EJTIR

Issue **9**(2)
June 2009
pp. 164-181
ISSN: 1567-7141
www.ejtir.tbm.tudelft.nl

Climate Adaptation of Railways: Lessons from Sweden

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Received June 2008; accepted March 2009

The current variability in weather and climate is posing a challenge for transport infrastructure. However, during the past decade the need to adapt to a changing climate has attracted increasing attention. This paper summarises a case study on the future vulnerability to climate change of the Swedish railway transport system and its adaptive capacity. The combination of a long time horizon in planning and an expected increasing demand for rail traffic raises many questions regarding how adaptation to climate change can be accounted for in future planning, design and management of railways. The case study was essentially based on interviews with key personnel within the Swedish Rail Administration. Views on vulnerability and adaptation to climate change were documented, and the need for improved methods to assess the vulnerability and adaptive capacity related to climate change for the Swedish railways was addressed. The conclusions of the paper are addressed to the European railway context at large. Firstly, systematic mapping of current climate vulnerabilities and their consequences is important in order to guide the implementation of adaptation measures. Secondly, climate change should be considered in the early stages of planning and included in risk and vulnerability assessments. In assessing future conditions with the aim of prioritising adaptation measures, current methodologies should be complemented with more future-orientated tools. When designing adaptation measures, the effects of potential goal conflicts should also be assessed, in order to avoid the implementation of counter-productive measures. The possibility of creating synergies with climate mitigation goals and other environmental goals should also be investigated.

Keywords: climate change; adaptation; vulnerability; transport; railway; Sweden; Europe

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1. Introduction

The need for societies to adapt to a changing climate is an issue that has gained an increasing amount of attention during the past decade. Warming of the global climate system is unequivocal, according to the latest evaluation of the scientific evidence by the IPCC (2007). Mean annual global temperature has increased by 0.74 °C over the past century (1906-2005) and this increase is very likely due to the observed increase in anthropogenic greenhouse gas concentrations. Global warming is projected to continue, with the mean annual temperature exceeding that in the period 1980-1999 by as much as 6.4 °C by the end of this century given an emissions scenario where anthropogenic emissions continue to increase (IPCC, 2007). Recent measurements of global levels of atmospheric carbon dioxide, the primary driver of climate change, show that the rate of increase in concentrations has accelerated (NOAA, 2008). For the Baltic Sea region, warming is predicted to be higher than the global average and the increase in mean annual temperature could be as high as 10 °C in the winter and 7 °C in the summer over land in north-eastern areas of this region by the end of the century (Bolle et al., 2008). Precipitation will also increase, by up to 70% in the winter and 20% in the summer for emission scenarios assuming business as usual (ibid).

Regardless of the influence of anthropogenic climate change, the current variability in climate is already posing a challenge for transport infrastructure. During the past decade a number of flooding and storm events in Europe have severely damaged railway networks, resulting in great negative consequences for the functionality of the rail system. In northern Europe, winter conditions have already proven to be problematic for the railway transport system. Climate change may worsen or improve future winter conditions. Temperature on the coldest days is predicted to increase dramatically in the future scenarios, while the frequency and intensity of heat-waves will also increase substantially. Heavy precipitation events will increase significantly, whereas projections of wind extremes are more uncertain (Bolle et al., 2008). Other projected changes of relevance for the railway sector are an increasing number of temperature fluctuations around zero in parts of the Baltic Sea region as well as fewer days below zero, indicating that the risk of wind-felled trees may increase (Swedish Commission on Climate and Vulnerability, 2007).

Climate-related events are already among the factors most frequently causing disturbances for railways. Flooding and storm events are considered major threats to the system. Climate change might in the long run produce new kinds of events and threats to the railway system, but the climate change will principally involve a strengthening of the already known threats, in terms of increased frequency as well as increased intensity. This is a challenge for the organisations managing railways and planning for future networks. Utilisation of the European railway transport system is expected to increase in the future (COM, 2008). Compared with the alternatives available, railways could provide an environmentally friendly transport solution and the relatively low energy use will probably favour railway transport in the transition towards more sustainable and energy-efficient transport solutions for society. Moreover, a long time horizon is used in the planning process for new investments in railway infrastructure. Typically, railways are expected to operate at full capacity for a 60-year period (Pyddoke, 2002) but looking in more detail, the lifetime of different installations can be substantially longer, up to 100 years for culverts and bridges (Swedish Commission on Climate and Vulnerability, 2007). The combination of a long time horizon in planning and design and an increasing demand for rail traffic in the future raises many questions regarding how adaptation to climate change can be accounted for in the planning, design and management of railways.

Against this background, climate adaptation of railways was studied through an independent case study of the Swedish Railway Transport System, which is summarised in this paper. The overall objective of this investigation was to study the vulnerability of the Swedish Railway System to future climate change and to investigate the adaptive capacity of the current system.

The scope of the study was limited to the Swedish Rail Administration, which is responsible for railway infrastructure in Sweden. The current views and considerations on vulnerability and adaptation to climate change were documented through interviews with key personnel. The need for improved methods to assess the vulnerability and adaptive capacity of railways was also addressed.

Since this paper is based on a case study, the empirical findings primarily relate to Swedish conditions. However, the general conclusions drawn are addressed to the European railway context at large. The intended beneficiaries of this study include those involved in planning issues within European Rail Administrations, but also those dealing with transport or infrastructure issues – or climate adaptation and risk and vulnerability issues – in other organisations.

The aim of this paper is to contribute to the body of empirical data, in terms of case-specific views and considerations, which can be recognised by researchers, planners and policy-makers in other European countries, where adaptation processes in most cases have not yet started (see overview in section 2.2). The case study also provides an example of a qualitative approach to begin addressing climate adaptation and vulnerability issues. In addition, it highlights the need for, and encourages, proactive planning regarding future climate adaptation through analysing ways of increasing the adaptive capacity of the rail systems in a systematic manner, which is a theme still in its infancy in academic literature (see overview in section 2.2.)

The case study used a descriptive and qualitative methodological approach (Holme and Solvang, 1996). Data were primarily collected through interviews with representatives of the Swedish Rail Administration. The interview methodology, and the way in which the results were systemised are further described in section 3. Moreover, documents on major climate-related events produced within the organisation or in collaboration with consultants were also collated and studied in order to collect data, validate interview data and increase the reliability of the results.

In the following background section (section 2), we discuss the concepts of climate adaptation and vulnerability (and related concepts), and present a review of the current literature on climate adaptation of railways (and transport in general), including some brief facts on the Swedish rail network (as the research object of the case study). Section 3 describes the interview methodology and presents the empirical results of the study, i.e. findings from the interviews and from reviews of existing documents. Section 4 provides a discussion on future adaptation of railways. Conclusion and recommendations aimed for the European context are presented in section 5.

2. Background: Climate adaptation and railways

2.1 Conceptual elaboration: Climate adaptation and vulnerability, adaptive capacity, and coping range

In response to impacts from anthropogenic climate change, policies aimed at mitigation and adaptation are being developed. Mitigation policies aim for a reduction in global greenhouse gas emissions, while adaptation – which is the focus in this paper – relates to initiatives and measures to reduce the vulnerability to climate change effects. Since past emissions are considered to involve some unavoidable warming and since the rate of increase in concentrations of greenhouse gasses has accelerated, the issue of adaptation is equally important to the already urgent mitigation issue (Parry et al., 2007; COM, 2007).

According to the latest research review concerning climate change impacts and adaptation carried out by the Intergovernmental Panel on Climate Change (IPCC), the term *adaptation* refers to 'adjustments in natural or human systems in response to actual or expected climatic stimuli or their effects which moderate harm or exploit beneficial opportunities' (Parry et al., 2007, p. 869). Adaptation can be anticipatory and proactive (before impact), autonomous and spontaneous (non-conscious response to impact), or planned, i.e. based on deliberate policy decisions and the awareness that conditions have changed or that they will do so (ibid. p. 869).

A wide array of adaptation options are available, e.g. technological, behavioural, managerial and those involving a change in policy. A number of different actors can be involved in adaptation, from private households to firms and authorities. There are barriers, limits and costs to adaptation measures. It is clear, however, that options for successful adaptation diminish with increasing climate change (Parry et al., 2007).

Vulnerability to climate change is defined as 'the propensity of human and ecological systems to suffer harm and their ability to respond to stresses imposed as a result of climate change' (Parry et al., 2007, p. 720). This approach implies that adaptation and adaptive capacity determine the vulnerability of the system. *Adaptive capacity* has in turn been defined as the ability or potential of a system to respond successfully to climate variability and change and includes adjustments in behaviour and in resources and technologies (Adger et al., 2007, p. 727).

A reduction in the vulnerability of a system could be achieved by reducing exposure or increasing adaptive capacity. A related conception is coping range, mirroring the variation in external influence that a system can absorb without producing significant impacts (IPCC, 2001, Smit and Pilifosova, 2003). Thus the system is vulnerable to conditions that fall outside the coping range. This means that there is an adaptive capacity through management options within the coping range. Extreme values falling outside, or near, the gradually decreasing coping range are more problematic. Climate change involves both a shift in mean values and a change of pattern in the frequency and magnitude of extremes. Without a change in coping range through adjustment and adaptation, the system will become more vulnerable.

The *coping range* of the system reflects the adaptive capacity and many systems, such as railway transportation systems, have built up resources based on a learning process from past deviations from the 'normal' condition. However, extreme events may not be part of the coping range that has evolved through this process. Consequently, an expansion of the adaptive capacity through planned adaptation measures also increases the ability to cope with current climate conditions. An understanding of the present coping range is a prerequisite for the assessment of future impacts on a certain system, for example a railway network.

2.2 *Literature review: Climate adaptation of transport and railways*

The increased attention being paid to climate adaptation is apparent in both policy and academic publishing. The Commission of the European Community and the European Environment Agency stress that Europe must boost climate adaptation efforts (COM, 2007; EEA, 2008). Moreover, there are government-initiated investigations and research programmes with a national focus, for example in the Netherlands, Sweden, Finland and Canada (Lemmen and Warren, 2004; Nillesen and van Ierland, 2006; Swedish Commission on Climate and Vulnerability, 2007; Carter and Kankaanpää, 2007). In these investigations, climate impacts on the transport sector are discussed and analysed to various degrees, but since most of the investigations have a very broad scope, detailed analyses of adaptive capacity, coping range or adaptation strategies for specific modes of transportation are not presented, for obvious reasons. The *Journal of Mitigation and Adaptation Strategies for Global Change* has also published a number of papers with similar regional or national approaches, indirectly relating to impacts and adaptation of transportation and infrastructure (e.g. Australia: (Jones et al., 2007); Bahrain: (Al-Jeneid et al., 2008); South Africa: (Koch et al., 2007); North-eastern U.S.: (Ashton et al., 2007; Frumhoff et al., 2008)).

There are some transport-specific investigations analysing potential impacts of climate change on the transport sector as a whole in certain nations (e.g. Transportation Research Board (U.K.), 2008; Transport Canada, 2003), and also some studies focusing on urban transport infrastructure in specific cities (e.g. U.K.: (London Climate Change Partnership, 2005); Boston, U.S.: (Kirshen et al., 2006, 2008); Hamilton, New Zealand: (Jollands et al., 2007); Dehli (and others), India: (Revi, 2008)). A common conclusion is that there is a need to better understand the consequences of climate impact (including costs, see e.g. Larsen et al. (2008)) and that adaptation options must be further developed and analysed (see also Kintisch, 2008). Another related research area is how to handle future climatic uncertainties when planning for adaptation in the infrastructure sector (e.g. Wilson and Burtwell, 2002; Auld and Maclver, 2006; Auld et al., 2006a, 2006b). An overview of empirical findings concerning the impacts of climate change and weather on transport is presented by Koetse and Rietveld (2009), concluding that the changes will alter the competitive positions of the different transport modes.

When it comes to the specific case of railway systems, there are some investigations dealing with the vulnerability to climate change, with the focus on incidents and extreme weather events:

- In Canada, Natural Resources Canada (NRCAN) (a government department) has concluded that the rail infrastructure is susceptible to temperature extremes and that extreme cold conditions are currently more problematic for railways than severe heat. On balance, it is expected that warming will provide a modest benefit for Canadian rail infrastructure, except in regions underlain by permafrost. NRCAN emphasises that there has been very little research on climate change impacts on rail infrastructure in Canada (NRCAN, 2009).
- In India, an evaluation has been made of the potential impacts of climate change on the Concan railway along the west coast of India (Shukla et al., 2003). The conclusion is that the main factor contributing to potential impacts is increased rainfall with subsequent landslides. The rainfall threshold for landslides has been identified as more than 200 mm precipitation in 24 hours but the projected rainfall level could exceed that threshold in 2080. A further conclusion is that a more detailed assessment is needed to cover other climate variables and to determine the value of impacts (Shukla et al., 2003).
- The U.S. Department of Transportation has commissioned an inventory and evaluation of potential climate impacts on railroad operators (Rossetti, 2002). The evaluation is based on past weather-related accidents and highlights extreme events such as floods, avalanches, thunderstorms, tornadoes and tropical cyclones. The evaluation concludes that the effectiveness of strategies to address (current) climate impacts needs to be assessed.

There is little or no mention of adaptation strategies or adaptive capacity in the publications above. An example of a conscious and planned adaptation is the Qinghai-Tibet railway. Parts of the railway rest on permafrost with a mean annual ground temperature ranging from 0 to -1 °C. Various elements such as insulation, shading boards and ground cooling systems have been introduced in order to maintain a solid foundation for the embankments in the future (Parry et al., 2007; Cheng et al., 2008).

In the case of the European Railway Administrators, there are very few examples of ongoing research or major adaptation initiatives. In the Netherlands, however, with its high density of rail infrastructure in low-lying coastal zones, adaptation to coastal flooding and sea-level rise is a major concern (Nillesen and van Ierland, 2006). In the Kampen/IJsseldelta region, the new Hanzelijn railway connection, planned to be operational from 2012, is part of the 'climate-proof' spatial planning programme for the entire region (Van Drunen, 2007).

Moreover, in 2003 the Railway Safety and Standards Board (RSSB) in the U.K., in collaboration with the railway industry and the national railway administration Network Rail, commissioned a report concerning the safety implications of weather, climate and climate change for the rail system (Eddowes et al., 2003). This report identifies the potential impacts on railways from climate factors such as excess or reduced rain, temperature and sea level rise. In response to the investigation, the RSSB concludes that although railway infrastructure and vehicles are robust, rail safety can be affected by extreme weather. Although the risks with climate change are low, they are not negligible and the RSSB recommends different types of technical research into vulnerabilities (RSSB, 2003). One example is the increased risk of rail buckling due to high summer temperatures (see e.g. Dobney et al., 2008)

Network Rail, which manages the U.K. rail infrastructure, recognises both climate change impacts and the need for adaptation as issues that will affect the performance and management costs for their infrastructure (Network Rail, 2007). In an inventory of existing adaptation measures within the U.K. railway sector, made within the Defra-funded project 'Linking adaptation research and practice', 22 adaptation measures are found. Three of these are classified as planned adaptation as a response to climate change, while the rest are aimed at building adaptation capacity (Tompkins et al., 2005). In addition, the railway in the Dawlish area of Devon in south-west England is used in the development of a general methodology for assessment of climate change impacts on the safety and performance of the railway coastal and estuarine defence assets (RSSB, 2008).

Few other documented examples of initiatives related to climate change adaptation can be found among the European Rail Administrations, but on the EU level climate change adaptation is recognised as an important issue, e.g. by the European Rail Research Advisory Council (2007), which is the advisory body to the EU Commission representing Member States and all stakeholders in the railway sector, including European Rail Administrations. However, adaptation to climate change can be concealed, for instance within other measures. Climate adaptation often takes the form of immediate responses to severe climate events such as flooding or storms, but measures may also be introduced as a slow process within the usual maintenance procedures without being labelled climate adaptation measures.

2.3 *Brief facts on the Swedish railway network and general vulnerabilities*

Since this paper presents a case study on the Swedish railway, some short facts about the Swedish network and its general vulnerabilities are provided here as background. The Rail Administration is the governmental authority responsible for operation and administration of the national track system, however not for the operation of trains. The Rail Administration also conducts and monitors developments within the railway sector and has the overall responsibility for ensuring that the railway sector develops in line with transport policy goals. The Swedish rail network (operating today) is approximately 12 000 km in length (harbour and industrial tracks excluded). Approximately 4 000 km consist of double tracks, and 10 000 km are electrified. Around 80% of all railways in Sweden are owned by the state and managed by the Rail Administration. The responsibilities of the Rail Administration also extend to 11 000 km of fibre optic cable positioned alongside the tracks and used for telecommunication, railway signalling systems and data communication (Banverket, 2007).

The total amount of freight transport in the Swedish rail network for 2005 was 21.8 billion tonne-kilometres and the amount of transported goods was 65.3 million tons. Viewed in a European perspective, the amount of freight traffic in Sweden in 2003 ranked number four after Germany, Poland and Italy, and was just above the figure for the U.K. (Eurostat, 2008). Within passenger traffic, 151 million journeys were made in the Swedish rail transport system during 2005, totalling 8.9 billion passenger-km (SIKA, 2006).

The Swedish network has a comparatively small amount of double tracks, around 20% compared with 35% in many other European countries (UIC, 2008). A redundancy in traffic and a substantial increase in capacity could be achieved by using double tracks. On the other hand the large traffic volume on double tracks might result in greater consequences from even minor disturbances. A substantial part of the Swedish rail network, mainly in the low priority classes, also consists of old types of tracks that are more sensitive to external impacts. Older tracks with joints are more vulnerable to movement in the ground and rail buckling incidents are more common than with new welded continuous tracks (Corshammar, 2006).

From a systems perspective, there is a lack of redundancy in many parts of the Swedish network. The newly constructed Bothnian link (north-east Sweden) is one example where new investment has provided an alternative route that creates redundancy in the network. However, even though the tracks are largely separated in space, both routes cross the same rivers and may therefore in some aspects experience similar vulnerabilities. The link along the Göta River (in south-west Sweden) towards Gothenburg lacks redundancy. Another vulnerable location in the network is the Stockholm region. A large amount of traffic is forced to pass through the narrow passage through central Stockholm and even small disturbances could affect the traffic in the whole Stockholm region.

3. Empirical results of case study on the Swedish railway network

3.1 Interviews with the Swedish Rail Administration

The primary data in this case study were collected through semi-structured interviews (Trost, 2004) with nine key individuals within the Swedish Rail Administration. The interviewees were selected from four sections within Head Office that are dealing with climate change and climate variability in different ways:

- Emergency Planning and Security.
- Environmental Issues.
- Track and Civil Engineering.
- Maintenance.

The selection was intended to capture views from different parts of the organisation with different responsibilities. The interviewees' opinions and thoughts relating to vulnerability and climate adaptation were collected and collated. The results were then re-organised using the same structure that guided data collection in the interviews under the following headings:

<u>General awareness</u>: The general view within the organisation and the specific section. Influences from other actors and triggers that increase awareness were also discussed.

<u>Responsibility</u>: Problem ownership and the sources from which the first initiatives should come. Since this aspect is specific to the Swedish organisation, it is not accounted for in this paper.

<u>Climate-related threats</u>: Present threats, but also future predicted threats. In the interviews, discussions on threats were closely related to vulnerabilities.

<u>Vulnerabilities</u>: Views on present and future weaknesses in the system and the ability to map these.

<u>Consequences</u>: Discussion of future consequences based on the experiences of current and past events.

<u>Adaptation measures</u>: The discussion centred around measures currently being taken to reduce the vulnerability to climate factors and future possibilities, placed in a decision-making context.

3.1.1 General awareness

The general awareness of climate change adaptation in the organisation was considered low. A number of measures have been taken to reduce the vulnerability to extreme weather events, but interviewees did not know whether there is a deliberate connection between these measures and the climate change issue. It is possible that recent flooding and storm events have raised awareness of climate change further in the organisation.

On section level, awareness was not consistent among the interviewees. The Track and Civil Engineering section had been given no clear indication that climate change is a problem to be acted upon; on the contrary, investigations carried out after flooding events indicated that the present measures are sufficient as long as maintenance work is carried out according to instructions. There was a high degree of awareness and empirical knowledge relating to normal climate variations and weather-related factors within the section. Other sections related more to climate change adaptation and the uncertainties connected with future actions as a separate issue. The Emergency Planning and Security section was representing the Rail Administration in the national inquiry on vulnerabilities to climate change and extreme weather events. The Environmental section is used to working on climate change mitigation and they strongly felt that the issue of climate change adaptation is an essential topic. The Maintenance section also believed that the issue is highly relevant. 'If we have a future with more extreme events […] we need a system that also works for those conditions', as one interviewee put it.

3.1.2 Climate-related threats and vulnerabilities

The interviewees believed that climate-related events are probably the main reason for disturbances after technical failures. However, no systematic mapping of either current or future climate-related threats has been performed. When discussing minor disturbances and delays in traffic in wintertime, problems associated with snow and ice on the track switches were seen as the main cause by all sections. Major climate-related threats that can cause severe damage to infrastructure include high water levels from intensive precipitation and high wind speeds, but also extreme temperatures. The Emergency Planning and Security and Maintenance sections in particular regarded temperature as an important issue. The main risk relating to warmer temperatures was the increased risk of rail buckling. Generally it is variations in temperature, rather than constant heat, that cause problems.

One of the most critical vulnerabilities in the railway transport system is the low physical flexibility in the event of disturbances. The Maintenance section also highlighted the difficulties rail-bound maintenance experiences in accessing the tracks, due to the lack of scope to redirect traffic. This affects the recovery time after incidents.

The Emergency Planning and Security section stressed the importance of interdependencies with other types of infrastructure. Disturbances in the power supply from external networks directly influence the functionality of the railway transport system. Telecommunications and other transport systems are other central areas where the system is dependent on the functionality of external infrastructure. Climate-related events often affect all of these systems at the same time.

The Environmental section highlighted vulnerability from a systems perspective. Measures to reduce vulnerability are often undertaken on high priority parts of the track network. The vulnerability of lower priority, but fundamental, parts of the system may not be reduced by the same measures. The functionality of the whole system may depend on the vulnerability in the lower priority parts of the system.

The Environmental section also discussed technical and physical vulnerabilities, e.g. movements in the ground. The initial ground conditions affect the sensitivity to increased precipitation or failures in the drainage system, a vulnerability component to which all sections referred. A reduction in maintenance and monitoring resources in combination with a loss of knowledge within the organisation has made the system vulnerable to extreme precipitation. With increased use of the railways, this factor will become more important. As one interviewee from the Emergency Planning and Security sections said, 'the heavier and faster trains we use, the more important dry and stable ground conditions become'. Movements in the track, initiated by movements in the ground, also affect the tension in the rail and could therefore trigger rail buckling incidents. According to the Track and Civil Engineering section, the railway is sensitive to a mismatch in the so-called *neutral temperatures* that are used in the construction of the railways and the actual temperatures, such that 'if we use the wrong temperatures then we will have more rail buckling or rail breakage'.

According to one interviewee from the Emergency Planning and Security section, rail traffic is one of the main causes of forest fires. For this reason, the vegetation type in the rail corridor could be an important factor in the system. According to the Emergency Planning and Security section, the establishment of tree-free zones around the tracks could result in increased vulnerability to heat and temperature variations, as well as reduced vulnerability to high wind speeds. According to this section, the effects of remedial measures have not been weighed against each other before implementation, and definitely not against climate change scenarios.

The Emergency Planning and Security section stressed that electric equipment that needs cooling to function has already reached a limit where additional measures have had to be taken. Fans have recently been installed in order to keep some equipment functional during periods of extreme heat. In the light of future climate change, the dependence on constant cooling of electronic equipment could make the system more vulnerable.

3.1.3 Consequences

The positive consequences of climate change discussed related primarily to a potential reduction in winter problems. If milder winter conditions occur, there will for instance be fewer problems with track switches, train set doors and train engines. However, according to the Maintenance section 'these problems are easier to predict than the other problems', referring to new and more uncertain problems related to climate change. Consequences can be graded into 1) limitations leading to delays, 2) disturbances leading to decreased capacity and complete stops, 3) extreme events creating system breakdowns and severe accidents. The Environmental section stresses that even the less extreme consequences, like minor delays in traffic, are strategically important for the Rail Administration. The railway transport sector has to be reliable in order to be chosen by the customer.

According to the Maintenance section, the most severe consequences of climate change relate to incidents with rail buckling and failures in the drainage system. There is a rapid chain of events behind these incidents and warning systems have only been installed where the largest known problems are likely to occur along the highest priority tracks. When considering the consequences of high water levels, the Track and Civil Engineering section pointed out that it is in the older parts of the network, or where maintenance has been reduced, that the most severe problems occur. The potential for combinations of new threats was also mentioned by a representative from the Emergency Planning and Security section, as a contributing factor to future, more severe, consequences. For example, very dry conditions followed by intensive precipitation might lead to unpredicted consequences for the drainage system (as the ability of the ground to absorb water is drastically reduced).

During the summer of 2006 there was an incident in Ånn (north-west Sweden), where due to extremely intensive rainfall over a small geographical area, the embankment collapsed while a train was passing through. Preliminary investigations showed that the drainage system was functioning and that it had recently passed an inspection. An interviewee from the Track and

Civil Engineering section concluded that 'as technicians we have to be better at highlighting the consequences, so we can make the correct priorities when conditions are changing'. Future increased use of the railway system – in order to reduce transport-related greenhouse gas emissions – means that the probability of similar events will increase.

3.1.4 Adaptation measures

A number of measures have already been taken to reduce the vulnerability of the railway transport system to climate-related factors. However, according to all sections of the Swedish Rail Administration interviewed, it is unclear whether these measures have been taken with the intention of adapting to future climate change, or of coping with current climate variations.

The largest adaptation measure in progress today is the establishment of tree-free zones in the railway corridor for high priority parts of the network. Approximately 4 000 km of the national railway tracks are to be protected from falling trees and branches in cooperation with landowners. This project was referred to by nearly all sections interviewed. According to the Environmental section, the project is a direct result of the consequences of the hurricane in January 2005 (further discussed in section 3.2).

Other important measures are those that have been taken against failures in the drainage system. According to the Track and Civil Engineering section, intensive work has been done after the problems with high water levels in the beginning of the new millennium and today new standard procedures have been developed that better meet the requirements.

Within a recent project, all drainage culverts were updated to withstand increased loads of traffic on some prioritised tracks, but as far as the interviewees from the Maintenance section knew, no consideration was given to climate change in that project. The same conclusion was reached by the Environmental section.

According to the Track and Civil Engineering section, temperature maps for neutral temperatures have been updated recently in order to better reflect the true mean temperatures. The representatives from the Track and Civil Engineering did not know exactly why these have been updated but 'it is probably not the climate change in itself, maybe, but the knowledge has increased, before we had regions as borders and within a certain region we had a specific temperature'.

When it comes to prioritising adaptation measures, the Maintenance section did not believe that there is any weighing up of different adaptation measures based on consequences. The head of the Maintenance section claimed that if the consequences were related to the measures taken, it might be more important to reduce different vulnerabilities than those first seen. The consequences of trees falling on infrastructure are different from those of embankment collapses. If the embankment is affected by high water levels, this could have more severe consequences for the safety of the railway system and the recovery time could be substantially longer so, 'if you think from that perspective, we should of course put more effort into making sure that nothing happens to the embankment'.

3.2 Documents on major climate-related incidents

The documents examined in the study, are produced by the Rail Administration or by external consultants and include reports on major weather-related impacts on the railway system (documents relating to the use of risk and vulnerability analysis as a tool in the planning process were also reviewed in the case study in order to validate interview results). Three recent reports were produced in direct response to major climate-related events that had severe consequences for both the Swedish railway transport system and the rest of society (initiated by the Ministry of Enterprise, Energy and Communications):

- Flooding Investigation: High water levels in the counties of Värmland and Norrland during 2000 and 2001
- Winter Investigation: Severe winter conditions in Stockholm in 2000
- Gudrun Report: The January hurricane in 2005.

The objective of the Flooding Investigation (Banverket, 2002a) was to determine whether there is a need to change the dimension criteria of railway installations, tunnels and bridges based on future precipitation patterns. The investigation examines the greatest damage in the regions most affected by flooding during the period 2000-2001. The inventory of damage shows that new railway structures suffered substantially less damage than older structures. According to the study, the major hazardous events relate to high water levels. Ground settling and flooding of the tracks are other incidents reported.

In the report the reasons for the damage are classified into inadequate dimensions, insufficient drainage and insufficient erosion protection. The predominant cause proves to be insufficient maintenance of the existing drainage system.

Regarding the influence of future precipitation, the conclusion is that the present methods for determination of characteristic water flows and levels, which build on frequency analysis of historical observations, are sufficient. The Flooding Investigation came to the conclusion that it is not necessary to change the dimension criteria of the railway infrastructure but that it is very important to improve the maintenance of the present facilities.

The Winter Investigation (Banverket, 2002b) dealt with an exceptional snowstorm in the Stockholm region during the turn of the year 2000. The capacity in the network was reduced during the whole period stretching from the 20th of December 2000 until the 8th of January 2001. The effect of the snowfall was worsened by strong winds that carried and accumulated the snow into drifts. The Rail Administration had severe problems keeping their infrastructure unaffected and functional for the train operators. The capacity in the railway transport system was drastically reduced in the whole Stockholm region.

The results from the Winter Investigation shows that the reasons behind the rail problems were a combination of weather factors, a delayed response in introducing measures to reduce the impact and a lack of resources for a continuous and sustainable recovery process. The Winter Investigation report concludes that vulnerability has to be reduced by both short-term and long-term measures and that the responsibility should be distributed between the operators and the Rail Administration.

The Gudrun Report deals with the hurricane on 8 January 2005 (Banverket, 2005), when south-west Sweden was hit by hurricane Gudrun. Over the following days, Sweden experienced one of the worst crisis events in decades. The hurricane had a severe impact on a number of important infrastructure systems. The electricity supply, telecommunications and the road and railway network were all hit at the same time. The Gudrun Report, produced by the Swedish Rail Administration, describes the sequence of events and the measures taken by the organisation. The incident provided an opportunity to study a critical event in order to learn more about the robustness of the system and the consequences for society.

The Gudrun Report charts the consequences of the hurricane and possible measures to reduce vulnerability to high wind speeds. It also provides information on specific vulnerabilities in the system. However, being an incident report, most of the focus is on the handling of the recovery process. Remedial measures are therefore also mostly orientated towards increasing the preparedness for a similar event, rather than advising on planning strategies for the future. However, some of the measures listed in the report are orientated towards prevention. The concluding recommendation that railway tracks especially vulnerable to overhanging trees should be identified is an example of a future-orientated adaptation measure to a climate factor. This recommendation formed the basis for the ongoing project aimed at tree-proofing high priority tracks. Another conclusion is that additional expertise is needed within the organisation in order to use and better understand available meteorological information.

4. Discussion: Future climate adaptation of railways

The empirical material from the case study shows that the railway system in Sweden is vulnerable to current climatic events and that adaptation measures already put in place have not fully succeeded in responding to current weather-related stresses. Some recent major climate events had huge impacts on the railway transport system, as well as the rest of society. Minor climate events are common and indeed during the case study the Swedish railway suffered two such events. In November 2006, intensive snowfall and winter conditions cancelled a large part of the rail traffic around Gävle (east-central Sweden) and six weeks later high water levels in the Gothenburg area severely affected the traffic as tracks were submerged and landslides damaged embankments. The railway is thus vulnerable to existing climate variation and the coping range is occasionally exceeded, a fact that was confirmed in the interviews in the present study.

Without doubt, it will be a challenge for the railway sector to cope with future climate change, and its adaptive capacity will be thoroughly tested during the coming decades. The results from this case study highlight several climate-related threats that could have severe negative consequences for the railway system. The most important of these relate to high water levels, both in streams and groundwater, high wind speeds and rapid changes in temperature. All of these are potential consequences of climate change. A positive aspect of climate change that may reduce the vulnerability, especially for Northern Europe, relates to milder conditions in winter. Below, some aspects of adaptation and some of the challenges that the railway sector will encounter in the adaptation process are discussed.

From the outset, it is important to point out that the character of the railway system makes it vulnerable to disturbances, more vulnerable than perhaps the road system, where it is often possible to redirect traffic in the event of severe disturbances. In addition, investments in railway infrastructure are long-term and investments made before the science of climate change was well known will now be in place for decades to come, with their eventual vulnerabilities. The increased demand for timely railway transport as part of a low-carbon transport system combined with climate change and the associated more extreme weather events may increase the vulnerability of the railway system if adaptation is not taken seriously.

The increase in temperature, for example, may not be seen as a problem since other regions in the world are already coping with these temperatures. However, for Northern European conditions the coping range for extreme heat has to be built up. Rail buckling, increased risk of fires, installation of cooling systems and passenger comfort are concerns relating to heat in a future transport system. Increased temperatures leading to longer vegetation seasons in Northern Europe can also increase problems with vegetation in the rail corridors and generate more leaves falling on tracks. For Southern Europe vegetation might decrease, but the fire risk will probably increase. In different ways, this may require adaptation in maintenance and surveillance procedures.

Higher water levels in streams and groundwater will not only have an effect on flooding, but the groundwater level and soil moisture content will also affect ground stability. Some regions that today are considered to be stable may shift towards unstable conditions. This will strongly affect the functionality of the present network as well as the available options for relocation of new railway tracks in Europe. The statistical calculations used to set the return periods for extreme water flows will be insufficient if precipitation levels change as indicated by climate scenarios for

Northern Europe (Bolle et al., 2008). There are also indications of a change in precipitation patterns, since according to the scenarios more rain will fall in the autumn and winter than previously. Consequently, there is a need to adapt both maintenance procedures and planning procedures for new infrastructure.

One important process that has to be improved in order to cope with future climate change is the systematic mapping of climate-related vulnerabilities and threats to the system. No such mapping has been carried out in Sweden, even for the present climate, and the empirical results from the case study show that the current strategies for adaptation are mainly event-driven or reactive. To a large extent these events have also functioned as the major drivers behind the increased awareness within the organisation of climate as a threat. If anticipatory and planned adaptation measures are to be implemented – and this is crucial for the railway sector with its long time frames – a change in both processes and organisation might be required.

During the interviews, some conflicting adaptation strategies emerged. For example, the measures to reduce the vulnerability to falling trees by establishing wider rail corridors may be counterproductive to some other objectives. A wider corridor can result in larger temperature differences in the track zone and this may challenge future objectives to reduce vulnerability to fires or rail buckling unless possible problems are further investigated.

Future settings based on current climate scenarios are associated with uncertainties on both temporal and spatial scale. Current regional climate scenarios are limited in terms of dimensions and also regarding emission scenarios and global models. This means that the span of possible change, especially in the longer term, is not adequately known for various regions at present. For long-term planning purposes regional climate scenarios need to be improved in order to enhance the adaptive capacity in the railway sector, although the information already available now is still useful for planning purposes. However, a review of the literature showed that the Swedish railway sector only uses probabilities for the magnitude, frequencies and distribution of weather events assessed through statistical data and other information from past events. This practice was confirmed by the interviewees and strengthens the conclusion that the present railway transport system has a coping range that has to change according to future settings. There are also indications that the present ability to cope with normal climate variation has been reduced during the past decade, especially as regards drainage systems.

Another weakness in the planning process revealed by the case study is the lack of consideration of climate change impacts in the early stages of planning. Risk and vulnerability aspects are often dealt with in the latter stages of planning and then with the focus on management of the risks rather than prevention (Håkansson et al., 2001). Climate change impacts have a geographical context that requires assessment at an early stage. Today, climate change is not included in the risk and vulnerability analysis methods used.

At best, adaptation measures should also mitigate climate change. For instance, any increase in the use of cooling systems that contributes to increased greenhouse gas emissions is counterproductive. The overall aim to which adaptation strategies aspire is sustainable development. The policies implemented for sustainable development and the protection of ecosystems, if correctly targeted and implemented, will also reduce the vulnerability to climate change. Ecosystem services (Millennium Ecosystem Assessment, 2005) could to some extent already be regarded as part of the railway system. Vegetation is often used as a buffer zone for noise and pollution along railway tracks. Apart from being one of the components that has to be examined from a climate change perspective, different vegetation types may be used as part of an adaptation strategy (Eddowes et al., 2003). Ecosystem services could be used in adaptation of the rail system to climate change in a variety of ways. Some trees withstand higher wind speeds than others, small meandering water courses could buffer high water levels better than man-made drainage systems and selection of suitable vegetation for near the rail corridor could reduce the risk of fires. Adaptation measures that use ecosystem services may also contribute to other environmental goals, for instance protection of biodiversity.

5. Conclusions in a European context

Overall, the results of the case study indicate that as regards adaptation to future climate change, the general awareness within the Swedish Rail Administration could be improved. Climate-related events are at present ranked high on the list of primary causes of disturbances and the knowledge of past and present climate variation exists, which has resulted in the implementation of some non-deliberate adaptation measures. However, anticipatory, proactive and planned adaptation strategies for future climate change are lacking. The increased risk of a higher frequency of climate-related events outside the present coping range and a larger degree of uncertainty in decision-making indicate deficiencies in the adaptive capacity of the system.

The future will pose a challenge to the European railway sector, where long-term, proactive and planned measures are needed to complement the reactive and piecemeal measures being carried out at present. In section 2.2, we showed that there are currently only a few railway organisations acting appropriately. Based on the findings in this paper, our recommendations for European Rail Administrations and other actors involved in infrastructure planning are as follows:

1. If systematic mapping of different types of climate threats, vulnerabilities and their consequences has not been carried out, this should be performed in order to guide the implementation of adaptation measures. Such mapping would also help in prioritising efforts to reduce vulnerability.
2. Climate change should be considered in the early stages of the planning process. Climate change should also be included in the risk and vulnerability analysis methods that are used in the planning process.
3. In order to make well-founded prioritisations among measures, potential consequences of climate events should be thoroughly evaluated and appropriate methodologies should be used when performing risk and vulnerability assessments, so that the results balance the frequency of events against their consequences in a systematic way.
4. Methodologies to perform risk and vulnerability assessments, aimed at analysing future climate impact, cannot be driven by past events alone. Explorative, rather than predictive, future-orientated tools should also be included. Scenarios, back-casting and expert opinion workshops are examples of methods that might be used to approach uncertain future conditions and that might prove to be essential for assessing future threats and evaluating adaptation measures.
5. When planning and designing adaptation actions, the effects of potential goal conflicts should be carefully assessed, in order to avoid the implementation of counter-productive measures. Moreover, the possibility of creating synergies with climate mitigation goals and other environmental goals should be investigated and exploited.

The research efforts being made to develop and refine regional climate scenarios should also be brought to attention (for example the U.K. Climate Impacts Programme). The outcome should be considered in common policy-making and in infrastructure strategy development processes throughout the entire European Union and within the Member States. Some strategies to cope with future impacts of climate change might be generalised in a European context, while other adaptation strategies need to be tailor-made to suit present and future regional differences – especially regarding differences between Northern and Southern Europe and between coastal and inland regions.

When future research is considered, a first step in assessing the adaptive capacity in a system is to examine the present coping range. For the future, it might be fruitful to examine the present coping range for the threats that might increase with climate change and to determine whether the range, at least for some parameters, is sufficient even for current climate variation.

The positive effects of climate change also need to be investigated further. Milder winters may increase the capacity to handle winter conditions, especially in Northern Europe, unless this scenario generates other unforeseen consequences. The incorporation of the long-term climate change issue into planning processes in far-seeing railway organisations could be documented in case studies from which other organisations could benefit. In addition, methodological development using improved regional climate scenarios in order to test settings of adaptation measures is an interesting area for future research.

As already discussed, adaptation measures may be counterproductive if they are not carefully selected. This might be an important topic for future investigation, since there are large costs involved when major adaptation measures are implemented. Adaptation measures could form part of regular maintenance routines, an issue that also needs further investigation.

Acknowledgements

The case study was carried out during 2006 and 2007. The four divisions within the Head Office of the Swedish Rail Administration selected for the interviews are thanked for their invaluable contributions. Since then, the Swedish Rail Administration has reorganised, principally on the divisional level, but the areas of responsibility for the sections studied remain.

The paper was written within the framework of the research programme Climatools, run by the Swedish Defence Agency (FOI), on behalf of the Swedish Environmental Protection Agency. The authors wish to thank two anonymous reviewers for constructive critique and useful suggestions for improvements.

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