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Title: Adapting Railways to Provide Resilience and Sustainability

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**Abstract**

The reality of anthropogenic climate change is increasingly apparent, with significant implications for railway and other infrastructure networks. As a transport mode with a relatively small environmental impact, rail has a potentially valuable role to play in climate change mitigation. However, this potential can only be realised if railways are adapted to withstand the effects of the increasingly extreme weather associated with climate change predictions.

This requirement is widely acknowledged by government and the railway industry, and the required responses to the specific potential effects of climate change are well-known and understood. However, a review of the literature indicates a need for a decision support system to prioritise the interventions required for adaptation in the face of considerable uncertainty about both the frequency and scale of future extreme weather events, and the nature and levels of future passenger and freight traffic on the railways.

This paper proposes a seven-step framework for the classification of the railway network, the assessment of the economic value of traffic using the network (and thus the economic costs of weather-related disruption), the identification of appropriate remedial measures and their costs, and thus the prioritisation of these measures by means of cost-benefit analysis.

**Keywords** **chosen from ICE Publishing list**

Railway systems; Sustainability; Infrastructure planning

**1. Introduction**

Heavy rainfall and coastal and inland flooding caused extensive damage and disruption to parts of Britain’s railway network, particularly in the south and west of the country, in early 2014. While individual occurrences of extreme weather cannot be linked explicitly to climate change, these events form part of a pattern that is consistent with climate scientists’ predictions of the effects of a changing climate.

This paper reviews a range of sources of information to assess the implications of climate change for transport systems in general, and for the railway industry in particular. It considers the role of railways in climate change mitigation, but focusses mainly on the need for the railway industry to adapt to it, and how it should do so, considering the distinct but complementary roles of infrastructural and operational resilience.

Following this introduction, the likely effects of climate change on transport systems are first reviewed, with a particular focus on railways. The possible responses to climate change are then considered, in the two broad categories of mitigation and, particularly, adaptation. Following a review of the literature on adapting railways to climate change, these effects and responses are considered in the context of a case study, and a framework for the assessment and improvement of network resilience is proposed. Finally, some conclusions are drawn.

**2. Assessing the Likely Effects of Climate Change**

The 2014 report from the Intergovernmental Panel on Climate Change (IPCC) states that

*warming of the climate system is unequivocal [and] will amplify existing risks and create new risks for natural and human systems.*

The growing consensus on the reality of this anthropogenic climate change is evident from the considerable effort that has been made to assess its likely effects on society, including transport infrastructure and systems, in Britain and elsewhere. In Britain, the government Department for Environment, Food and Rural Affairs prepared a report (Defra, 2011) entitled *Climate Resilient Infrastructure: Preparing for a Changing Climate*, in which it warned that “the scientific evidence [of climate change] is overwhelming” and stated the need for Britain to increase the resilience of the national infrastructure to the impacts of climate change, while also putting society on a low-carbon trajectory.

The report covers four major infrastructure categories: energy, ICT, transport and water. It emphasises the need to adapt existing infrastructure and design new infrastructure to prepare for a changing climate, with the aim of providing networks with resilience to both contemporary weather-related events and those projected to occur as a consequence of climate change.

The report includes examples of actions being taken internationally to adapt infrastructure to climate change, and provides guidelines for successful adaptation approaches, to ensure that it is effective, efficient, equitable and evidence-based. It also notes the “uncertainties surrounding the scale, timing and nature of exactly how the climate might change”, increasing the challenge of deciding what should be done for adaptation purposes, and how and when to adapt. It provides examples of good practice for existing and new assets of varying lifespans.

For the purposes of the report, Defra received individual, sector- and mode-specific adaptation plan reports (Defra, 2012) from the relevant organisations, including Network Rail, the Infrastructure Manager (IM) of Britain’s heavy rail network. The Network Rail (2011a) contribution concludes that the various components of the railway system will be affected by climate change, as therefore will “most of Network Rail’s roles, responsibilities and functions.”

It also notes Network Rail’s focus on the likely effects of climate change on the ability to operate a safe and reliable railway, while simultaneously providing additional capacity and enhanced value for money. Specific potential impacts identified in the report include the following:

* Track buckling and associated speed restrictions arising from increased temperatures
* The effects of heat stress on staff and passengers
* Sagging of overhead line equipment (OHLE) due to increased temperatures
* Increased river and groundwater flooding, damaging bridges, earthworks, track and lineside equipment
* Sea level rises and increased storm surges

Uncertainty about the nature and effects of climate change is again cited as a barrier and a challenge to the preparation of adaptation plans, exacerbated by uncertainty about required industry outputs, funding and “the precise network size, shape and traffic volume in the very long term.”

At the European level, the objective of the EU project *Management of Weather Events in the Transport System* (MOWE-IT, 2014a) was to

*identify existing best practices and to develop methodologies to assist transport operators, authorities and transport system users to mitigate the impact of natural disasters and extreme weather phenomena on transport system performance.*

The effects of climate change were considered within its remit, and the project’s output includes a *Guidebook for Enhancing Resilience of European Rail Transport in Extreme Weather Events* (MOWE-IT, 2014b). The Guidebook presents examples of extreme weather events, including heavy rain, high winds, heavy snow and extreme cold, and provides guidelines for dealing with these categories, including preparations in the long term and immediately prior to such events, during the events themselves, and in the aftermath of events. It also provides general recommendations and guidelines, but does not explicitly consider the wider issue of climate change and adaptation.

It can thus be seen that government and the railway industry clearly recognise the reality of, and the risks and challenges posed by, climate change, and the need to both mitigate and adapt to these.

**3. Responses to Climate Change**

As indicated above, responses to climate change fall into two broad categories: (i) mitigation (i.e. limiting its extent and effects), and (ii) adaptation to the effects that do occur; the IPCC (2014) describes them as “complementary strategies for reducing and managing the risks of climate change.” Defra’s 2011 report defines the two approaches as follows:

* *Adaptation to climate change: Adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities.*
* *Mitigation ([of] climate change): Action taken to reduce the impact of human activity on the climate system, primarily through reducing net greenhouse gas emissions, for example carbon dioxide.*

As noted by Armstrong and Preston (2011), rail, as a transport mode with a comparatively small environmental impact, has a potentially valuable role to play in climate change mitigation, as well as a need to adapt to its effects. Duck (2015) notes the

*irony … that, at a time when climate change is very much favouring rail as a means of both passenger and freight transport, many of our already vulnerable coastal lines are becoming increasingly exposed to extreme weather and … attack by the sea.*

As Duck implies, railways need to adapt particularly in terms of reducing the vulnerability of their infrastructure to both individual extreme weather events and the longer-term effects of sea level rise. The mitigation role of railways is implicitly acknowledged by Network Rail (2011b): in its Initial Industry Plan (IIP) for Control Period 5 (CP5: 2014-2019), it establishes the objective of

*pursu[ing] initiatives to achieve long term reductions in carbon emissions through improved energy efficiency, new technology and lower carbon power sources and [to] facilitate modal shift, helping others make more carbon efficient journeys.*

The IIP does, however, acknowledge that the railway industry’s ability to mitigate the effects of climate change by means of electrification depends on decisions made by others on the energy sources used for the generation of electricity. It also confirms that

*rail needs to plan for the longer term impacts of a changing climate and its impact on infrastructure and operations [and] develop and implement a long term programme for adaptation.*

The Rail Safety and Standards Board (RSSB) commissioned the development by Arup, with support from the University of Southampton, of an *Operational Philosophy for the GB Mainline Railway* (RSSB, 2014a). The Operational Philosophy repeatedly observes the need for greater railway system resilience to deal with the effects of climate change, further emphasising the need for system adaptation.

***3.1 Adaptation to Climate Change***

Of the two general categories of response, adaptation is the more obviously urgent and tractable, since the industry is able (and needs) to improve its operational resilience, and can do so independently of other agencies; this is in contrast to mitigation, which requires a much broader response, including, as noted above, the energy mix used for power generation.

A recent review of transport resilience by the UK Department for Transport (DfT, 2014) observed that the effects of extreme weather on the railways are compounded by the age of much of the network’s earthworks and their relatively poorly-engineered (by contemporary standards) construction. The review acknowledges that “much progress has been made [in this area] by Network Rail in recent years”, but identifies its “18,200km of embankments and cuttings [as] a particular area of risk, with … 105 earthworks failures” in the winter of 2013/14, some of which caused lengthy line closures. This risk was illustrated again in 2015 by the closure in January of the Chiltern Main Line between Banbury and Leamington Spa because of a landslide in a cutting on the approach to Harbury Tunnel. The route is normally used by 50 freight and 80 passenger trains daily, and it was anticipated that the line would be closed for two months (New Civil Engineer, 2015). In the context of Harbury, Modern Railways (2015a) reiterated the threat posed to the resilience of the railway by ageing earthworks in a changing climate.

In addition to their vulnerability to rainfall, the historic construction of lines along river valleys and coasts, to serve settlements in these areas and to take advantage of favourable topography, makes them particularly vulnerable to inland flooding and coastal storms (Pant et al., 2014; Duck, 2015). Notable recent examples in Britain include the destruction and closure of the coastal line at Dawlish, severing the railway network in Cornwall and parts of Devon from the rest of the national system, flooding and damage on the west Wales coast, and flooding of inland routes in Somerset and elsewhere (DfT, 2014). As sea levels rise, so will the risk of flooding to low-lying coastal and estuarine railway alignments.***3.2 Increasing Railway Network Resilience***

It can be seen from the foregoing material that railways face distinctive and significant challenges in adapting to the effects of climate change to ensure their resilience. DfT’s 2014 Transport Resilience Review identifies three ‘layers’ of resilience to extreme weather:

* *It is about increasing the physical resilience of transport systems to extreme weather, so when extreme weather is experienced, people and goods can continue to move.*
* *It would be both very difficult and prohibitively expensive to ensure total physical resilience, so secondly it is equally about ensuring processes and procedures to restore services and routes to normal as quickly as possible after extreme weather events have abated.*
* *Thirdly, as part of this, it is essential to ensure clear and effective communications to passengers and transport users so that the impact of disruption on people and businesses is minimised.*

The second and third of these layers are concerned primarily with recovery from disruption and operational failures, whereas the focus of this paper is on the prevention of such failures, or, at least, minimising their immediate impact. With this in mind, the first layer of resilience above is subdivided into the two categories below:

* ‘Infrastructural resilience’ can be achieved by reinforcing individual routes and critical locations, or ‘single points of failure’ (DfT, 2014), by relocating routes to make them resistant to predicted changes, and by measures such as the replacement of track circuits in areas vulnerable to flooding with the use of axle counters, to reduce the vulnerability of the signalling system.
* ‘Operational resilience’ can be enhanced through a variety of means, from the use of available network redundancy and diversionary routes to enhance operational flexibility and ‘spread the infrastructural risk’, and thus reduce the impact of local failures, to short-term, temporary measures such as the use of portable flood barriers and temporary automatic signalling systems to maintain services at a reasonable level (DfT, 2014).

The first category focusses particularly on maintaining the operational integrity of individual links and nodes of the network, particularly those ‘single points of failure’ whose loss would cause significant severance of the network. Recent examples cited by DfT (2014) of such locations in Britain include the route along the sea wall at Dawlish, already mentioned above, and Cowley Bridge Junction, immediately north of Exeter. As the DfT review notes, the risk to coastal routes like that at Dawlish “will clearly grow in future as sea levels rise [and] storms become more intense”, with the implication that at least some are likely to face relocation or abandonment. Duck (2015) reiterates this warning, observing that important routes may need to be moved inland in the face of increasingly severe weather conditions.

The second category, ‘operational resilience’ includes the use of temporary measures to resolve partial or potential infrastructure failures, but also seeks to maximise the use of diversionary routes to maintain services between train origin and destination points, albeit possibly at the expense of planned stops at some intermediate locations. The value of such redundancy, including the clearance where necessary of routes to accommodate 9’6” high container traffic, was illustrated by the diversion via the West Coast Main Line (WCML) of container trains during the blockage of the Chiltern Main Line by the landslide at Harbury (Modern Railways, 2015b). This aspect of resilience, together with the third ‘layer’ referred to by DfT (2014), is a recurring theme in the RSSB (2014a) Operational Philosophy for Britain’s railways.

The situation in some parts of Britain is quite favourable for the use of diversionary routes, since the original, largely uncoordinated, 19th century development of the network resulted in the construction of many parallel, competing routes (Casson, 2009), some of which remain in use or are available for reinstatement. Two examples of this redundancy can be seen in Figures 1 and 2, showing schematic representations of parts of the network in the south-west and the south of England respectively.

Figure 1 shows that, while there are several different possible routes between London and Exeter, the number of direct links to Exeter reduces to two: one from the north, via Taunton, and one from the east, via Yeovil. South and west of Exeter, there is only a single route into Cornwall, via Dawlish (labelled D) and Plymouth. As noted above, the winter of 2013/14 saw significant disruptions and severance on this part of the network, with lengthy closures at Dawlish, and, to a lesser extent, at Cowley Bridge Junction (labelled CBJ in Figure 1). As described below, consideration is being given to the provision of an inland route between Exeter and Plymouth, one of the options being the reinstatement of the route (shown dashed in Figure 1) between Meldon and Bere Abbas (labelled M and BA respectively), which has the additional advantage of restoring rail links to the main settlements along the route, Okehampton and Tavistock. However, the proposed route runs through Cowley Bridge Junction, which has experienced repeated closures due to flooding in recent years, so the successful provision of network redundancy in the form of an alternative route depends upon the completion of work to reduce the likelihood of future closures of the junction.

Figure 1. Schematic partial representation of the railway network in south-west England

Bristol

B

Taunton

CBJ

M

BA

Plymouth

Exeter

Castle Cary

Dorchester

Yeovil

London

London

London

London

D

The limitations of network redundancy in the area were illustrated during the winter of 2013/14 when, while Cowley Bridge Junction was closed, flooding also resulted in the temporary closure of the line between Yeovil and Exeter, severing Exeter and the area to its south and west from the rest of the national network.

Figure 2. Schematic partial representation of the railway network in southern England

Basingstoke

Southampton

Portsmouth

Eastleigh

Salisbury

Woking

Guildford

Fareham

Romsey

London

Brighton

A

M

W

A similar example, of shorter duration, occurred on 25th January 2014, due to fallen trees caused by high winds. It can be seen from Figure 2 that there are several route options between Woking/Guildford and Portsmouth/Southampton (although the route between Basingstoke, Salisbury, Romsey and Eastleigh/Southampton is not yet electrified, unlike the rest of the network shown). However, on that date, trees were blown onto the tracks at Witley (labelled W), Micheldever (labelled M) and Andover (labelled A) in rapid succession, thus severing all possible routes shown between Woking/Guildford and the south coast (alternative, but more circuitous, routes are available). It can thus be seen that a combination of infrastructural and operational resilience is required to maintain train services in the face of the increasingly extreme weather conditions associated with climate change.

***3.3 Adapting the Railway to Address Climate Change: Review of Requirements***

The foregoing text clearly illustrates the need for the railway and other industries to adapt to the effects of climate change, but the systematic identification, prioritisation and implementation of the required interventions is a significant challenge. A search and review of the academic literature revealed only limited coverage of climate change adaptation in the railway industry. This mirrors the findings of Eisenack et al. (2011), who undertook a comprehensive review of the literature on climate change adaptation in the transport sector, and found that there was relatively little coverage of railways and that, in general, there was a

*gap in the literature between very unspecific and vague guidelines for adaptation … and very specific and concrete adaptations [and] that the literature does not report much about how to actually implement adaptations in management or administration.*

They observe that “developing strategies to support or enable adaptation seems difficult” and that most of the practical proposals that would be of use to decision-makers were found in the ‘grey literature’ (i.e. non-academic publications and reports, often commissioned by public bodies). In their conclusions, they identify a “need for research on adaptation instruments that should be as generic as possible.”

In the UK context, Hooper and Chapman (2012) reviewed the likely impacts of climate change on the national road and railway networks under a series of headings including changes in temperature, precipitation, seasonal timings and sea levels, and the effects of extreme weather events. They list a range of potential specific interventions, and note the importance of building “strategies for both adaptation and mitigation into plans for future developments.” However, reflecting and supporting the observations of Eisenack et al. described above, they do not indicate how such strategies should be developed, and similarly conclude that

*future research in this area is of paramount importance to inform decision making, design and planning for future transport networks and infrastructure to ensure that the UK’s transport networks are well equipped to cope with a changing climate.*

In the context of a case study based on Sweden’s railways, Lindgren et al. (2009) confirm the importance of “proactive planning regarding future climate change adaptation.” They note the role of rail in climate change mitigation, but also caution that the vulnerability of railway systems to climate change may be exacerbated by “increased demand for ... railway transport as part of a low-carbon transport system [if] adaptation is not taken seriously” (conversely, such increases in traffic also serve to enhance the potential benefits of improved system resilience and performance resulting from adaptation measures). In their conclusions, they recommend that adaptation measures should be guided and prioritised by means of a “systematic mapping of different types of climate threats, vulnerabilities and … consequences”, and that such prioritisations should be guided by the use of “appropriate methodologies … when performing risk and vulnerability assessments.” They also recommend the use of exploratory (using scenario-based approaches, for example) rather than purely predictive approaches, to reflect the uncertainty surrounding climate change and its consequences.

The need for a “formalised impact assessment method” is endorsed by Jaroszweski et al. (2010), who also emphasise the need to consider a range of potential future socio-economic scenarios, including changes to travel and transport patterns and the associated potential impacts of climate change, as well as the uncertainty associated with climate change itself. Similarly, Love et al. (2010) emphasise the need for “focused adaptation measures that consider all aspects of the socio-economic and political dimensions of the issue”, while accommodating significant uncertainties. Again, they conclude that there is a need for new methodologies and tools to inform infrastructure investments and projects, including “more appropriate economic decision criteria” and the handling of uncertainty, taking a whole-life approach and “constantly updating risk assessments and the benefit and cost analyses of adaptive strategies.”

As an example of the ‘grey literature’ mentioned above, within the railway industry, the RSSB project T925, *Adapting to extreme climate change*, produced two reports on Tomorrow’s Railway and Climate Change Adaptation (Tracca), to which Network Rail (2011a) also contributed. The Phase 1 Tracca report (RSSB, 2014b), based on work managed by Network Rail with inputs from the Met Office and the Association of Train Operating Companies (Atoc), describes the development of an adaptation strategy, to enable the “provision of improved reliability for the railway network, taking into account the impact of climate change.” In addition to the safety, reliability, capacity and value for money objectives set out by Network Rail (2011a), the report identifies the need for “a ’predict and prevent’ ethos” for assessing and responding to the implications of climate change for the industry. The report lists an agreed set of priority industry topic areas (which form the basis of the potential impacts listed by Network Rail (2011a)), and summarises government requirements for Network Rail. The Phase 1 Tracca report also sets out the Phase 2 and Phase 3 Tracca deliverables, including the development of models, tools and maps, preliminary assessments and recommendations, and the provision of industry guidance on climate change issues and how to deal with them.

The Phase 3 report (RSSB, 2014c) describes a revised package of work, and presents the progress made in and findings of Phases 2 and 3, including Met Office assessments, recommendations for potential ‘quick wins’, and preliminary asset management recommendations. The Met Office assessments of the impacts of climate change on the priority industry topic areas are presented, indicating increasing cause for concern in most areas. The development of route-based vulnerability maps and a visualisation tool is described, and some general guidance is provided for informing the industry of likely climate change issues and how to deal with them. The report also considers the possibility of and requirements for geographically-based Standards development, reflecting the variations in climatic conditions in different parts of Britain. Finally, recommendations for further research, building on the Tracca outcomes, are made. A proposed continuing programme of work is set out in Appendix A to the document, including the development of ‘Adaptation policy evaluation tools’; such a tool is proposed below.

As the first deliverable of the follow-up project, T1009, *Further research into adapting to climate change – Tomorrow’s Railway and Climate Change*, RSSB (2015) produced a summary of the work undertaken for Work Package 1 (WP1), i.e. project T910. This includes a list of identified potential impacts of climate change on Britain’s railways, and proposed responses to those impacts, It also includes a list of recommendations, including improvements to integration of data, lifecycle costing and approaches to adaptive pathways, and modelling and prediction. Again, some of these objectives are addressed below.

In the course of work undertaken for the Infrastructure Transitions Research Consortium (ITRC), Pant et al. (2014) developed a means of assessing the “systemic risk to Britain’s rail infrastructure from a range of disruptive events”, as advocated by Lindgren et al., and thus of prioritising investment to improve the resilience of the network. The proposed methodology takes account of passenger numbers using different links on the network, and the availability of potential diversionary routes, but does not explicitly consider freight movements; neither does it differentiate by different types of passenger travel, i.e. commuting, business and leisure, and the varying values of time (and thus economic value) associated with them. Including these elements entails only a relatively straightforward modification of the proposed approach, however. More significantly, the approach does not consider the costs of the interventions required to reduce the vulnerability of the identified critical elements of the network to climate change: when these costs are taken into consideration, and the cost-benefit ratios of the required interventions are examined, the prioritised order of interventions may be very different. Pant et al. also note the “greater economic and social impact” of railway asset failures in the event of significant modal shift to rail as part of a climate change mitigation strategy, but, as noted above, this would also serve to increase the potential economic benefits arising from climate change adaptation measures.

***3.4 Case Study: Improving Rail Connectivity in the South West of England***

A student Group Design Project (GDP) (Aston et al., 2014) was undertaken at the University of Southampton in 2013/14, co-supervised by one of the authors, with the aim of identifying and developing proposals for “rail improvements that may lead to increased social and economic performance, by enhancing connectivity in South West England.” Its overall focus was on the improvement of socio-economic conditions in the south-west of England, by means of improvements to rail services to, from and within the region.

The report highlights the recent growth of overall rail use in the region, which has

*been seen to be rapidly increasing, with some routes experiencing a growth of more than 100% over the last 10 years, approximately double the national average.*

In parallel with this increasing demand, the report warns that

*many parts of the track infrastructure are already [operating] at high levels of capacity utilisation, leaving little scope for additional services without significant infrastructure investment.*

The parts of the network with the least spare capacity include those in western Cornwall, but also “parts between Exeter and Plymouth, in particular the Dawlish Sea Wall section.” The project report concluded that, in addition to increasing speeds and thus reducing journey times, improved resilience and robustness are required “to improve the transport network and consequently boost economic performance.”

Recent historic data relating to flooding and other weather-related disruption were examined in the course of the project, and it was found that “the main problem areas are Cowley Bridge Junction and the Dawlish Sea Wall”, as already highlighted above. Short-term measures were assessed and proposed for both locations. However, on the basis of a predicted sea level rise of up to 0.81m by the end of the century, the report estimates that the annual number of Days with Line Restrictions (DLRs) at Dawlish could increase from approximately 10 to between 84 and 120, inevitably including some major disruptive events which could result in lengthy line closures.

The report therefore considers various options to provide alternative routes between Exeter and Plymouth, avoiding Dawlish, including the restoration of the link between Meldon and Bere Abbas, already referred to above (the railway industry has been conducting a similar exercise (Network Rail, 2014a)). A Multi-Criteria Analysis (MCA) approach was used to assess the various options for improvements to robustness and resilience (and journey times). The results of the MCA indicate that the top two ranked combinations of options include the reinstatement of the route via Meldon and Bere Abbas, and that two of the top three options include work in the Cowley Bridge Junction area to reduce its vulnerability to flooding. Subsequent Cost Benefit Analysis (CBA) indicated that the route reinstatement should take the form of a single-track line with passing loops.

The recommended measures thus provide enhanced ‘operational resilience’ for rail services to and from Cornwall and Devon by means of the provision of an alternative route between Exeter and Plymouth, while also providing improved ‘infrastructural resilience’ by reducing the likelihood of a ‘single point failure’ at Cowley Bridge Junction. This type of approach is likely to be increasingly relevant to and important for the railway industry (and other transport modes and infrastructure sectors) as society seeks to adapt to the likely consequences of climate change. It also has the wider benefit of providing enhanced resilience to non-weather-related disruptive events, such as accidents and train failures, and provides potential diversionary routes which may be used to reduce the impact of track possessions on passenger and freight traffic.

***3.5 A Proposed Framework for Assessing and Improving Network Resilience***

The case study described above had socio-economic concerns and objectives beyond the resilience of the railway network, but the provision of resilient railway services is essential to the meeting of those wider objectives. The study also considered a wide range of issues in considerable detail, from the economic performance and travel patterns of the south-west, to the detailed civil engineering requirements and costs of restoring train services between Exeter and Plymouth via Okehampton and Tavistock.

Such a detailed and extensive approach is perhaps inappropriate for an initial general review of resilience to the effects of climate change across the national railway network. As noted by Modern Railways (2015a), Network Rail has moved from a condition-based to a risk-based approach to maintaining its earthworks, while Network Rail’s (2014b) Asset Management Strategy indicates a more general move towards a risk-based maintenance strategy, allowing the organisation

*to progressively optimise maintenance intervals for a cost effective level of performance and risk, quantifying the trade-off between the cost of undertaking maintenance and the increasing risks associated with a deteriorating asset.*

A similar approach to the assessment of the risks posed by climate change to the resilience of different parts of the national railway network provides the opportunity to develop a coherent and consistent national framework for the assessment of risk and the identification of appropriate remedial action. The proposed approach is outlined as follows:

* Divide the railway network into significant nodes (primarily junctions) and the links between them (this could initially be done on the basis of ‘Constant Traffic Sections’ (CTSs), for example, as used in the recalibration of Network Rail’s Capacity Charge by Arup (2013)).
* Assess the social and economic value of the traffic passing through each node and link, taking account of and building upon the work undertaken by Pant et al. (2014) and incorporating different socio-economic scenarios.
* Using historic data (where available) on weather-related closures and disruptions, and estimates of likely future weather conditions in conjunction with the use of Monte Carlo-type simulation techniques and scenario analysis (to take account of the considerable uncertainty inherent to the effects of climate change), assess the probable frequency and duration of future disruptive events, and, using the assessed value of the traffic on the affected section of the network and taking account of potential alternative routes, the resulting economic impact and, thus, costs of disruption.
* Prioritising those elements of the network with the highest probable costs of disruption, identify measures to reduce the likelihood of weather-related disruption, by upgrading the element(s) in question and/or providing alternative routeings (including infill electrification and gauge enhancement where necessary), and their associated capital and maintenance costs. The primary benefits arising from such schemes are the reduction or avoidance of the costs of disruption associated with extreme weather events, but, where enhancements include the provision of alternative routeings that serve new markets, as in the case of the proposed reinstatement of services via Okehampton and Tavistock, these additional benefits should be taken into account.
* In each case, taking the benefits and costs determined in the preceding steps, identify the intervention with the most favourable Benefit-Cost Ratio (BCR, i.e. the ratio of the Present Value of Benefits (PVB) to the Present Value of Costs (PVC)), taking account of the fact that some schemes may provide benefits to multiple sections of the network, e.g. flood control measures on a river affecting two or more nodes or links on the network. The use of a Net Present Value (NPV, i.e. PVB - PVC) ranking is inappropriate in this context, since the projects under consideration would not, in general, be mutually exclusive. The discounting of costs, and, particularly, benefits in these circumstances is not straightforward, given the timescales involved and the longevity of the assets under consideration, and reference to the Treasury ‘Green Book’ would be required to identify the appropriate discount rates and assessment timescales.
* Undertake the interventions in approximately descending order of predicted BCR, taking advantage where possible of scheduled renewals and enhancement activities.
* Review the programme of assessment and interventions as and when additional data and improved estimates of future conditions become available.

Given the uncertainties surrounding climate change and the resulting weather conditions and their effects on the railway’s infrastructure, this is inevitably an inexact exercise, but it provides a useful starting point to a coherent approach to assessing the requirements for climate change adaptation. It also embodies the ‘predict and prevent’ ethos advocated by Tracca, and provides a framework for the evaluation of adaptation policy, as also recommended. The proposed approach also allows for the application of geographically-based Standards.

The foregoing work is based upon a review of academic and industry- and government-generated literature and documentation, which has demonstrated the need and provided the basis for the development of the proposed approach to assessing and improving railway network resilience in the face of climate change. The proposed approach, while meeting industry and social needs, is relatively abstract, and requires further development to enable its practical application. The next stage of the work entails the collection of existing and projected rail traffic data and its combination with infrastructure and projected weather data to undertake an assessment of risks and proposed remedial measures on a selected section of the network, and then analyse the associated costs and benefits. This will require liaison with Network Rail and the Train and Freight Operating Companies, and may be undertaken in collaboration with the proposed ITRC successor project.

**4. Conclusions**

The science underlying, explaining and predicting climate change is increasingly certain, with significant implications for the railway industry, among other human systems, particularly those with extensive infrastructure vulnerable to extreme weather.

The railway industry has a potentially valuable role to play in helping to mitigate the effects of climate change, but recent spells of extreme weather in Britain and elsewhere have demonstrated the industry’s vulnerability to the already apparent and likely future effects of a changing climate. In order for this potential role to be fulfilled, the industry must adapt its systems, and particularly its infrastructure, to enable it to accommodate the anticipated increasingly extreme weather conditions. The required adaptation takes a range of forms, from strengthening (or relocating) individual and multiple network nodes and links to reduce their likelihood of failure, to enabling resilience of operations through flexible responses to weather-related perturbations, to the provision of improved information to system users. In many locations and situations, a combination of these responses will be required to enable the railway to provide continuity of service to its customers, as demonstrated by the responses to recent events in south-west England. Such adaptation has additional advantages, in that it can improve the general quality and resilience of operations, providing valuable additional capacity and transport options, and enabling the industry to respond better to non-climate-related disruptive events.

The scale and frequency of recent weather-related disruptions of the railway network provide an indication of the potential scale of the challenge facing the industry, and emphasise the need to approach the challenge in a systematic, cost-effective manner. A review of the literature indicates that there is a ‘gap’ between the broad acknowledgement of the need for adaptation and the details of the required interventions (such as improved resistance to track buckling and flooding), and that a decision support system is required to identify and prioritise the most urgent and cost-effective interventions. This paper proposes a framework and approach to meet this need and to provide the industry with the resilience needed to minimise the predicted disruptive effects of climate change on its operations and its passenger and freight customers, and thus to fulfil its role as a viable and sustainable alternative to other mechanised transport modes. The next stage of the work entails the application of the proposed framework to a section of the network to further develop and validate the approach, and enable its wider application across the network.

**Practical Relevance and Potential Applications**

Following a sequence of increasingly frequent and severe weather-related disruptions to Britain’s railway system, this paper reviews assessments of the likely effects of climate change on infrastructure in general, and on Britain’s railway system in particular. It then considers rail’s role in climate change mitigation, and, in particular, the requirements for adapting to it, especially in terms of infrastructure enhancements to improve the railway system’s resilience to the effects of climate change, an area of particular practical relevance to the civil engineering profession.

The paper then sets out a proposed framework for classifying the railway network by socio-economic importance and vulnerability to climate change by ‘constant traffic section’ or similar, and thus for identifying and prioritising the measures required to improve network resilience to climate change (and also other disruptive events, as a ‘beneficial side-effect’). This approach could be applied by the civil engineering profession to the targeted upgrading of the railway network, and a similar approach could be applied to other transport and infrastructure systems.

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