A Climate Change Report Card for Infrastructure

Working Technical Paper

Transport : Rail

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Highlights and key messages

Rail studies into climate change impacts identify significant changes to infrastructure operations on the UK rail transport system, owing to a projected warmer climate generally and wetter winter weather.

Concerning a warmer future climate, there is likely to be:

- A marked difference in climate, north/ south across the country;
- An increase in track buckling owing to hot weather, more so in the south and east;
- An increase in the number of days where track maintenance cannot be carried out;
- An increase in overhead power cables sagging in hot weather; and an attendant increase in 'dewirement' risk;
- An increased exposure of staff to heat stress;
- Fewer cold – snow and ice – days; and
- Issues with air quality in urban areas through the urban heat island effect.

Concerning wetter winter weather, there is forecast to be:

- A higher incidence of river flooding, increasing the possibility track inundation and of scour affecting river bridges' stability; and
- An increased incidence of landslips occasioned by prolonged or intense rainfall.

Comprehensive baselining of current climate conditions against asset behaviour generally, has not been undertaken.

Confidence in the climate change science is seldom high.

Gaps and uncertainties are apparent in the science as regards the granularity of spatial detail and the prediction of extremes – future conditions are stated mostly as averages in the UKCP09 projections. There are significant uncertainties in the predictions for wind, humidity and lightning.

Hard adaptation measures and plans per-se are not strongly evident across all aspects of the railway system, however there is evidence that Network Rail is preparing site-specific resilience measures for each of its eight routes.

Priorities should be to:

- Improve the confidence and availability of climate projections to suit the analysis needs of the infrastructure systems affected;
- Investigate whether new infrastructure-related metrics are required to facilitate better operational management and research;
- Establish baseline, and future, impacts, operating costs and economics of adaptation, across a wide set of asset types;
- Integrate research and analysis work, under a 'systems thinking' evidence-based framework;

- Improve and embed the knowledge and understanding of climate change impacts at local/ asset and strategic/ route levels.

This would ideally involve other parts of the infrastructure sector owing to the way that infrastructure systems are interdependent.

1. Introduction

UK railway infrastructure and its operation

This report discusses the 'main line' railways in the UK, which include Network Rail's system on the British mainland; Northern Ireland's 'Translink' network; and London Overground. Other railway infrastructure in the UK include urban tramways and underground networks such as those in Manchester, Leeds, Nottingham, Glasgow and London.

The term 'infrastructure' encompasses railway tracks, track supporting structures (bridges and culverts, embankments), earthwork cuttings, trackside structures and equipment including those for signals and overhead power lines, and drainage.. Network Rail, by far the largest railway infrastructure owner in the UK, has assets comprising some 38,000 bridges and tunnels, around 2,500 stations and over 20,000 miles of track. Parts of the Network Rail system date back to the 1820s[1].

The main line network is a 'system of systems' where a variety of sub-systems operate or are operated to permit the whole to perform its task of transporting people or freight. Between 2009 and 2013, passenger traffic on Network Rail infrastructure increased from 50.4 to 59.2 passenger-KM per year while freight train mileage has fallen from c. 43,000KM to c. 40,000KM[2]. Each railway sub-system can be thought of as a collection of assets and components some of which have particular behavioural characteristics when impacted by weather. These sub-systems can exhibit dependence upon each other, and on externalities such as power supply and ICT[3]. Existing sub-systems are known to be vulnerable to extreme weather, particularly the landslip vulnerability of earthworks, and earthworks are receiving attention through a 20% increase in investment levels in earthworks and drainage resilience measures during the current five-year regulatory control period (CP5), which started in April 2014[4].

Train service reliability is dependent, inter alia, upon the resilience of the infrastructure to external impacts such as extreme weather. Safety controls can require operations to be restricted when weather-related hazards are forecast[5], normally this is by reducing train speeds or by suspending services, and occasionally line closures can be imposed. Climate change is likely to mean more frequent occurrences of weather-related hazards and a reduction in rail service reliability, all else being equal, as safety measures are invoked more often.

Overview in the context of UKCP09 scenarios

UKCP09[6]medium emissions scenarios for the 2040s were used for the RSSB railway climate change analyses in the T925 Tomorrow's Railway and Climate Change Adaptation (TRaCCA) project[7]. The UKCP09 projections of increased temperatures, increased rainfall in winter and reduced rainfall in summer, increased storminess, sea level rise, and wind have all been examined for their potential impacts on railway infrastructure. However this has been with varying degrees of success owing in part to the uncertainties evident in the science and, as mentioned in the first T925 TRaCCA report, the paucity of relevant infrastructure data available[8]; whilst heat impacts and increased precipitation have been examined in some detail in T925 TRaCCA, the outputs have necessarily been at regional and national level.

Rail-related research and reporting

Rail-related fact-finding and research was first undertaken by RSSB in 2003 to identify vulnerabilities to current and future weather patterns[9]. A report into specific sea-level rise impacts on coastal railways followed in 2008[10] and since 2009 the main line network has been subject to studies on the potential impacts on safety and performance of climate change, with assistance from the UK Met Office and with reference to nine Regional Climate Models. These are the RSSB and Network Rail co-funded 'T925 TRaCCA' project, and a subsequent set of work (known as T1009 TRaCCA), which proposes staged outputs until 2016[11]. T1009 TRaCCA features in the Government's National Adaptation Programme[12].

Other individual studies or reports on self-contained railway systems or sub-systems have been undertaken; TfL's and Network Rail's 'Adaptation Reports' for Government[13], Dawson's PhD thesis of the impact of sea level rise on the London – Penzance Railway,[14] and Dobney's PhD thesis on track management regimes[15] are examples of studies mentioned later in this report.

Published research projects and reports have been found to focus on impacts affecting mainly track and earthwork assets; they however do not provide the means to identify vulnerabilities at a local level nor is there evidence of region-wide, strategic, or systemic analyses.

2. Vulnerability

T925 TRaCCA listed priority topics for the main-line network for current weather and clustered these for further investigation with respect to climate changes (Table 1).

Climate Impact Group	Cluster	Consequence
Heat	Track	Management of track buckle risk
Heat	Track	Reduced window of opportunity to carry out maintenance/ renewals work due to heat
Heat	People	Passenger health and impact on freight from train failure in extreme temperatures, including heat and cold
Heat	People	Staff working conditions, eg: use of heat watchmen
Heat	Power/ Telecoms/ Signalling	Floating electrical earth leading to stray earth currents caused by dry ground/ low groundwater; heat (solar gain) affecting lineside equipment; sag in tethered overhead line systems at terminal stations
Rainfall	Fluvial flood	Track and lineside equipment Failure
Rainfall	Groundwater flood	Track and lineside equipment Failure
Rainfall	Pluvial flood	Track and lineside equipment Failure
Rainfall	Fluvial flood	Scour and water effects at bridges
Rainfall	Fluvial flood	Scour at embankments due to high river levels and culvert washout
Rainfall	Fluvial flood	Safety of workforce carrying out inspections during an extreme flood event
Rainfall	Pluvial flood	Landslips
Rainfall	Fluvial flood	Accessibility of fleet and of maintenance depots
Insolation/ heat/ rainfall/ wind	Vegetation	Change in type, falling trees causing obstructions, poor adhesion, and track-circuit non-activation

Sea level rise and storms	Coastal and estuarine defences	Wave overtopping and flooding at defended coastal and estuarine railways

Table 1: T925 TRaCCA Prioritised Areas for Investigation

These priority areas were taken forward for further analyses, which was successful to a degree only for the consequences 'management of track buckle risk', 'reduced window of opportunity to carry out maintenance/ renewals work due to heat', 'staff working conditions', 'sag in tethered overhead line systems', 'scour and water effects at bridges', and 'landslips'. These are discussed in section 3.

TfL in its adaptation report for Government has identified 'weather risks' for its underground and surface networks as outlined in Tables 2 and 3, again based upon current weather knowledge:

1- Extreme Hot Weather - Key track, signals, & communications assets and staff & passengers.

2- Rain & Flooding - Track & signal drainage

3- Cold & Freeze - Impact on track integrity

4- Rain & Flooding – Key infrastructure drainage

5- Drought - Vegetation impact

6- Snow – track, signalling and depot operations

7- Cold & Freeze - Train system components

8- Cold & Freeze – Slips/trips for staff and customers.

9- Rain, Flooding and snow - Damage to inside of carriages

10- Wind- Damage to infrastructure, track and vegetation.

11- Drought - Ground stability impacts

Table 2: London Underground Weather Risks

1 Heat – key signal, power, communications assets

2 Snow and Ice – slips/trips for staff and customers

3 Snow - Depot operations

4 Snow – Track and street clearances

5 Wind – Damage to overhead lines

6 Flooding – Depots and Tracks

7 Rain – Track drainage

Table 3: London Rail Weather Risks

There is considerable overlap between the 'priorities' found by RSSB and the risks noted by TfL; all represent vulnerabilities to weather in the current operation of the main-line and TfL networks.

Whilst no evidence has been found to suggest that tools are available to determine climate-change vulnerabilities on a location basis, Network Rail has tools and processes to manage current risks. Network Rail's 'Washout and Earthflow Risk Mitigation' (WERM) tool[16] uses LiDAR technology to identify earthworks likely to experience water-induced problems; Drainage condition surveys are mandated by Network Rail's Railway Drainage System Manual[17] and earthworks' surveys are captured in the 'RT065' management tool[18]. These surveys help to identify poor condition and vulnerable assets. Similarly, railway standards require registers of bridges and earthworks likely to suffer from scour[19], and track condition is monitored to identify sections of track at risk from heat-induced track buckles[20]. These tools and standards for useful starting points for further analyses, however none are strategic or systemic in nature.

3. Potential impacts of climate change

Climate-related impacts on railway sub-systems

T925 TRaCCA assessed the potential impacts of increased temperature, increased precipitation, changes in wind and sea level rise but was unable to determine in detail local, system or strategic impacts across the network. Some of the scientific challenges experienced were related to the uncertainties in predictions of wind and the lack of projected data on extremes. Asset information was scarce for other than track buckle risks and challenges highlighted by T925 TRaCCA included the lack of data at a component and location-specific level to permit comprehensive analyses.

Among the key findings from T925 TRaCCA, however, were lists of potential impacts for the 2040s. This was against a modelled baseline period, of 1971 to 2000. The Met Office provided details as follows, from an assessment methodology developed by the Met Office Hadley Centre in collaboration with experts from the GB railway industry:

Heat-induced track buckling: An increased incidence of temporary speed restrictions (TSRs) is likely, owing to risk mitigation measures for track buckling, and consequent degraded performance owing to these measures. For example, across South West England, for the track condition *'Tamped/lined with slues/lifts > 25mm'*, the average modelled number of days with 30/60mph TSRs is roundly 0.5 per summer season in the baseline period. By the 2040s, this is projected to increase by a factor of around four on average, though this factor could range from around two-and-a-half to around seven. In general, the number of heat monitoring days and the frequency of speed restrictions are projected to remain most frequent across the South and East of Great Britain, but the largest percentage changes are projected to be in the North and West of Great Britain, with a marked difference in climate north/ south across the country.

Heat impact on track maintenance: An increase in the number of days is forecast, where track maintenance cannot be carried out; a precautionary measure to reduce the likelihood of track buckles owing to sustained high temperatures. For example, across Scotland, the average modelled number of non-track-work-days in the baseline period is roundly 9 days per summer season. By the 2040s, this is projected to increase by a factor of around two-and-a-half on average, though this factor could range from around one-and-a-half to around three-and-a-half. In the future, the occurrence of these events is projected to remain most frequent across south-eastern areas of Great Britain. The largest percentage changes, however, are generally projected to be in north-western parts of Great Britain.

River flooding affecting bridges: More precipitation causing river flooding can increase the likelihood of scour affecting vulnerable river bridges. Detailed river flow analysis has not been conducted; rather future flood risk has been inferred from analysis of multi-day rainfall totals that have caused flooding in the past. Case study analysis suggests an increase in these extreme rainfall totals through to the 2040s with model mean changes of 10% to 40% across the different basins. However a larger range of changes is seen across different model versions, including reductions as well as much larger increases. The results point towards an increased risk of river flooding; however the magnitude of change remains uncertain.

Extreme precipitation causing landslips: The future risk of landslips caused by large monthly rainfall totals has been investigated and there is mixed evidence for whether critical events could become more or less frequent. Further data, analysis and science are required to ensure landslip risk is sufficiently well represented. Total daily rainfall extremes have been analysed to understand future localised surface water flood risk. Across Great Britain, very wet day frequencies are projected to increase on average by between 0% and 30% by the 2040s, although a larger range of changes, both positive and negative is seen across the different model versions. Consequently, the results point towards an increased risk of surface flooding (although a reduction cannot be ruled out), although the magnitude of change remains uncertain. Further analysis would be required to quantify the impacts and future vulnerability of heavy rainfall events on Network Rail infrastructure.

Heat-related sagging of overhead power lines: The sag of overhead line equipment (OLE) has been investigated via a temperature threshold exceedance analysis. For the lowest threshold (33°C), there is a small projected increase in the modelled average occurrence of sag by the 2040s with respect to the baseline period. For example, across central England, the average modelled number of days with temperatures exceeding 33°C is 1.4 (per 30 summers) in the baseline period, and by the 2040s this is projected to increase by a factor of around four on average, though this factor could range from around one-and-a-half to around seven. However, there are some parts of Great Britain where the two higher thresholds (35°C and 38°C) are exceeded neither during the modelled baseline period nor during the 2040s. Where exceedance does occur, its rarity during the baseline period means that even large projected relative changes are consistent with continuing rare exceedance in the future.

Increased exposure of staff to heat stress: Heat stress was assessed using the existing Met Office Heat-Health Watch threshold temperatures therefore taking no account of the potential for a population to acclimatise to higher temperatures over time. During the modelled baseline period there are relatively few heat stress episodes, but by the 2040s, more episodes are projected, especially in the south. For example, across Wales, the average modelled number of heat stress episodes in the baseline period is 5 (per 30 summers). By the 2040s, this is projected to increase by a factor of around five-and-a-half on average, though this factor could range from around two to around eleven. Percentage changes in numbers of heat stress episodes are projected to be greatest in the North and West of Great Britain.

Reduced incidence of cold conditions: The occurrence of cold conditions is problematic for the performance of the rail network, and is projected to decrease – but not to cease altogether – by the 2040s. For example, across North West England, the average modelled November-March ("winter") occurrence of days with minimum temperatures below 0°C during the baseline period is roundly 48 per winter season. By the 2040s, this is projected to decrease by around 45% on average, though this could range from around a 35% decrease to around a 50% decrease.

TfL's Adaptation Report provides 'Business Climate Change Risk Maps' and has summarised the changes in weather leading to impacts for the 2050s:

Flooding: TfL states that flooding has a very low likelihood due to the level of flood protection that London receives from the Environment Agency flood protection systems and the range of mitigation actions that have already been put in place.

Pluvial flooding can impact on TfL's rail, tram and Tube tracks, stations and signals. In both cases, TfL's records shows that consequences are medium impact although short term.

Extreme high temperatures: TfL's analysis has shown that currently the main source of heat in the underground system is from the trains themselves.

Other (medium to low) risks from high temperatures include the potential communications and substation equipment being affected, points equipment drying out, shrinkage and ageing of wiring, increased risk of fires damaging cable runs, overheating signalling equipment rooms and heat haze distortion for drivers viewing signals.

Low temperatures and temperature fluctuations: Extreme levels of snow can impact on system delivery of transport from hazards at TfL depots where approach roads, tracks and equipment can become iced up. Extremely heavy snow loading on depot roofs may cause problems. There can also be impacts on station assets, such as approaches, signs, lifts, public address systems, stairs and platforms.

Snow and ice can be a risk to passengers and staff such as slips, trips and falls, staff unable to get to work, staff fatigue. There can be associated issues with availability of grit supplies which can be more of a regional or national issue.

Other initiatives by TfL include studies currently in progress into heat and passenger discomfort[21].

These potential impacts from climate change are similar or the same as impacts experienced recently during extreme weather events or prolonged or combined weather conditions which, while not 'extreme' per se can have deleterious safety and performance impacts across the railway system.

A conclusion is that with current rules, the provision of safe railway operation in a changing climate is highly likely to result in degraded railway system performance, all else being equal.

4. Assessment and management of climate change risks

Network Rail

Network Rail is developing Route-based weather resilience and climate change adaptation plans, as noted in the Office of Rail Regulation's (ORR) Control Period 5 (CP5) Final Determination[22]. Network Rail will submit eight Route plans by the end of September 2014. In the Western Route, investment at the following locations is planned [23]:

- Dawlish Sea Wall – affected by coastal storms and sea level rise;
- Chipping Sodbury Tunnel – frequently affected by groundwater floods
- Exeter – Cowley Bridge Junction – affected by river flooding;
- Hinksey, south of Oxford – affected by river flooding.

Items are noted in the Network Rail draft Delivery Plan[24] for CP5 that afford better 'weather resilience'; for example in CP5 drainage assets feature in a degree of detail previously unseen in regulatory documents, and expenditure on earthworks will increase by 20% when compared with CP4 plans.

Network Rail has set up a national Weather Resilience and Climate Change Steering Group[25] which effectively is building 'adaptive capacity'. This group, supported at Board level, sponsors and directs activity to increase infrastructure resilience both to current weather and the future climate. Because of the wide-ranging nature of its work and the amount of current work this report necessarily summarises at high level Network Rail's activity; the following provides some examples of intended practice:

- Allocating funds to protecting tracks and bridges against floods and heat waves;
- Delivering analyses of impacts from projected climate change, both internally and externally;
- Increasing adaptive capacity to provide a strong and informed base for effective climate change adaptation decision making;
- Supporting the new phase of the TRaCCA research programme to deliver step changes in the knowledge of railway asset vulnerabilities and system inter-dependencies;
- Developing decision support tools to drive an increase in climate change resilience of the GB railway industry.

TfL: Metro and Underground

All TfL's operational business areas have assessed the risks from a changing climate and these are shown in the TfL Adaptation Report. The key results from TfL's review of its risk assessments have been incorporated into TfL's risk management system, which generates snapshots of the then key current, mitigated risks. The Mayor's Adaptation Strategy refers to these risks.[26]

Translink - Northern Ireland Railways

Climate change is on the Translink agenda, and liaison with the Department for Regional Development and with the Department of Agriculture and Rural Development on impacts and possible futures has taken place.[27]

RSSB rail industry studies

The rail industry recognises that more detailed evidence and data are required as to how infrastructure assets react to current extreme weather, and in the context of climate change.

There is no evidence of a strategic or systemic assessment of climate change risks across the entire railway system. Strategic risk assessments will be necessary if the industry is to develop coherent investment programmes for adaptation[28], and T925 TRaCCA identified a need to consider the challenges - from the perspective of systemic risks, and opportunities - from systemically resilient design.

5. Costs and/or relative magnitudes of impacts

In view of the uncertainties surrounding the UKCP09 climate change projections and the evolving understanding of how infrastructure reacts to weather events, detailed accurate predictions of the costs resulting from climate change concerning the railway as a system have yet to be developed. Indeed there have been debates as to the ways costs are measured and utilised, with the use of 'delay minutes' (the most used metric) questioned in T925 TRaCCA, as possibly not the most appropriate metric for network management or for research purposes.

Papers have been found to analyse single topics:

Dawson's analysis of the economics of sea level rise and the impact on the London – Penzance railway account for disbenefits in the south west of England and changes in socio-economic trends in order to demonstrate plausible future impacts of line closures at Dawlish. Illustrative costs of climate change over and above a 'no climate change' scenario show an annual average cost ranging from £1.01M - £1.32M in the 2020s to £15M- £24M by the end of the century.

Jaroszweski[29] examines the spatial propagation of delays across the GB rail network caused by three weather-related incidents, at Barnt Green, Shap and Newcastle on 28th June 2012, a day of severe thunderstorms across the UK[30]. Jaroszweski's paper gives indications of how extreme weather can cause impact at a regional and national scale and can been used as an analogy for the extent of impacts possible with climate change. For example, the incident at Shap was a landslip on the arterial West Coast Main Line at a two-track section between Penrith and Oxenholme. Trains were unable to travel over the damaged section of track until the next day and disruption to the railway network was recorded as far afield as Basingstoke, London and Llandudno. See Figure 1.

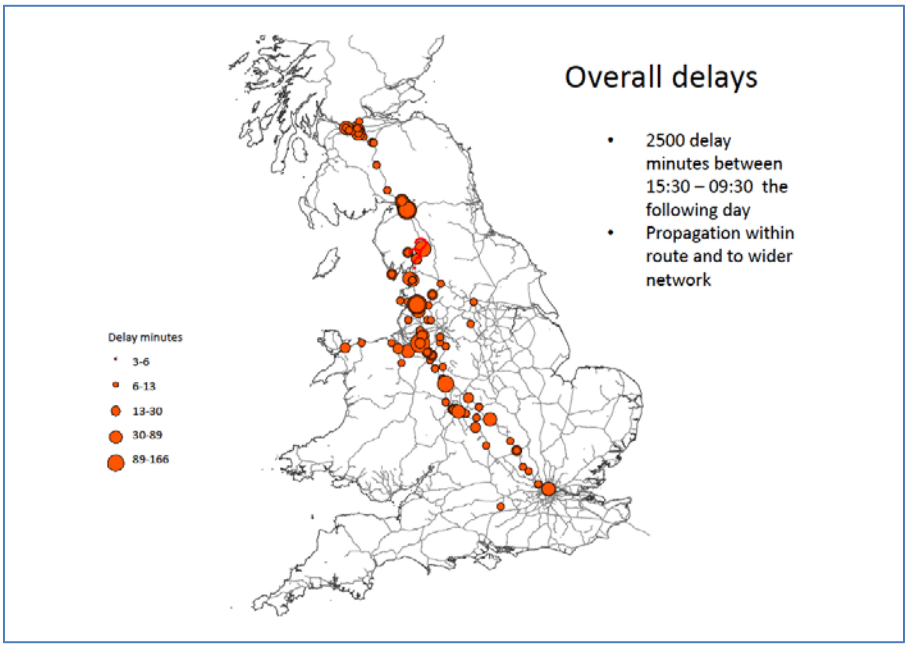

Figure 1: Propagation of delays from a landslip at Shap, 28th June 2012

Dobney assessed the impacts of climate change relating to damage and delays caused by hot and cold weather on track systems, quantifying the change in delays owing to climate change against current conditions. Dobney made recommendations for alleviating the adverse impacts of climate change; in this analysis it is believed that GB railways can operate with a stress free (rail) temperature of 27°C (this is the same as existing) under future climate scenarios, provided the tolerable range is narrowed upwards from 21°C towards 27°C and that the quality of track, track-bed and subgrade are improved. These actions should limit the potential damage caused by more challenging temperature extremes. If changes are not made to make the track more resilient to hotter summers the cost of buckles and heat related delays are projected to increase from £3.3m under baseline climate conditions to £24.7m in the 2080s under the high emissions scenario.

Baker et al discuss the need to consider wider economic disbenefits when examining the costs of climate change and railways and make links to the system thinking required not just related to rail but into the needs of a wider transport system. This paper mentions that the technical issues are fairly well understood, but an overall framework for the quantification of the likely effects of these issues on the railway industry and a method for assessing which are the most critical effects to which resources should be given a priority.[31].

Collectively these studies show that the economic impacts, both direct and indirect, of extreme weather and climate change cannot be isolated or limited to particular ‘elements’ of the rail network; strategic and systemic assessments of costs and impacts are not evident and should be undertaken.

6. Adaptation opportunities

Engineering and asset lifecycle considerations.

‘Engineering’ covers the installation, maintenance, renewal or refurbishment of engineered measures on the infrastructure.

The opportunity to modify an asset to provide improved resilience and redundancy at asset renewal stage is identified in Network Rail’s Adaptation Report; adaptation carried out during the routine renewals process might permit adaptation at marginal cost. This approach is facilitated by guidance given in Network Rail specifications for the design of bridges[32] and of drainage, in the Railway Drainage Systems Manual. These documents require designers to design new or refurbished assets with the future climate in mind.

Examples of potential adaptation measures are described in Table 4. The risks and issues have been sourced from T1009 TRaCCA:

Climate Risk	**Issue**	**Potential engineering measures**
High temperatures	Track buckle and associated mitigation management measures	Maintain tracks to narrower temperature tolerances ie: change to more resistant specifications
Low temperatures	Ice build up on rolling stock which can detach and damage the	Clutter-free design for underside of vehicles De-icing tents for use prior to entry into service

	stock or the infrastructure	
	Freeze thaw at rock cuttings	Rock removal activity on a cyclic basis Netting of rock cuttings
Rapid change in temperature	At lineside electronic equipment affecting power, signalling, telecomms	Use of more benign electronics Use of temperature stabilising 'design' for lineside equipment – green roofs, siting in benign location
High precipitation	Scour at bridges	Improve scour resilience during routine renewal of scour protection systems (design life c 20 years) Design future bridges to withstand climate change
	Landslips	Identify and introduce resilience measures at vulnerable sites such as shaping to reduce slope angles Vegetation management Improve drainage
Low precipitation	Desiccation of clay embankments	Identify at-risk locations Vegetation management Rebuild embankment removing desiccation-prone material
High winds	Trees being blown on to the line	Identify at-risk locations Vegetation management
	Dewirement of overhead traction power lines	Identify at-risk locations Strengthen existing equipment, at renewal stage if possible Design new equipment with uncertainty in mind, making provision to retrofit or– if economically sound – build in resilience
Humidity	Increased leaf-fall and adhesion (braking) hazards	Identify at-risk locations Vegetation management
Lightning	Affecting power, signalling,	Identify at-risk locations Protect equipment from lightning strike

	telecomms	Consider redundancy as a mitigation (eg provide power on a grid basis)
Sea level rise	Increased damage on coastal railways	Identify at-risk locations Factor in resilience measures for routine renewal programme - design future defences works with sea level rise in mind

Table 4: Potential engineering adaptation measures

Operational management

Opportunities exist to develop further the knowledge gained through adaptation studies – the models, visualisations and concepts - to provide operational forecasting tools for railway operators that aid the safe and efficient use of the network[33]. One example in use is the Dawlish Forecasting System, that in 2008 extended the RSSB T643 on coastal railways into a forecasting tool that offers a 36-hour forecast and currently is 'run' twice daily. The system gives an hour-by-hour projection depicted in Green (low risk) to Black (high risk) status, providing Network Rail and train operators advance information as to potential performance and safety issues in enough time to react and modify train schedules and inform passengers of possible disruption. Its most notable use was in February 2014 when its first 'Black' forecast was issued, the resulting storm causing a serious breaching of the sea wall in Dawlish requiring weeks of repair work and suspended train services[34]. This particular warning allowed a safe, controlled shutdown of the line before the storm arrived protecting passengers, staff and rolling stock.

The reduced future incidence of cold winters indicates a positive climate change impact on railway resilience and reliability (at least from fewer snow and ice days), but as cold conditions are likely not to cease altogether, operational readiness will still feature as a requirement. This will entail the continued need for cold weather precautions and response procedures. One challenge here might be the retention of operational knowledge – for winter response; and corporate knowledge – for winter preparedness; should a run of warm winters be experienced as happened prior to the winter of 2010.

7. Broader drivers and interactions

Resilience planning and capacity

The Government has a strategic priority to increase rail's capacity and to accelerate journey times between key cities as identified in the DfT's High Level Output Specification (HLOS)[35]. It has also recognised a need for improved resistance and resilience of infrastructure to weather events and climate change[36]. In response, the railway industry has taken up the resilience challenge exemplified by Network Rail's CEO stating that the weather issues experienced during the winter of 2012/13 'had been a wake up call'[37]. Additionally ORR's final determination for CP5 says "We expect Network Rail to set itself ambitious environmental targets, with challenging carbon reduction trajectories and a greater focus on making assets resilient to climate change and extreme weather".

Rail network capacity – sometimes defined as 'timetabled train kilometres' – is linked to infrastructure resilience. If weather impacts upon the infrastructure causing disruption to services, this in turn reduces capacity; weather-induced disruption can cause delays and cancellations and so a loss of timetabled train paths. Examples of such perturbations include landslips, sea wall breaches, and the dewirement of OLE (the latter can be caused by high winds, heat or combinations of weather effects such as winds and desiccation of earthworks[38]).

The relationship between infrastructure system resilience and capacity is not yet well understood and Network Rail is investigating and identifying weather-related thresholds for infrastructure sub-system failures and the likely root causes of these via internal studies.

Modal shift

The European Union's 2011 Transport White Paper[39] calls for a 50% shift of medium distance intercity passenger and freight journeys from road to rail and waterborne transport by 2050. This would have a significant impact on the existing networks, bearing in mind that the modal shares in rail (2009/ 2010) are 10% for long-distance passenger[40] and 8.4% for freight[41]. The arguments set out above concerning capacity are relevant here also; to increase market share requires an increase in capacity. The link between capacity, resilience and climate change is implicit, a theme picked up by Doherty et al[42] where weather events are noted as causing performance impacts and so a reduction in capacity. Increased capacity can be delivered by physical works – more tracks or grade separation at junctions are two examples – but improved resilience improves capacity by reducing 'down time' or improving the recovery time after disruption.

8. Confidence in the science

Guidance for assessing confidence in the science has been provided by LWEC with a '3 x 3 matrix' taken from the IPCC 5th Assessment Report (IPCC, 2010)[43]. While this has been developed to provide consistency across climate change analyses activities, the material reviewed in support of this report had not been categorised according to the IPCC guidance.

Taking the emerging outputs from T1009 TRaCCA, a brief assessment of confidence in the climate change projections, with examples of potential future impacts, is offered in Table 5.

High Agreement	**HIGH PRECIPITATION:** Increased risks of scour at railway bridges **HIGH PRECIPITATION:** Increased risk of landslips **LOW PRECIPITATION:** Increase in desiccation of clay embankments **RAPID CHANGE IN TEMPERATURE:** Impact on electronic equipment	**LOW TEMPERATURES:** Reduction in incidence of snow and ice affecting rolling stock, operations and safety of rock cuttings	**HIGH TEMPERATURES:** Delays and safety from track buckle risks **SEA LEVEL RISE:** Impact on coastal railway infrastructure
Medium Agreement	**LIGHTNING:** Impact upon power, signalling and telecomms **CHANGE IN HUMIDITY:** Impact on leaf-fall and	**HIGH TEMPERATURES:** Track worker safety **HIGH TEMPERATURES:** Increase in sag of overhead power lines	**HIGH TEMPERATURES:** Safety and comfort of passengers in failed trains

	vegetation growth		
Low Agreement	**CHANGE IN WIND SPEEDS/ DIRECTION:** Impact of trees and other obstructions being blown on to the line		
	Limited Evidence	**Medium Evidence**	**Robust Evidence**

Table 5: Brief assessment of confidence

(from T1009 TRaCCA emerging outputs as related to the projected climate, with examples of potential impacts)

9. Research gaps and priorities

Data

While some gaps and priorities for UK rail transport have been identified above, the CCRA reinforces this stating that data availability is the key issue leading to reduced confidence in analyses, and that "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)". Areas of uncertainty for future climates mean there is a need for predictions of wind, humidity and lightning, with the magnitude of precipitation and flood events and of heat build-up in cities (urban heat island) also being of concern.

Looking forward the 2013/14 IPCC AR5 assessment includes results from the next generation of global models with improved stratospheric, ocean and earth system modelling. It is important for the credibility of the ongoing adaptation work that this scientific progress is reflected in updates and enhancements to UKCP09. This might include additional variables, improved prediction of extremes relevant to adaptation and joint probabilities of the weather variables of concern.

Weather, asset and system behaviour

T925 TRaCCA acknowledges that the baseline relationships between weather and disruption on the railway network have not been validated. Understanding the current relationships between weather and asset behaviour is fundamental to projecting the potential impact of future climates, as well as forecasting current operational failures. The work Network Rail has undertaken in its internal studies will provide valuable baseline information.

There is a need also to consider impacts in system terms – how single points of failure such as at Shap in June 2012 can compromise operations at a network level is an area requiring systemic analyses.

Knowledge retention

Weather records have shown periods of drought followed by floods (1992, 2012); runs of warm winters followed by extremely cold and snowy/ icy winters (1963, 2010); years of benign sea conditions then a set of coastal storms accompanied by storm surges (1953, 2013/14); and rainfall events deluging large parts of the country (August 1948, June/ July 2007). Investigations are carried out after these events and recommendations are made, such as the DfT Transport Resilience Review published in July 2014[44]. Incident/ accident reports can be compiled where necessary. Reports over time (compare Bye's report into the 1998 floods[45] with Pitt's report into the 2007 floods[46]) are seen to tackle the similar or the same issues and one could ask 'why have these lessons not been learnt?' Those that experience the response and aftermath of such events carry that knowledge with them throughout their careers, however the transfer of that knowledge from generation to generation is sometimes difficult, perhaps owing to day-to-day pressures and priorities.

For 'knowledge retention' there is a need at both operational and corporate level to improve the embedding and sharing of learning, particularly from those who gain hands-on experience of reacting to weather events. Further to this there would be merit in devising evidence or research-based tools that can help organisations predict and prevent failure.

Costs and benefits

Strategic and systemic assessments of impacts, costs and wider economic benefits are not evident and steps should be made as a priority to integrate climate change analyses activities towards these aims.

10. Conclusions

The UK rail industry acknowledges climate change as a long term threat and has engaged in a number of studies which have shown some vulnerabilities, mostly related to increases in temperature (eg: track buckle risks, and staff stress related) and precipitation (eg: landslip risks and scour at bridges), because climate projections in these areas are more confident than for other types of weather. From these studies it is concluded that warmer summers and wetter winters will mean a less reliable railway service, but there will be fewer cold winter days leading to poor performance on the network. This is against a background of increasing passenger patronage, UK policy drivers that require an increase rail capacity, and EU requirements for a 50% modal shift to rail by 2050.

Confidence in the climate change science is seldom high. Gaps and uncertainties are apparent in the science as regards the granularity of spatial detail and the prediction of extremes – future conditions are stated mostly as averages in the UKCP09 projections. There are significant uncertainties in the predictions for wind, humidity and lightning.

Whilst studies have attempted to quantify future climate-related impacts, they have been unable to do so comprehensively; nor have attempts been made to establish system-wide costs or strategic priorities. Quantification of impacts at best has been found to relate only to a general increase in days of exposure and delay minutes at a regional level; more granular, location-specific information is not available. The baselining of current climate conditions generally, has not been undertaken and the utility of the most commonly used metric – 'delay minutes' – has been questioned.

Work has been undertaken by Network Rail to analyse and set current weather-related thresholds for sets of its assets, however further assessment of climate change impacts at local and strategic levels is needed.

Better ways to retain and pass on climate and weather impact knowledge can help provide the experience and tools to 'predict and prevent' failures.

Opportunities exist to set out and act upon low-cost adaptation strategies – such as adapting assets when they are undergoing major works – and adaptation modelling can help to improve current operational management as the Dawlish forecasting system shows.

Proactive adaptation investment plans have not generally been seen; however Network Rail's route weather resilience and climate change adaptation plans are a step in the right direction towards a coherent adaptation strategy.

Priorities should be to:

- Improve the confidence and availability of climate projections to suit the analysis needs of the infrastructure systems affected;
- Investigate whether new infrastructure-related metrics are required to facilitate better operational management and research;
- Establish baseline, and future, impacts, operating costs and economics of adaptation, across a wide set of asset types;
- Integrate research and analysis work, under a 'systems thinking' evidence-based framework;
- Improve and embed the knowledge and understanding of climate change impacts at local/ asset and strategic/ route levels.

This would ideally involve other parts of the infrastructure sector owing to the way that infrastructure systems are interdependent.

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