Research Programme
Operations and Management
Adapting to extreme climate change (TRaCCA)
Phase 3 report
Tomorrow's railway and climate change adaptation
The climate change assessment methodology has been developed by the Met Office Hadley Centre in collaboration with experts from the GB railway industry.
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Background

Project background

Our climate is changing. The scientific evidence from the Intergovernmental Panel on Climate Change points strongly to these changes being largely caused by human activity. Beyond the middle of the 21st century, the climate change we experience will depend on the actions we take now to mitigate the effects of man-made greenhouse gas emissions. However, over the next few decades, we expect to have to adapt to rising temperatures, changing rainfall patterns and more extreme weather events (such as increased incidence of high wind speed for example). These changes in the climate are expected to have an impact on many of the railway system components (for example traction, services, staff, subsystems covering track, rolling stock, stations, depots, structures, electrification and signalling and other train control systems) and, consequently, most aspects of Network Rail's role, responsibilities and functions.

In particular, Network Rail and the railway industry are focused on how the current and future climate could affect the ability to achieve and deliver:

- A safe railway
- A highly reliable railway
- Increased capacity
- Value for money
- A 'predict and prevent' asset management policy

This report presents the findings from the RSSB and Network Rail sponsored T925 Adapting to extreme climate change (TRaCCA) and will be reissued with a supplement following the completion of current work in progress on an 'adaptation policy evaluation tool' (APET) in March 2012.

The project was delivered by Network Rail in association with the Met Office, representatives from the railway industry including RSSB, the Association of Train operating Companies (ATOC) and Government (DfT Rail, Office of Rail Regulation, and Transport Scotland). The work was sanctioned by the railway industry Technical Strategy Leadership Group and was guided by a cross-industry steering group.
The aim of *Tomorrow's railway and climate change adaptation* (TRaCCA) was to assess the potential impacts of climate change across the GB railway to inform the industry's Rail Technical Strategy, the Industry Investment Plan (IIP), and to provide input to a statutory requirement on Network Rail to assess the impacts of climate change on its operations (Box 1). The UK Government’s vision is for ‘An infrastructure network that is resilient to today's natural hazards and prepared for the future changing climate’ (HMG, 2011).

The Met Office involvement in TRaCCA was planned in three phases:

- Phase 1 identified over 60 weather sensitivities of the railway industry highlighted through collaboration between Network Rail and the Met Office, a sub selection of which were prioritised.
- Phase 2 investigated 16 of these priority sensitivities, however the study was solely focused along the West Coast Main Line (WCML), to test and validate the modelling methodology.
- Phase 3 expanded analyses of selected priority topics to cover the whole of the GB railway network.

The degree of detail of each assessment study has been determined by the extent of railway and climate knowledge, and the availability of information. The studies assumed that the future size of the network, asset management policies and traffic patterns will remain the same as 2009/2010.
As well as the Met Office involvement and the detailed reporting that follows, TRaCCA aimed to:

- Provide for two climate change adaptation reports to Government - an 'interim' high-level report for September 2010, and a 'full' report for April 2011.

**Box 1 - Government Requirements**

Network Rail is required to report to Government [Defra] under a statutory direction the impacts of climate change on rail *operations* (2009). Network Rail 'must prepare and send to the Secretary of State [of the Environment] a report' containing:

a. an assessment of the current and predicted impact of climate change in relation to the reporting authority's functions;
b. a statement of the reporting authority's proposals and policies for adapting to climate change in the exercise of its functions and the time-scales for introducing those proposals and policies.

The assessment of impact referred to [above] must include:

a. a summary of the statutory and other functions of the reporting authority;
b. the methodology used to assess the current and predicted impacts of climate change in relation to those functions; and
c. the findings of the assessment of the current and predicted impact of climate change in relation to those functions.

This report must be prepared by 30 April 2011.

In addition, Network Rail has been identified as an organisation recognised for its expertise in climate change adaptation, engineering and risk management.

Because of this Defra wishes to 'encourage Network Rail to submit the risk assessment part of its report by 30 September 2010'.
Background

- Make recommendations for potential 'quick wins' in terms of adaptation and procedural options for dealing with the impacts of current weather patterns.
- Make preliminary recommendations for asset management policy and planning for Control Periods CP5 - CP8.
- Arrange a climate change adaptation seminar to raise awareness and to inform the railway industry of likely climate change issues.
- Deliver policy evaluation tools for the priority and other topic areas for use by the railway industry.
- Produce route-based climate change vulnerability maps.
- Provide an interactive mapping visualisation tool.
- Outline guidance to inform the railway industry of likely climate change issues and how they will be dealt with.
- Make recommendations for geographically-based Standards development and further research requirements to support this.

Scope of the project

TRaCCA was scoped to cover the whole GB railway network, and to examine climate impacts over the decades 2010s to 2040s.

The scope of this work has been defined on the basis of liaison with RSSB, Network Rail and the Met Office. In particular, the following is of note:

- The latest time horizon considered was the 2040s. The railway industry felt this was appropriate given the control period reporting requirements with the current IIP looking to CP10, which ends in 2044, and the Rail Technical Strategy, which covers 30 years and is due for an update in 2012. This decision was reinforced by the knowledge that the divergence in climate projections will increase after the 2040s, owing to uncertainties over how the global communities will react to reducing greenhouse gas emissions.
- The period from 2010 to 2020 is not modelled per-se, rather the baseline period (the thirty year weather records from 1971 to 2000) was deemed suitable to describe weather patterns for the current decade.
A threshold-based approach was chosen for the scientific analysis. An alternative would have been to formalise a baseline relationship between weather/climate parameters and disruptions on the railway network. However, this was felt to be too complex given the timescales and the budget available for the project.

For the various priorities, relevant thresholds were selected through collaboration with railway industry experts, in order to ensure maximum relevance.

Providing adaptation solutions (or options for these) is out of scope of this project. However, recommendations are made for longer-term asset management policy and planning, and for potential ‘quick wins’ in terms of adaptation, procedures and current weather patterns.

Planning assumptions

TRaCCA analyses were based on the assumption that railway traffic levels and asset management policies remain the same as those that were in place at 2009/10.

Demographic change, change in travelling patterns and other changes will not be considered; such work is over-complicated for this first stage of railway climate change impact assessment and policy making. The railway industry is aware of research such as the EPSRC funded ‘Futurenet’ (2011). This work and other EPSRC-funded research will, in the longer term, be able to inform railway-specific studies in these topic areas, but will not be available in time to support the work specified here.

Urban parts of the UK are known to presently be a few degrees warmer compared to surrounding rural regions. The models used in UKCP09 (and therefore in this work) do not take into account this urban heat island effect. As a consequence, if these areas change geographically, for example due to an increase in urbanised areas, a further uncertainty in temperature changes may be possible.
Background

**TRaCCA deliverables**

The deliverables originally planned for TRaCCA included:

- *Mathematical models for extreme weather/ asset systems (including infrastructure and TOC assets) for the selected priority topic areas from Phase 1 for the decades 2010s, 2020s, 2030s, 2040s.*

- *Verification of the modelling (‘proving’) on the London - Glasgow West Coast Main Line.*

- *Configuration of the mathematical models for the whole GB railway network.*

- A high-level climate change impact assessment as required by Government for September 2010.

- Recommendations for potential 'quick wins' in terms of adaptation and procedural options for dealing with the impacts of current weather patterns.

- Preliminary recommendations for asset management policy and planning for Control Periods CP5-CP8.

- *A specification for a tool to enable the railway industry to evaluate policy options (Adaptation Policy Evaluation Tool) for adaptation and weather resilience for priority and other topic areas.*

- Climate change adaptation seminars, to raise awareness and to inform the railway industry of likely climate change issues; one for Phase 2 and one at the end of the project.

- Priority climate change impacts for the whole GB railway industry for the four decades as above.

- Policy evaluation tools for the priority and other topic areas for use by the railway industry.

- A report covering the Government requirements including adaptation options, timescales, costs, benefits, expected reduction in risks.

- Route-based climate change vulnerability maps.

- An interactive mapping visualisation tool.

- Guidance to inform the railway industry of likely climate change issues and how they will be dealt with.
• Recommendations for geographically-based Standards development and further research requirements to support this.

• A report or reports summarising the above.

_Deliverables shown in italics comprise developmental activities, that is activities that were necessary to the production of this final report. Details of these activities are not included in this report unless material to the conclusions._

### Progress with deliverables

Owing to the limitations of the current climate science and variability in the quality of the available data and its coverage, a revised package of work has been delivered under the guidance of the TRaCCA Steering Group and RSSB. This report acknowledges that further work is necessary, particularly as regards APET and in making best use of the current science and the available data in the priority areas. It was agreed that the approach adopted would be the most effective use of the available budget. This report will be reissued with a supplement following the completion of current work in progress on an 'adaptation policy evaluation tool' (APET) in March 2012.

The revised package covered the analyses undertaken by the Met Office, and a summary of these analyses is shown in Table 1.

<table>
<thead>
<tr>
<th>Group</th>
<th>Risk</th>
<th>Initial analysis</th>
<th>Full analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>Track buckles and temporary speed restrictions</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Temperature</td>
<td>Windows of opportunity for track maintenance</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Temperature</td>
<td>Incidence of sag of overhead line equipment</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Temperature</td>
<td>Staff exposure to heat stress</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>
Background

The high-level assessment required by Government for 30th September 2010 was prepared by Network Rail (2010) and drew upon a 'Preliminary Findings' report from the Met Office. This interim report will be superseded by a final Network Rail Report, available from www.defra.gov.uk when published. Recommendations for potential 'quick

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<table>
<thead>
<tr>
<th>Group</th>
<th>Risk</th>
<th>Initial analysis</th>
<th>Full analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>Passenger and freight risk from train failure in extreme weather</td>
<td>✗</td>
<td>✓</td>
</tr>
<tr>
<td>Temperature</td>
<td>Heat affecting lineside equipment</td>
<td>✗</td>
<td>✗</td>
</tr>
<tr>
<td>Fluvial Flooding</td>
<td>Scour and flooding of bridges</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Fluvial Flooding</td>
<td>Scour of embankments due to high river levels &amp; culvert washout</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Fluvial Flooding</td>
<td>Depots (TOC and maintenance)</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Fluvial Flooding</td>
<td>Track and lineside equipment failure</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Pluvial Flooding</td>
<td>Track and lineside equipment failure</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Pluvial Flooding</td>
<td>Landslips</td>
<td>✓</td>
<td>✗</td>
</tr>
<tr>
<td>Ground Flooding</td>
<td>Track and lineside equipment failure</td>
<td>✗</td>
<td>✗</td>
</tr>
<tr>
<td>Various</td>
<td>Trees - obstruction risk from wind at the lineside</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Various</td>
<td>Leaves on line/Signal Clear When Occupied'('SCWO)</td>
<td>✗</td>
<td>✗</td>
</tr>
<tr>
<td>Sea</td>
<td>Overtopping and damage of sea defences</td>
<td>✓</td>
<td>✗</td>
</tr>
</tbody>
</table>

Table 1 - Summary of analyses

- The high-level assessment required by Government for 30th September 2010 was prepared by Network Rail (2010) and drew upon a 'Preliminary Findings' report from the Met Office. This interim report will be superseded by a final Network Rail Report, available from www.defra.gov.uk when published. Recommendations for potential 'quick
wins' in terms of adaptation and procedural options for dealing with the impacts of current weather patterns are covered in the _Conclusions and Recommendations_ section.

- Preliminary recommendations for development of asset management policy and planning for Control Periods CP5 - CP8 are covered in the _Conclusions and Recommendations_ section.

- Adaptation Policy Evaluation Tool:
The specification for a tool to enable the railway industry to evaluate policy options was subject to review; advice from experienced Network Rail modellers suggested that the development of a model as planned, within Phase 3, would most likely (owing to time, budget, data and science limitations) deliver a coarse, high level model of questionable value. This might be a model that would show impacts in general terms (eg: 'high', 'medium', 'low' rather than quantified) and at low resolution (by region rather than by sections of route).

It was also recognised that different degrees of complexity and detail would arise between the topics modelled. An approach involving user input at the model specification stage has been adopted, with staged development towards a more comprehensive and expandable tool (or set of tools) for each priority weather event/asset combination, as the science and data are improved.

A workshop has been arranged for June 2011 to agree the practicalities associated with the development programme for the APET.

- The climate change adaptation seminar for Phase 2 was delivered as a workshop to aid both dissemination of the issues and contribute to specification of the APET.

- The final climate change adaptation seminar has yet to be delivered and is scheduled for later in 2012.
Background
Findings

Met Office Analyses

Heat and track buckle risk management

The number of heat watchman days and the frequency of speed restrictions being imposed (associated with track buckle risk and high temperatures) is projected to increase out to the 2040s for all track conditions examined. 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 speed restrictions is 16 (per 30 summers) 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 watchman 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.

The number of days associated with track work being prevented because of forecasts of unsuitable temperature conditions is projected to increase by the 2040s across the GB railway network. For example, across Scotland, the average modelled number of non-track-work-days in the baseline period is 345 (per 30 summers). 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.

Heat and sag of electrification overhead line equipment

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 OLE 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
Findings

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.

An example of the graphic output from the Met Office report is shown in Figure 1. In Figure 1, the modelled incidence of exceedance of 33°C per 25km grid square per thirty-year period is indicated. The baseline period (1971-2000) average is shown at the top, while the modelled range of possible outcomes for the 2020s, 2030s and 2040s is shown in the remaining panels. These results were obtained under the UKCP09 medium emissions scenario.

Heat and stress on the workforce

The number of episodes of human heat stress is projected to become more frequent by the 2040s. Heat stress was assessed using the existing Met Office Heat-Health Watch threshold temperatures, which take 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.

Note: Care should be taken when interpreting any result involving a high temperature threshold (33°C or higher) as projected exceedances of these thresholds are sensitive to the choice of analysis method.
Figure 1 - Example from the Met Office report
Findings

Extreme cold

The occurrence of cold conditions is problematic for the performance of the railway network and is projected to decrease, but not to cease altogether, by the 2040s. For example, across North West England, the average modelled winter-time daily occurrence of minimum temperatures below 0°C during the baseline period is 1430 (per 30 winters). 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.

Precipitation and river flooding

River flooding can lead to many railway industry problems including scour and flooding of bridges, embankment scour and culvert washout, depot flooding and track and lineside equipment failure. 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.

Precipitation and surface water flooding

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 (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, with detailed consideration of the most suitable metrics for this type of analysis.

Precipitation and landslip risk

The future risk of landslips related to large monthly rainfall totals has been investigated and there is mixed evidence for whether critical weather events could become more or less frequent. Further data, analysis and improved science providing a link between rainfall and landslip occurrence are required to ensure landslip risk is sufficiently well represented.
High winds and obstructions on the line

Railway speed restrictions and track disruption can result from trees being blown onto the line when there are high winds. Projections for the 2040s suggest little change in the overall wind speed distribution, although a higher future frequency of the more extreme (70mph) wind gusts is seen alongside a mean reduction in the frequency of lower thresholds (30 and 40 mph) being exceeded. There are, however, large uncertainties in these projections due to the limitations of the model, the gust parameterisation used and the observation datasets. Further research is required to better relate wind speeds to railway disruptions, with detailed consideration of the most suitable metrics for this type of analysis.

Sea level rise

At key locations across Great Britain where railway infrastructure is at risk from inundation by the sea, sea level rise and storm surge level projections for 2045 have been made. The sea level rise projections presented range from 3cm to 32cm, depending on local factors, with storm surge presenting an additional risk. Further analysis is required to translate the sea level rise projections into future impacts on the railway infrastructure.

Notes on the analyses

All baseline period event frequencies quoted throughout the Met Office analyses are based on bias-corrected modelled climate data. The relationships between modelled and actual event frequencies during the baseline period using true incident data from Network Rail have not been assessed, mostly due to the nature of the records which were found to be variable in data quality and spanning a relatively short time.

The analyses presented here have not investigated the impacts of natural climate variability, for instance where the predicted trends remain within the expected bounds observed for current weather patterns. Further statistical analysis would be required to understand how this limitation could affect the conclusions drawn, particularly for wind and precipitation.
Findings

Potential 'quick wins'

There is an opportunity to extend the current research beyond the minimum statutory obligations of Network Rail, to report the impacts of climate change on railway operations on behalf of the railway industry. The topic of potential 'quick wins' was raised at an industry workshop on 1st December 2010 and the findings are recorded in Table 2. (The 'ideas' are transcribed from the notes of the industry workshop held 1 December 2010.)

Some of these findings relate more to longer-term aspirations.

Table 2 - Potential 'Quick wins'

<table>
<thead>
<tr>
<th>Ref</th>
<th>Idea</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Develop localised rainfall &amp; wind monitoring stations</td>
<td>To permit a more targeted response to weather alerts, as happens with the East Coast Main Line where wind alarms allow near 'real-time' reaction to high wind speeds</td>
</tr>
<tr>
<td>2</td>
<td>Improve Emergency Response competence.</td>
<td>To improve reactions to perturbation from infrequent weather events; for example, by extending training and carrying out exercises</td>
</tr>
<tr>
<td>3</td>
<td>[Develop] long-term organisation needs for CC adaptation</td>
<td>Embed into railway industry planning now?</td>
</tr>
<tr>
<td>4</td>
<td>Agree a single focus in the railway industry for system resilience,</td>
<td>Embed life-cycle cost analysis into option development capability across the railway industry planning now?</td>
</tr>
<tr>
<td></td>
<td>with the ability to make prioritised decisions, geared to a customer</td>
<td></td>
</tr>
<tr>
<td></td>
<td>focus (ie: passengers and freight companies)</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Look at use of DTS on maintenance sites to mitigate the effects of</td>
<td>DTS = Dynamic Track Stabiliser, a rail mounted machine that consolidates ballast following maintenance works. The intention would be to use DTS to make track systems more resilient to buckling and so permit more maintenance to be carried out where otherwise such work might be prevented</td>
</tr>
<tr>
<td></td>
<td>low critical rail temperatures</td>
<td></td>
</tr>
</tbody>
</table>
System-wide forecasting to cover system resilience issues

Initiate cross-sectoral business continuity discussions - cross-sectoral plans are required because of inter-sectoral dependencies and we need to factor in the important interdependencies with other aspects of climate change adaptation.

Hold stocks of emergency repair materials for civil engineering assets (temporary structures). Equipment is thought less of an issue; items can be procured from engineering contractors. Consider also other sectors - ICT.

Make sure climate change is included in current CP5 development work.

How can we design & build for long term resilience when funding is based on short term (5 year) cycles or franchise lengths?

Improve cooperation across corporate boundaries to break down 'silo' thinking

Look at proportionality of work involved - compare costs with benefit and asset life - prioritise and rank.

<table>
<thead>
<tr>
<th>Ref</th>
<th>Idea</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>System-wide forecasting to cover system resilience issues</td>
<td>Linking cross-asset vulnerabilities; for example dessication of earthworks and impacts on track quality</td>
</tr>
<tr>
<td>7</td>
<td>Initiate cross-sectoral business continuity discussions - cross-sectoral plans are required because of inter-sectoral dependencies and we need to factor in the important interdependencies with other aspects of climate change adaptation</td>
<td>For example, transport power needs and information communication technology and vice-versa</td>
</tr>
<tr>
<td>8</td>
<td>Hold stocks of emergency repair materials for civil engineering assets (temporary structures). Equipment is thought less of an issue; items can be procured from engineering contractors. Consider also other sectors - ICT.</td>
<td>For example, the railway industry used to have stocks of temporary bridging held for Government. A strategic store of such material to maintain railway transport and potentially to support other transport modes?</td>
</tr>
<tr>
<td>9</td>
<td>Make sure climate change is included in current CP5 development work.</td>
<td>Some identified in interim report to Government - need to put in 'right place' in the railway industry - which organisation?</td>
</tr>
<tr>
<td>10</td>
<td>How can we design &amp; build for long term resilience when funding is based on short term (5 year) cycles or franchise lengths?</td>
<td>The Rail Technical Strategy can be used to address this.</td>
</tr>
<tr>
<td>11</td>
<td>Improve cooperation across corporate boundaries to break down 'silo' thinking</td>
<td>Synergy with 4</td>
</tr>
<tr>
<td>12</td>
<td>Look at proportionality of work involved - compare costs with benefit and asset life - prioritise and rank.</td>
<td>Embed life-cycle cost analysis into option development for the railway industry (synergy with 4).</td>
</tr>
</tbody>
</table>
Findings

Table 2 - Potential ‘Quick wins’

<table>
<thead>
<tr>
<th>Ref</th>
<th>Idea</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>Look at ‘compound’ effect as well as individual effects</td>
<td>A research need - synergy with 4 - - combined probability of events occurring and system-wide impacts</td>
</tr>
<tr>
<td>14</td>
<td>Seek to understand more about change in temperature on overhead line systems</td>
<td>A research need - impact on resilience of the OLE system and its impacts on the system performance</td>
</tr>
<tr>
<td>15</td>
<td>Weather monitoring (wind, rain etc.) with near real-time information overlaying asset knowledge. Use of this with 3-hour or 3-day forecasts could allow better network planning</td>
<td>Synergy with 1</td>
</tr>
<tr>
<td>16</td>
<td>Consider non-railway impact of railway failure to discover real economic cost/ value</td>
<td>A research need - examine climate impacts on other transport modes and other areas, as a result of disruption to railway service.</td>
</tr>
<tr>
<td>17</td>
<td>Multi-disciplinary teams focused on ‘the journey’ not the silo</td>
<td>‘the journey’ = railway product</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Synergy with 4</td>
</tr>
<tr>
<td>18</td>
<td>‘Think railway’ - also think transport system - railway staff need to travel to work in extreme weather by car, bus, etc</td>
<td>Synergy with 4</td>
</tr>
<tr>
<td>19</td>
<td>Consider use of novel track forms (eg embedded slab track) which in theory are not at risk of track buckles. They also reduce the need for humans to be on track in high/low temperatures</td>
<td>A research need - track forms with increased resilience to buckling in high temperature and the consequential impacts on other aspects of the railway system</td>
</tr>
<tr>
<td>20</td>
<td>Standardise train couplings to facilitate recovery by ‘Thunderbird’ locomotives or following units</td>
<td>Worthy of investigating business case, recognising this will take time to introduce</td>
</tr>
</tbody>
</table>
### Table 2 - Potential ‘Quick wins’

<table>
<thead>
<tr>
<th>Ref</th>
<th>Idea</th>
<th>Comment</th>
</tr>
</thead>
</table>
| 21  | Reduce train crew dependence on road (taxi) transport at start/end of diagram  
• start/end diagrams at home depots  
• reintroduce lodging turns | Worthy of investigating business case                                                      |
| 22  | Relationship between track quality and soil moisture.                | A research need - resilience of track structure (ballast, sub-ballast, sub-grade) to changes in pore water pressure. |
| 23  | Investigate heat in trains at different external temperatures and how much/ little time do we have to get people to safety. | A research need - threshold temperatures for passengers in trains and consequential impact on train design functions (eg. ventilation in degraded power mode), communication requirements (especially passengers), impact on management procedures for detraining where necessary. |
| 24  | Remove trees - they affect soil moisture content and embankment stability. | Worthy of investigating business case                                                      |
| 25  | Adaptation can lead to better planning for today, so capitalise on what we learn from having better data on thresholds and weather impacts | A research need - establish what data exists today and where are the gaps?         |
| 26  | For CP5 and CP6 we should plan to use the Surface Water Concentration features database to locate high risk sites from surface water flooding and then have a programme to mitigate these risks through drainage maintenance and new drainage schemes. This would reduce the risk of cutting failures. | Embed into workplans                                                                 |


Findings

Table 2 - Potential ‘Quick wins’

<table>
<thead>
<tr>
<th>Ref</th>
<th>Idea</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>27</td>
<td>We should broadcast current use of techniques (for example digital mapping, computational fluid dynamics (CFD)) and how we can (and have) proven new concepts for analyses. Utilise these more to predict hazards on a location by location basis</td>
<td>Can then target resources for:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Wind</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Cold - Ice, Snow</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Heat</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Humidity</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Flooding generally</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Coastal storms</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Others</td>
</tr>
</tbody>
</table>

Preliminary recommendations, asset management policy and planning

These recommendations are drawn from various discussions including the December 2010 workshop and the reports for Government and are, in no particular order:

- Think system wide, and outside the railway sector.
- Review other organisations’ research and procedures (eg: studies on landslips and Scotland’s trunk road network).
- Build up supplies and stocks of emergency repair materials and equipment with appropriate processes for deployment.
- Include climate change adaptation in the current CP5 development work.
- Think about emerging/ alternative technologies to reduce heat and flood risks such as green landscaping, a technique particularly effective in urban environments.
- Consider designing and building for long term resilience in the Rail Technical Strategy.
- Review likelihood of recurrent extreme events (such as the recent extreme winters) to determine if a case exists for enhanced preparations, such as investment in snowblowers for example.
• Consider developing partnerships with flood, local and highway authorities to share resources eg: to preserve access to critical infrastructure during extreme weather events.

• Build cross-industry expertise that can develop robust adaptation strategies using targeted research and development and keep abreast of improving science and developments.

• Develop route-by-route adaptation strategies during CP5 for investment CP6 onwards.

• Keep things in proportion - prioritise against impact and benefits.

• Consider timing of decisions - organisations do not need to make decisions now for all operations.

• Broaden scope of any work emanating TRaCCA to include other influences such as supply chain vulnerability.

• Enhance industry weather/operational measures tailored to science, and vice-versa.

• Make stronger links between adaptation studies and current operations.

• Look abroad for current examples of what will be the GB climate to learn how others manage their railways and other networks of assets.

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**Route-based vulnerability maps and visualisation tool**

In order to provide a visual summary of the results from Phases 2 and 3, and to complement the written reports from these phases, a scientific summary tool has been developed.

The tool provides a visual summary of the results from the full Met Office report. The tool, entitled TRaCCA4Rail, is a web-based product and gives users the ability to compare baseline results with future projections for the 2020s, 2030s and 2040s time horizons. An example indicating the loss of track maintenance days due to excess heat for the 2030s is illustrated in Figure 2.

The purpose of the tool is to display key results from the scientific analysis undertaken for each of the priorities. Note that the tool presents data for the whole of Great Britain (or, for any priorities
Findings

where this is not possible, for selected sites with an appropriate geographical coverage of Great Britain).

Members of RSSB may access the tool via http://www.metoffice.gov.uk/premium/discoverclimate/tracca4rail/

Figure 2 - A screenshot of ‘TRaCCA4Rail’ for track maintenance

Guidance to inform the rail industry of likely climate change issues and how they will be dealt with

During the evolution of the TRaCCA project, a number of issues have been raised and discussed within various railway industry forums, notably the Steering Group meetings, the seven Phase 1 workshops, the December 2010 workshop and at Network Rail internal meetings.

This section refers to unique issues which are not covered elsewhere, as the robustness and applicability of the climate science, and the quality and coverage of data on climate impacts, are not sufficient.

Scientific and data issues

The Met Office collaboration with the railway industry has resulted in a better understanding of climate threats to railway operations.

However, the opportunity to review current knowledge in climate science as coordinated under the ARCC network (www.ukcip-
arcc.org.uk/) for example, was not possible within the time-constraints of the TRaCCA project. The ARCC network brings together those involved in EPSRC and other grant-funded research into resilience and climate change. Some of this research would enable the railway industry to better understand the impacts in areas not yet studied, an example being the urban heat-island effect.

Detailed analyses undertaken by Network Rail on asset behaviour, such as landslip risk, for example, is now possible utilising a web-based tool acquired by Network Rail in June 2010, that can aid identification of locations where surface water can concentrate. Another area might be the risks to railway operations from trees where a national tree survey was completed in 2010.

An emerging area of interest is in the study of system dependencies and cross-sector resilience, and the UK government is sponsoring research in these fields. For railways, there is much reliance on interactions with other transport networks (highways), telecoms and energy (electricity and liquid fuel). Coordination and collaboration across UK infrastructure owners (including Network Rail) will take place over the next five years and this will provide an improved opportunity for synergy between organisations which should lead to benefits for the railway industry.

**Strategic issues**

In terms of strategy, the TRaCCA work set out as a project with specific aims. In its development, matters of wider importance were recognised and recorded for consideration. These are listed here:

- **Governance**
  - TRaCCA, as a single project under the governance of a steering group worked well. However, wider communication, including consultation with senior staff with relevant expertise, will add value for future stages of the research.

- **Embedding adaptation into business planning**
  - There is a need to set a wider Policy for climate change adaptation; while Network Rail has started work in this area, this is a topic the railway industry in general should consider.
Findings

- Network Rail is factoring asset adaptation planning into the Initial Industry Plan with route-by-route analyses being mooted as an activity during CP5. This work should be resourced with the right balance of skills, science and data, and any outcomes considered in terms of system impacts to the extent that is currently possible.

- Review of the original priorities
  - As skills and knowledge of adaptation issues improve through the research, the original workshop outputs should be reviewed to identify new or changed priorities.

- Temporal span
  - While for good reasons the 2040s decade was chosen as the limit for TRaCCA analyses with the Met Office, external best practice has used 2100 (eg: Environment Agency, National Grid, Defra analyses). Future analyses should consider extending climate analyses to 2100 to benefit planning for long life assets.

- Funding
  - As well as railway sourced research funding, there are opportunities to source research council grants through alliances with universities and coordination networks, and such avenues should be explored.

- Awareness
  - A communications strategy should be developed, providing a wide source of information for the railway community.
  - Ideas mooted include describing how employees can make a difference; hosting an online web event on climate change adaptation; expanding the TRaCCA4Rail tool to provide source material for reference;

- Asset life cycle
  - Long-term asset management planning in the railway industry recognises the importance of life-cycle costing in obtaining best value solutions.
  - Life-cycle planning uses predictions of (for example) rail traffic in terms of tonnage, speed, axle weights and cyclic loading and how these loadings influence the rate of deterioration of the assets. TRaCCA outputs can be
used to identify how climate changes might increase asset deterioration rates;

- TRaCCA outputs will be used to develop potential cost-profiles for adaptation investment from the Control Periods 5 to 10; that is, up to 2044.
- Planning for the long term shows that short-life asset components are likely to be replaced several times over the next 100 years. These asset components should be identified and the opportunity taken to change standards to improve their resilience to future weather patterns. In this way, increased resilience through adaptation would be achieved at nominal, if any, cost.

Dealing with the issues

In response to ‘How they [the issues] be dealt with, rather than list a range of actions in detail, because of the variety and diversity of the issues, a programme of work is recommended.

This work is likely to require a programme of discrete work packages that operate at different timelines. Overall programme management and governance arrangements both within Network Rail and the wider railway industry should be agreed.

The programme would adopt and manage the existing liaison arrangements with externally-funded research such as Futurenet www.arcc-futurenet.org and ITRC www.itrc.org.uk

Geographically-based Standards development and further research requirements to support this

Table 3 lists the priority climate hazards/asset risks examined with a commentary on the potential for developing geographically-based standards based on current knowledge and what research might be needed to achieve such an outcome. While this captures potential requirements based on the priorities identified during the TRaCCA project, any future work ought to reassess the lesser-priority areas for geographically-based Standards development.
Findings

Table 3 - Potential for geographically-based Standards

<table>
<thead>
<tr>
<th>Hazard</th>
<th>Asset or risk</th>
<th>Potential (High/medium, low) Comments</th>
<th>Potential areas of research</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat</td>
<td>Track buckle</td>
<td>High - spatial variance proven</td>
<td>Establish topography and orientation correlations</td>
</tr>
<tr>
<td></td>
<td>Track maintenance</td>
<td>High - spatial variance proven</td>
<td>Establish topography and orientation correlations</td>
</tr>
<tr>
<td></td>
<td>OLE sag</td>
<td>High - spatial variance proven</td>
<td>Establish thresholds for disruption</td>
</tr>
<tr>
<td></td>
<td>Lineside equipment</td>
<td>High - spatial variance proven</td>
<td>Establish thresholds for disruption</td>
</tr>
<tr>
<td></td>
<td>Staff</td>
<td>Low - risks might apply across country depending on acclimatisation for example</td>
<td>Understand more on human factors involved</td>
</tr>
<tr>
<td></td>
<td>Passenger risk - heat</td>
<td>Low - railway vehicles can be in any part of the country</td>
<td>Understand more on human factors involved, resilience of cooling systems, power demand</td>
</tr>
<tr>
<td></td>
<td>Freight risk - cold</td>
<td>Low - railway vehicles can be in any part of the country</td>
<td>Understand future incidence of extreme cold weather</td>
</tr>
</tbody>
</table>
Table 3 - Potential for geographically-based Standards

<table>
<thead>
<tr>
<th>Hazard</th>
<th>Asset or risk</th>
<th>Potential (High/medium, low)</th>
<th>Potential areas of research</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precipitation and fluvial flooding</td>
<td>Scour and flooding at bridges</td>
<td>Medium - risk is partially spatially dependent</td>
<td>Studies at individual catchment level</td>
</tr>
<tr>
<td></td>
<td>Scour of embankments</td>
<td>Medium - risk is partially spatially dependent</td>
<td>Studies at individual catchment level</td>
</tr>
<tr>
<td></td>
<td>Depots</td>
<td>Medium - risk is partially spatially dependent</td>
<td>Studies at individual catchment level</td>
</tr>
<tr>
<td></td>
<td>Lineside equipment</td>
<td>Medium - risk is partially spatially dependent</td>
<td>Studies at individual catchment level</td>
</tr>
<tr>
<td>Precipitation and pluvial flooding</td>
<td>Lineside equipment</td>
<td>Medium - risk is partially spatially dependent</td>
<td>Studies using NR Washout and Earthworks Risk Model (WERM) tool for surface water concentration</td>
</tr>
<tr>
<td>Landslip risk</td>
<td></td>
<td>Medium - risk is partially spatially dependent</td>
<td>Studies using NR WERM tool for surface water concentration</td>
</tr>
<tr>
<td>Groundwater flooding</td>
<td>Lineside equipment</td>
<td>Medium - risk is partially spatially dependent but science needs developing</td>
<td>Understand more about longer term weather patterns and groundwater movement. Identify locations of potential groundwater flooding</td>
</tr>
</tbody>
</table>
Findings

Table 3 - Potential for geographically-based Standards

<table>
<thead>
<tr>
<th>Hazard</th>
<th>Asset or risk</th>
<th>Potential (High/medium, low) Comments</th>
<th>Potential areas of research</th>
</tr>
</thead>
<tbody>
<tr>
<td>Various</td>
<td>Trees - wind and obstruction risk</td>
<td>Medium - risk is partially spatially dependent</td>
<td>Establish thresholds for disruption</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Make use of NR tree survey</td>
</tr>
<tr>
<td></td>
<td>Leaves on the line</td>
<td>Low - science does not support analyses at this stage</td>
<td>Improved science related to relevant factors - eg humidity, wind speed, temperature.</td>
</tr>
<tr>
<td>Sea level rise</td>
<td>Sea defences</td>
<td>Medium - seek bespoke solutions</td>
<td>Understand bathymetry on a location by location basis</td>
</tr>
</tbody>
</table>
Conclusions and recommendations

Conclusions and recommendations are set out within Section 2 for:

- Potential 'quick wins'
- Preliminary recommendations, asset management policy and planning
- Guidance to inform the railway industry of likely climate change issues and how they will be dealt with
- Geographically-based Standards development and further research requirements to support this

This section draws together conclusions and recommendations from the Met Office work and the work so far undertaken on the APET, and closes with general recommendations.

Met Office analyses

The following paragraphs, shown in boxes, are adapted from the Met Office final report (HMG, 2011).

Introduction

This project has investigated the potential impact of climate change on the operation of the GB railway network. The work focussed on 16 weather-related priorities identified in a series of expert workshops. A basic understanding of the relationships between railway operations and weather has been established through the investigation of climate-related thresholds and associated vulnerability metrics (where possible) for each priority. Further analysis is required to validate these relationships and thresholds. The use of delay minutes has provided a useful starting point for investigating the vulnerability of the railway network; ways of extending the vulnerability assessments are discussed.

By analysing regional climate model data, Met Office and railway experts have worked to understand how the frequency of weather-related incidents affecting railway operations could change by the 2020s, 2030s and 2040s. Projected frequency changes are given, with estimates of their possible ranges. Results can also be viewed on the web-based TRaCCA4Rail tool.

The following pages show summary findings from the Met Office work and recommendations on ways in which further investigation could build on the results.
Conclusions and recommendations

Met Office general recommendations

- The baseline relationships between weather and disruption on the railway network have not been validated. For example, we have not investigated whether the modelled baseline number of heat-related track patrols is truly representative of the actual number. This type of assessment would be helpful in terms of checking whether the expected relationships between weather and disruption are true.
- This work has considered timescales relevant out to the 2040s, to cover Network Rail's currently defined control periods. However, it is recognised that some aspects of railway infrastructure have a longer projected lifespan than would be covered by these assessments. This could be addressed by using climate projections covering time periods out to 2100.
- Some of the climatic conditions which could cause problems to the GB railway network in future are already experienced, and managed appropriately, in other parts of the world. There is an opportunity to learn from these countries regarding potential adaptive options for the GB network.
TRUST data: Overarching comments and recommendations

- Route boundaries may have changed during the period of data coverage; it has not been possible to account for this in the assessment. At the resolution of the vulnerability assessment undertaken here, minor route boundary changes are not likely to be important, but major ones may have an impact. Knowledge within Network Rail regarding any changes in route boundaries, and any legacy information prior to the TRUST data coverage period, could be helpful in this respect.

- Vulnerability indicators calculated in this work are totals - they are not normalised in any way. So, for example, a route may appear more vulnerable if it has a greater number of kilometres of track than another route, or carries a greater number of services than another route. It is recommended that some consideration be given to this issue so that appropriate normalisation methods may be defined for the priorities.

- The TRUST database covers a period of only five or six years; a longer record would facilitate a more robust assessment. It may be possible to address this by considering vulnerability data which pre-date TRUST, but the quality of these data is not known. As newer data become available, these could be incorporated into vulnerability assessments, but changing the definition of baseline vulnerability in this way would have an impact on any risk metric that were calculated. The implications of this should be considered carefully before decisions are made regarding which data to use for a vulnerability assessment.

- The vulnerability analysis that has been conducted in this work has been at a route-region resolution; it has not been possible within the timescale of the project to conduct a more in-depth analysis. If data were available for the stations and Engineers' Line References (ELRs) along particularly important routes, it would be possible to identify area/route specific delays.
Conclusions and recommendations

Priority-specific summaries and recommendations

Track buckling, temporary speed restrictions and heat-related track patrols

Summary

- The number of heat watchman days and the frequency of speed restrictions being imposed (associated with buckle risk and high temperatures) is projected to increase out to the 2040s for all track conditions examined.
- There are some exceptions in the case of track conditions with higher critical temperatures; here, exceedance is rare or absent in modelled baseline and may remain rare or absent in future.
- Care should be taken when interpreting any result involving a high temperature threshold (33°C or higher) as projected exceedances of these thresholds are sensitive to the choice of analysis method.
- For this priority, vulnerability data from TRUST were categorised as far as possible according to the reported speed of restrictions (20 or 30/60mph as used in Network Rail’s track management standards) However, this depended on the quality of the reporting.
- The relationship between an entry for a work order in Ellipse (from which the data for heat-related track patrols were taken) and the duration/number of track patrols was not clear.

Recommendations

- Our findings for this priority are based on an empirical conversion factor between rail temperature and air temperature. The use of a more rigorous relationship between these two quantities could be advantageous.
- Changes to the way in which buckling and related incidents are recorded could be of assistance in any future vulnerability assessment.
Windows of opportunity for track maintenance

Summary

- The number of non-track-work-days associated with unsuitable temperature conditions is projected to increase by the 2040s across the GB railway network.
- 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.
- Assessing the vulnerability of the network for this priority was difficult as there was no suitable filtering criterion in TRUST - for example, no specific phrase could be identified which could be used to query the incident description field in order to identify heat-related track maintenance issues.

Recommendations

- Changes to the way in which heat-related track maintenance issues are recorded could be of assistance in any future vulnerability assessment.
Conclusions and recommendations

Incidence of heat-induced sag of overhead line equipment

Summary

• 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 OLE sag by the 2040s with respect to the baseline period.
• 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.
• Care should be taken when interpreting any result involving a high temperature threshold (33°C or higher) as projected exceedances of these thresholds are sensitive to the choice of analysis method.
• Vulnerability was assessed by filtering the TRUST data for occurrences of ‘sag’ in the incident description.

Recommendations

• Our findings for this priority are based on a number of assumptions about the relationship between air temperature and overhead line temperature. The use of a more rigorous relationship between these two quantities could be advantageous.
• There may be a better method for identifying sag incidents in the vulnerability data. This should be investigated.
Staff exposure to heat stress

Summary

- 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.
- The number of episodes of human heat stress is projected to become more frequent by the 2040s.
- During the modelled baseline period there are relatively few heat stress episodes, but by the 2040s, more episodes are projected, especially in the south. Percentage changes in numbers of heat stress episodes are projected to be greatest in the North and West of Great Britain.
- A vulnerability assessment was not possible for heat stress as no agreed metric could be identified.

Recommendations

- Alternative heat stress analysis methods could be investigated, that represent better the impacts of heat on the railway industry workforce.
- Consideration should be given to identifying an appropriate metric for recording the workforce’s vulnerability to heat stress.
Conclusions and recommendations

Passenger and freight risk from train failure in extreme weather

Summary: freight risk (extreme cold)
- The issue of cold weather safety performance was addressed via a threshold exceedance analysis of winter minimum temperatures.
- The occurrence of cold conditions (with reference to two specific thresholds, 0°C and -5°C) is projected to decrease, but not to cease altogether, by the 2040s.

Summary: passenger risk (extreme heat)
- Previous work found that intolerable conditions on trains were caused chiefly by a rise in humidity at elevated temperatures, to a point where passengers were significantly uncomfortable and heat stroke was an imminent danger.
- This issue has therefore not been investigated as part of this work, due to the difficulty in relating the internal carriage temperature and humidity to a parameter that could be easily modelled, such as the external air temperature.

Recommendations: freight risk (extreme cold)
- Our findings for this priority are based on an analysis of minimum temperatures alone. It would be of interest to investigate the extent to which other climate parameters - such as snow and humidity - are relevant to this priority.

Recommendations: passenger risk (extreme heat)
- It is recommended that this area is investigated in collaboration with technology such as Ventilation of Linked Enclosures software (VOLE) which will allow climate information to be incorporated in a more complete model of the situation. From communications between the Met Office and Network Rail, there was interest in trying to take account of the nature of the failure and investigating possible relationships between climate factors and loss of traction current.
Heat affecting lineside equipment

Summary

Preliminary data from an ongoing research project into location cases were too sparse to develop a thorough methodology for investigation of this priority.

It was felt that there was insufficient information about the relationship between ambient air temperature and the temperature inside the equipment to allow any assessment of the impact of changing temperatures upon the operation of the equipment.

This priority was therefore not investigated further in this study.

Recommendations

- It is recommended that this priority area is taken forward once sufficient information to derive a relationship between ambient temperature and that inside location cases becomes available from the signalling engineering team.
- Appropriate vulnerability metrics could also be established.
Conclusions and recommendations

River flooding and localised rainfall flooding priorities

Summary

- River flooding can lead to many railway industry problems including scour and flooding of bridges, embankment scour and culvert washout, depot flooding and track and lineside equipment failure. 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.
- The results point towards an increased risk of river flooding; however the magnitude of change remains uncertain.
- Total daily rainfall extremes have been analysed to understand future localised surface water flood risk. 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.
- Vulnerability was assessed by examining TRUST data for flooding events. The source of the flooding, that is whether it is from a fluvial, pluvial or groundwater source, is rarely recorded; nor is the specific asset which was flooded. This made it difficult to assess accurately the vulnerability of different assets to different types of flooding.

Recommendations

- The analysis presented here has not investigated the impacts of natural climate variability. Further statistical analysis would be required to understand how this limitation could affect the conclusions drawn for flooding priorities.
- Changes to the way in which flooding events are recorded, whereby flood depths, durations, and spatial extent at specific locations are recorded, could be of assistance in any future vulnerability assessment.
Landslip risk
Summary
- This priority was assessed via a preliminary analysis for the WCML only.
- 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.
Recommendations
- Our findings for this priority are based on a preliminary analysis which involved a number of assumptions about the relationship between rainfall and landslips. A more detailed assessment is required, considering this relationship (and its potential spatial variation across Great Britain) more closely.

Groundwater flooding
Summary
- The influences on groundwater flooding are not limited to short-term weather conditions but also geology and longer-term (monthly to annual to multi-year) variations in climate.
- Projected seasonal variations could have a significant impact on the frequency and severity of groundwater flooding in prone areas.
- Both the IPCC’s third and fourth assessment reports state that much more research is needed into the interplay of groundwater levels and climate change on a seasonal basis.
- Anecdotal evidence has suggested that delay minutes from groundwater flooding account for a relatively low proportion of the total delay minutes from flooding.
- This priority was therefore not investigated further in this study.
Recommendations
- Since many factors (which may or may not be climate-related) affect this priority, progress on this would rely on significant advances in scientific research.
Conclusions and recommendations

Trees - obstruction risk on the line, leaves on the line

Summary: trees on the lineside
- Railway speed restrictions and track disruption can result from trees being blown onto the lineside when there are high winds.
- Projections for the 2040s suggest little change in the overall wind speed distribution, although a higher future frequency of the more extreme (70mph) wind gusts is seen alongside a mean reduction in the frequency of lower thresholds (30 and 40 mph) being exceeded.
- There are, however, large uncertainties in these projections due to limitations of the model, the gust parameterisation used and the observation datasets.

Summary: leaves on the line
- Many factors - both climatic and non-climatic - affect the occurrence and severity of the impact of leaves on the line.
- Some of the climatic parameters are not modelled well or at all by the current generation of climate models.
- This priority was therefore not investigated further in this study.

Recommendations: wind, obstructions and trees on the lineside
- Further work is required to understand better the relationship between wind speeds and railway disruptions.
- It was also not clear how incidents relevant to this priority are recorded. Clarification and/or improvements to the recording of these would be useful.
- Knowledge of locations that are particularly susceptible to wind-related disruption would also be useful.
- Recent work by Network Rail, investigating large tree condition and the density of vegetation across the network, will be useful in taking this priority forward.

Recommendations: leaves on the line
- Recent work by Network Rail, investigating large tree condition and the density of vegetation across the network, will be useful in taking this priority forward.
Flooding from the sea

Summary

- At key locations across the UK where railway infrastructure is at risk from inundation by the sea, sea level rise and storm surge level projections for 2045 have been made, to provide an indication of coastal flood hazard.
- The sea level rise projections presented range from 3cm to 32cm, depending on local factors, with storm surge presenting an additional risk.
- Vulnerability data were not investigated for this priority.

Recommendations

- Further analysis is required to translate the sea level rise projections into future impacts on the railway infrastructure.
- A vulnerability assessment of the railway network would require an assessment of other factors including the current sea defences for an asset at risk.
- In-depth studies could be completed at specific sites, to allow quantitative projections of future maximum sea levels at those sites.

Further analyses, and APET

Further phases of the Met Office's contribution to the TRaCCA project would be to develop a full climate change risk assessment for the GB railway network. This would involve more detailed collaboration with a range of railway industry and wider stakeholders in order to develop better understanding of the baseline vulnerability (and the possible actions that could be taken to reduce this in future), and to combine this with better understanding of the projected hazard posed by climate change to the railway industry.

This would facilitate the further evolution of the web-based visualisation tool into the APET, which would include an estimate of risk both now and into the future, together with ways to evaluate the costs for the railway industry as a consequence of a changing climate.
Conclusions and recommendations

Climate change - positive outcomes

While much attention has been given to the negative outcomes of climate change, the impacts and possible adaptation measures, there are potential positive outcomes, and some are listed here:

- Cold winters become rarer, meaning that the impact of severe winters on railway transport will diminish on average over future decades. In the longer term, if the absolute low-end temperatures increase then the opportunity to raise the installation stress-free temperature of rail might present itself, so reducing track buckle risk and the disruption caused by the risk management procedures.

- There is likely to be an increased demand for leisure railway travel and people might choose to holiday in a warmer climate at home. Expensive oil-based fuels for road transport coupled with sustainability targets and greenhouse-gas emission controls, could make railway a 'greener' choice.

- Climate change and adaptation modelling has the potential to become an enabler for prioritised, targetted and economic investment for renewal and maintenance programmes, and for operational forecasting tools such as the storm forecasting system developed for Dawlish Sea Wall, where RSSB research6 provided the basic modelling for daily, 36-hour forecasts as are currently provided.

- Investment in adaptation creates improved railway system resilience, consequently making the railway a more reliable and attractive mode of passenger and freight transport.

- The TRaCCA project has recommended the use of geographically differentiated standards to take account of the wide forecast variation in climate and weather impacts around the network. Adopting such an approach could enable lower industry costs to be achieved as infrastructure would be built, operated and maintained to suit local conditions rather than national extremes.
General recommendations

For the future, it is recommended that the railway industry builds upon the knowledge and expertise gained through the TRaCCA project.

A comprehensive programme of research, development and implementation activity is proposed, a programme that:

- Takes forward the planned development of the APET for those priority topic areas where the data on existing climate impacts and the science required to provide a link between the changing climate and the climate impact, are available.
- Works with the Met Office, research organisations and academia to refine the science.
- Revisits the 'Phase 1' priorities and looks at wider issues such as supply chain security.
- Develops and adapts the existing liaison activity with externally-funded climate-related R&D to provide railway industry benefits.
- Works with the railway industry to improve, redefine, create appropriate metrics or seek alternative ways of using existing data and data capture processes for climate impacts, taking account of existing data sources that are relevant to climate impacts.
- Develops an implementation plan for the TRaCCA research outputs with definable benefits.
- Considers the challenges from the perspective of systemic risks, and opportunities from systemically resilient design with the potential for early benefit realisation.
- Looks forward to the year 2100.
- Seeks funding from the widest possible sources - Europe, EPSRC, NERC, TSBs, RSSB and Network Rail, for example.

The Appendix outlines a structured approach that builds on these recommendations.
References

Defra. Defra advice for ‘reporting authorities’,

Futurenet. EPSRC-funded research project FUTURENET (Future Resilient Transport Networks) http://www.arcc-futurenet.org


RSSB. Assessing the impact of climate change on transport infrastructure. (http://www.rssb.co.uk/SiteCollectionDocuments/pdf/reports/research/T643_rpt_final.pdf, 2007)

Outline for a continuing programme of work

Figure 3 shows a possible framework for a continuing programme of work, showing seven overarching work packages and ten discrete work packages, for delivery over 5 years.

Figure 3 - A programme management framework for future work
Work package remits and timelines

Table A1 describes each work package in outline and provides a possible timeline for delivery.

Table 4 - Outline work package remits and timelines

<table>
<thead>
<tr>
<th>Work package theme</th>
<th>Description and Remit</th>
<th>Timeline</th>
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<tbody>
<tr>
<td>Knowledge</td>
<td>WP A: Review scientific knowledge from TRaCCA and from external bodies (eg ARCC, Environment Agency) and from railway industry as relevant to WPs 1-9. Form knowledge sharing partnerships where beneficial. Influence external research programmes.</td>
<td>A continuing activity</td>
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<td></td>
<td>WP B: Seek funding from Research Councils/ Knowledge Transfer Networks via alliances with academia and research bodies, from railway industry sources (Network Rail, RSSB), etc.</td>
<td>December 2011</td>
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<tr>
<td>Metrics</td>
<td>WP C: Review available measures for appropriateness - are they representative and of utility for research and policy evaluation purposes? Propose new metrics or ways to make better use of existing metrics, such as using temporal or spacial multiplication factors or data mining techniques based on sample data. For example TRUST delay minutes as used in TRaCCA show only part of the 'cost', being related to (a) a system developed to attribute costs within the railway industry for delays (b) a financial transaction not representative of loss to the economy (c) the time until (if actioned) a line closure is imposed. Neither do TRUST delay minutes take account of any material damage caused by weather events.</td>
<td>March 2012</td>
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### Priorities

WP D: With the benefit of WP’s A and C, review the priorities identified in TRaCCA Phases 1 to 3 and confirm or reprioritise WPs 1 to 9.

Consider whether other activities or areas need to be examined as a matter of priority - for instance are there issues over supply chain security/biodiversity/skills and competence that need early examination?

**Timeline:** March 2012

### System dependencies

WP E: The aim of WP E is to consider resilience of the railway as a system, to identify locations of vital importance by virtue of (eg) the density of dependent critical infrastructure, its potential for cascade failure and options for increasing its resilience.

Initially WP E will review academic work in this area (ITRC http://itrc.org.uk/home/ and City University www.csr.city.ac.uk) and consider engaging in 'proof of concept' work with City University.

WP E will consider also timing with respect to potential ITRC outputs, for best value and efficiency reasons.

**Timeline:** Initial work March 2012

Potential engagement with ITRC and City University up to and beyond the start of CP5 (2014)

### Future programme

WP F: Dependent on the priorities’ review in WP D, WP F will set out the CP5/future programme to tackle (eg) areas where science and data have improved allowing robust analyses; areas of lesser priority as exist now and new priorities as may be required

**Timeline:** Late 2015

### Adaptation Policy Evaluation Tools

WP G: This will embrace the development of evaluations tools in phases, as is being proposed at the time of drafting this report.

**Timeline:** Phased: with a Track tool by March 2011, and other topics to follow.

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### Table 4 - Outline work package remits and timelines

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Appendix A

Table 4 - Outline work package remits and timelines

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<tr>
<td>Heat and Track Buckle Risk Management</td>
<td>WP 1: This will investigate the relationships between rail and air temperatures, and delay attribution and metrics from WP C, examining the worth of taking into account topographic and orientation features with a view to producing a robust quantified climate risk map of the network that permits targeted investment.</td>
<td>2016</td>
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<td>Heat and Overhead Line</td>
<td>WP 2: This will investigate the relationships between conductor wires of different materials and form and air temperatures, and delay attribution and metrics from WP C, examining the worth of taking into account topographic and orientation features with a view to producing a robust quantified climate risk map of the network that permits targeted investment.</td>
<td>2016</td>
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<tr>
<td>Heat and Lineside Cabinets</td>
<td>WP 3: This will investigate the relationships between in-cabinet and air temperatures, the reliability of equipment and delay attribution and metrics from WP C, examining the worth of taking into account topographic and orientation features with a view to producing a robust quantified climate risk map of the network that permits targeted investment.</td>
<td>2016</td>
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<tr>
<td>Heat and workforce risk</td>
<td>WP 4: This will investigate relationships between air temperatures, insolation and heat stress on people, with alternative analysis methods compared. Metrics from WS C will be considered. Work on heat thresholds, heatwaves and uncertainties from the EQUIP programme (<a href="http://www.nerc.ac.uk/research/programmes/uncertainty/background.asp">http://www.nerc.ac.uk/research/programmes/uncertainty/background.asp</a>) will be examined.</td>
<td>2016</td>
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Heat and rolling stock risk

WP 5: This will investigate relationships between air temperatures, insolation, cold, snow and ice on railway vehicles. Metrics from WS C will be considered.

A wide range of impacts from risks to passengers on failed trains from heat, to (eg) snow and ice on traction motors and maintenance equipment will be investigated.

Work on heat thresholds, heatwaves and uncertainties from the EQUIP programme (http://www.nerc.ac.uk/research/programmes/uncertainty/background.asp) will be examined.

Precipitation and landslip risk

WP 6: This will build upon knowledge on the behaviour of over-consolidated clays, soil moisture deficit and rainfall thresholds along with the NR Water Environment Risk Model tool to determine relationships for other soils and the potential spatial variation across the network with a view to producing a robust quantified climate risk map of the network that permits targeted investment.

WP 6 will consider also timing with respect to potential FUTURENET outputs, for best value and efficiency reasons.

Precipitation and flooding - scour

WP 7: This will make use of catchment-wide analyses potentially in collaboration with CEH Wallingford, the Environment Agency and SEPA, alongside NR’s detailed asset information regarding bridges and earthworks at risk from scour, with a view to producing a robust quantified climate risk map of the network that permits targeted investment.

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### Appendix A

#### Table 4 - Outline work package remits and timelines

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<tr>
<td>Precipitation and flooding - property, lineside, track</td>
<td>WP 8: This will make use of surface water risk mapping and fluvial, catchment-wide analyses potentially in collaboration with CEH Wallingford, the Environment Agency and SEPA, alongside NR's detailed asset information regarding drainage, depots, stations, lineside equipment and track, with a view to producing a robust quantified climate risk map of the network that permits targetted investment.</td>
<td>2016</td>
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<tr>
<td>Wind and obstructions - fallen trees, debris, rolling stock</td>
<td>WP 9: This will investigate the relationships between wind speeds and delay attribution and metrics from WP C, knowledge of locations particularly sensitive to wind-related disruption will be considered as will examining the worth of taking into account topographic and orientation features and the recently-compiled NR national tree survey, as well as data on OLE, vehicle and debris will be examined, a view to producing a robust quantified climate risk map of the network that permits targetted investment.</td>
<td>2016</td>
</tr>
<tr>
<td>Sea level rise</td>
<td>WP 10: This will make use of coastal flood and erosion risk mapping potentially in collaboration with CEH Wallingford, the Environment Agency and SEPA, alongside NR's detailed asset information regarding coastal and estuarine defences, drainage, depots, stations, lineside equipment and track, with a view to producing a robust quantified climate risk map of the network that permits targetted investment.</td>
<td>2016</td>
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