A Climate Change Report Card for Infrastructure

Working Technical Paper

Transport: Road transport (inc. cycling and walking)

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Key Messages

The weather can have a significant negative impact on the road network which can often be running close to capacity in parts of the UK

Meteorological hazards are frequently the cause of disruption and accidents, and this situation will be compounded by the effects of climate change

The 2012 Climate Change Risk Assessment identified 33 threats and opportunities to road transport due to climate change

Key impacts include increased flooding and subsidence (i.e. landslips) as well as increased thermal loadings on roads and control equipment

Increasing adaptation measures (including both engineering solutions and new smarter technologies) are likely to be needed to keep the surface transport system running efficiently regardless of changing weather conditions.

Given the complexities in considering socio-economic drivers, system interdependencies and a general paucity of detailed scientific studies, confidence in the science is rarely high.

More research is required to collect data on sensitivities to help improve the confidence in the science and to drive an adaptation agenda. Guidance is also required on how to prioritise adaptation measures to achieve the greatest resilience for the available funding.

1. Introduction

The road transport network is a key enabler of the UK economy (Eddington, 1996), and has been highlighted as the UK's most expensive asset (DfT, 2005a). The network is subdivided into 4300 miles of strategic network (managed by the Highways Agency) and 183,300 miles of local roads managed by 152 highway authorities (DfT, 2014). It is presently used by 34 million licensed vehicles - a number which has increased almost every year since 1950 (DfT, 2013). This increase has severely outstripped growth in capacity which often leads to congestion estimated to cost the UK economy £7-8 billion per year (Eddington, 1996). The weather can be a significant factor on a network which is running close to capacity and meteorological hazards are frequently the cause of disruption and accidents (Thornes, 1992; Edwards, 2002). The majority of these risks stand to increase due to the impacts of a changing climate, which will have 'profound' impacts across all infrastructure systems (IPCC, 2014). Indeed, the transport sector is seen as being particularly vulnerable to the impacts of climate change (IPCC, 2007; DEFRA, 2012), to the point where this is now viewed as a crucial overarching issue for the sector (Hall, 2010). Ultimately, achieving resilience on the transport network is crucial to allow goods and people to continue to move – essential given the 'just in time' principles now used by the logistics sector (DfT, 2014)

1.1 Climate Change Scenarios

It is now broadly accepted that the climate of the Earth is changing and this will have consequences for the UK. The exact nature and magnitude of the impact will depend on how quickly, and successfully, global greenhouse gas emissions are reduced (DEFRA, 2009). However, given the inherent uncertainties in climate change mitigation, it is often difficult to fully quantify the risks posed by a changing climate and it is for this reason that a range of possible futures need to be considered. The UK Climate Projections 2009 (UKCP09) provide the basis of a climate analysis tool which helps in understanding the future climate (Jenkins et al, 2010). A probabilistic range of outcomes are presented which take into account different emission scenarios. From these, general conclusions can be made about how the climate of the UK will change (Box 1) from which potential impacts on the road sector can be identified and explored. DfT (2014) summarise the main events that require planning for include; more rainfall over sustained periods in winter, more intense localised storms (particularly in the summer), drier and hotter summers and rising sea levels.

1.2 Key Risks & Opportunities

The overwhelming focus of the academic literature with respect to climate change and road transport is on ways in which the sector can reduce emissions to help with mitigation efforts (see Chapman, 2007 for a detailed review). However, towards the end of the last decade, a number of reviews were published that specifically focussed on the potential impacts of climate change on the sector. For example, Peterson et al (1998) was the first to summarise the key implications for transport systems. Although the review was US-centric, it signalled a solid starting point for subsequent reviews conducted by Koetse & Rietveld (2009) and Jaroszweski et al (2010).

The first significant broad review for the UK was the DEFRA commissioned Climate Change Risk Assessment (CCRA) for the Transport Sector (DEFRA, 2012) which highlighted 59 potential impacts of climate change on the sector. The CCRA acts as a benchmark for this technical paper which uses the 33 threats and opportunities contained in the CCRA of particular relevance to the road transport network (Table 1).

Box 1: Key messages highlighted in the UKCP09 Briefing Report (from Jenkins et al, 2010)

- Mean temperatures will increase across the UK, more so in summer than in winter. Changes in summer mean temperatures are greatest in parts of southern England (about 4.2ºC (2.2 to 6.8ºC)) and least in the Scottish islands (just over 2.5ºC (1.2 to 4.1ºC)).
- Mean daily maximum temperatures increase everywhere. Increases in the summer average are up to 5.4ºC (2.2 to 9.5ºC) in parts of southern England and 2.8ºC (1 to 5ºC) in parts of northern Britain. Increases in winter are 1.5ºC (0.7 to 2.7ºC) to 2.5ºC (1.3 to 4.4ºC) across the country.
- Mean daily minimum temperature increases on average in winter by about 2.1ºC (0.6 to 3.7ºC) to 3.5ºC (1.5 to 5.9ºC) depending on location. In summer it increases by 2.7ºC (1.3 to 4.5ºC) to 4.1ºC (2.0 to 7.1ºC), with the biggest increases in southern Britain and the smallest in northern Scotland.
- Central estimates of annual precipitation amounts show very little change everywhere at the 50% probability level. Changes range from –16% in some places at the 10% probability level, to +14% in some places at the 90% probability level, with no simple pattern.
- Potentially large increases in winter precipitation, with increases up to +33% (+9 to +70%), are seen along the western side of the UK. Decreases of a few percent (–11 to +7%) are seen over parts of the Scottish highlands.
- Summer precipitation in summer potentially down by about –40% (–65 to –6%), are seen in parts of the far south of England, although changes close to zero (–8 to +10%) are seen over parts of northern Scotland.
- The range of absolute sea level rise around the UK (before land movements are included) is projected to be between 12 and 76 cm for the period 1990–2095 for a medium emissions scenario. However, taking vertical land movement into account gives slightly larger sea level rise projections relative to the land in the more southern parts of the UK where land is subsiding, and somewhat lower increases in relative sea level for the north. The land movements are typically between –10 and +10 cm over a century.

Table 1: The Tier 1 list of (road transport) impacts identified in the Climate Change Risk Assessment for the Transport Sector. The Tier 2 list of key impacts are *italicised* and were subsequently investigated via a detailed risk assessment. (DEFRA, 2012)

Increased frequency of intense precipitation events	*Increased flooding of infrastructure*	Threat
Increased heavy precipitation	*Increased road submersion and underpass flooding*	Threat
Increased frequency of high precipitation events	Changes in incidence of road speeds	Threat
Increased heavy precipitation	*Increase in earthworks failures, increased landslides and undercutting and bridge scour*	Threat
Increase infrequency of intense rainfall events	Increased erosion of footpaths and cycleways	Threat
Drier summers	Greater opportunities for walking and cycling	Opportunity
Increased frequency of high precipitation events	Poor driving conditions and increased number of accidents	Threat
Rainfall	Prevention of road repairs	Threat
Sea level rise / storm surge	Flooding of coastal infrastructure. Increased rate of inundation in vulnerable areas, increased area considered vulnerable.	Threat
Increased number of hot days	*Increased thermal loading on road pavements*	Threat
Decreased number of cold days	Reduced winter maintenance costs for road and rail	Threat
Decreased number of cold days	Improved working conditions for personnel	Opportunity
Increased frequency of high or extreme temperature episodes, increased number of hot days	Increased heat exhaustion	Threat
Increased frequency of high or extreme temperature episodes, increased number of hot days	Overheating of equipment	Threat
Increased average temperature / decreased rainfall	*Increased subsidence*	Threat
Warmer winters	Less need for heating on transport in winter	Opportunity
Increased average temperature	More demand for air conditioning in vehicles	Threat
Warm summer weather	Overheating of car engines	Threat
Increase in average summer temperature	Increased road rutting	Threat
Increased frequency of high or extreme temperature episodes	Change in road speed	Threat
Reduction of snowfall and frost / ice incidence	Reduced winter protection (gritting)	Opportunity
Higher average summer temperature	Change in travel demand	Opportunity
Increased average temperature / reduction in snowfall and ice	Reduction in cold weather disruption. Improvements in road safety	Opportunity
Seasonal temperature	Impact on maintenance regimes due to degradation, soil shrinkage / subsidence	Threat
Decreased number of cold days	Reduction in winter travel problems on average could lead to inadequate preparation for extreme events	Threat
Increased frequency and intensity of storms	Increased incidence of damage (e.g. to bridges, signs, etc), blocking roads	Threat
Winds above 30 knots	Increase in problems for suspension bridges and high sided vehicles	Threat
High wind speed (above 25 knots); temperatures below 10°C	Increase in interference to asphalting and concreting as wind chill cools the surface to quickly	Threat
Seasonal Changes – longer summers / shorter winters	Changes in timing of winter maintenance regimes	Threat
Related to all climates and subsequent risks	Changes to insurance premiums	Unknown
Changes in incidence of fog	Changes in road speeds	Threat
All	Increased opportunities for design of new vehicles to cope with climate change	Opportunity

2. Weather Impacts on Road Transport

Before detailed consideration can be given to the potential impacts of climate change on UK road transport, there is a need to establish a baseline of existing weather impacts on the network. With this knowledge, it becomes possible to identify the key thresholds and trigger mechanisms which can then be used to form the physical basis of response functions in a climate change impact assessment (Jaroszweski et al, 2010). Whilst a small number of the impacts identified in Table 1 begin to manifest as a direct result of climate change, the vast majority are already impacting upon the sector, and indeed have been for decades. What follows is a discussion of these impacts by individual weather parameter.

2.1 Temperature & Humidity

It is useful to subdivide temperature as a parameter into air temperature and surface temperature. The two parameters are ultimately controlled by the local radiation budget and are therefore related, but manifest over considerably different ranges and each will therefore produce different thresholds of failure. Extremes of surface temperature largely impact hard infrastructure, where as extremes of air temperature impact the users and personnel maintaining / operating the network (DEFRA, 2012). Due to the relationship between surface and air temperatures, these extremes will occur in tandem.

During spells of prolonged high temperatures, the road network becomes prone to rutting and melting which can cause a safety issue for all modes of transport using the network. Regionally, this problem is more acute in the southeast of the UK due to the higher temperatures normally experienced in this region (Clarke et al, 2002). A more minor impact to rutting is 'bleeding' where the road begins to melt. No clear threshold exists, but roads start to become vulnerable at surface temperatures above a temperature of 50°C, which is not uncommon in the UK when air temperatures begin to exceed 25°C. On roads which use chippings as a surface dressing, these can rise to the surface and become detached resulting in reduced skid resistance increasing accident risk for users (Standley et al, 2009; London Climate Change Partnership, 2005).

High air temperatures and humidity also cause overheating and thermal comfort issues. Vehicles and ICT equipment may overheat leading to delays on the road network (e.g. McEvoy et al, 2012), where as travel conditions may become unpleasant for network users. Whilst this can be mitigated using air conditioning in cars and on public transport, it is more problematic for operatives on the network who still need to carry out maintenance tasks (DEFRA, 2012). Similarly, it has been shown that thermal discomfort caused by high temperature and humidity result in reduced walking and cycling, although lower temperatures (<5°C) have been shown to be more of a barrier (Brandenburg et al, 2007). However, a recent review of existing studies concerning the impact of weather conditions on travel behaviour was largely inconclusive which makes planning for activities under the future climate particularly difficult (Böcker et al, 2013).

With respect to low temperatures, road surface temperatures below 0°C, coupled with sufficient available moisture, will result in the formation of hoar frost and ice on roads. Inadequate maintenance will result in an insecure road network, but this longstanding issue in the UK rarely causes problem as the spatial forecasting of road surface temperatures in now a mature science (Chapman & Thornes, 2006). Ice continues to be an issue across all of the UK, but the problems are particularly more acute with increasing latitude and altitude. Conversely, snow events continue to be problematic nationwide. Indeed, a recent run of very cold winters preceded by mild winters led to many problems and resulted in a detailed governmental review. In this review, Quarmby et al (2010) praised winter resilience preparedness, and highlighted the fact that it is not justifiable to stockpile specialist apparatus to deal with such rare events. However, the disruption caused in recent winters underline the danger of further complacency in the sector (Anderson & Chapman, 2011).

2.2 Precipitation & Visibility

Precipitation poses a number of significant threats to the surface transport network, ranging from poor visibility to flooding. Indeed, a quarter of the impacts highlighted in CCRA Transport Sector Report (DEFRA, 2012) were related to precipitation. Flooding is clearly the most visible and significant impact of prolonged precipitation and is a major cause of weather related disruption on the road network (Standley et al, 2009). Indeed, Arkell & Darch, 2006 estimate that flooding costs approximately £100k per hour for each main road affected. Some areas of the network are clearly more vulnerable than others, for example roads built on floodplains (subject to fluvial flooding) and underpasses (susceptible to pluvial flooding). Significant flood events continue to cause disruption long after the floodwaters subside, as road surfaces / footpaths will need repairing after the damage caused by scouring and washout (Peterson et al, 2008). Likewise, embankments and bridges can become compromised and periodically require significant structural repairs (Lindgren et al, 2009). Landslides and debris flows can frequently lead to partial / full closures of roads and paths in problem areas (Winter et al, 2005).

Smaller precipitation events may not lead to flooding / significant surface water and the impact of these mostly relates to road safety (Keay & Simmonds, 2006) as visibility will become restricted due to both precipitation and spray from other users (Edwards, 2002). To mitigate this, drivers have a tendency to slow down and clear reductions in traffic speed and flow become evident during events (Hooper et al, 2014a). However, no threshold is apparent and it appears that the presence of precipitation is sufficient to alter driver behaviour (Hooper et al, 2014b). Likewise, the onset of precipitation was found to significantly reduce commuting and recreation cycling (Nankervis, 1999; Brandenburg et al, 2007). Finally, fog is a major cause of road accidents (Edwards, 1998) and significantly increases journey times (Tu et al, 2007).

2.3 Wind

Wind is a difficult parameter to measure and whilst average wind speeds may not be particularly damaging to users of the road network, peak gusts can be considerably problematic. Winds above 30 knots can cause problems for high sided vehicles and for suspension bridges (DfT, 2014; DEFRA, 2012). Vegetation and other debris can also be blown onto highways adding significant further hazard for all users (Clarke et al, 2002). This can be particularly problematic in Autumn when coupled with high soil moisture which lead to trees still in leaf falling and obstructing highways (DfT, 2014). For example, one local authority in the south east had to deal with 200 fallen trees in one 12 hour period during the 2013/14 winter storms (Winter, 2014). There are also maintenance issues as high winds can prevent concreting and asphalting due to the surface cooling too rapidly (DEFRA, 2012). Wind chill also has implications for walking and cycling by reducing thermal comfort (McGinn et al, 2007).

However, individual wind events are less problematic to those caused by storms where the wind is accompanied by intense precipitation where the impacts of wind are compounded by additional flooding (see previous section).

3. Climate Change Interactions

As has been highlighted in the previous section, the weather is already a significant cause of disruption on the UK highways network. In a changing climate, the nature of these risks will also change, some risks will lessen and indeed in some areas of impact, the resilience of the network will improve thanks to the new climate (e.g. reduced average winter road maintenance costs: Anderson & Chapman, 2011). These changes can be broadly subdivided into gradual changes and extreme events (Schwartz, 2011).

3.1 Gradual Changes in the Climate

3.1.1 Shifts in the mean

In many cases, gradual changes in the climate will also gradually increase the probability of a threat occurring and indeed the magnitude of the impact (Table 1). UKCP09 highlights that the UK will face a warming climate with increased mean temperatures experienced throughout all the year (Jenkins et al (2010): Box 1). Conceptually, climate change can be most easily visualised a series of changes around the mean (Figure 1). This presents a very simple means to conduct a CCRA, and highlights the increased probability of how key thresholds may be breached.

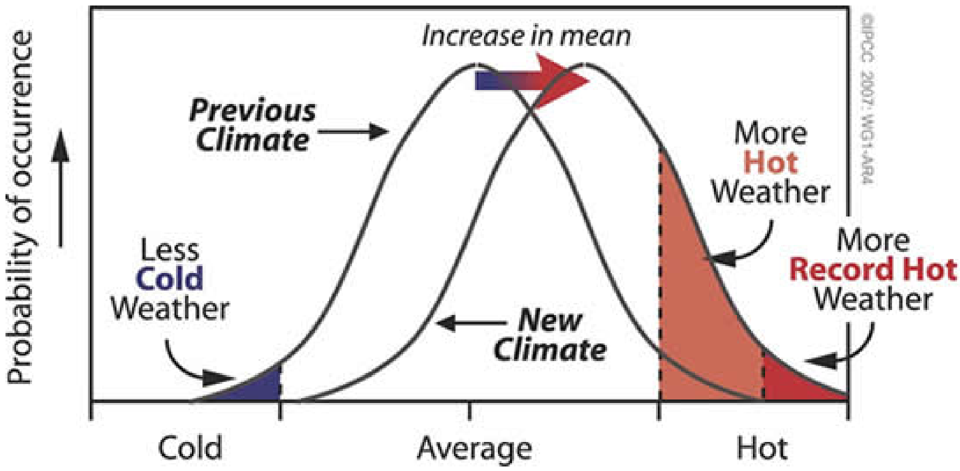

Figure 1: An example changes in mean weather caused by climate change (From Solomon, 2007)

The increase in summer temperatures will lead to summer maintenance issues for the road network with increased incidences of rutting and bleeding as critical thresholds become more frequently exceeded. As such, there will be a need to modify design codes for new road sections to cope with the new climate above the standard equivalent temperature commonly used of 20°C (see Willway et al, 2008; for more deatials), where as increased delays will become commonplace on older sections of road as repair work is conducted (Hunt et al., 2006). In contrast, the road network will become more secure in winter with snow and ice becoming less of a problem (Peterson et al, 2008). Expenditure in this sector will be significantly reduced (Clark et al, 2002; Alcamo et al, 2007) and road safety should therefore also improve during the winter months (Peterson et al, 2008; Keay & Simmonds, 2006). However, even in the most extreme climate change scenarios, there is still a significant frost and ice risk and so it is imperative that the UK does not become overly complacent (Andersson & Chapman, 2011).

As highlighted in Box 1, the UKCP09 projections for precipitation are complicated due to marked regional and seasonal differences. Although the trend is often generally summarised as drier summers and warmer winters, there is likely to be an increase in precipitation on the wettest day in both seasons (Hooper & Chapman, 2011). For regions which experience increased average precipitation, there will be a related decrease in safety due to the reduced friction of surfaces (Keay & Simmonds, 2006) and poor visibility due to spray (Edwards, 2002). Note, it is unclear how visibility more generally (i.e. mist and fog) will be affected by climate change (Koetse & Rietveld, 2009). However, the biggest threat to the road network is a higher probability of intense precipitation events leading to severe flooding, causing significant disruption (e.g. Standley et al, 2009) as well as being costly to repair (Peterson et al, 2008). Again, design codes for highways will need modification to include anti-skid surfaces and the use of porous asphalt and flood defences in flood prone areas (Hooper & Chapman, 2011).

The general trend of warmer, drier summers projected for much of the UK (Box 1) also brings other opportunities. Walking and cycling will potentially become an increasingly attractive option (Böcker et al, 2013), particularly helpful for reducing CO_2 emissions (Chapman, 2007) and improving the health of the population (Pooley et al, 2012). Opportunities for tourism are also significant and are likely to lead to increasing movements of people on hot days from cities to coastal regions. However, this may also impact upon the transport network leading to increased congestion on roads. This is already a problem in peak season (McKenzie Hedger et al, 2000), with congestion frequently noted around London during heatwave events (Standley et al, 2009).

3.1.2 Antecedence

Whereas changes to the mean broadly relate to climate response functions based on thresholds, trigger mechanisms for some impacts are often more complex, requiring an investigation into the nature of weather conditions preceding an event. For example, antecedent rainfall is particular relevant when assessing the threat from landslips and debris flows. Landslips are not easily repaired and can therefore cause significant disruption over extended periods of time (Lindgren et al, 2009). Regions which are projected to have drier summers and wetter winters will be particularly prone to increased landslide risk due to soil shrinkage and desiccation on embankments in dry summer periods which precede intense precipitation events (Manning et al, 2008). The problem can be further compounded by changes in vegetation (e.g. dieback) on embankments brought about by climate change (DfT, 2005a). Clarke et al, (2006) highlight particular threats to landslip risk in the UK, notably the motorway network as well as the impact of clay shrinkage on London's road network. Overall, the impacts are not fully clear and more research is needed to fully assess the scale of the problem and thus minimise impact (Dijkstra & Nixon, 2010), as climate change may well create new problem sections where landslips have not previously occurred.

Highway retaining walls are also a problem – many old walls on local highway networks have been constructed by “rule of thumb” and the hydrostatic pressure on them by high water levels caused by prolonged above-average rainfall can lead to failure. For example, one local authority dealt with 106 retaining wall collapses in 2012/13 compared to about 10 experienced in a year of more typical rainfall (Winter, 2014).

3.2 Extreme Events

Whilst there is ongoing debate relating episodes of extreme weather with climate change, the consensus view appears that the number of extreme events will increase in the future (DfT, 2014).

3.2.1 Storms

As the previous section has highlighted, changes in the mean will be problematic for the transport sector as key thresholds are increasingly breached. However, it is widely acknowledged that the sector is most sensitive to changes in local extremes (Wilbanks et al, 2007). Any increase in the severity or frequency of extreme events will be very problematic for the sector (West & Gawith, 2005), causing increasing debris, accidents and ultimately disruption on the road network. However, there is presently limited confidence in available projections for wind and extreme events (Sexton & Murphy, 2010) which this has so far restricted risk assessments (Hermans et al, 2006 in Koetse & Rietveld, 2009).

3.2.2 Sea Level Change

Areas of the road network in low lying coastal areas will be at risk of increasing inundation as a result of climate change (Walsh et al, 2007). Current projections (Box 1) highlight that while increases of this magnitude will cause localised problems, the main issue is how this exacerbates the impact of storm surges (e.g. Woth et al, 2006). These cause extensive tidal flooding, both on the coastline and upstream in estuaries rivers as the river discharge cannot exit into the sea as normal. At the moment, IPCC modelling suggests an increased frequency and intensity of storm surges under some scenarios (Alcamo et al, 2007). However, specific studies remain limited (Koetse & Rietveld, 2009).

3.3 Interactions and Interdependencies

The UK Climate Change Risk Assessment analysed cross sector interactions via a systematic mapping methodology. The assessment considered 10 different sectors independently, but it emerged that all had overlaps with the transport sector (DEFRA, 2012). Box 2 outlines the interactions that are specifically mentioned in the report.

Box 2: Interactions with the transport sector highlighted in UK Climate Change Risk Assessment (DEFRA, 2012)

- Increased risk of flooding of road and rail infrastructure (considered in the Flooding sector report)
- Increased risk of coastal erosion on coastal infrastructure including roads and railways (considered in the Flooding sector report)
- Overheating of buildings, airports, stations etc (considered in the Built Environment sector report)
- Increased subsidence (considered in the Built Environment sector report)
- Changes in fire risk, that could affect road travel (considered in the Forestry sector report)
- A decrease in output for UK businesses due to an increase in supply chain disruption and consequent loss of output as a result of extreme events. (Considered in the Business sector report).
- 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.

Such cross-sectoral interactions add significant complexity to a risk assessment, but where these interactions lead to interdependencies they can be a cause of significant increased risk across several sectors. The road transport network ultimately forms part of a broader integrated transport network which in turn is interdependent on linkages with other infrastructure networks. Indeed, by visualising the UK infrastructure network as an interconnected collection of assets (DEFRA, 2012), the importance of considering these independencies via a cross-sector approach becomes evident (Kollamthodi et al, 2011). For example, the ongoing electrification of the transport network leads to an increasingly significant dependency on the energy network to ensure mobility. Hence, it will be of paramount importance to ensure that UK electricity supplies are as climate resilient as possible to ensure the continued functioning of transport networks (Chapman et al, 2013). A failure on the electricity network could have major consequences (RAE, 2012) quickly cascading onto the transport network, preventing the charging of electric vehicles as well as causing disruption via a failure in ICT traffic management systems (e.g. McEvoy et al, 2013). Likewise, significant disruption on the surface transport network will impact other sectors due to interactions such as those identified in Box 2. For example, key personnel would not be able to get to work impacting the health sector (DEFRA, 2012) or other infrastructure sectors when major repairs are needed (i.e. after an extreme event).

4. Assessment and management of climate change risks

4.1 Costs and/or relative magnitudes of impacts

Climate change risk assessments are needed to quantify the exact nature and cost of impacts in the transport sector (Jaroszweski et al, 2010). From detailed and extended assessments, the increased costs of maintaining and repairing road transport networks can be estimated (IPCC, 2014) and the exact role of adaption can be justified and quantified. The aim is to develop a consequence response function which links the climate driver to the potential outcome or consequence. Though such ideas are increasingly proposed, such detailed studies are very rare and the UK Climate Change Risk Assessment for the transport sector (DEFRA, 2012) was unusual in the sense that it attempted to cost future impacts based on the response function. This approach requires a broad leap of faith, but can yield meaningful results where recent case studies are available. However, given a frequent lack of quantitative data for assessment, there is often limited confidence in the exact magnitude of the impact and as such, these are frequently derived qualitatively from expert opinion (e.g. IPCC, 2010; DEFRA, 2012) Given the increasing incidence of flooding in the UK in recent years, flooding is one impact where there is high confidence in this approach. Indeed, of all the climate risks identified to the surface transport network in the UK CCRA, flooding was identified as the key risk incurring the most significant costs (DEFRA, 2012). Penning Rowsell et al (2002) estimated that flooding in Autumn 2002 cost the road sector in the region of £73m. Similarly, total costs for the summer 2007 floods, to include disruption, was estimated at £100m (Environment Agency, 2010). These figures were then used to identify the likely costs associated with estimated changes in flood frequency.

4.2 Adaptation Opportunities

The importance of risk assessments was highlighted in the recent Transport Resilience Review which recommended that "*operators of strategic transport infrastructure should revisit their climate change risk assessments and adaptation plans in light of recent experiences*" (DfT, 2014). Indeed, increasing adaptation measures are likely to be needed in order to keep the surface transport system running efficiently regardless of changing weather conditions. A challenge exists in how to adapt (or design new) infrastructure to be resilient to future climates (Chapman & Ryley, 2012). Although there is a focus in the scientific literature to document impacts without highlighting the required adaptation measures (Arnell, 2010), a review by Eiesenack et al (2011) actually identified a total of 245 different adaptations mentioned in the scientific and grey literature. However, many of these are non-specific and not all are related to surface transport networks. For the purpose of this report, a broad compendium of common measures can be elucidated from key publications in the grey literature. These are summarised in Table 2, and can be further subdivided into two categories; low cost measures and major schemes.

Table 2: Suggested adaptation measures highlighted in the literature (adapted from Schwartz, 2011 and Eichhorst, 2009)

Heat Waves	Use of heat resistant surfacing materials Replacement of bridge expansion joints More night-time construction to avoid undue heat stress for construction workers* Use of tinted windows and air conditioning on public transport* Provide shade for roads, footpaths and cycle-ways* Improved hard infrastructure for walking and cycling
Increased Precipitation	Periodically revise flood risk maps Improve flood defences Modify design codes for both road surfaces and nearby hydraulic structures Protect existing vulnerable structures (e.g. Bridge Piers) Strengthen embankments and cuttings Better drain and culvert maintenance* Improved pumping facilities at underpasses Control flash flooding with storm retention basins Better landuse planning on floodplains* Provide good evacuation routes
Extreme Events	Assess if current design codes are sufficient to more frequent and intense storms Build more robust and resilient structures
Sea Level Rise	Elevate the road network Abandon or move coastal roads (managed retreat) Change planning policy with respect to building in coastal locations Install sea defences / storm surge barriers Use of corrosion resistant materials Provide good evacuation routes

* indicates a low cost measure

As Table 2 demonstrates, many adaptation measures are essentially 'engineering solutions', many of which are *overengineering* for the present climate, yet providing sufficient adaptive capacity for the future climate. The inclusion of adaptive capacity in the network by providing redundancy essentially improves the resilience (Eichhorst, 2009). However, given the present adaptation deficit, overengineering is also likely to need to be accompanied with blue skies thinking to yield smarter and often more elegant solutions. A good example of this is dual-use infrastructure such as the SMART road tunnel in Kuala Lumpar which becomes a stormwater channel when required (RAE, 2011). Alternatively, improved monitoring via sensor networks can highlight areas of risk before problems manifest (Radow & Neudorff, 2011). This approach is becoming increasingly viable given the recent growth in smart infrastructure enabled by the recent proliferation of ubiquitous and pervasive sensing techniques embedded with an Internet of Things approach (e.g. Chapman et al, 2014). ICT will continue to play a big role in improved communication with users via websites and variable message signs to minimise disruption and impacts (DfT, 2014).

DEFRA co-ordinates the cross-government *Adapting to Climate Change Program* which will steer adaptation in the UK transport sector with the aim of taking early action to maximise the economic benefits (Kollamthodi et al, 2011), promoting flexibility in infrastructure designs to cope with climate change uncertainty yet minimising adaptation costs (Krebs et al, 2010).

However, as is common with many adaptation measures, they only provide a local solution to what is ultimately a larger problem (Ryley & Chapman, 2012). The difficulty lies in assessing the relative national importance of a piece of local infrastructure - local authorities are expected to identify a resilient network for priority treatment (DfT, 2014). To this end, the UK Department of Transport produces specific guidance on Local Transport Plans with respect to improving the climate resilience of local transportation (Kollamthodi et al, 2011), however this is still very limited and there is still a need to produce more guidance in the general area of improving climate resilience. There is tremendous scope to learn from others and share best practice in this area (DfT, 2014).

5 Broader Discussion

5.1 Confidence in the Science

Guidance is available from the Intergovernmental Panel on Climate Change (IPCC) with respect to the consistent treatment of uncertainties in climate science (as used in the 5th Assessment Report: http://www.ipcc.ch/). By adopting this guidance, it becomes possible to provide a common approach and "calibrated language" to communicate findings (IPCC, 2010). Ideally, uncertainty should be expressed probabilistically, where as confidence is expressed qualitatively using a combination of theory, data and expert judgement (Figure 2)

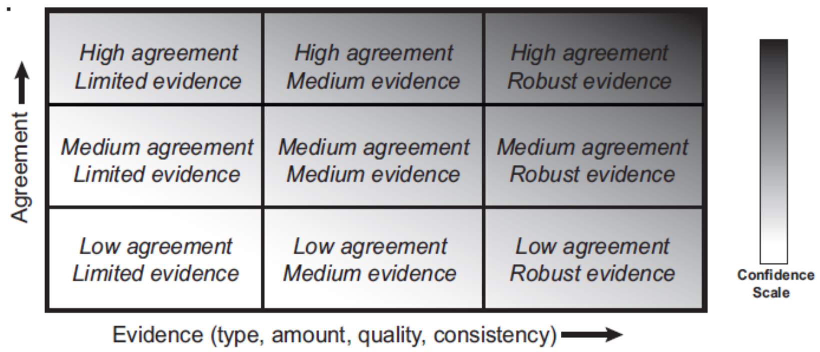

Figure 2 A depiction of evidence and agreement statements and their relationship to confidence (From IPCC, 2010)

Although predating the 5th Assessment report, the previous UK CCRA for the transport sector (DEFRA, 2012) broadly used these guidelines in an attempt to assess confidence in the evidence base. This was attempted for all Tier 1 impacts (Table 1), scoring each of the threats and opportunities as 1 (low), 2 (medium) or 3 (high) depending on confidence in the science, environmental impact (i.e. risk) and urgency to take action. However, achieving confidence in an evidence base is not straightforward and is generally dependent on gauging expert opinion (Box 3).

Box 3: Definition of confidence levels used in the UK CCRA for the transport sector (DEFRA, 2012)

- Low: Expert view based on limited information such as 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'.

However, this process underlined a lack of confidence in the exact magnitude of future impacts. For example, high confidence was expressed in the locations of fluvial flooding on the network, disruption due to other types of flooding could only be projected with low confidence (DEFRA, 2012). The majority of Tier 2 impacts (Table 1) were classified as medium confidence (e.g. landslides, heat impacts and bridge scour). Given the complexities involved in projecting climate impacts, and indeed other drivers of change, it is unrealistic to predict the exact magnitude of future threats and impacts with anything greater than medium confidence (Table 3).

Table 3 Agreement and confidence of Tier 2 impacts

Increased frequency of intense precipitation events	*Increased flooding of infrastructure*	High Agreement, Medium Confidence
Increased heavy precipitation	*Increase in earthworks failures, increased landslides and undercutting and bridge scour*	Medium Agreement, Medium Confidence
Increased number of hot days	*Increased thermal loading on road pavements*	Medium Agreement, Medium Confidence
Increased average temperature / decreased rainfall	*Increased subsidence*	Medium Agreement, Medium Confidence

5.2 Other Drivers

Climate change risk assessments need to be a multidisciplinary exercise embracing other drivers such as a socio-economic change (Jaroszweski et al, 2013). This can be achieved as a final step in the assessment which enables the response functions to be modified via scenarios (or storylines) as to how the sector might develop over time (Tol, 1998). For example, socio-economic scenarios can be included in the assessment (e.g. UKCIP02 – Figure 3) to provide a starting point for expert discussion of a range of possible outcomes. A range of techniques can then be employed to either forecast or backcast to these storylines (DfT, 2005b; Goulden & Dingwall, 2012). However, this step is frequently missing (Berkhout et al, 2002) which can further undermine confidence in the assessment. An example of how this can be applied to the transport sector is provide by Jaroszweski et al (2010) who highlighted the need to include exposure (i.e. how the network is used) as well as sensitivity (i.e. the relationship between the weather and users).

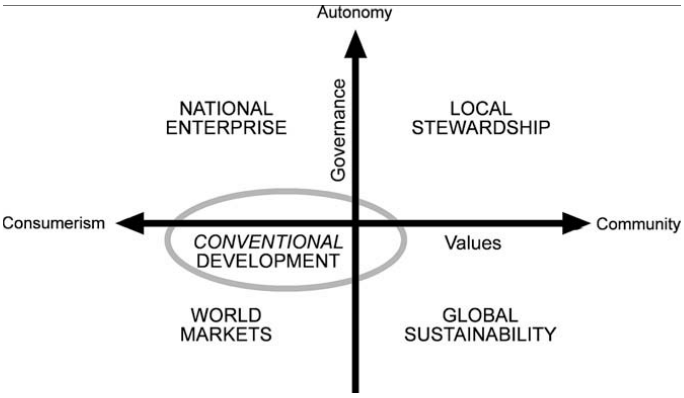

Figure 3: Example socio-economic scenarios (from UKCIP, 2000)

The challenging nature of applying socio-economic scenarios in the sector was also identified in the UK CCRA for transport report (DEFRA, 2012). Accounting for quantified uncertainty by taking into account population change and the subsequent impact on demand framed by policy and governance (Jaroszweski et al, 2010) was ruled out and instead, commentaries were provided for each of the identified risks or opportunities (DEFRA, 2012). Consideration was also given to social vulnerability. Different social groups will experience different impacts of transport disruption, with the most vulnerable struggling to adapt to significant changes (Lucas & Pangbourne, 2012). This was dealt with in the UK CCRA by using a social equity checklist linked to place (i.e. areas with limited transport options such as Scottish Islands), social deprivation and social disempowerment (DEFRA, 2012). Again this is a complex issue to take into account in a risk assessment due to the role of governance in sustainable development strategies (Mitchell, 2005) with equity across individuals being a key pillar of sustainability (Greene & Wegener, 1997). An example of good practice is to create high quality sustainable communities in urban areas (Banister, 2000), avoiding floodplains, reducing dependence on transport infrastructure and increasing opportunities for walking and cycling (DfT, 2005a). All of which feature heavily in the adaptation measures outlined in Table 2.

Technological change also provides a significant challenge to risk assessments in the sector. The surface transport sector is presently in a state of flux as the fuel base diversifies away from oil towards hydrogen and electricity (see Chapman, 2007) and therefore increasing interdependency issues with the energy and ICT sectors (Chapman et al, 2013). This provides an excellent example of how technologies can result in new vulnerabilities (DEFRA, 2012). Conversely, disruptive technologies may also improve climate resilience. Future surface transport networks will undoubtedly look very different from today, with automonous connected vehicles increasing road capacity and therefore reducing disruption. Vehicles may develop to become less climate sensitive (e.g. amphibious vehicles to cope with frequent flooding). Likewise, new technologies will improve the climate resilience of hard infrastructure such as road surfaces (e.g. Werkmeister et al, 2003).

Overall, improved methodologies which take into account these other drivers is an important area of future research to move risk assessment on from what is frequently a qualitative approach. As a result the expression of risk in terms of monetary values is extremely limited, although the cost rankings used in the UK CCRA is of value, but ultimately is always expressed with low confidence (DEFRA, 2012). It is accepted that quantifying the exact economic cost of an impact, taking into account maintenance, congestion, delays and safety is an area which needs significant further attention. Indeed, strengthening the economic case for investing in transport resilience was highlighted in the recent transport resilience review (DfT, 2014).

5.3 Other research gaps and priorities

Many key gaps have already been highlighted in this report. In particular, the complexities of dealing with interdependent networks of infrastructure as well as the inclusion of other social drivers. However, the main limitations actually reside in our fundamental knowledge of thresholds, trigger mechanisms and sensitivities of the road network to weather and climate needed to produce the response functions in a risk assessment. Where thresholds exist, these have been given in this technical report, but it is clear that many still need further research. In particular, precipitation (e.g. Hooper et al, 2014b), and urban pluvial flooding (DEFRA, 2012) are key areas which need attention. Furthermore, a lack of sufficient asset data for the transport sector has been highlighted in a number of studies (e.g. Bouch et al, 2012) and was identified as a key issue reducing confidence in the UK CCRA (DEFRA, 2012), ultimately restricting our knowledge of weather sensitivities.

With respect to climate sensitivities, the scientific basis for identifying the impact of climate change on the surface transport network ultimately rests in the quality of the climate change projections. Whilst the UK is fortunate to have some of the best available downscaled projections in the world, there are still a number of ongoing improvements which will help to improve confidence in assessments in this sector. Firstly, wind was not accounted for in the UKCP09 climate projections which restricted previous risk assessments for wind and extreme events. However, probabilistic wind projections are now available (Sexton & Murphy, 2010) which should improve the development of response functions in this area. A further issue has been with the spatial coherence of projections (Bouch et al, 2012). This is an area of ongoing improvement, but as an interim measure eleven spatially coherent snapshots are now available to permit a UK wide climate risk assessment (Sexton et al, 2010). Finally, as highlighted by DEFRA (2012), many climate impacts are caused by short-lived climatic extremes. These extremes are presently not handled particularly well in the UKCP09 projections. Specific urban impacts on the transport network are also difficult to model due urban areas not being specifically included in the projections (Chapman et al, 2013).

5. Conclusions

Regardless of the success of future mitigation efforts, society is now committed to having to adapt to some degree of climate change. Surface networks are the most vulnerable in the transport sector (Chapman & Ryley, 2012) and as this report has highlighted, the impacts on road transport are potentially numerous. Extreme events expose present day resilience and provide a useful insight into the nature and magnitude of future climate impacts. Recent experiences in the UK have shown that widespread severe weather can quickly lead to multi-mode failure on transportation networks which has the potential to cascade across the entire UK infrastructure. In a changing climate, these vulnerabilities will increasingly become exposed, highlighting far-reaching interactions and interdependencies, meaning it is no longer appropriate to consider resilience purely on a sector by sector basis (RAE, 2011). It is therefore important to ensure that the future road network is designed and built with sufficient adaptive capacity to improve resilience across not only the broader transport sector, but UK infrastructure as a whole. Furthermore, this response needs to be managed so that it is coherently, and fairly, applied across the country (Hooper & Chapman, 2012) ensuring that the road network, and subsequently the UK economy, functions effectively regardless of future weather conditions.

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