.

Changes in technology may lead to changes in climate risks. For example, large scale electrification could increase the reliance of transport on the Energy sector and ICT. Transport may also be affected by changes in social behaviour in the future, resulting in changes in transport modes and travel patterns.

Each of the risks considered in this sector have been analysed to pose a Low to Medium risk to the UK. However, what is important about this sector is its integral role in society. It could be argued that every single person in the UK relies upon the transport network.

Some of the impacts identified are moderate at a national scale but to communities in risk areas (such as those who rely upon roads in landslide risk areas for access to work, shops, etc) there are issues such as isolation which will disproportionately impact vulnerable members of the community. Conversely, with consequences such as increased fuel consumption, the per capita impact is small and likely to be masked by fluctuation in fuel prices, but when consolidated into a UK risk this becomes more significant, especially given its contribution to national carbon emissions.

The analysis has concentrated on road and rail transport as risks associated with aviation and marine transport did not have a high enough score in this first CCRA to be selected for analysis. An important element in this decision is the way in which storms,

[45] This can be taken as a surrogate measure of the cost of ameliorating passenger discomfort

particularly high wind speed and direction, are likely to change in the future, as this has a direct effect on these forms of transport. According to UKCP09 there may be little change in the frequency or intensity of winter storms, and probabilistic projections of future changes in extreme wind speed are not provided in UKCP09.

What underlies all of the analysis completed here is a lack of coherent data or datasets across the UK. This resulted in a predominantly qualitative assessment and significant uncertainty in the outcomes.

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Data sets

UKCP09 web site: http://ukclimateprojections-ui.defra.gov.uk

Met Office Hadley centre observation datasets web site: http://hadobs.metoffice.com/index.html

Total petroleum consumption by road transport in Great Britain and Northern Ireland (DfT and the DRDNI)

Road maintenance cost data (qualitatively estimated from the HA and Leicestershire CC)

Road length and classification statistics for the UK (DfT and DRDNI)

Cost of traffic disruption from flooding (EA, Foresight)

Appendices

Appendix 1 The Tier 1 List of Impacts

This Appendix contains the Tier 1 list for the transport sector including impacts and consequences.

The impacts on transport can be classified as:

- Damage to transport infrastructure and the associated disruption caused by extreme storm events (including extreme rainfall and wind).
- Disruption to transport modes (vehicles, trains, aircraft and ships) caused by extreme storm events. This can range from precautionary closures of roads and rail/air/ship services to catastrophic damage caused by a storm (e.g. an air crash caused by extreme weather).
- Disruption to transport caused by gradual changes in the climate, particularly increases in temperature.

Climate change also presents opportunities for transport, particularly in the reduction in the risk of sub-zero temperatures and the problems caused by ice and snow. However, because of the variability of the climate, there is a risk that resources may not be available for these conditions when needed.

The following points should be considered when using the data:

- Where the same or similar impacts have been identified, attempts have been made to remove duplicates. However, where there are subtle differences between impacts, similar impacts have been retained as separate impacts in the spreadsheet.
- There are many potentially adverse impacts but also a number of opportunities have been identified. A preliminary assessment has been made of threats (adverse impacts) and opportunities in the tables using the following colour code:

  T= threat (red), O = opportunity (green); N = neutral impact (amber).

  However it is recognised that there may be both positive and negative aspects of the same impact.

Transport Sector

Tier 1 list of climate change impacts

Climate effects	Impacts	T/O/N	Consequences	Comments
Main climate driver: Changes in annual, seasonal or extreme precipitation				
1. Increased frequency of intense precipitation events	Increased flooding of infrastructure		Transport affected by increased **infrastructure damage /disruption**. Can be caused by insufficient drainage capacity. Can lead to pollution of surface water.	Significant impact. Clustered with impacts 2, 3, 4 and 15. Assessed in analysis (Metric TR1)
2. Increased heavy precipitation	Increased road submersion and underpass flooding		Road transport affected by increased **infrastructure damage /disruption.**	Significant impact. Clustered with impacts 1, 3, 4 and 15. Assessed in analysis (Metric TR1)
3. Increased heavy precipitation	Increased flooding of underground rail networks		Underground rail networks affected by increased **infrastructure damage /disruption**	Significant impact. Clustered with impacts 1, 2, 4 and 15. Assessed in analysis (Metric TR1)
4. Heavy rainfall events	Pluvial flooding around London Underground		London Underground affected by increased **infrastructure damage /disruption**	Significant impact. Clustered with impacts 1, 2, 3, and 15. Assessed in analysis (Metric TR1)
5. Changes in precipitation, including extreme precipitation (high and low river flow)	River flows affect river transport		Increased **transport disruption** to river transport	Low score. Not taken forward.
6. Increased frequency of high precipitation events	Changes in incidence of road or rail speed restrictions or service delays		Potential road and rail **transport disruption**	Marginal score. Discussed in Section 3.5. Clustered with impacts 11, 12, 14 and 53.
7. Increased heavy precipitation	Increase in earthworks failures; Increased landslides and undercutting; rail track blockages, particularly in cuttings		Road and rail transport affected by increased **infrastructure damage**	Marginal score. Discussed in Section 3.5. Clustered with impact 8.
8. Increase in frequency of intense rainfall events	Increased erosion of foot paths and cycleways		Foot paths and cycleways affected by increased **infrastructure damage**	Marginal score. Discussed in Section 3.5. Clustered with impact 7.
9. # Increase in heavy rainfall events; increase in winter rainfall	Rising water tables affecting underground infrastructure		Increasing risk of flooding of underground infrastructure	Low score. Not taken forward.
10. Drier summers (decrease in summer rainfall)	Greater opportunities for walking and cycling, particularly in summer		# Associated health benefits	Low score. Not taken forward.
11. Increased frequency of heavy precipitation events	Poor driving conditions - increased number of accidents		Increased **transport disruption** caused by more accidents (e.g. aquaplaning and impaired braking); increased loss of life. Increased need for vehicles to tolerate extremes	Marginal score. Discussed in Section 3.5. Clustered with impacts 6, 12, 14 and 53.
12. Increase in heavy rainfall events	Reduction in visibility causing problems for aircraft take-off and landing		Increased **transport disruption** to air travel	Marginal score. Discussed in Section 3.5. Clustered with impacts 6, 11, 14 and 53.
13. Rainfall	Prevention of road repairs		Increased **transport disruption** to road travel	Low score. Not taken forward. Clustered with impact 50.
14. Increased frequency and intensity of storms	Increases in delays for air take-off and landing		Increased **transport disruption** to air travel	Marginal score. Discussed in Section 3.5. Clustered with impacts 6, 11, 12 and 53.

Climate effects	Impacts	T/O/N	Consequences	Comments
		Main climate driver: Sea-level rise		
15. Sea level rise (and also storm surge risk)	Flooding of coastal infrastructure. Increased rate of inundation in vulnerable areas, increased area considered vulnerable, increased corrosion of track, points and signals and overhead line equipment in vulnerable areas, road infrastructure.		Increased **infrastructure damage /disruption** affecting all forms of transport, particularly road and rail. Locations of ports become inappropriate. More frequent closures of coastal roads and promenades. Changes to river transport, embankment stability.	Significant impact. Clustered with impacts 1, 2, 3 and 4. Assessed in analysis (Metric TR1)
		Main climate driver: Changes in annual, seasonal or extreme temperature		
16. Increased number of hot days	Increased thermal loading on road pavements		a. Melting tarmac b. Roadway buckling c. Expansion / buckling of bridges d. Increased numbers of tyre blow-outs	Significant impact. Clustered with impacts 26, 27 and 32. Assessed in analysis (Metric TR4)
17. Decreased number of cold days	Reduced winter maintenance costs for road & rail		**Opportunity** to reduce costs	Low score. Not taken forward. Clustered with impact 51.
18. Decreased number of cold days	Improved working conditions for personnel in cold environments		**Opportunity** to improved working conditions and practices	Marginal score. Discussed in Section 3.5.
19. Increased frequency of high or extreme temperature episodes/ number of hot days	Increased incidence of rail buckling		Increase in need for air conditioning for signalling	Significant impact. Clustered with impacts 21, 27 and 41. Assessed in analysis (Metric TR5)
20. Increased frequency of high or extreme temperature episodes, increased number of hot days	Increased passenger discomfort, customer and staff heat stress. Increased driver discomfort/heat exhaustion e.g. London Underground		Serious adverse impact on transport users	Marginal score. Discussed in Section 3.5.
21. Increased frequency of high or extreme temperature episodes, increased number of hot days	Overheating of equipment both on infrastructure and trains/underground.		Rail transport affected by increased **infrastructure damage /disruption**	Significant impact. Clustered with impacts 19, 27 and 41. Assessed in analysis (Metric TR5)
22. Increased average temperature / decreased rainfall	Increased subsidence (road, rail, waterway embankment stability)		Transport affected by increased **infrastructure damage /disruption**	Significant impact. Clustered with impact 37. Assessed in analysis (Metric TR2)
23. Warmer winters (increase in average winter temperature)	Less need for heating on transport in winter		# Reduced demand on energy resources	Clustered with impacts 24 and 25. Analysis undertaken but not considered an important impact.
24. Increased average temperature	Increased demand for air conditioning (cooling) and energy use on public transport/ road vehicles		Increase in energy use on public transport/ road vehicles	Clustered with impacts 23 and 25. Analysis undertaken but not considered an important impact.
25. Warm summer weather	Overheating of car engines		Increased **transport disruption** to road travel	Clustered with impacts 23 and 24. Analysis undertaken but not considered an important impact.

Climate effects	Impacts	T/O/N	Consequences	Comments
26. Increase in average summer temperature (high temperatures)	Increased rutting on roads		Road transport affected by increased **infrastructure damage /disruption**	Significant impact. Clustered with impacts 16, 27 and 32. Assessed in analysis (Metric TR4)
27. Increased frequency of high or extreme temperature episodes	Changes in incidence road or rail speed restrictions or service delays		Potential increased **transport disruption** to road and rail travel	Significant impact. Clustered with impacts 16, 26 and 32 (road) and impacts 19, 21 and 41(rail). Assessed in analysis (Metrics TR4 road and TR5 rail).
28. Reduction snowfall and frost/ice incidence	Reduced winter protection (gritting)		**Opportunity** to reduce maintenance requirements	Low score. Not taken forward. Clustered with impact 39.
29. Reduction ice incidence	Reduced icing of rails, points and overhead cables (see also impact under increased average wind speed)		**Opportunity** to reduce disruption to rail travel	Low score. Not taken forward. Clustered with impacts 30 and 34.
30. Reduction snowfall and ice	Reduced number of blockage incidence, improved safety on platforms		**Opportunity** to reduce disruption to rail travel	Low score. Not taken forward. Clustered with impacts 29 and 34.
31. Higher average summer temperature (cooling degree days)	Changes in travel demand (e.g. increased tourism or recreational activity)		Changes to transport requirements. **Opportunity** to improve transport services.	Marginal score. Discussed in Section 3.5.
32. High or extreme temperature episodes	Melting of airport runway surface (above 45°C)		Air transport affected by increased **infrastructure damage**	Significant impact. Clustered with impacts 16, 26 and 27. Assessed in analysis (Metric TR4)
33. Higher temperatures - reduction in air density	Older planes may struggle to take off in time (not issue for new planes)		Old aircraft require replacement. Runway length may become inadequate. Increase in air travel cost	Low score. Not taken forward. Clustered with impacts 36 and 40.
34. Increased average temperature / reduction snowfall/ frost/ice	Reduction in cold weather related disruption, speed restrictions and accidents - improvements in road safety		**Opportunity** to improve road transport	Low score. Not taken forward. Clustered with impacts 29 and 30.
35. Increased average temperature; reduction in air density	Increase in amount of aviation fuel needed		Increase in fuel usage and cost of air travel	Low score. Not taken forward.
36. Increased number of hot days	Higher density altitudes affecting aviation: reduced engine combustion efficiency; increased runway lengths required		Changes to air travel aircraft and infrastructure. Increase in air travel cost	Low score. Not taken forward. Clustered with impacts 33 and 40.
37. Seasonal temperature	Impact on maintenance regimes due to degradation, soil shrinkage/ subsidence etc.		Change in maintenance regimes	Significant impact. Clustered with impact 22. Assessed in analysis (Metric TR2)
38. Warm and dry weather	Decrease in weather interference to construction activities		**Opportunity** to improve the efficiency of construction activities	Low score. Not taken forward. Clustered with impact 50.
39. Decreased number of cold days	Reduction in winter travel problems on average could lead to inadequate preparation for extreme events		Lack of preparation for extreme events. Resource pressures (i.e. road salt issue); more "marginal calls", i.e. gritting; provision of resources / allocation increasingly difficult	Low score. Not taken forward. Clustered with impact 28.

Climate effects	Impacts	T/O/N	Consequences	Comments
40. High temperatures (above 25°C)	Aircraft payloads may have to be reduced for take-off owing to the lower air density.		Increase in air travel and cost.	Low score. Not taken forward. Clustered with impacts 33 and 36.
41. Heat waves	Failed air conditioning on rail vehicles		Potential increased **transport disruption** and discomfort to rail travel	Significant impact. Clustered with impacts 19, 21 and 27. Assessed in analysis (Metric TR5)
		Main climate driver: Wind speed/storms		
42. Increased frequency and intensity of storms	Increased incidence of damage (e.g. to bridges, signs, etc)		Transport affected by increased **infrastructure damage /disruption**	Analysis includes metric TR6 (scour at bridges) which was not identified as a separate Tier 1 impact.
43. Increased frequency and intensity of storms	Increased damage to infrastructure (e.g. electric network for rail including power lines, signalling and electric equipment), damage or blocking of road or rail lines or (tree fall) etc		Road and rail transport affected by increased **infrastructure damage**	Evidence for increased storm intensity is weak. Not taken forward. Clustered with impacts 42, 48 and 49.
44. Wind and rainfall; severe weather	Day-to-day running of ports affected		Increased **transport disruption** to ports	Low score. Not taken forward. Clustered with impacts 45 and 47.
45. Winds above 30 knots	Increase in problems for suspension bridges, high-sided vehicles and construction cranes		Increased **transport disruption** to road travel	Low score. Not taken forward. Clustered with impacts 44 and 47.
46. Increased frequency of intense storms; longer summers and shorter winters	Changes to annual patterns of leaf fall.		Rail transport affected by **infrastructure disruption.** Leaves on railway tracks can cause problems	Low score. Not taken forward.
47. Increased frequency and intensity of storms	Increased disruption of marine transport (commercial and passenger)		Increased **transport disruption** to marine transport (commercial and passenger)	Low score. Not taken forward. Clustered with impacts 44 and 45.
48. Severe weather	Catastrophic loss of a vessel		Increased **transport disruption** to shipping; loss of life and property	Evidence for increased storm intensity is weak. Not taken forward. Clustered with impacts 42, 43 and 49.
49. Severe weather	Increase in 'wear and tear' of aircraft during take-off and landing		Increase in cost of air transport	Evidence for increased storm intensity is weak. Not taken forward. Clustered with impacts 42, 43 and 48.
50. High wind speed (above about 25 knots); temperatures below 10°C	Increase in interference to asphalting and concreting as wind-chill cools the surface too quickly		Increased **transport disruption** to road travel; increased cost of road repairs	Low score. Not taken forward. Clustered with impact 13 and 38.
		Main climate driver: Seasonal changes		
51. Seasonal changes - longer summers / shorter winters	Changes in timing of winter maintenance regimes		Timing of **winter maintenance** regimes will change	Low score. Not taken forward. Clustered with impact 17.
		Main climate driver: Other		
52. Related to all climates and subsequent risks	Changes to Insurance cover/premiums		Potential **increase in Insurance cover/premiums**	Marginal score. Discussed in Section 3.5.
53. Changes in incidence of fog	Changes in incidence of road or rail speed restrictions or service delays, or airport restrictions		Potential increased **transport disruption** (but depends on changes in incidence of fog due to climate change)	Marginal score. Discussed in Section 3.5. Clustered with impacts 6, 11, 12, and 14.

Climate effects	Impacts	T/O/N	Consequences	Comments
54. High humidity (above about 98%)	Condensation or sublimation from high humidity leading to possible aircraft engine starting problems and wing-icing		Potential increased **transport disruption** to air travel (but depends on changes in humidity due to climate change)	Low score. Not taken forward.
Additional impacts identified in DA workshops and systematic mapping				
55. All	Increased opportunities for design of new generation vehicles to cope with climate change		Business opportunity	Low score. Not taken forward.
56. Changes in wind speed	Change in wind chill factor		Adverse effects on passengers and transport staff	Future changes in wind speed are not projected in UKCP09. Low score. Not taken forward.
57. Sea level rise	Sea level rise in ports		Increase in disruption to port operations and potential erosion near port facilities	Low score. Not taken forward.
58. Increased frequency of intense storms	Increased lightning strikes		Damage and disruption to transport	Low score. Not taken forward.
59. High wind intensity and frequency	Increased storminess and high winds at ports		Disruption to port operations	Future changes in wind speed are not projected in UKCP09. Low score. Not taken forward.

Appendix 2 Social Vulnerability Checklist

Sector	Transport			
Cluster/Theme	**Vehicles**			
Category of social vulnerability factor	**Questions to ask**	**Comment (general answer)**	**Evidence (opinion, reports, research)**	**Extent (specifics including data where available)**
Place	Which locations are affected by these impacts? Is it spread evenly across regions or not?	UK wide No	Sector Team opinion and research	Nationally
Social deprivation	How will people with poor health (physical or mental) be affected by these impacts?	Potential inability to access jobs, shopping, leisure facilities and services and subsequent knock-on effects	Sector Team opinion and research	Nationally
	How will people with fewer financial resources be affected?	Inability to afford repairs or necessary expenses	Sector Team opinion and research	Nationally
	How will people living or working in poor quality homes or workplaces be affected?	N/A		
	How will people who have limited access to public and private transport be affected?	Even more limited access as a result	Sector Team opinion and research	Nationally
Disempowerment	How will people with lack of awareness of the risks be affected?	Potential for delays and loss of earnings	Sector Team opinion and research	Nationally
	How will people without social networks be affected?	Isolation and potential effect on health and well-being	Sector Team opinion and research	Nationally
	How will people with little access to systems and support services (e.g. health care) be affected?	Even more limited access and increase in health problems	Sector Team opinion and research	Nationally
Other	Are any other social vulnerability issues relevant?	Not at this stage	N/A	N/A

Category of social vulnerability factor	Questions to ask	Comment (general answer)	Evidence (opinion, reports, research)	Extent (specifics including data where available)
Place	Which locations are affected by these impacts? Is it spread evenly across regions or not?	UK wide No	Opinion and research	Nationally
Social deprivation	How will people with poor health (physical or mental) be affected by these impacts?	Potential inability to access jobs, shopping, leisure facilities and services	Opinion and research	Nationally
	How will people with fewer financial resources be affected?	Potential loss of earnings due to inability to get to work	Opinion and research	Nationally
	How will people living or working in poor quality homes or workplaces be affected?	N/A	Opinion and research	Nationally
	How will people who have limited access to public and private transport be affected?	Even more limited access as a result	Opinion and research	Nationally
Disempowerment	How will people with lack of awareness of the risks be affected?	Potential for people to be stranded and subsequent knock-on effects	Opinion and research	Nationally
	How will people without social networks be affected?	Isolation and potential effect on health and access to jobs, shopping, leisure facilities and services	Opinion and research	Nationally
	How will people with little access to systems and support services (e.g. health care) be affected?	Potential for delayed services and subsequent knock-on effects	Opinion and research	Nationally
Other	Are any other social vulnerability issues relevant?	Not at this stage	N/A	N/A

Sector	Transport			
Cluster/Theme	**Resources**			
Category of social vulnerability factor	**Questions to ask**	**Comment (general answer)**	**Evidence (opinion, reports, research)**	**Extent (specifics including data where available)**
Place	Which locations are affected by these impacts? Is it spread evenly across regions or not?	UK wide No	Opinion and research	Nationally
Social deprivation	How will people with poor health (physical or mental) be affected by these impacts?	Potential increase in stress and worry due to lack of awareness	Opinion and research	Nationally
	How will people with fewer financial resources be affected?	Potential increase in costs and delays	Opinion and research	Nationally
	How will people living or working in poor quality homes or workplaces be affected?	Potential increase in energy/utility bills	Opinion and research	Nationally
	How will people who have limited access to public and private transport be affected?	Even more limited access as a result and potential increase in costs	Opinion and research	Nationally
Disempowerment	How will people with lack of awareness of the risks be affected?	Potential for people to be caught out with price rises and subsequent knock-on effects (e.g. stress)	Opinion and research	Nationally
	How will people without social networks be affected?	Isolation and potential effect on health	Opinion and research	Nationally
	How will people with little access to systems and support services (e.g. health care) be affected?	Potential for delayed services and subsequent knock-on effects (e.g. increase in severe illness)	Opinion and research	Nationally
Other	Are any other social vulnerability issues relevant?	Not at this stage	N/A	N/A

Sector	Transport			
Cluster/Theme	Staff & passengers			
Category of social vulnerability factor	**Questions to ask**	**Comment (general answer)**	**Evidence (opinion, reports, research)**	**Extent (specifics including data where available)**
Place	Which locations are affected by these impacts? Is it spread evenly across regions or not?	UK wide No	Opinion and research	Nationally
Social deprivation	How will people with poor health (physical or mental) be affected by these impacts?	Potential increase in illness and mortality rates	Opinion and research	Nationally
	How will people with fewer financial resources be affected?	Potential increase in costs	Opinion and research	Nationally
	How will people living or working in poor quality homes or workplaces be affected?	N/A for passengers but likely to impact on staff	Opinion and research	Nationally
	How will people who have limited access to public and private transport be affected?	Potential increase in costs and loss of earnings due to days off work	Opinion and research	Nationally
Disempowerment	How will people with lack of awareness of the risks be affected?	Potential for people to be stranded and subsequent knock-on effects	Opinion and research	Nationally
	How will people without social networks be affected?	Isolation and potential effect on health and well-being	Opinion and research	Nationally
	How will people with little access to systems and support services (e.g. health care) be affected?	Potential for severe illness or worse	Opinion and research	Nationally
Other	Are any other social vulnerability issues relevant?	Not at this stage	N/A	N/A

NOTES ON USING THE SOCIAL VULNERABILITY CHECKLIST

1.1 When defining/scoring the magnitude of consequences, the impact on vulnerable groups needs to be considered as part of the **assessment of magnitude of social consequences**. This checklist can be used as a means of capturing the answers to the key questions regarding social vulnerability.

1.2 The **cluster/theme** refers to the broad categories of impacts/consequences identified for the sector. For the water sector these were water availability; water quality and ecology; water company assets; and water use and recreation. It would be impractical to complete an assessment using the above table for every impact (or rationalised group of impacts). However, a Y/N check box is provided in the 'selection_of_tier_2_impacts_template' to indicate whether the assessment has identified vulnerable groups as being particularly affected by each impact/rationalised group of impacts. It is important to capture this, so that suitable risk metrics are identified.

1.3 In filling in the checklist, information can be drawn from the sector scoping reports, current research and expert opinion. In the **evidence column**, it will be important to note a) if there is evidence and b) what sort it is i.e. expert, published research, modelled etc., and the same measures that are applied to the impact evidence (e.g. pedigree) would be useful to apply here.

1.4 The **extent column** is where information on how many people might be affected could be indicated. Initially, this will help with identifying suitable risk metrics. Later on, when the selection of Tier 2 impacts is being revisited as part of the DA/Regional assessments, these data might be available from the sector-based Tier 2 assessment based on baseline socio-economic data, the use of Government projections (for the near term) and scenarios (for the longer term).

1.5 The final row will capture any **other social vulnerabilities** not explicitly included in the checklist.

1.6 The information from this assessment is designed to feed into the selection of Tier 2 impacts, but it could also be updated during other stages of the project. Further thought needs to be put into this yet.

HUC, 23/06/10

Appendix 3 Scoring and Selection of the 'Tier 2' Impacts

A3.1 Magnitude, confidence and presentation of results

Magnitude

Table A3.1 defines the magnitude classes used in the assessment. These were used for scoring impacts in the Tier 2 selection process as well as for scoring risk levels for the scorecards presented for each metric in Chapter 5. For scoring purposes 3 = High, 2 = Medium and 1 = Low. For the scorecard, the risk/opportunity level relates to the most relevant of the economic/environmental/social criteria.

Confidence

The levels of confidence used by the CCRA can be broadly summarised as follows:

Low - Expert view based on limited information, e.g. anecdotal evidence.

Medium - Estimation of potential impacts or consequences, grounded in theory, using accepted methods and with some agreement across the sector.

High - Reliable analysis and methods, with a strong theoretical basis, subject to peer review and accepted within a sector as 'fit for purpose'.

The lower, central and upper estimates provided in the scorecards relate to the range of the estimated risk or opportunity level. For risk metrics that have been quantified with UKCP09 and response functions, this range relates to the results that are given for the low emissions, 10% probability level (lower); medium emissions, 50% probability level (central); and high emissions, 90% probability level (upper). For the risk metrics that have been estimated with a more qualitative approach, these estimates cover the range of potential outcomes given the evidence provided.

Presentation

The CCRA analysis uses three discrete time periods to estimate future risks up to the year 2100: the 2020s (2010 to 2039), 2050s (2040 to 2069) and the 2080s (2070 to 2099). This is consistent with the UKCP09 projections.

Table A3.1 Guidance on classification of relative magnitude: qualitative descriptions of high, medium and low classes

Class	*Economic*	*Environmental*	*Social*
High	• Major and recurrent damage to property and infrastructure • Major consequence on regional and national economy • Major cross-sector consequences • Major disruption or loss of national or international transport links • Major loss/gain of employment opportunities *~ £100 million for a single event or per year*	• Major loss or decline in long-term quality of valued species/habitat/landscape • Major or long-term decline in status/condition of sites of international/national significance • Widespread Failure of ecosystem function or services • Widespread decline in land/water/air quality • Major cross-sector consequences *~ 5000 ha lost/gained* *~ 10000 km river water quality affected*	• Potential for many fatalities or serious harm • Loss or major disruption to utilities (water/gas/electricity) • Major consequences on vulnerable groups • Increase in national health burden • Large reduction in community services • Major damage or loss of cultural assets/high symbolic value • Major role for emergency services • Major impacts on personal security e.g. increased crime *~million affected* *~1000s harmed* *~100 fatalities*
Medium	• Widespread damage to property and infrastructure • Influence on regional economy • Consequences on operations & service provision initiating contingency plans • Minor disruption of national transport links • Moderate cross-sector consequences • Moderate loss/gain of employment opportunities *~ £10 million per event or year*	• Important/medium-term consequences on species/habitat/landscape • Medium-term or moderate loss of quality/status of sites of national importance • Regional decline in land/water/air quality • Medium-term or Regional loss/decline in ecosystem services • Moderate cross-sector consequences *~ 500 ha lost/gained* *~ 1000 km river water quality affected*	• Significant numbers affected • Minor disruption to utilities (water/gas/electricity) • Increased inequality, e.g. through rising costs of service provision • Consequence on health burden • Moderate reduction in community services • Moderate increased role for emergency services • Minor impacts on personal security *~100s thousands affected, ~100s harmed, ~10 fatalities*
Low	• Minor or very local consequences • No consequence on national or regional economy • Localised disruption of transport *~ £1 million per event or year*	• Short-term/reversible effects on species/habitat/landscape or ecosystem services • Localised decline in land/water/air quality • Short-term loss/minor decline in quality/status of designated sites *~ 50 ha of valued habitats damaged/improved* *~ 100 km river quality affected*	• Small numbers affected • Small reduction in community services • Within 'coping range' *~10s thousands affected*

Table A3.2 Scoring of impacts

Initial selection of Tier 2 impacts is shown by the blue shading. ‘Energy demands’ was subsequently removed from the list and ‘Scour at bridges’ was added.

Name of 'rationalised' consequences (incl. individual impact reference numbers from sectors summary report) *Note 5*	**Economic Score**	**Environ. Score**	**Social Score**	**Vuln. Groups Y/N**	**Likelihood Score**	**Urgency Score**	**Total Score**	**Ranking**	**Average Pedigree**
Flooding and inundation (1,2,3,4,15)	3	2	3	Y	3	3.00	89	1	3
Subsidence (22,37)	2	2	3	Y	3	2.00	52	2	2
Energy Demands (23,24,35)	2	2	3	Y	3	2.00	52	2	2
Thermal Loading on Hard Surfaces (16,26,27,32)	2	2	1	N	3	2.00	37	4	2
Heat Stress on Rail Infrastructure (19,21,27,41)	2	1	2	N	3	2.00	37	4	2
Coastal erosion (15)	1	2	1	N	3	2.00	30	6	4
Cold Weather Working/Travelling (18,23)	2	2	2	N	2	2.00	30	6	3
Heat Stress of Staff & Passengers (20,24)	2	2	2	N	3	1.00	22	8	3
Demands for transport (31)	2	2	3	Y	2	1.00	17	9	2
Insurance Cover/Premiums (52)	2	1	3	Y	2	1.00	15	10	3
Wind/storm damage (42,43,48,49)	2	2	2	N	2	1.00	15	110	2
Poor 'driving' Conditions (6,11,12,14,53)	2	1	2	N	2	1.00	12	12	1
Erosion & Landslides (7,8)	2	2	1	N	2	1.00	12	12	2
Snow/Ice Disruption (29,30,34)	2	2	1	N	2	1.00	12	12	2
Winter Maintenance (17,51)	2	2	1	N	2	1.00	12	12	3
Winter Gritting (28,39)	2	2	1	N	2	1.00	12	12	2
Heat Stress of Vehicles (21,25)	1	1	1	N	2	1.00	7	17	3
Air Density (aviation) (33,36,40)	1	1	1	N	2	1.00	7	17	1
Fair Weather Transport Options (10)	1	1	1	N	2	1.00	7	17	1
Disruption to Road Repairs (13,50)	1	1	1	N	2	1.00	7	17	1
Disruption to Construction (38,50)	1	1	1	N	2	1.00	7	17	1
Sea Level rise in ports	1	1	1	N	2	1.00	7	17	
Leaf fall (46)	2	1	2	N	1	1.00	6	23	1
Wind/storm disruption (44,45,47)	2	1	1	N	1	1.00	5	24	2
Groundwater (9)	1	1	1	N	1	1.00	4	25	2
Humidity Problems (aviation) (54)	1	1	1	N	1	1.00	4	25	1
River navigation (5)	1	1	1	N	1	1.00	4	25	
High winds at Ports increased storminess	1	1	1	N	1	1.00	4	25	

Appendix 4 Response Functions

TR2 – England

Additional information used in support of the metric TR2 is provided below, including the assumptions used.

Table A4.1 Road risk data for England

Total road length	**Km**	**Proportion (assumed) at medium-high risk**	**Proportion (assumed) at severe risk**	**Commentary on qualitative assumptions**
HA network (including motorways and trunk roads)	7,000	5%	1%	Values obtained from the Highways Agency, with reference to monthly geotechnical asset data reports.
Leicestershire values				
Local authority A roads	4,367	-		Total for Leicestershire
A roads	420	5%	1%	Assume the same proportion as for the HA
B roads	241	4%	1%	Assume similar for HA roads but reduce by 25% as less likelihood of these classifications being adjacent to problem slopes
C roads	1,306	4%	1%	
Unclassified	2,410	0.04%	0.01%	Road length of this classification currently at risk in the network
Extrapolated to England's road network				
	Total km	Medium-high risk (km)	Severe risk (km)	
Motorways – trunk	2,970	149	29.7	These values extrapolate the values provided by the HA and the local authority. The total km figures 631km to 4,997km define the lower and upper limits of the magnitude classes in the response function matrix.
Motorways – principal	41	2	0.41	
A roads	32,255	1,613	161.28	
B roads	19,853	744	99.27	
C roads	64,358	2,413	321.79	
Unclassified	181,489	75	18.83	
Total	300,966	4,997	631	
Total proportions		1.7%	0.21%	

Source: Highways Agency and Leicestershire County Council

TR2 – Scotland

Table A4.2 Road risk areas for Scotland

Road type	Km	Proportion (assumed) at priority 1, 2 or 3	Proportion (assumed) in priority 1 risk category	Commentary on qualitative assumptions
Motorways	559	11%	4.8%	Severe risk values obtained from the *Scottish Road Network Landslides Study (2005)* which specifies specific road locations and lengths. Percentage values here provided by Transport Scotland.
Trunk roads	3405[1]			
A roads	11,045			
All other roads	40,829			90% of these roads are in the north west of Scotland – not specific information has been provided.
Extrapolated road totals				
Motorways	559	61	27	
Trunk roads	3405[1]	375	162	
A roads	11,045	1,215	525	
All other roads	-	-	-	Not included
Totals		1,651	714	

Note: road lengths sourced from Scottish Executive Transport Statistics

TR5- Rail Buckling

Regional correlation figures linking incidence of rail buckle with regional average temperature are presented below.

Region	Correlation	R-square	Equation
East Midlands	0.76	0.57	y = 2.32x - 34.8
East of England	0.78	0.61	y = 4.17x - 66.2
Scotland	0.39	0.15	y = 1.35x - 15.9
London	0.76	0.58	y = 8.63x - 144.2
North East	0.67	0.45	y = 2.51x - 33.2
North West	0.82	0.68	y = 7.50x - 104.9
South East	0.66	0.43	y = 5.13x - 80.1
South West	0.82	0.68	y = 4.83x - 73.3
Wales	0.57	0.33	y = 1.89x - 26.2
West Midlands	0.73	0.53	y = 6.00x - 89.7
Yorkshire & Humber	0.62	0.38	y = 3.64x - 48.7
Great Britain (1997-2009)	0.84	0.7	y = 48.78x - 710.2