Enabling Resilient Railway Operations in the Context of Climate Change

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Abstract
As a relatively environment-friendly transport mode, railways have a valuable role to play in mitigating anthropogenic climate change. However, this can only be achieved if railways can adapt to withstand the effects of the increasingly extreme weather associated with climate change. The primary challenge lies in protecting infrastructure from flooding, sea level rise, the effects on earthworks of heavy rainfall and/or drought, buckling of rails in extreme heat and the effects of lightning strikes on signalling systems. This challenge is exacerbated by the extent of railway networks, by the adaptation costs and the variable levels of vulnerability, and by the uncertainties associated with future climate conditions and traffic volumes and values. This emphasises the need for a systematic approach to adaptation, to ensure that the work undertaken is organised and scheduled to maximise the potential benefits arising from the limited funds and resources available. This paper proposes a framework for the segmentation of a railway network, assessment of the economic value of traffic using the network (and thus the economic costs of weather-related disruption), assessment of vulnerability of different segments of the network to the effects of climate change, identification of appropriate remedial measures and their costs, and their prioritisation by means of cost-benefit analysis. The proposed approach provides a comprehensive, prioritised approach to climate change adaptation, reflecting current and anticipated traffic and infrastructure vulnerability, and the varying costs and benefits of different intervention types. Proposed interventions can be prioritised by ranking them in descending order of Benefit-Cost Ratio.

Keywords
Railways, climate change, infrastructure, adaptation

1 Introduction

The science underlying anthropogenic climate change is increasingly certain, and emerging weather patterns reflect climate scientists' models and predictions. This has significant implications for railway and other infrastructure networks and systems, which are vulnerable to the effects of increasingly extreme weather conditions.

Two complementary courses of action are available to deal with climate change: (i) mitigation, whereby steps are taken to lessen the causes and consequences of climate change, for example by reducing greenhouse gas emissions or by using geoengineering to reduce the effects of climate change; and (ii) adaptation, whereby human and other systems are amended and adapted to cope with the effects of climate change. Examples of the latter include the installation of flood barriers and the strengthening of buildings and structures to resist higher wind speeds.

As a transport mode with a relatively small environmental impact, railways have a potentially valuable role to play in climate change mitigation. However, this can only be successfully achieved if railway infrastructure and operations are adapted to withstand the effects of the increasingly extreme weather associated with climate change. A systematic approach to infrastructure adaptation, as proposed in this paper, is required to ensure that the necessary enhancements are introduced in a timely and cost-effective manner.

Following the introduction, this paper reviews assessments of the implications of climate change for infrastructure in general, and on Britain's railway system in particular. It considers railways' role in climate change mitigation, but concentrates mainly on 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.

The paper then sets out a proposed framework for segmenting and classifying the railway network by socio-economic importance and vulnerability to climate change, and thus for identifying and prioritising the measures required to improve network resilience to climate change (and also to other disruptive events, as a 'beneficial side-effect'). This approach could usefully be applied to the targeted upgrading of the railway network, and a similar approach could be applied to other transport modes and infrastructure systems. Finally, some conclusions are drawn.

2 Background: Problem Statement and Objectives

The Intergovernmental Panel on Climate Change (IPCC, 2014) has reported that

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

This growing certainty and consensus on the reality of anthropogenic climate change is reflected in considerable efforts to assess its likely effects on society, including transport infrastructure and systems, in Britain and elsewhere. In Britain, the government Department for Environment, Food & 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 emphasised 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.

Four major infrastructure sectors are included in the report: energy, ICT, transport and water. The report emphasises the need to adapt existing and design new infrastructure for a changing climate, with the aim of providing networks with resilience to both current weather-related events and those anticipated as a consequence of climate change.

The report includes international examples of infrastructure adaptation being undertaken to deal with climate change, and provides guidelines to ensure that adaptation activities are effective, efficient, equitable and evidence-based. It acknowledges the inherent "uncertainties surrounding the scale, timing and nature of exactly how the climate might change", which increase the difficulty of deciding what should be done to adapt, and how and when. It also provides examples of good practice for existing and new assets of varying lifespans.

The report reflects individual, sector- and mode-specific adaptation plan reports provided for DEFRA (2012) by relevant organisations, including Network Rail, the

Infrastructure Manager (IM) of Britain's heavy rail network. Network Rail's (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." Network Rail's concerns about the potential effects of climate change on operational safety and reliability are set within the wider context and challenges of providing additional capacity and improved value for money. The Network Rail report includes the following specific potential effects of climate change:

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

The Network Rail document also cites uncertainty about the nature and effects of climate change as a barrier and a challenge to the preparation of adaptation plans, exacerbated by further uncertainty about required industry outputs, funding and "the precise network size, shape and traffic volume in the very long term."

The Executive Report for Britain's Rail Safety and Standards Board (RSSB, 2016) on Tomorrow's Railway and Climate Change Adaptation (TRaCCA) similarly found

> *unequivocal evidence that Britain's railway will, as our natural environment and socio-economic systems, be affected by changes in weather conditions caused by climate change.*

Again, the implications for the railway that are listed in the TRaCCA report include higher average temperatures, sea levels and rainfall, increasingly "frequent and severe adverse weather events", including not only floods and heatwaves (and thus the risk of track buckling), but also heavy snowfall. All of these will present additional risks to railway infrastructure and vehicles, operations and maintenance, and to users and staff.

At the international level, the European Union project *Management of Weather Events in the Transport System* (MOWE-IT, 2014a) aimed 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 included in the project remit, and its output includes a *Guidebook for Enhancing Resilience of European Rail Transport in Extreme Weather Events* (MOWE-IT, 2014b). Examples of extreme weather events, including heavy rain, high winds, heavy snow and extreme cold, are presented in the Guidebook, together with guidelines for dealing with each category, including appropriate long- and short-term preparations for them, activities 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.

These examples demonstrate that governments and the railway industry acknowledge the reality of, and recognise the risks and challenges posed by, climate change, and the need to both mitigate these and adapt to them. It can also be seen that the primary challenge posed to railway operations by climate change lies in reducing the vulnerability of the infrastructure to the predicted effects of climate change, and that related challenges include the size of railway networks, adaptation costs, the variable and uncertain levels of vulnerability, and the variations in current and likely future passenger and freight traffic volumes and values. These combined factors emphasise the need for a systematic approach to adaptation, to ensure that the work undertaken is organised and scheduled to maximise the potential benefits arising from the limited funds and resources available. The main objective of this paper is therefore to develop such an approach and methodology, to meet this need.

3 Review

3.1 Responding to Climate Change

As indicated in the preceding text, there are two main categories of response to climate change: mitigation (i.e. limiting the extent and effects of climate change), and adaptation to those effects that do occur. They are described by the IPCC (2014) as "complementary strategies for reducing and managing the risks of climate change." DEFRA's 2011 report includes the following definitions:

- *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.*

Armstrong and Preston (2011) observe that railways, being a transport mode with a relatively limited environmental impact, can help to mitigate climate change, but also need to adapt to its effects. This is supported by Duck (2015), who 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.*

Reporting on the International Union of Railways' (UIC's) 13th Sustainability conference, held in October 2016, the International Railway Journal (IRJ, 2016) observed that rail, by increasing its use of renewable energy, has the opportunity to "position itself as the natural transport partner to governments as they strive to reduce their emissions." Network Rail's (2011b) Initial Industry Plan (IIP) for Control Period 5 (CP5: 2014-2019) implicitly acknowledges the mitigation role of railways by establishing 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 concedes, though, that the effectiveness of electric traction in reducing carbon emissions depends on the energy sources used for electricity generation, over which the railway industry has limited control. It 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.*

Arup, supported by the University of Southampton and others, developed an *Operational Philosophy for the GB Mainline Railway* on behalf of RSSB (2014). The philosophy emphasises the need for enhanced railway system resilience to the effects of climate change, and thus the requirement for adaptation.

3.2 Climate Change Adaptation Needs

Of the two broad types of response listed above, mitigation is crucial in the long term, if a habitable planet is to be maintained. For the railway industry, the need for adaptation is already apparent, and the industry can proceed with this independently, whereas its wider role in mitigating climate change depends to some extent on other organisations, notably the electricity generation sector, and the source energy mix that it uses (coal-fired power generation being a much greater emitter of carbon dioxide than gas, or, especially, nuclear or renewable energy sources).

A review by the UK Department for Transport (DfT, 2014) found that the impact of severe weather on Britain's railways is exacerbated by the age of much of the earthworks across the network, and their relatively low (by today's standards) quality of construction. While the review commends the recent progress made by Network Rail in this area, it highlights "18,200km of embankments and cuttings [as] a particular area of risk, with … 105 earthworks failures" having occurred in the winter of 2013/14, with some lines closed for considerable periods of time as a result. In its latest Annual Return, Network Rail (2016) recorded 163 reportable earthworks failures for 2015/16, including "a number of significant failures" following the second wettest winter on record.

Many railways were built along coasts and river valleys, to serve the towns and cities often found in these locations, and to take advantage of the topography, such as gentle gradients along valley floors. However, such locations also expose them to the risks of inland flooding and coastal storms (Pant et al., 2014; Duck, 2015), hazards that are being increased by the effects of climate change. Recent examples in Britain include the collapse of sea walls carrying railway lines at Dawlish, in the south-west of England, in 2014, and between Folkestone and Dover in late 2015, both of which resulted in the respective lines being closed for several months while repairs were undertaken. The Dawlish closure was particularly significant, in that it severed Cornwall and west Devon from the rest of Britain's railway network.

3.3 Increasing Network Resilience

The preceding text shows that railways face significant challenges if they are to maintain their resilience in the face of climate change. DfT (2014) identified three elements of resilience in its Transport Resilience Review:

- *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 elements focus on recovery from disruption, whereas the primary focus of this paper is on prevention of failures where possible, and, failing that, minimising their immediate impact. The first element of resilience is therefore split into the two following sub-elements:

- 'Infrastructural resilience', which can be achieved by enhancing and strengthening 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 sub-element aims to maintain 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 (such as the line along the sea wall at Dawlish, mentioned above). The second sub-element, '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. A focus on operational resilience is consistent with the 'Journey Availability' metric advocated by the TRaCCA project (RSSB, 2016): this measure would focus on the combination of infrastructure and service availability, with a view to monitoring and improving levels of service continuity. This aspect of resilience, together with the third 'layer' referred to by DfT (2014), is also a recurring theme in RSSB's (2014) 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, 19^{th} 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. 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.

It can be seen from Figure 1 that there are several different possible routes between London and Exeter, but only two available ‘upstream’ links to Exeter: 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 due to the sea wall collapse at Dawlish, and, to a lesser extent, due to flooding at Cowley Bridge Junction (labelled CBJ in Figure 1). Because of the continuing vulnerability of the railway at Dawlish, 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 Alston (labelled M and BA respectively), which has the additional advantage of restoring rail links to the main settlements along the route, Okehampton and Tavistock (plans are already in place to re-open the route between Bere Alston 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.

The current 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.

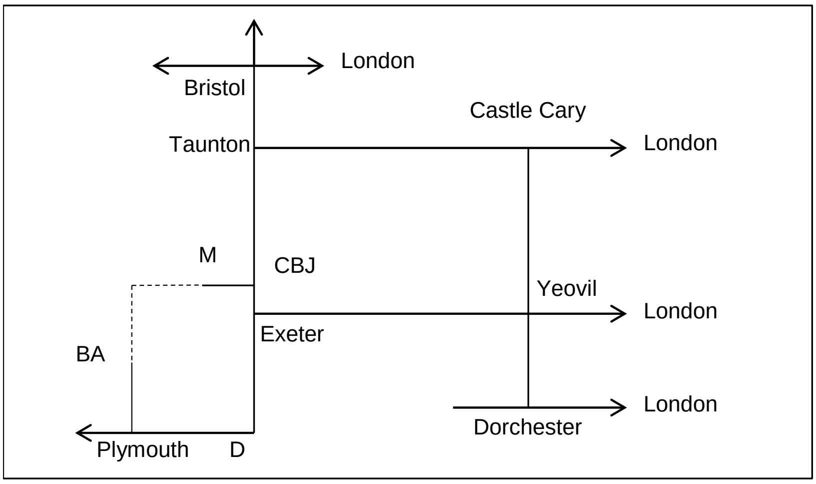

Figure 1: Part of the railway network in south-west England

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.

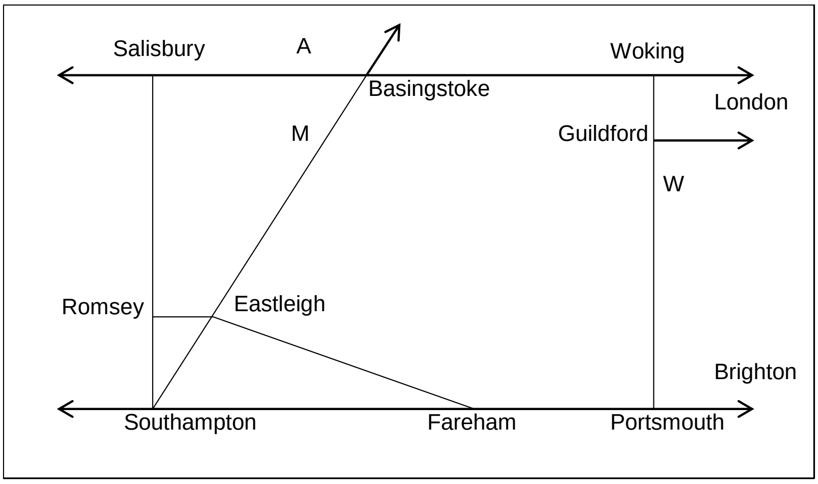

Figure 2: Part of the railway network in southern England

3.4 Developing Adaptation Strategies

The foregoing text demonstrates the need for the railway and other industries to adapt to the consequences of climate change; however, the systematic identification, prioritisation and implementation of the required interventions is a significant challenge in itself. A review of the literature revealed limited coverage of climate change adaptation in the railway industry. This reflects 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 note 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. in non-academic publications and reports, often commissioned by public bodies. They conclude that there is 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 headings including changes in temperature, precipitation, seasonal timings and sea levels, and the effects of extreme weather events. They present a range of potential specific interventions, and advocate the development of "strategies for both adaptation and mitigation into plans for future developments." However, mirroring the observations of Eisenack et al. described above, they provide no indication as to how such strategies should be developed, but conclude similarly 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 (when passenger services in Britain are affected by planned or unplanned disruption, the railway industry tends to rely on road transport as an alternative, with potentially negative environmental consequences in addition to impacts on overall journey times and passenger comfort and convenience). In their conclusions, they recommend the guiding and prioritisation of adaptation measures by means of "systematic mapping of different types of climate threats, vulnerabilities and … consequences", and the guidance of such prioritisations by means of "appropriate methodologies … when performing risk and vulnerability assessments." They also recommend the use of exploratory approaches (using scenario-based techniques, for example) rather than purely predictive methods, to reflect the uncertainty associated with climate change and its effects.

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

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 network's resilience. The proposed methodology considers passenger numbers using different links on the network, and the availability of potential diversionary routes, but does not explicitly consider freight movements; nor does it discriminate by different passenger journey purposes, i.e. commuting, business and leisure, and the varying time (and thus economic) values associated with each. Including these elements requires only a relatively minor variation on the proposed approach, however. More significantly, the approach excludes the costs of the modifications required to the identified critical elements of the network to reduce their vulnerability to climate change: when these costs are included, and the cost-benefit ratios of the required interventions are assessed, 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. However, as already indicated above, this would also increase the potential economic benefits arising from climate change adaptation measures.

The reports produced by RSSB's TRaCCA and predecessor projects are an example of the 'grey literature' referred to above. Project T925, *Adapting to extreme climate change*, produced two reports on Tomorrow's Railway and Climate Change Adaptation, to which Network Rail (2011a) also contributed. The Phase 1 TRaCCA report (RSSB, 2010), 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 and identifies the need for "a 'predict and prevent' ethos" for assessing and responding to the implications of climate change for the industry. The Phase 3 report (RSSB, 2011) identifies the need for an 'Adaptation Policy Evaluation Tool', "to enable the railway industry to evaluate policy options … for adaptation and weather resilience"; such a tool is proposed below.

As the first deliverable of the T1009 follow-up project, entitled *Further research into adapting to climate change – Tomorrow's Railway and Climate Change*, RSSB (2015) produced a summary of previous work. 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. The final project Executive Report (RSSB, 2016) reiterates the need for "detailed vulnerability mapping of assets and locations" and the replacement of "vulnerable assets based on life-cycle costs analysis, [taking] a long-term view of climate change adaptation policy."

4 A Proposed Framework for Assessing and Prioritising Improvements to Network Resilience

Network Rail has moved from a condition-based to a risk-based approach to maintaining its earthworks (Modern Railways, 2015), while the company's Asset Management Strategy (Network Rail, 2014) 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.*

If a similar approach is to be taken to the assessment of the risks posed by climate change to the resilience of different parts of the national railway network, a coherent and consistent national framework for the assessment of risk and the identification of appropriate remedial action would be useful. Such an approach is proposed and outlined below:

- 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), supported by the University of Southampton.
- 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 described above, 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 in the UK context 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, 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.

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. Future 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 relevant Railway Undertakings (RUs), i.e. the passenger Train and Freight Operating Companies, and may be undertaken in collaboration with the ITRC successor project.

5 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 mitigation 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 and elsewhere. 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 increased resilience. This is needed to minimise the predicted disruptive effects of climate change on the railway's 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.

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