Tomorrow's Railway and Climate Change Adaptation: Executive Report

RESEARCH AND
DEVELOPMENT

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Executive summary

This Executive Report, aimed at a non-specialist audience, presents the main findings and actionable insight that RSSB, working with a consortium led by Arup and with Network Rail, has derived from its research on Tomorrow's Railway and Climate Change Adaptation. The overall objectives of the research project were to enhance and disseminate knowledge within the GB railway industry about how climate and weather are projected to change in the future, the potential impact on the GB railway, what is already being done by the GB rail industry to respond and adapt, and what else can be done.

Our analysis has been carried out on the basis that Britain's rail network is part of the country's essential infrastructure.

We found unequivocal evidence that Britain's railway will, as our natural environment and our socio-economic systems, be affected by changes in weather conditions caused by climate change. Global average temperatures are higher than they were in past centuries and they are still increasing. Seas and oceans are warming and expanding as a result, polar ice caps are melting, sea levels are rising, and there are more varied and extreme weather patterns. Temperatures will be on average higher, there will be more record hot weather, precipitation levels and flooding risk will be higher, and there will be more frequent and more severe extreme weather events.

Global warming is changing the face of the planet and may have a profound lasting impact on our societies and our economies. Coastal regions, and low land areas in general, will be the most severely impacted by the rise in sea levels and higher precipitation, and vast areas of low lying ground - currently served by railway lines - may be lost due to climate change. Impacts from extreme weather events may lead to alterations of ecosystems, disruption of food production and water supply, damage to infrastructure and settlements, morbidity and mortality, and adverse consequences for health and well-being. The severity of these impacts is expected to be correlated with the level of preparedness for climate change. In the worst case scenarios, climate change will endanger critical infrastructure and territorial integrity, challenging the resilience of socio-economic systems.

As regards the railway, higher average temperatures, higher sea and precipitation levels, more frequent and severe adverse weather events such as floods, heat waves, and heavy snowfall, create specific risks for railway assets, operations and maintenance, staff and passengers.

The costs of adverse weather effects are already high, and are expected to increase dramatically with climate change in the coming decades, with more disruption to rail operations, more damage to railway infrastructure and assets, and more negative impact on people's health and wellbeing. Beyond the railway network, disruptions due to climate change will also incur significant costs to other dependent infrastructure networks and systems, and to our socio-economic system at large. For this reason, the long term benefits of climate change adaptation projects should be assessed with appropriate economic and financial methods (comparing the costs of doing nothing vs doing something, analysing knock-on effects and interdependencies in cases of railway disruption, complementing traditional cost benefit analysis with other methods, and designing new metrics based on the concept of Journey Availability).

The rail industry has a good understanding on what the risks are, and has already started to meet the challenges faced by climate change. However it cannot do this on its own and greater investment and support is required to maintain an effective rail system.

The railway industry in Great Britain has already introduced a wide range of measures to mitigate climate change. For example, Network Rail has developed and published climate change adaptation plans for all routes. It has also established a climate change resilience steering group to strengthen governance and adaptive capacity, and has recruited a range of specialists in the field. The climate change adaptation project has reviewed existing general weather management provisions, operational guidance, and design standards for assets. Some gaps have been identified, notably related to weather and climate related thresholds, wet weather management procedures, and upper temperature for design standards.

While the GB railway is relatively advanced in climate change adaptation and/or weather management, compared to other rail systems, it still has the opportunity to learn from its international counterparts' good practice. The project has identified some measures that other national railways have put into place or are recommending for addressing climate change challenges. There is however no silver bullet, as is recognised by specialists and professionals in the field.

Based on the gap analysis conducted on current preparations, and on identified good practice in the literature review (compendium) and among other national rail systems, the project made a number of recommendations to improve the climate change resilience of the GB rail network, including:

- Develop a multi-agency co-operation model.
- By use of detailed vulnerability mapping of assets and locations (including buildings, track, lineside equipment and trees, vegetation and adjacent land), it is possible to better identify those assets most at risk from climate change.
- Enhance weather incident reporting and asset condition monitoring. Incident reporting requirements should include associated local weather conditions, and the consistency and accuracy of recorded weather conditions where delays occur or assets fail should be increased.
- Expand the utilisation of GIS-based alert systems and weather susceptibility mapping, so that extreme weather conditions can be better understood. This will allow the targeting of mitigation resources where they will have the greatest impact.
- Review and revise standards (such as: increasing the maximum temperatures used in rail asset design standards to fit with future climate predictions, changing workforce safety standards to take into account working in adverse weather conditions) and make rail assets 'climate change proof'.
- Replace vulnerable assets based on life-cycle costs analysis, and take a long-term view of climate change adaptation policy (for instance, consider vegetation planting to reduce temperatures at vulnerable sites and to ensure more stable earthworks).
- Develop and apply a Journey Availability metric rather than one based on delay minutes to measure long-term performance of the railways.

These recommendations can be implemented in the short to medium term, and progress could be regularly monitored and assessed by the relevant experts. Climate change adaptation is a learning journey and therefore expert discussions should continue, and methods and approaches should be refined, taking into account the complexity of climate change issues and the many remaining uncertainties.

1 The British railway will be affected by changes in weather conditions caused by climate change

Scientific evidence shows that the warming of the global climate system is unequivocal: global average temperatures are higher than they were in past centuries and they continue to increase. As a result, seas and oceans are warming, polar ice caps are melting, sea levels are rising, and there are more varied and extreme weather patterns.

- Temperatures will be on average higher
- There will be more incidents of record hot weather
- Precipitation levels and flooding risk will be higher
- There will be more frequent and more severe extreme weather events

Global warming is changing the face of the planet and may have a profound lasting impact on our societies and our economies. Coastal regions, and low-lying land in general, will be the most severely impacted by the rise in sea levels and higher precipitation. Vast areas of low-lying land - currently served by the railway - may be lost due to climate change. Impacts from extreme weather events, such as heat waves, droughts, floods, cyclone, and wildfires may lead to alterations of ecosystems, disruption of food production and water supply, damage to infrastructure and settlements, morbidity and mortality, and adverse consequences for health and well-being.

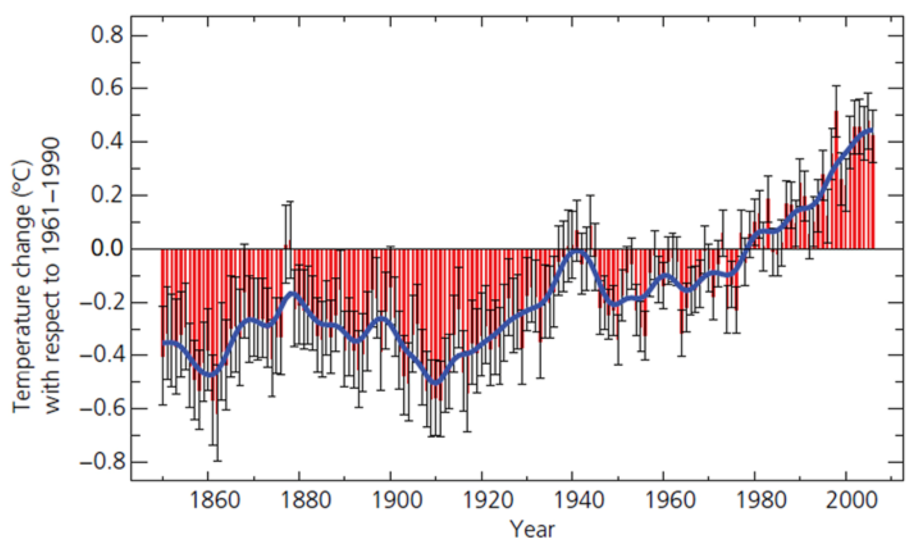
The severity of these impacts is expected to be correlated to the level of preparedness for climate change. In the worst case scenarios, climate change will endanger critical infrastructure and territorial integrity, challenging the resilience of socio-economic systems.

1.1 Warming of the global climate system is unequivocal

Warming of the climate system is unequivocal, as is evident from observations[1] of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level.

There is strong scientific, geographical and meteorological evidence that the world's climate is changing. Warming of the global climate system is unequivocal, with global average temperatures having risen by nearly 0.8 °C since the late 19th century, and rising at about 0.2 °C per decade over the past 25 years.

Figure 1 - Global temperatures have risen by 0.8 °C since late 19th century



Source: The climate of the United Kingdom and recent trends, UKCP09 scientific report, Met Office Hadley Centre

1 Observations of the climate system are based on direct measurements and remote sensing from satellites and other platforms. Climate change refers to a change in the state of the climate that can be identified in statistical terms by changes in the mean and/or the variability of its properties, and that persists for an extended period of time. Climate change may be due to natural earth processes, external phenomena such as modulations of the solar cycle, and human activity, such as CO_2 emissions in the atmosphere and changes in land use.

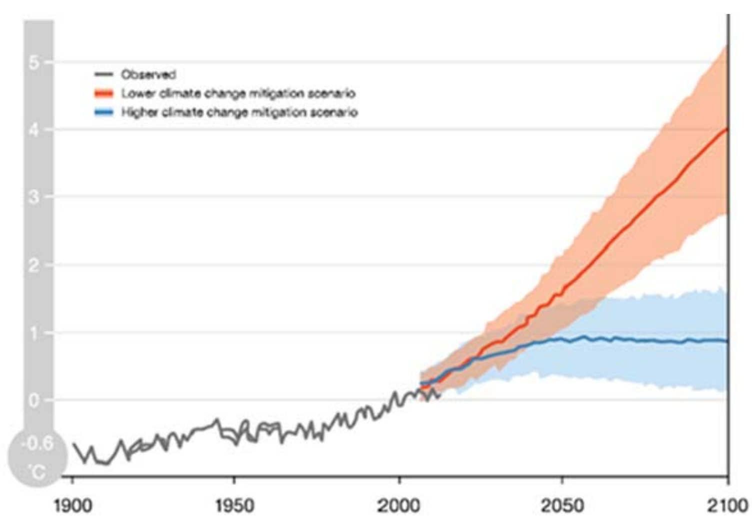
The Greenland and Antarctic ice sheets have been losing mass over the last two decades, and glaciers worldwide have been shrinking.

The rate of sea level rise since 1850 has been larger than in the two previous millennia.

Other long-term changes have been observed, such as widespread changes in precipitation amounts, ocean salinity, wind patterns and aspects of extreme weather including droughts, heavy precipitation, heat waves and the intensity of tropical cyclones.

This trend is projected to continue during the 21st century, and the combined emissions of greenhouse gases will cause further warming and changes in the global climate system, whether we consider a high emissions scenario (lower mitigation against climate change) or a low emissions scenario (higher mitigation against climate change).

Figure 2 - Global temperatures are expected to rise dramatically if mitigations are not put into place



1.2 Global warming is changing the face of the planet and may have a profound lasting impact on our societies and our economies

Changes in climate are causing impacts on natural and human systems on all continents and across the oceans. Changing precipitation or melting snow and ice are altering hydrological systems, affecting water resources. Many terrestrial, freshwater, and marine species have shifted their migration patterns.

Coastal regions, and low-lying land in general, are the most severely impacted by the rise in sea levels and higher precipitation. Vast areas of low lying land, currently served by rail lines, may be lost due to climate change.

Impacts from recent climate-related extreme weather events, such as heat waves, droughts, floods, cyclone, and wildfires, reveal significant vulnerability and exposure of some ecosystems and many human systems: alterations of ecosystems, disruption of food production and water supply, damage to infrastructure and settlements, morbidity and mortality, and consequences for health and well-being.

The severity of these impacts is expected to be correlated to the level of preparedness for climate change.

The key risks identified by the Intergovernmental Panel on Climate Change (IPCC) (2014) are:

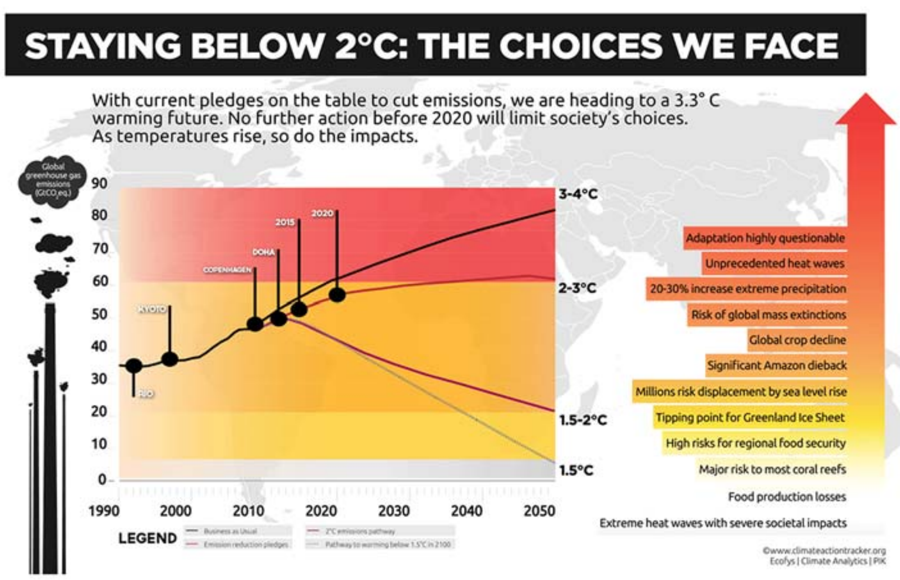
- Risk of death, injury, ill-health, or disrupted livelihoods in low-lying coastal zones and small island developing states and other small islands, due to storm surges, coastal flooding, and sea level rise.
- Risk of severe ill-health and disrupted livelihoods for large urban populations due to inland flooding in some regions.
- Systemic risks due to extreme weather events leading to breakdown of infrastructure networks and critical services such as electricity, water supply, and health and emergency services.
- Risk of mortality and morbidity during periods of extreme heat, particularly for vulnerable urban populations and those working outdoors in urban or rural areas.

- Risk of food insecurity and the breakdown of food systems linked to warming, drought, flooding, and precipitation variability and extremes, particularly for poorer populations in urban and rural settings.
- Risk of loss of rural livelihoods and income due to insufficient access to drinking and irrigation water and reduced agricultural productivity.
- Risk of loss of marine and coastal ecosystems, biodiversity, and the ecosystem goods, functions, and services they provide for coastal livelihoods, especially for fishing communities.
- Risk of loss of terrestrial and inland water ecosystems, biodiversity, and the ecosystem goods, functions, and services they provide for livelihoods.

These risks will impact human health and well-being, and are projected to lead to an increase in human migration. In the worst case scenarios, climate change will endanger critical infrastructure and territorial integrity, challenging the resilience of socio-economic systems.

Global climate change risks are high to very high with global mean temperature increases of 4˚C or more above pre-industrial levels, and some of them are still considerable at 1 or 2˚C above pre-industrial levels. It is estimated that additional temperature increases of 2˚C would cost from 0.2 % to 2 % of GDP.

Figure 3 - The importance of limiting temperature increases to below 2˚C.



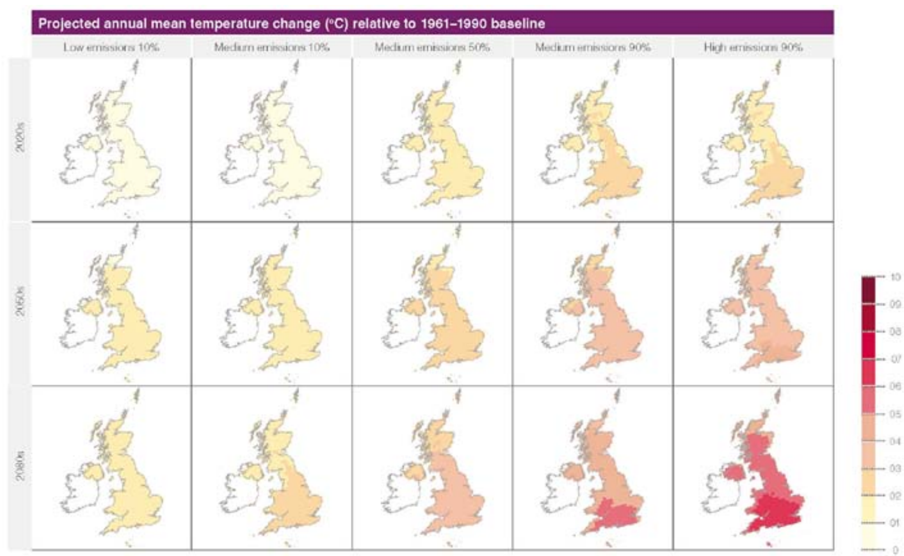
Source: *Weak Doha climate deal leaves world on pathway to 3^{o}C by 2040*, Climateaction-tracker.org (10/12/2012)

1.3 Climate change projections for the UK

1.3.1 Temperatures will be on average higher

All areas of the UK will become warmer, and average daily maximum temperatures will increase everywhere. According to UKCP09 scenarios and projections, future average temperature increases by 2080 are likely to amount to between +2 and +4 degrees Celsius throughout the UK.

Figure 4 - Temperatures are expected to increase throughout the UK

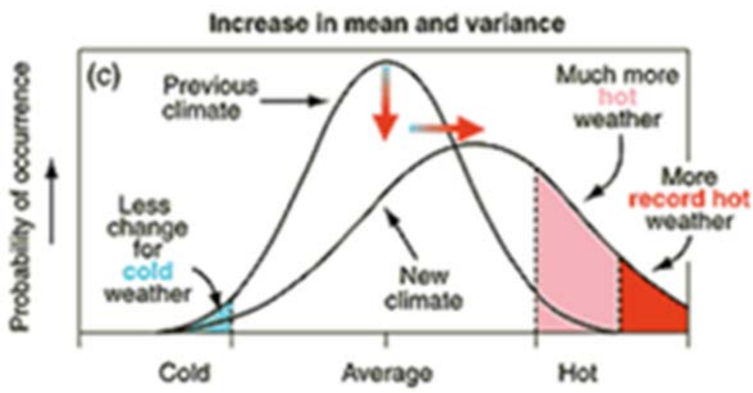


Source: UKCP09, TSB 2010, Design for Future Climate

1.3.2 There will be more record hot weather

An increase in the average temperature value will mechanically change the properties of its extreme distribution points, since cold and hot thresholds will not move. As a result, there should be less cold weather and more hot weather in the tails of the distribution. The figure below illustrates this point. It also reflects the fact that an increase in weather variance, as is anticipated, will maintain the likelihood of occurrence of cold weather events.

Figure 5 - There will be an increased probability of extreme hot weather events



Source: IPCC 2007

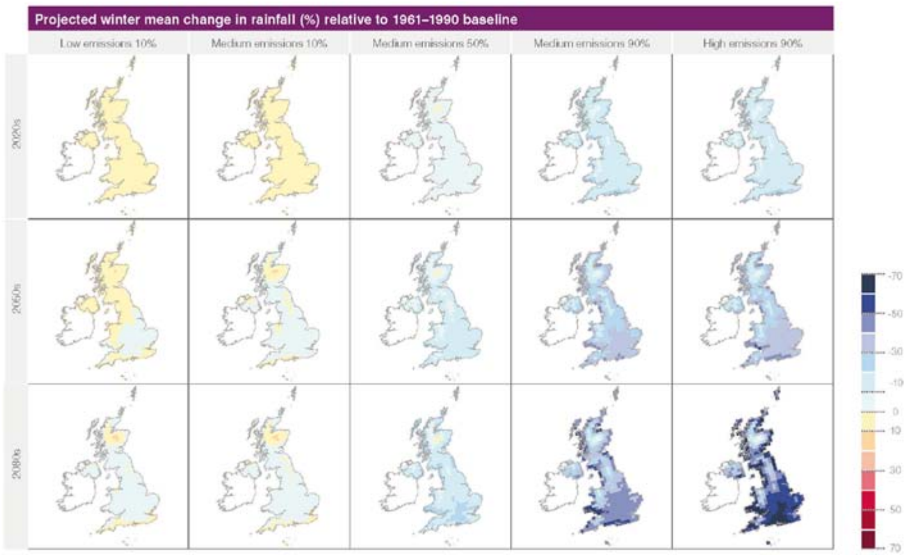
In other terms, according to this mechanical effect of climate warming, summers should be hotter and drier, with more hot extremes, and winters should be warmer and wetter, with less cold extremes.

The UKCP09 Probabilistic climate profile (ProCliP) projections confirm this point: summer temperatures in London and Birmingham are projected to be by 2080 between 4-6 degrees Celsius higher than they are now.

1.3.3 Precipitation levels and flooding risk will be higher

As seen with the IPCC 2012 climate change forecasts, there is high confidence in the increase of precipitation in Northern Europe during all seasons. UKCP09 notes that by 2080 (medium scenario), the greatest projected increases in winter precipitation are foreseen to take place along the western side of the UK, up to +33 %. On average, the UK should experience in winter from -10 % to + 30 % change in precipitations; although these projections remain uncertain, it is clear that their probability distribution is skewed towards an increase.

Figure 6 - Winter rainfall is expected to increase throughout the UK



Source: UKCP09, TSB 2010, Design for Future Climate

Winter precipitation is projected to increase from + 0.1 to +0.5 mm in London and Birmingham, and from +0.1 to + 1.0 mm in Glasgow.

Flooding risk will rise with the likelihood of excess precipitation: surface water flooding as a result of direct accumulation, riverine/fluvial flooding as a result of excess runoff and river bank bursts, and groundwater flooding as a result of rises in groundwater levels, depending on diverse geology factors, land use, drainage condition and succession of weather events.

Sea level will rise and storm surges will increase: projections of absolute sea level rise for the UK (UKCP09) suggest a rise by 2095 of between 12 and 76 cm above the 1980-1999 baseline.

1.3.4 There will be more frequent and more severe extreme weather events

There will be more intense, more frequent occurrences of severe weather events, particularly with intense rainfall, floods and heat waves, but also, although less frequent, very cold weather and snow, frost and ice.

1.3.4.1 High temperature events (heat waves)

High temperature events, including heat waves, are projected to occur more frequently in the next decade, as shown in Table 1. [Source: URS (2011)].

Table 1 - Future frequency of defined high temperature events under the high emissions scenario (90%) - values in brackets denote the medium scenario (50%)

High temperature event (UK-wide)	Baseline observed (average for 1961-90)	2020s	2050s
Annual number of heatwaves (2 days with max daily temp of >29°C and min daily temp of >15°C	<1 day	Up to 3 (1)	Up to 7 (3)
Annual number of days when temperature is >25°C	Up to 7 (3)	Up to 26 (9)	Up to 58 (22)
Annual number of days when temperature is >28°C	<1 day	Up to 12 (6)	Up to 28 (12)
Annual maximum temperature (°C)	27.0°C	Up to 30.1 (27.9)	Up to 35.9 (31)

1.3.4.2 Extreme precipitation events

Excess precipitation events, including flash flooding, are projected to occur more frequently in the next decade. [Source: URS (2011)]

Table 2 - Future frequency of defined excess precipitation events under the high emissions scenario (90%) - values in brackets denote the medium scenario (50%)

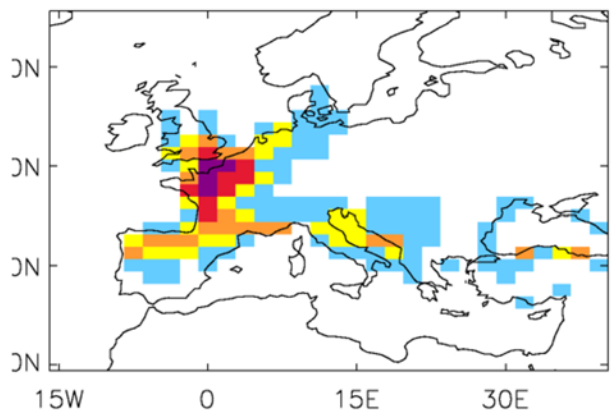
Excess precipitation event (UK-wide)	Baseline observed (average for 1961-90)	2020s	2050s
Number of days per year when precipitation is greater than 25 mm (Met Office definition of 5 mm per day)	3 days	Up to 10 (7)	Up to 18 (10)
Number of days per year when precipitation is greater than 40 mm (likely to cause flash flooding as defined by UKCIP)	<1 day	Up to 2 (1)	Up to 2 (1)
Annual number of prolonged rainfall events (3+ consecutive days when precipitation is >25 mm)	0 days	Up to 1 (0)	Up to 1 (0)

1.3.5 The UK will have by 2080 a climate similar to that of central France today

With such forecast changes to the UK climate system caused by global warming, by 2080 the UK will have a climate similar to that of central France, using temperature and rainfall as indicators.

On this basis, temperatures will be higher, summers will be hotter and drier, and precipitation will increase. Extreme weather events, such as heat waves, drought, heavy rain and snowfall, and storm surges will be more frequent and more severe.

Figure 7 - Climate in South East England in the mid-21st century is likely to be similar to the current climate of the locations shown in purple and red.



2 Climate change creates specific risks for rail assets, operations and maintenance, and staff and passengers

Warmer temperatures, higher precipitation and more frequent and severe extreme weather events can cause significant damage or disruption to the railway.

More than 200 vulnerabilities affecting GB railway assets due to climate change have been identified in the project.

The following is a non-exhaustive list of identified risks and damage or disruption channels brought by climate change to the railways:

- Risks for rail infrastructure, rolling stock and other rail assets
- Risks for rail operations and maintenance
- Risks for staff and passengers
- Risks for other networks (electricity, communications, water) on which the railways depend

2.1 Risks for infrastructure, rolling stock and other rail assets

High temperatures

- Rail buckling

- Expansion of swing bridges
- Overheating of electrical equipment in location cases
- Overhead line sag

Excess precipitation and flooding

- Earthworks failure
- Scour of bridges
- Risk to signalling systems
- Electronic equipment and track circuits failures

Drought

- Earthworks failure due to desiccation
- Movement of overhead lines (OHL) due to soil shrinkage around foundations

Heavy snow

- Traction motor failures due to snow ingress

- Trees falling onto tracks and OHL

High winds

- OLE damage from fallen trees, branches and objects

Lightning

- Damage to electronic equipment

Sea levels and storm

- Coastal erosion of earthworks, structures and tracks
- Damage to sea walls

2.2 Risks for rail operations and maintenance

Excess precipitations and flooding:

- Train running affected if water reaches the railhead

- Trains cannot run if flood water reaches the third rail

Heavy snow

- Trains prevented from running

High winds and lightning

- Trees and branches being blown down, causing obstructions on tracks
- Increased autumn leaf fall
- Local practice may include speed restrictions

Higher sea levels and storm frequency

- Sea water inundation of earthworks, structures and tracks

Higher temperature

- According to the Met Office, the number of non-work days for maintenance (May-Sept) where track maintenance cannot be carried out due to adverse weather conditions will increase, from 30-40 % in the London region in 1970-2000 to 50-60 % in 2030-2089.

2.3 Risks for staff and passengers

High temperatures and heat waves

- Passenger discomfort in glazed buildings and shelters
- Inadequate ventilation in trains (particularly stranded trains and overcrowded trains)
- Heat stress on workers

Higher precipitation and high winds

- Trips and falls

2.4 Risks for other infrastructure networks and systems the railways depend on

Key external networks and systems on which the railway system depends

- Electrical power supply
- Fuel supply
- Water systems (including managed water networks, surface and groundwater)
- Other transport systems
- Supply chains

Any effect of global warming on these other essential services could indirectly impact on the ability to deliver a rail service, as the rail network would not be able to operate at the same capacity, staff could not work, and other consequences.

3 When climate change impacts the railways, this has wider socio-economic consequences

Taking into account the forecast climate change and its impact on the railway, as discussed in chapters 1 and 2, there is a need for both climate change adaptation as well as climate change mitigation. Carbon reduction policies and resilience or emergency response deal with the latter. Even if, and after, emissions of CO2 are reduced or stopped, climate change adaptation preparations and investments remain crucial.

However, assessments of adaptation and resilience projects often find it difficult to estimate the economic and social costs of disruptions due to extreme weather, and therefore fail to appreciate the long term benefits (wider socio-economic costs avoided) of such adaptation and resilience investments. The analysis of railway climate change adaptation projects could consider:

- The costs of doing nothing vs doing something
- Knock-on effects and interdependencies: the wider context of rail disruptions
- Guidance for measuring the potential benefits of climate change adaptation projects
- The concept of a Journey Availability metric

3.1 The costs of doing nothing vs doing something

The costs to GB railway of weather related events include:

- The average cost of weather related disruption is estimated to be around £40m-50m each year (in delay and cancellation costs), excluding the maintenance costs incurred after such disruptions. [Based on Network Rail analysis (2013).]

- The economic costs of track buckling are currently estimated at £4.8m each year; and are likely to double by 2020, quadruple by 2050, and be tenfold by 2080.
- Flooding in 2013 alone cost Network Rail around £12m in compensation and a further £15m in damage repairs.
- Weather-related precursors have a total contribution of 5 equivalent fatalities a year in the RSSB Safety Risk Model.
- There have been 12 derailments recorded since 2005 due to earthworks failure following heavy rain.

These costs are likely to increase significantly with higher temperatures, higher precipitation and more frequent and severe adverse weather events.

Table 3 from the case study of Network Rail Western Route Flooding compares the delay costs per year of doing nothing to relieve flooding at Cowley Bridge Junction (CBJ) with options, for improving flood resilience at CBJ, which include Permanent Option 3.1 (enlarge the flood relief culvert, install slab track, sheet pile wall to protect slab track) and Permanent Option 3.2 (enlarge the flood relief culvert, install slab track and lift 500 mm, sheet pile wall to protect slab track, lift Cowley Bridge).

Table 3 - Delay costs in the do nothing vs do something to reduce Cowley Bridge Junction flooding vulnerabilities Source: Network Rail Western Route Flooding case study

	Frequency (events each year)	Number of trains affected per event	Delay hours per event	Delay cost per event (£m 2010)	Delay cost per year (£m 2010)
Do nothing					
2025	0.11	1,605	82,697	4.7	0.5
2050	0.12	1,605	132,978	12.62	1.46
Permanent Option 3.1					
2025	0.01	1.605	82,697	4.7	0.05
2050	0.01	1,605	132,978	12.62	0.15
Permanent Option 3.2					
2025	0.00	1.605	82,697	4.7	0.00
2050	0.00	1,605	132,978	12.62	0.00

3.2 The wider socio-economic context

Considering that the railways contribute to economic, social and environmental well-being, the wider socio-economic effects should be quantified, or included in the overall business case for climate change adaptation projects. The Brown review (DfT 2014) highlights that traditional transport economic appraisal methodologies are usually unable to assess spending decisions related to adaptation and resilience, failing in particular to capture many of the economic and social costs of transport disruption due to extreme weather, and therefore the costs avoided (benefits) of adaptation. Rail is a system, and its complex socio-economic contributions to society are not easy to isolate or estimate. The true consequences of rail disruption, including the lack of alternative routes, and the true benefits of adaptation are hence hard to assess. The Dawlish case study demonstrates this.

3.2.1 Dawlish case study

The collapse of the railway at Dawlish in the storms of February 2014 prompted a new investigation into the necessity for alternative routes. The West of Exeter Route Resilience Study (Network Rail, 2014) used the cost-benefit methodology laid out in the Treasury Green Book and WebTag to assess the benefit-cost ratio (BCR) of a number of potential additional routes. It found that all the technically feasible alternative routes identified had low BCRs, and therefore, under current DfT guidelines, are unlikely to be funded. However, these calculations did not include the wider economic and social impacts, such as the effects on local business and communities.

The cost of constructing an additional route was estimated to be far higher (£400m to £3 billion) than the cost to the railway industry (quoted as around £40m-45m for repairs and compensation payments) for the existing route. However, the true cost of the February 2014 event is far higher in terms of indirect economic costs to UK plc, when social and environmental impacts such as community severance are taken into account. Indeed, businesses in the area are requesting improved rail links, stating the difficulties of running a business without a reliable rail link and suggesting that improvements would stimulate economic growth.

3.2.2 Network Rail Western Route Flooding case study

A case study was undertaken on the Western Route, which demonstrates the impact of using socio-economic benefit estimates on investment scenarios. It proposed several options for improving flood resilience at Cowley Bridge Junction (CBJ) and provided capital cost estimates for two of these: **Option 3.1** (enlarge the flood relief culvert, install slab track, sheet pile wall to protect slab track: projected cost £6.5m) and **Option 3.2** (enlarge the flood relief culvert, install slab track and lift 500mm, sheet pile wall to protect slab track, and lift Cowley Bridge: projected cost £13.4m).

Table 4 compares results based on the current Network Rail cost minimisation approach and the Arup proposed methodology, which takes into account wider socio-economic benefits. According to the traditional cost-benefit analysis (CBA), the case for Option 3.1 is reasonably strong (a BCR of 1.6), and Option 3.2 would not be considered for investment based on its negative net present value (NPV). However, the consideration of wider socio-economic benefits (user time savings, severance minimisation, reputation) dramatically increases the NPV of both adaptation projects.

Table 4 - The inclusion of wider economic costs and benefits present stronger arguments for investments in rail resilience

Issue	Network Rail Study – Option 3.1	Network Rail Study – Option 3.2	Arup method – Option 3.1	Arup method – Option 3.2
Capital costs	6.3	12.9	6.3	12.9
Present Value of costs	6.3	12.9	6.3	12.9
Schedule 8 costs prevented	4.7	5.2	5.3	5.8
Schedule 4 costs prevented	2.7	3.0	3.0	3.3
Maintenance and other costs	2.4	2.7	2.7	3.0
User time savings	Not quantified		19.1	21.2

Table 4 - The inclusion of wider economic costs and benefits present stronger arguments for investments in rail resilience

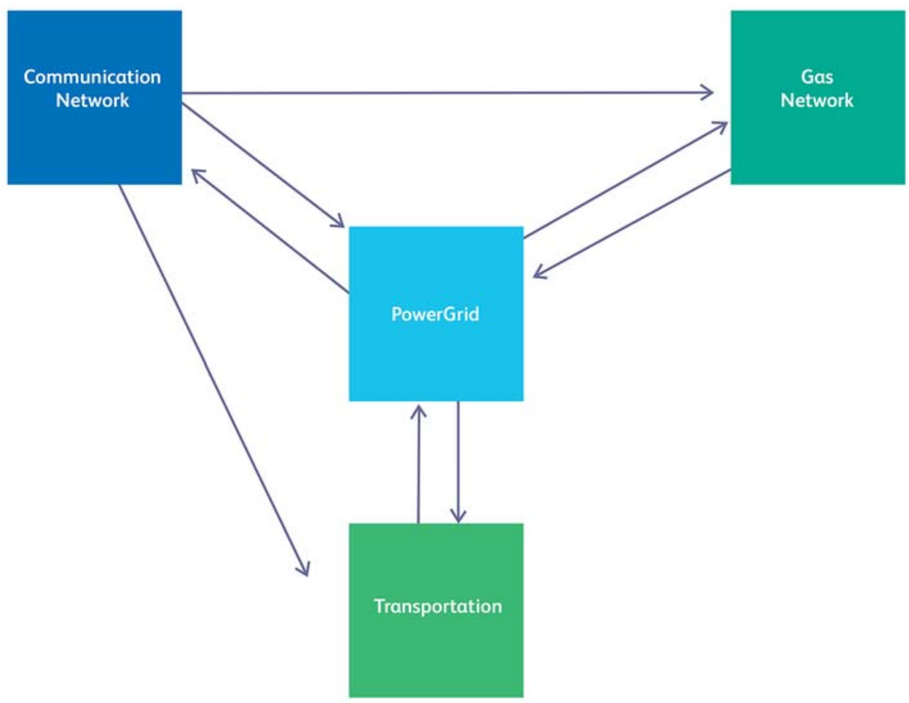
Issue	Network Rail Study – Option 3.1	Network Rail Study – Option 3.2	Arup method – Option 3.1	Arup method – Option 3.2
Wider economic benefits – severance	Not quantified		24.3	27.0
Wider economic benefits – reputation	Not quantified		12.8	14.3
Present value of benefits	9.8	10.9	67.1	74.6
Net present value (NPV)	3.5	-2.0	57.7	55.3
Benefit-cost ratio (BCR)	1.6	0.8	7.1	3.9
Payback period (years)	13.2	25.2	3.0	6.3

3.3 Knock-on effects and network interdependencies

The rail network is heavily dependent on external non-rail infrastructure networks it must use for its operations. Similarly, these networks are often reliant on the rail network to function normally. Disruption of the rail network has a knock-on effect on external infrastructure networks and other transport modes. A potential major disruption of railway traffic would have a range of impacts on other sectors. For instance, roads would have to be used to replace rail freight traffic, affecting local communities through traffic congestion and emissions. Traffic congestion would in turn have a range of knock-on effects on residents who would have problems with access to schools and offices as well as access to emergency services. Transport of coal and biomass for the energy supply industry (power stations) would be affected, as well as transport of oil for other sectors (including aviation), and transport of resources for manufacturing industries.

If a rail asset is at an intersection with other types of infrastructure (road, water) fails, this other infrastructure's service may be stopped during the repair work (such as closing roads or turning off water supplies).

Figure 8 - Interdependent networks



3.4 Measuring the potential benefits of projects: cost benefit analysis, multi-criteria analysis and other methods

For the reasons set out in Sections 3.1 to 3.3, the assessment of the relative merits of climate change adaptation or resilience projects should take into account the wider socio-economic benefits of rail and the knock-on effects it has on other networks.

The project results suggest that any future climate change resilience appraisal framework be based on the WebTAG and Green Book frameworks. Indeed, the return on climate change resilience projects is likely to be in conventional benefits, principally the impact on the reliability of the network. In that sense, a climate change adaptation project is no different from any other investment. So, HM Treasury discount rate guidance is applicable. Furthermore, analysis has shown that the existing scale and scope of DfT's WebTAG tool is comprehensive in valuing the direct and indirect economic costs of severe weather on the rail network.

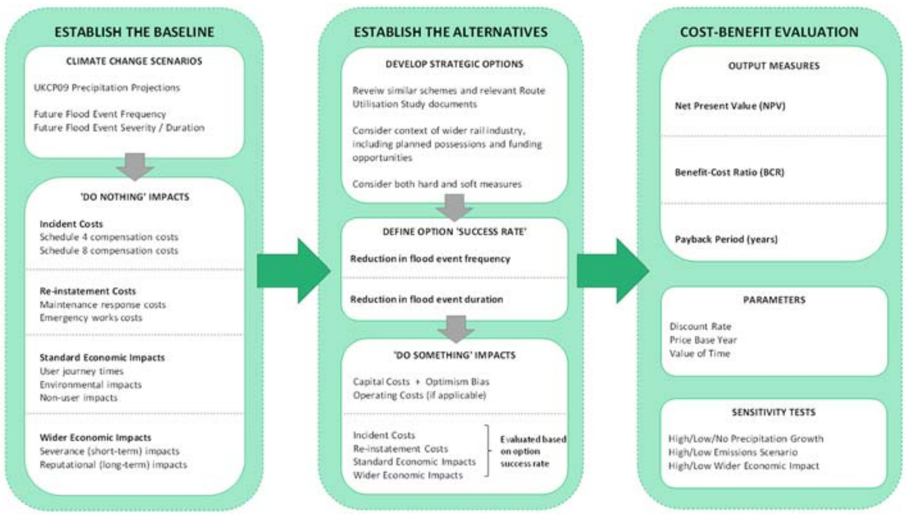
WebTAG does not however include:

- **The wider socio-economic costs of transport disruption**, such as the effects on the UK's competitiveness, economic output and economic welfare. It is therefore recommended that CBA be used initially, and that it be augmented with Multi Criteria Analysis[2] in future.
- **Measures of full resilience**. The Environment Agency's approach to appraising investments that offer increased resilience seems best suited for the railways and should be considered. It uses the notion of level of protection to characterise the scheme being appraised: the appraisal is carried out on the basis of a move from an existing level of protection of 1 in x years, to a greater level of protection of 1 in x+n years (for example, achieved by building a higher wall).

Taking into account the above factors, Figure 9 illustrates the approach that could be taken to estimate the value of investment in rail resilience.

2 MCA uses more qualitative criteria than CBA, and is therefore often more suited to variables that are difficult to quantify.

Figure 9 - CBA process advocated by Arup



3.5 The concept of Journey Availability metric

Having reviewed performance metrics used by the railways in the UK and elsewhere, Arup found that the delay minutes metric traditionally used by the GB railway imperfectly captures performance in the long term perspective of resilience. It proposed that a Journey Availability metric be calculated, which would be a compound function of infrastructure availability (Network Rail's responsibility) and service availability (train operating companies' (TOC) responsibility). This Journey Availability metric would have the merit to go beyond the life cycle of Control Periods, to focus on long term adaptation requirements to keep both the infrastructure and train services available and running, while still allowing to reflect shorter term maintenance, renewal and break fix activities.

4 The GB railway industry already has some mitigations in place to address adverse weather conditions

The GB railway industry has introduced a wide range of measures to mitigate climate change. For example, Network Rail has developed and published climate change adaptation plans for all routes. It has also established a Climate Change Resilience Steering Group to strengthen governance and adaptive capacity, and has recruited a range of specialists in the field. As a result, it has reviewed standards and specifications for critical assets, and is altering its asset management policy. Examples of these changes are listed below, covering general weather management provisions, operational guidance, and design standards for assets. Some gaps are identified, notably related to weather and climate related thresholds, wet weather management procedures, and upper temperature for design standards.

4.1 General provisions for weather management

General provisions for weather management include:

- Network Rail Standard: *Weather – managing the operational risks* (NR/L2/OCS/021) is a standard process that covers the GB railway system as a whole for forecasting weather phenomena. It provides a high level framework for operational weather management across the railway systems; individual sub-systems, such as rolling stock, or individual routes, have their own operational standards to mitigate specific risks.
- Network Rail Standard: *National Control Instruction Procedure 7-1, Weather and seasonal management* (NR/L3/OCS/043/7.1) supports the real-time management of floods, high winds, snow and high temperatures.

These standards foresee that at the whole rail system level, three trigger levels (Alert, Adverse and Extreme) are set, with threshold values and measures of performance for each trigger level. Network Rail has carried out threshold analyses in 2012, 2013, and 2014, to identify how often the existing trigger thresholds are exceeded. The same work includes a thorough analysis of the impacts of weather on asset reliability across a variety of asset types. Network Rail uses, additionally, a range of weather forecasting tools, including SMTweather, Met Office National Severe Weather Warnings, and JBA flood risk products.

TOCs also have procedures to cope with adverse weather. The ATOC Guidance Note – *Extreme Weather Arrangements including Failure or Non-Availability of OnTrain Environment Control Systems* is an example of a specific operational standard managed by the train operators. Some individual TOCs have their own weather monitoring and management procedures, and route weather resilience and climate change plans have been recently published.

4.2 Design standards for infrastructure and rolling stock

- The risks of track buckling in hot weather and rail breaks in cold winter are initially managed by setting the stress free rail temperature. Rails are currently set to a stress free temperature of 21°C to 27°C (NR/L2/TRK/3011). The major mitigation for track buckles is to deploy heat watchmen when temperature thresholds are reached to look for risk signs and impose speed restrictions.
- Control of the impact of high winds on existing bridges is achieved through a limit on the peak velocity pressure above which trains are not permitted to run. Bridge scour is controlled based on the design, which is a 1 in 200 years return period rainfall event for new construction, with a 20% allowance for climate change. For existing bridges and culverts, each structure is assessed to determine if a flood warning plan is necessary.
- New drainage systems are designed based on a return period storm event of 10 to 50 years, with a 20% allowance for climate change.
- Overhead line equipment is designed for an air temperature range of -18°C to 38°C (NR/GN/ELP/27088).
- Rail vehicle design standards specify that rail vehicles should be designed for temperatures between 25°C and 40°C (GMRT 2100 Requirements for rail vehicle structures) and that brakes should work from -20°C to 35°C (GMRT 2045 Braking principles for rail vehicles).
- Managing the risk of rail vehicles overturning during high winds is covered by the Railway Group Standard GMRT 2142 (maximum design wind speeds of 36m/s for passenger trains, 30 m/s for freight trains).

4.3 Operational procedures for weather management

- The operation of trains in snow is controlled by the GE/RT 8000 Rule Book, which states that if the snow is 8 inches above the railhead, signallers must suspend normal running of trains.
- Railway Guidance Note GE GN 8628 – Guidance on preparation and operating during winter indicates how to prepare rolling stock (coupler bags, anti-freeze for air systems, fuel treatments) to minimize low temperature issues.
- The presence of stationary flood water is addressed by the GE/RT 8000 Rule Book: a 5 mph speed limit is imposed when flood water is between the bottom and the top of the rail head, and operations can only proceed under controlled instructions when flood water is above the rail head.

4.4 Procedures for passengers and staff

- There are procedures in place to mitigate the occurrence of heat stress problems for passengers and staff in trains (ATOC/NR Good Practice Guide SP01 – *Meeting the needs of passengers when trains are stranded*, ATOC/ Guidance Note 015 – *Extreme weather arrangements including failure or non-availability of on-train environment control systems*).
- No standards exist for heat stress affecting outdoor railway workers, but workers are regularly briefed on the need to wear sun cream, hats and hydrate in summer, and the Met Office and Public Health England operates a Health Watch system from June to September.
- There are various mitigations in place for stations and buildings. The Managed Stations manual (NR/L3/OCS/044/MS-41) describes procedures for heat, ice and snow, high winds, rain and flooding.

4.5 Identified gaps

There are nevertheless gaps which need to be addressed by the GB rail sector:

4.5.1 General

- There exist **different weather and climate related thresholds** in effect for informing the design criteria of new assets and for triggering operational management procedures for existing assets.
- It is sometimes unclear what scientific consideration underpins some thresholds. Notably, some of the new proposed thresholds for rainfall could require some rationalisation.

4.5.2 Infrastructure

- Given that the intensity of rainfall events is projected to increase in most GB regions, there is a need for refining current **wet weather management procedures** for the infrastructure.
- A better understanding of how different amounts of rainfall and levels of flooding impact earthworks, along with better warning systems, could lead to better targeted mitigations.
- The **common upper temperature** of 38°C for the design of OHL equipment should be reviewed in the light of projected maximum temperature for all GB regions by 2080 and in the light of their long asset life.

4.5.3 CCS

- The common upper temperature of 40°C for Control, Command and Signalling equipment should be reviewed in the light of the projected maximum temperature for all GB regions by 2080.

4.5.4 Lineside

- Fire risks during drought conditions could be researched further.

4.5.5 Staff and outdoors workers

- There is a potential gap in the Track Working Instructions for specific guidance on what constitutes suitable personal protective equipment, welfare facilities, and lengths of working time during work in adverse conditions.

4.5.6 Rolling stock

- Guidance was found on the preparation of rolling stock for high temperatures.

5 Good practice and lessons learned from similar railway systems

While the GB railway is relatively advanced in climate change adaptation and/or weather management, compared to other rail systems, it still has the opportunity to learn from its international counterparts' good practice.

The list below is a short, indicative example of what some railways in other countries have put into place or are recommending for addressing climate change challenges. It has to be recognised that there is no silver bullet, as is recognised by all the specialists and professionals involved with climate change adaptation.

EU: The emphasis on the need for maintenance was highlighted in the work of the ongoing EU FP7 MOWE-IT project (Jaroszweski et al 2014) which sought to identify existing best practices and develop methodologies to assist EU rail transport infrastructure operators to mitigate the impact of natural disasters and extreme weather phenomena on transport system performance. This project took a case-study approach to identify common factors before, during and after hazard events to mitigate impacts. Of the three hazards considered, heavy rain, wind or storm, and snow or winter conditions, two (heavy rain and snow or winter conditions) explicitly highlighted prior maintenance as important and two (heavy rain and wind or storm) highlighted the need for reconstruction to include upgrading to improve resilience . Overall the guidelines also recommended that rail infrastructure managers should maintain a detailed asset condition database which could be integrated with weather forecasting to give early warning of high-risk vulnerable areas

Germany: adapting land use adjacent to railways to mitigate risk of trees falling onto tracks or fires on adjacent slopes.

Netherlands: vulnerability assessment for water related climate change risks ('Blue spots' study). Subsequent studies may focus on specific vulnerable components. Trouble-shooting at location-specific level.

Austria: weather warning systems; special maintenance inspections after extreme weather events.

Japan: focus on resilience improvements of key structures on important lines.

6 Recommendations for improving the weather resilience of GB railways

The rail industry has a good understanding on what the risks are, and has already started to meet the challenges faced by climate change. However it cannot do this on its own and greater investment and support is required to maintain an effective rail system.

Based on the gap analysis conducted on current preparations, and on identified good practice in the literature review (compendium) and among other national rail systems, the research project made the following recommendations to improve the climate change resilience of the GB rail network.

- Conduct detailed vulnerability mapping of assets and locations
- Enhance weather incident reporting and asset condition monitoring
- Develop GIS-based alert systems and weather susceptibility maps
- Revise standards and make rail assets 'climate change proof'
- Develop a multi-agency cooperation model

6.1 Develop a multi-agency co-operation model

Infrastructure systems are inter-dependent, requiring a multi-agency response to climate change. The project also recommended that we should:

- Get involved in multi-agency working (evidence based decision making, lessons learnt, public communications).
- Introduce a collaborative cross-modal and cross-sectional approach, working with relevant government departments and agencies.
- Engage with relevant multi-agency forums to influence the development of European standards where climate change initiatives are already in progress.

These recommendations can be implemented in the short to medium term, and progress should be regularly monitored and assessed by the relevant experts. Expert discussions should go on, and methods and approaches be refined. Climate change issues are extremely complex, with many remaining uncertainties, and climate change adaptation is for this reason a learning journey.

6.2 Identify those assets most at risk from climate change

An enhanced programme of **detailed vulnerability mapping** for all assets and locations would be a useful exercise. Vulnerable assets should be identified, by location and by railway sub-system. Critical interdependencies should be studied. **A database of assets** could be compiled, including buildings, which are vulnerable to either excess rainfall, drought, fluvial flooding or coastal flooding. For instance, registers could be developed in the manner of Network Rail's critical rail temperature register of locations that are particularly sensitive to track buckling.

The location of all critical lineside equipment and equipment cabinets for control, command and signalling should be established, and temperature data obtained at these locations.

Topographic and geographical characteristics of sections of the GB railway network and related site risk need to be researched further.

Mapping can help to show specific asset types at risk from the impact of weather and the following Figures map soil cuttings at risk using Washout and Earthflow Risk Mapping 2 (WERM2). Flooding appears to be concentrated to the rail bed with two main channels of water flowing in/out of the area. Velocities (shown in Figure 11) are above 2.0 m/s in this area. As such again it would be an area at significant risk from failure due to washout.

Figure 10 - WERM2 cuttings identified at MLN1 174.0000 – 174.0440 showing flooding areas

Figure 11 - WERM2 cuttings identified at MLN1 174.0000 – 174.0440 showing water velocity in above flooding area

A **better collection of data** relating to trees, vegetation and adjacent land use is also recommended. Improved understanding of the relationship between climate or weather and asset life would be a benefit.

6.3 Enhance weather incident reporting and asset condition monitoring

Improved monitoring and recording of local weather conditions across the network, alongside incident reporting requirements, would assist in the analysis of the impact of weather events and climate evolutions on specific railway assets and railway vulnerabilities.

In particular, an increase in the quantity and the quality (consistency and accuracy) of **recorded observations of weather conditions** at sites where asset failures or delays occur can be recommended. Such an approach would include the capture and assessment of delay minutes associated with rainfall incidents and failures, regional variations in the exposure of assets to rainfall risk.

Meteorological data could be combined with incident data, from Network Rail, TOCs, suppliers and passenger surveys (RailMet approach). This approach would also **integrate smart technologies, telemetry and remote sensing technology** and data management systems into flood risk management.

Network Rail's ORBIS (Offering Rail Better Information Services) asset info system should ultimately be linked to TRUST (Train Running Under System TOPS), a computer system used for monitoring the progress of trains and tracking delays, and weather stations data.

A better understanding of how combined or sequential weather events or conditions impact asset performance and asset degradation would be highly beneficial, albeit a more medium term goal (for instance, the impact of soil desiccation followed by heavy rain, high tide combined with high winds, multiple rainfall events).

A better understanding of off track slope and drainage issues would also be beneficial.

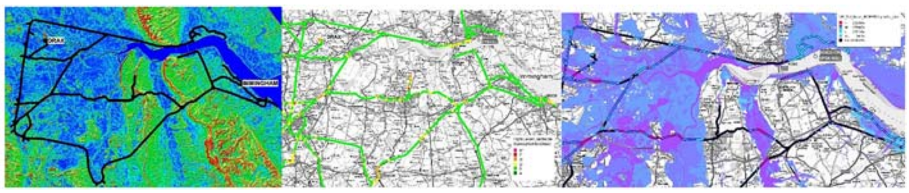
6.4 Expand use of GIS-based alert systems and weather susceptibility maps

Increased spatial and temporal resolution for rainfall information would allow the development of better vulnerability mapping techniques and lead to more accurate **rainfall risk assessment and prediction tools**.

Geographic Information Systems (GIS) could be used to support the identification and mapping of earthworks located in flood sensitive hotspots. Good practice and lessons learned could be gathered from the London Underground Comprehensive Review of Flood Risks (LUCRFR), which developed a **GIS-based flood risk prediction model.**

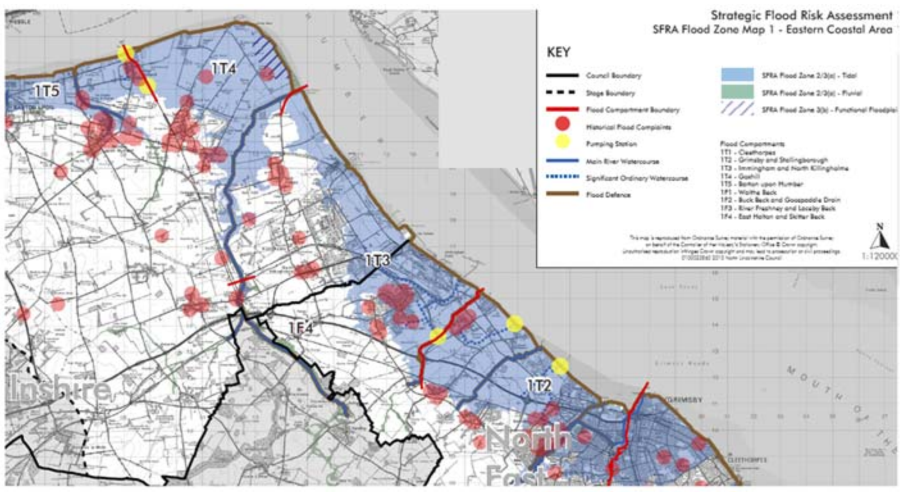
In the Drax case study, the project trialled how GIS data could be used and combined to establish flood risk maps around Immingham port.

Figure 12 - From left to right, Topographic view of Immingham port terrain, High-level landslide susceptibility around Drax and Immingham Port, Risk of Flooding from Rivers and Seas around Drax and Immingham Port.



Source: Drax case study, GIS data.

Figure 13 - Flood risk map around Immingham port



GIS-based systems benefit from using higher resolution imaging technologies: the opportunities for increased use of LiDAR and/or satellite observations to manage weather and climate related risks (such as LiDAR providing 1km2 resolution rainfall data) could be explored in the medium term.

Beyond forecasting and mapping, meteorological and geographical data can be used as operational triggers and shared between all rail stakeholders. For example, ways should be identified for improving the cascade of communication from meteorological forecast providers to Network Rail to TOCs to passengers, before and during hot weather, snow, rain, wind and storm surge events.

6.5 Revise standards and make rail assets 'climate change proof'

6.5.1 Design standards, thresholds and other standards

Many design standards for assets include a maximum temperature. These values should be reviewed in the light of projected maximum temperatures up to 2080 for each GB region, to check whether these design standards are high enough (tracks, electronic equipment, rolling stock, OLE).

Likewise, new rainfall threshold values for both design and operations should be reassessed, to guarantee more resilience in the future.

The impact of high winds and soil movements should also be reassessed for the design standards of OHL assets and infrastructure.

Rolling stock could in the future include temperature monitoring equipment.

Weather related staff and workforce safety standards and procedures should be reviewed and improved, for instance by establishing relevant thresholds and definitions of appropriate forms of personal protective equipment to be issued in different weather conditions, or requirements for working hours in different seasons or conditions.

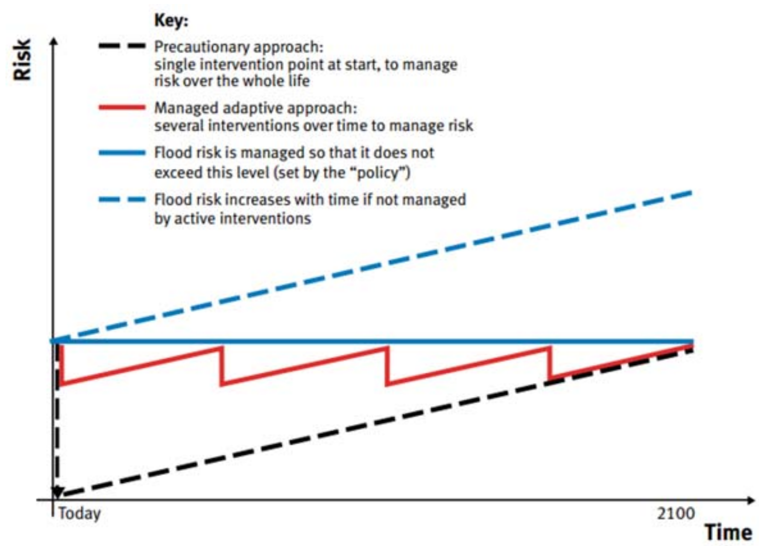
6.5.2 Replace vulnerable assets based on life-cycle costs analysis

Vulnerable assets could be replaced or relocated in the longer term, based on lifecycle costs comparisons.

Investment in automation and remote monitoring would reduce the need for staff and workforce to be exposed to adverse weather conditions. Targeted planting of vegetation around tracks could reduce air and surface temperatures at vulnerable sites. A longer-term vegetation strategy could be developed to ensure the stability of earthworks and soil structure and to reduce risks from high winds, leaf fall and flooding. Station canopy design could ensure that passengers and staff have adequate cover from a full range of adverse weather conditions.

The Thames Estuary 2010 project's approach to climate change (adaptive pathways), could be an appropriate example for the long term management of the GB railway, to improve the resilience of infrastructure to flood risk and storm damage. The replacement and strengthening of the Thames flood barrier is a good example of a staged resilience project. If a certain water level is exceeded a certain number of times, a series of actions are triggered to review the existing defence levels, to build upon them, and to begin to create adequate designs for eventual replacement of the barrier once upgrades have been exhausted, as shown in Figure 14.

Figure 14 - Managing flood risk through the century using the Thames Estuary 2010 adaptive approach



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