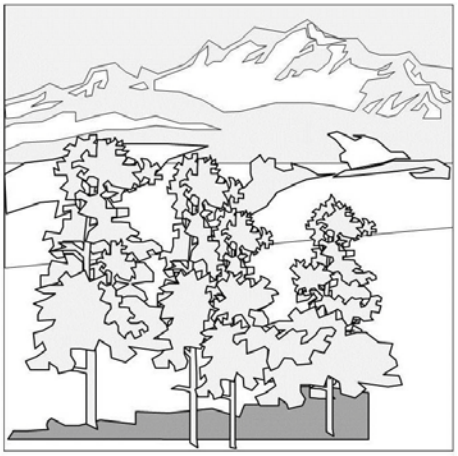

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Risk Assessment Of Climate Change Impacts On Railway Infrastructure

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RISK ASSESSMENT OF CLIMATE CHANGE IMPACTS ON RAILWAY INFRASTRUCTURE

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ABSTRACT

Although it has been known for a while that climate-related factors account for the performance development of infrastructure, it remains difficult for infrastructure manager to estimate the effect of the anticipated climate change. The impact of climate factors differs very much between geographical locations and therefore a climate change assessment requires a more detailed analysis of the particular network. In this paper data about actual infrastructure performance of two railway tracks in the mostly populated area of the Netherlands are correlated with regional climate data in order to model future performance and apply appropriate interventions to cope with climate change effects. After establishing the correlation between weather conditions and failure modes, threshold values for probabilities of occurrence of certain failures are determined. This is enabling then the development of risk matrix based on the likelihood and risk impact, which would support an effective maintenance plan and adaptation strategies in the long term sense to mitigate or reduce likelihood of failures caused by climate change.

KEYWORDS: risk assessment, climate change, maintenance, performance, railway infrastructure

INTRODUCTION

Over the last decade climate change has been on the top of the political agenda and many organizations have undertaken various efforts to determine the effects of climate change on our daily and future life, including judgments about mitigation and adaptation costs. Climate models indicate that mean annual temperature will rise by 1° to 5,5°C; while the annual precipitation is likely to increase in the north and decrease in south, the intensity of daily precipitation and the probability of extreme precipitation intensities can increase in all regions. (CEDR, 2012)

Large investments related to the transport infrastructures are expected in the future to adapt to climate change. In order to be able to develop sustainable adaptation strategies, the assessment of the vulnerability of infrastructure and its effect on infrastructure service provision is needed . Several research projects have already tried to reveal the influence of climate change on infrastructure networks (e.g. Chinowsky et al. 2011, Leviäkangas et al. 2011, Enei et al. 2010, Papanikolau et al. 2011, Koetse & Rietveld, 2009; Dobney et al., 2009 & 2010; Baker et al. 2010; Bles et al., 2010). These studies suggest that climate change will modify the risk of weather-induced impacts on infrastructure which challenge design rules and procedures for the

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operation and maintenance of infrastructure. However, most of these studies remain on global or national level of analysis which makes the results less applicable for infrastructure management organizations. Since climate factors differ very much between geographical locations, it can be expected that climate change effects differ as well across regions. In order to develop effective adaptation strategies, more detailed analysis of particular networks is required, addressing local climate conditions and infrastructure peculiarities.

In this paper we focus on the effects of climate change on the railway network in the Randstad area, the most populated region of the Netherlands. Data about weather-related failures of two railway tracks in this region are analyzed and correlated with the regional climate data, in order to assess the vulnerability of the railway tracks to climate change.

CLIMATE EFFECTS ON RAILWAY PERFORMANCE

There are many weather-related effects on infrastructure performance which differ very much between geographical locations. Moreover the severity of the effects depends on infrastructure design, age and usage.

Duinmeijer and Bouwknegt (2004) have done research on rail infrastructure failures due to adverse weather conditions in the Netherlands in year 2003. It appears that approximately 5 to 10 % of all failures is weather related. Most of the weather-related failures are caused by high temperatures, icing, storm and lightning. (Koetse and Rietveld, 2007)

When exposed to the high temperatures, railway tracks may develop heat kinks causing track misalignments, or so called buckle, which can consequently cause train derailments. The study of Dobney et al. (2009) shows that increased failures of rail buckles on the UK railway network are associated with extreme high temperatures. They conclude that an increased frequency of high temperature (greater than 25°C) occurrence will increase track buckling and the associated costs of heat-related delays, if the track is maintained to the current standard. It has been also shown that present-day adverse weather conditions cause 20% of all unplanned delays on the UK railway network (Thornes and Davis, 2002). The main goal of climate change impact assessment is to determine the relationships between the intensity of a given meteorological parameter and infrastructure performance parameters (e.g. observed disruption and accident rates). This also involves the identification of key thresholds when problems occur. The threshold at which, for example, a rail may buckle is highly dependent on the condition of the track. (Dobney et. al 2009, Rosetti 2002). To overcome problems with buckling and decrease the risk of derailments, speed restrictions are usually introduced at certain rail temperature, which correlates to the air temperature.

A similar condition may occur in winter, when extreme cold results in brittle track, increasing the risk of breakage. The formation of ice on the tracks can cause slippery conditions, which may cause derailments, therefore trains have to proceed at slower speed and they need to start to break earlier. The main problem of the ice formation is that it can block the switches. To prevent this problem, the switch can be provided with a heater, either electrical or by gas. (Leviäkangas et al. 2011)

Table 1 gives an overview of the potential impacts of climate change on railway assets and railway performance.

Table 1: Relationship between climate effects and railway infrastructure (Leviäkangas et al. 2011)

Climate Factor	Impacts	Consequences to infrastructure	Consequences to services, operations
Snowfall	• Flooding • Freezing • Damage to cables • Loss of electricity • Blowing snow • Blocking tracks and yards	• Damage to railway embankment and slope • Scour of bridge supports • Water on track or in underground structures • Damage to rail track • Other material damage to equipment and infrastructures	• Stopped and / or cancelled rail services • Inefficient acceleration and braking → slower speeds → delays • Accidents • Material damage to rail fleet, equipment and infrastructures • Freezing of switches, blocking of railway yard and equipment, snow accumulating on cuttings → slower speeds → delays • Changes in accessibility by train • Changes in quality of transport services
Heavy precipitation	• Flooding	• Damage to railway embankment and slope • Scour of bridge supports • Water on track or in underground structures • Damage to rail track • Other material damage to equipment and infrastructures	• Stopped and / or cancelled rail services • Inefficient acceleration and braking → slower speeds → delays • Accidents • Material damage to rail fleet, equipment and infrastructures • Changes in accessibility by train • Changes in quality of transport services
Wind gusts	• Changes in sea level; flooding • Damage to cables • Falling trees • Loss of electricity • Freezing • Blocking tracks	• Damage to railway embankment and slope • Scour of bridge supports • Water on track or in underground structures • Damage to rail track • Other material damage to equipment and infrastructures • Supply cable sag or tensional failure	• Stopped and / or cancelled rail services • Inefficient acceleration and braking → slower speeds → delays • Accidents • Material damage to supply cables, rail fleet, equipment and infrastructures • Freezing of switches, blocking of railway yard and equipment, snow accumulating on cuttings → slower speeds → delays • Changes in accessibility by train • Changes in quality of transport services
Low temperature	• Damage to cables • Loss of electricity • Freezing, frost	• Overheating of safety device • Other material damage to equipment and infrastructures • Frost cracking, freezing of equipment and structures on track • Supply cable sag or tensional failure • Damage to rail track	• Stopped and / or cancelled rail services • Inefficient acceleration and braking → slower speeds → delays • Accidents • Material damage to supply cables, rail fleet, equipment and infrastructures • Freezing of switches, blocking of railway yard and equipment, snow accumulating on cuttings → slower speeds → delays • Changes in accessibility by train • Changes in quality of transport services
Blizzard	• Low temperature + snowfall + wind gust impacts	• Low temperature + snowfall + wind gust impacts	• Low temperature + snowfall + wind gust impacts

RESEARCH METHODOLOGY

The Randstad case

With over 16.5 million people and a population density of 488 people per km2, the Netherlands is the most densely populated country of the European Union and is one of the mostly densely populated countries in the world. More than 40% of the total population live in the Randstad, the agglomeration of the cities of Amsterdam, Rotterdam, The Hague and Utrecht. which can in many ways be regarded as a single metropolitan area, with about 7 million inhabitants and one of the largest conurbations in Europe. The railway network plays an important role for the accessibility and the economic and social development of the Randstad area. (Randstad monitor, 2010)

In close collaboration with ProRail, the Dutch railway network operator, two main railway tracks in the Randstad area were selected for analyzing weather-related failures and climate change vulnerability. The selection was based on one or more of the following criteria:

- the track is critical for the network performance;
- the track had performance failures due to the extreme weather conditions in the past;
- the track required a high level of maintenance in the past;
- weather-related failures are systematically collected for the track.

The selected tracks include the track between Utrecht and Amsterdam (45 km) and the track between Utrecht and Rotterdam (55 km).

Data collection and analysis

A risk assessment methodology based on cause-and-effect analysis has been used for the assessment of climate change impacts on railway infrastructure. The risk assessment methodology consists of the following stages (EC 2010):

1. Identifying weather-related failures of railway infrastructure
2. Analyzing the failure probability of railway infrastructure due to weather events
3. Determining the vulnerability of railway infrastructure to climate change
5. Developing adaptation strategies

Climate-related risks are identified based on historical data which include delays and disruptions of train operation (duration), technical failures related to signaling, catenary, drainage systems, structures, etc., and weather data from the closest measurement station within the period 2000 to 2010. Weather data include temperature or precipitation, which are then used for building climate scenarios.

The correlation between weather data and technical failures is established and based on that the probabilities of occurrence of certain failures (e.g. switch failure, catenary failure, track under water etc.) are determined. Threshold values for an increased risk of infrastructure failure are proposed. Taking the climate scenarios into account the vulnerability of the railway infrastructure to climate change is determined.

RESULTS

Identifying weather-related failures

For the selected tracks the weather-related failures and their frequency were analyzed. In the following paragraphs the number of failures are set in relation to years, seasons, and locations. In addition, they were related to failure causes (weather events), failure modes and assets that failed (Figure 1). Failure effects were not included due to inconsistency in the data.

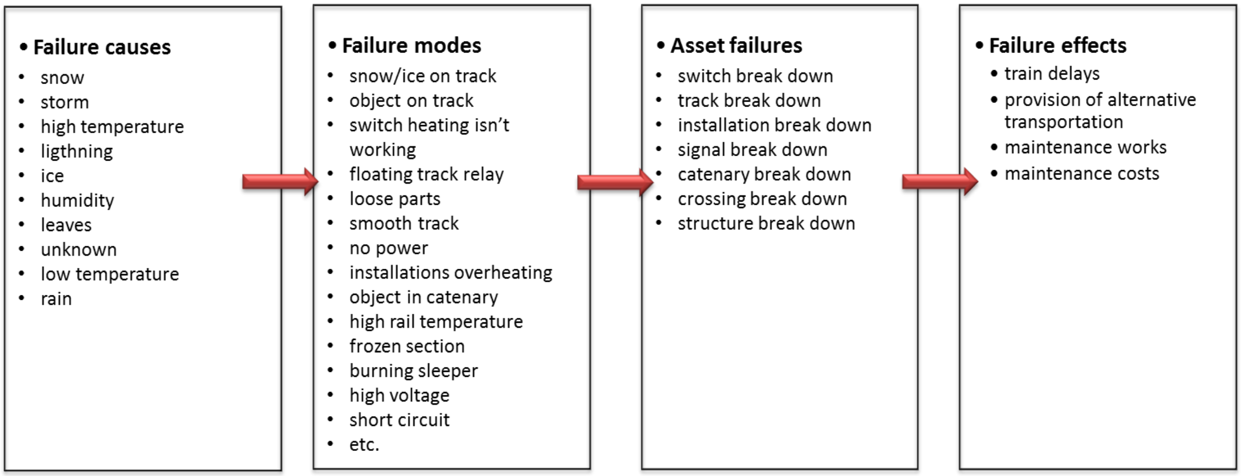

Figure 1: Overview of weather-related failure causes, modes and effects on rail infrastructure

Within the period 2000-2010, 868 weather-related failures were recorded for the two tracks, which gives in average the 0.7 failures per km per year. (Stipanovic Oslakovic et al. 2012) In Figure 2a) and 2b) the distribution of the 868 failures are related to year and season within the observed period. It is noticeable from Figure 2a) that the number of failures has increased over the last years. This may indicate more vulnerable infrastructure assets and/or an increase of severe weather events. Another explanation could be an improved recording of weather-related failures and maintenance of the associated data base. Figure 2b) suggests also that the winter represents the most critical season in terms of weather-related failures.

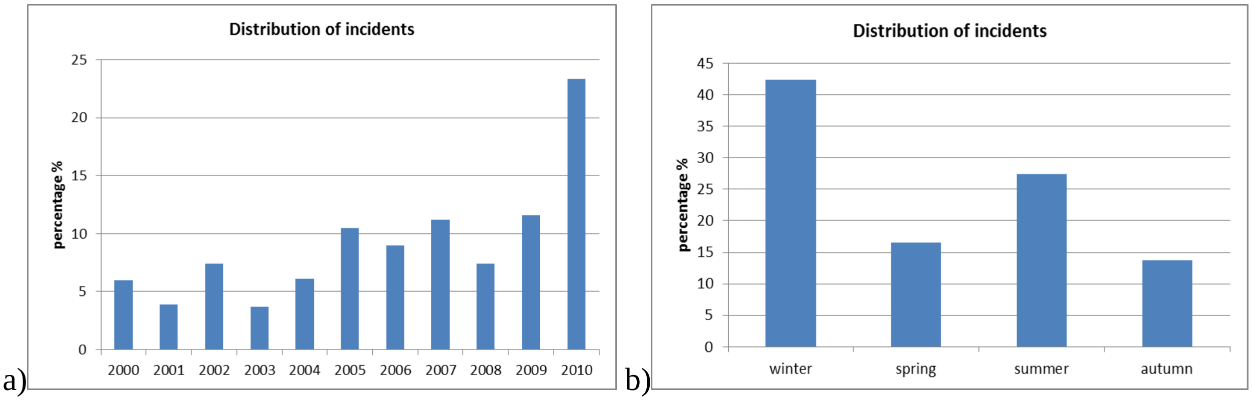

Figure 2: Distribution of failures within the observed period (2000-2010) a) per years, b) per seasons

After analyzing the descriptions of the failures in the database it was decided to divide the causing weather events into the 10 following categories: snow; ice; low temperatures; storm; high temperature; lightning; rain; leaves; humidity; and unknown. Figure 3 presents the distribution of failures related to the type of weather event. It suggests that the problems in the winter are mainly caused by snow. It is also interesting to note that storm causes a majority of failures, but occurred in every season. High temperature as another critical weather event is, as expected, a problem during summer, whereas lightning appeared from spring to autumn.

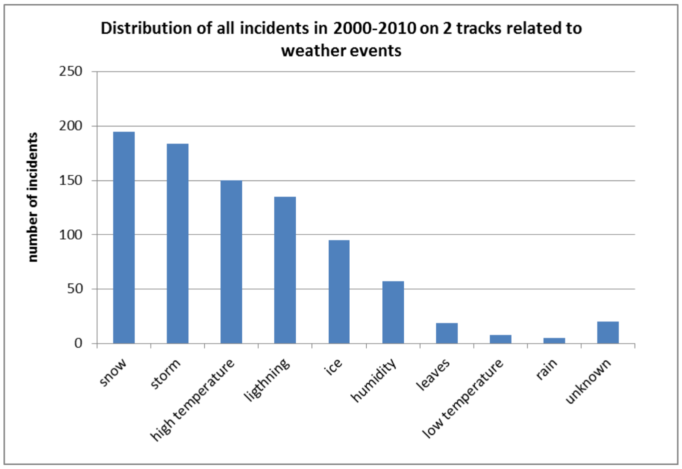

Figure 3: Number of failures caused by weather effects in the period 2000-2010

Analyzing the failure probability

Temperature analysis

Before predicting impacts of climate change on railway performance, the impact of existing weather on the two tracks must be reviewed and analyzed. This section outlines the analysis of all failures in relation to the temperature at the moment of an failure.

In order to establish correlation between temperature and failure occurrence, the frequency of failures was compared to the temperature at the moment of failure occurrence. First, the number of failures was related to temperature range of 1°C. Analysis was separately done for maximum daily temperatures and for minimum daily temperature during the days when failures occurred.

In Figure 4 the frequency of failures related to high air temperatures is presented. Since the number of days with a certain temperature differs within the period of observation, the probability (chance) of an failure related to the air temperature was calculated. The probability of an failure is calculated as a ratio between the days with an failure in a certain temperature range and the total number of days in that temperature range:

$$P(x) = \textit{\# of days with an failure in temperature range / total \# of days in temperature range (\%)} \qquad (1),$$

both counted for the observed period, in our case the period of 11 years, from 2000 to 2010. In Figure 5 the calculated probability (chance) that an failure occurs at a certain air temperature is presented.

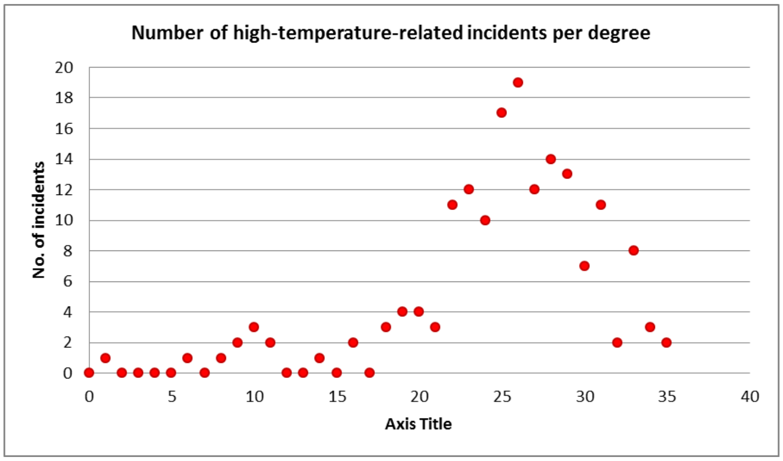

Figure 4: Frequency of failures related to the high temperatures / warm weather

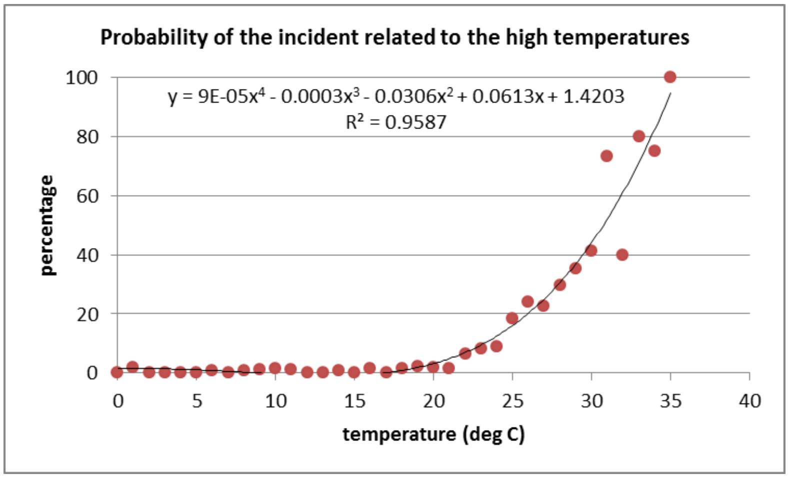

Figure 5: Probability of the event of failure related to the air temperature

Figure 5 shows that with the increase of temperature the probability of an failure is exponentially increasing. At a temperature of 35°C the chance of an failure happening is 100%. The 33% and 66% probabilities of an failure are reached at 28°C and at 33°C respectively.

The same type of analysis has been performed for the low temperatures. In Figure 6 the frequency of failures related to cold temperature is presented.

Again, the probability (chance) that an failure will occur at a certain air temperature was calculated applying the relation (1). Results are presented in Figure 7. The probability of failure occurrence is exponentially increasing with a temperature decrease. A probability of 100% is achieved at a temperature of -12°C. The 33% probability of an failure is reached around -5°C, and the 66% probability below -9°C.

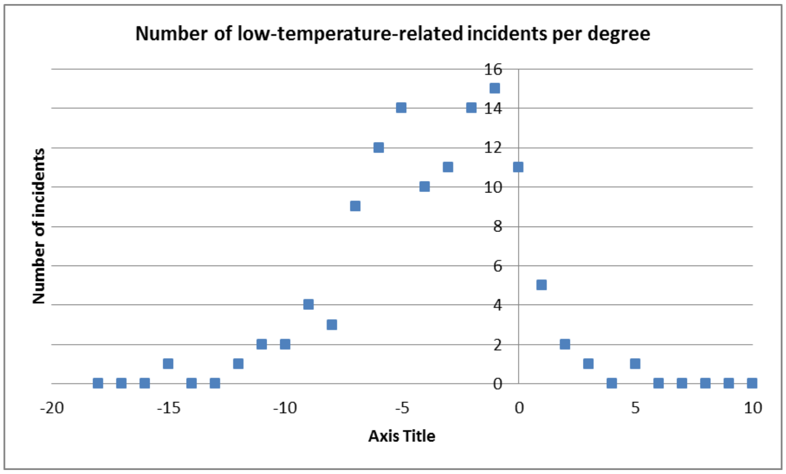

Figure 6: Frequency of failures related to the low temperatures / cold weather

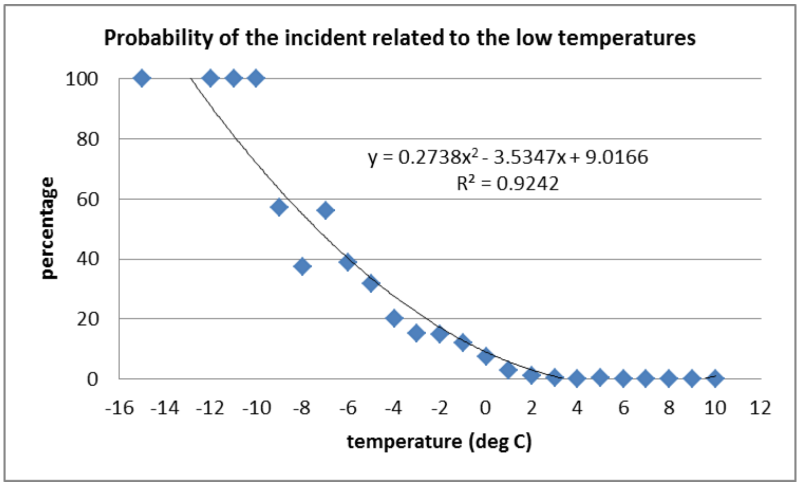

Figure 7: Probability of the event of failure related to the air temperature

Snowfall analysis

Further analysis has been performed in relation to the snowfall weather conditions. In Figure 8 probability of failure related to the snowfall is presented, calculated as a ratio between number of days when failures occurred and total number of days with snowfall recorded at the meteorological station Schiphol, observed per year.

In Figure 9 results of analyzing the number of failures in relation to the amount of snowfall per day are presented. It can be seen that the probability of failure occurrence is exponentially increasing with snowfall increase. A probability of 100% according to the correlation curve is achieved at 58 mm of snowfall per day, while 33% and 66% probabilities of an failure are reached at 9 mm and 22 mm of snowfall per day respectively.

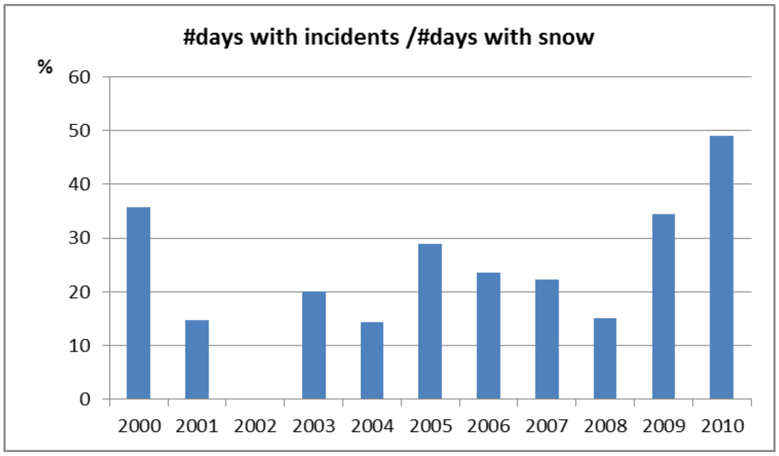

Figure 8: Probability of failures on a day involving snowfall

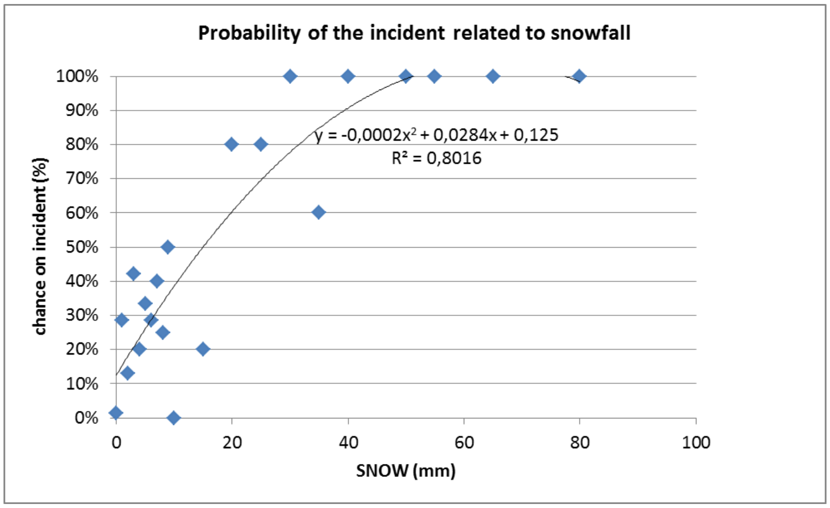

Figure 9: Probability of failures related to the amount of snowfall per day

By analyzing current weather conditions and failures of the railway infrastructure, baseline relations have been established, from which threshold values for certain likelihood of the potential impacts on the railway infrastructures are suggested. Threshold values are related to the likelihood of the failure to happen under certain conditions, where the three categories are: unlikely below 33%, possible between 33% and 66%, likely between 66% and 99%, and certain above 99% of probability. In Table 2 suggested thresholds are presented.

Table 2: Threshold values for different weather events and the likelihood of infrastructure failures

	Failure occurence				Component most endangered
Weather event	Unlikely, < 33 %	Threshold 1 Possible, 33 – 66 %	Threshold 2 Likely, 66 – 99 %	Threshold 3 Certain, > 99%	
High temperature	T < 28°C	28°C < T ≤ 33°C	33°C < T ≤ 35°C	T > 35°C	track failure
Low temperature	T > -4.5°C	-9°C ≤ T < -4.5°C	-12°C ≤ T < -9°C	T < -12°C	switches
Snowfall	< 10 mm/d	10 mm/d < s ≤ 22 mm/d	22 mm/d < s ≤ 50 mm/d	> 50 mm/d	switches

In order to develop adaptation strategies it is necessary to analyze components of the system which are failing under certain weather conditions. In Figure 10 types of failures of the system components are related to the weather phenomena. It can be see that most switch failures are caused by snow and ice on a track. Next most frequent failures are railway track failures cuased by high temperatures, storm or wet leaves causing sleepery tracks. Storm is causing catenary and switch failures. Installation failures are mainly caused by lightning, high temperature and high humidity conditions.

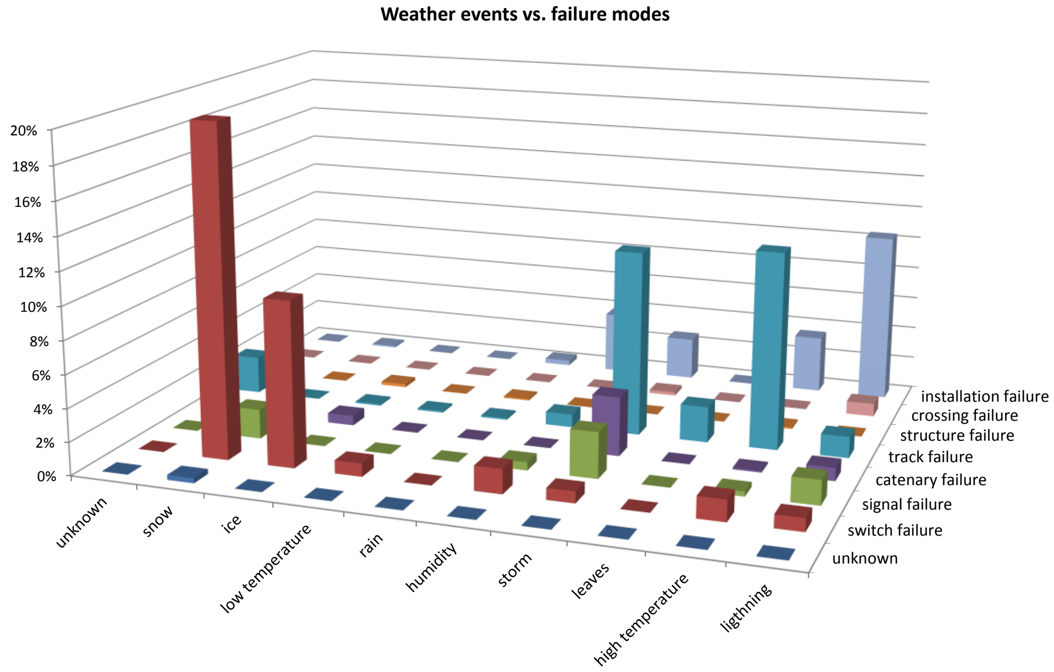

Figure 10: Frequency of asset failures related to the weather phenomena

IMPACTS OF CLIMATE CHANGE

Climate change scenarios

Predictions on climate change in the Netherlands require insights into regional climate expectations as well as global trends. In 2006 the KNMI (Royal Netherlands Meteorological Institute) has published four different climate scenarios into which Dutch climate may develop. These four scenarios differ in the degree of global temperature rise and the degree of change in atmospheric circulation patterns in our region, see Table 3. By making a simple assumption the influence of future climate on the railway for winter conditions and heat can be qualitatively assessed (Hurk et al., 2006). In 2009 the KNMI evaluated the KNMI ’06 scenarios with the state of knowledge at that time. The conclusion was that there is no reason to change the KNMI’06 scenarios. Important changes since the introduction of the KNMI ’06 scenarios include: the observed rapid warming of the Netherlands and Western Europe, the observed rapid decrease of large ice sheets on West-Antarctica and Greenland, and new research on precipitation patterns on the local and regional scale. The assessment was that the changes fall largely within the four

KNMI’06 scenarios (KNMI 2009). To relate rail failures to weather, the above mentioned datasets were combined with weather data which was obtained from the database of the KNMI.

Table 3: Values for the steering parameters used to identify the four KNMI’06 climate scenarios for 2050 relative to 1990 (KMNI 2009)

Scenario		**G**	**G+**	**W**	**W+**
Global temperature increase in 2050		+1°C	+1°C	+2°C	+2°C
Change of atmospheric circulation		No	Yes	No	Yes
Winter	Average temperature	+0.9°C	+1.1°C	+1.8°C	+2.3°C
	Coldest winter day per year	+1.0°C	+1.5°C	+2.1°C	+2.9°C
	Average precipitation amount	+4%	+7%	+7%	+14%
	Number of wet days (≥ 0.1 mm)	0%	+1%	0%	+2%
	10-day precipitation sum exceeded once in 10 years	+4%	+6%	+8%	+12%
Summer	Average temperature	+0.9°C	+1.4°C	+1.7°C	+2.8°C
	Warmest summer day per year	+1.0°C	+1.9°C	+2.1°C	+3.8°C
	Average precipitation amount	+3%	-10%	+6%	-19%
	Number of wet days (≥ 0.1 mm)	-2%	-10%	-3%	-19%
	daily precipitation sum exceeded once in 10 years	+13%	+5%	+27%	+10%

Failures related to the temperature change in winter

Based on the historical data about the performance of two tracks during 11 years of observations, most critical sections on the two tracks have been selected. Weather data were collected from the meteorological station at Schiphol, closest to the selected track section. Time series of temperature are generated by transforming a time series of temperature using a program which is provided by KNMI on their website (http://climexp.knmi.nl/Scenarios_monthly/). This transformation can be executed for the average daily temperature, daily minimum and daily maximum temperature.

In order to investigate how future number of failures will change under the four KNMI climate scenarios, a simple theoretical relationship between the climate at Schiphol (DJF 2000-2010) and baseline failures (DJF 2000-2010) was used based on Andersson and Chapman (2011):

Number of failure at Temp x / Number of day per winter at daily minimum Temp x (2)

Under future climate the number of failures will decrease in the wintertime (Figure 12). This is a direct results of the increase of temperature in wintertime as can be seen from Figure 11. In the W+ scenario the number of failures is even half of the failures observed during 2000-2011. Note that this analysis is only based on temperature and not on snowfall. However, the amount of snowfall is about to decrease in the 21st century as a results of climate change with atmospheric conditions more suitable for rainfall.

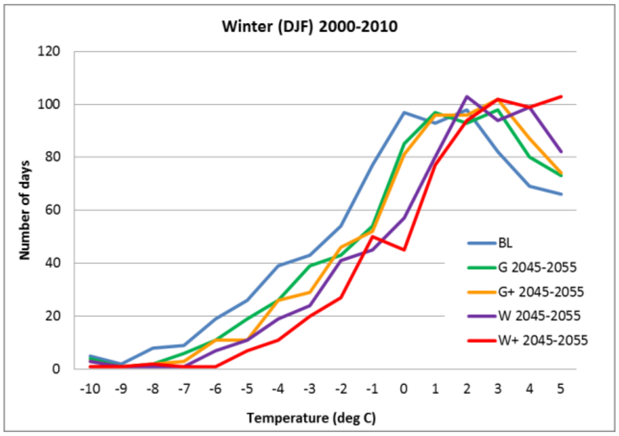

Figure 11: Frequency distribution of temperature for baseline and the KNMI climate scenarios for Cabauw

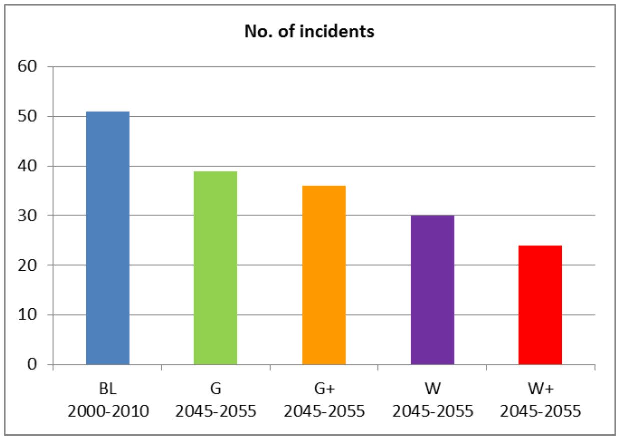

Figure 12: Projected number of failures for period 2045-2055 based on KNMI climate scenarios and compared to the baseline (2000-2010)

Failures related to the temperature change in summer

The same analysis as above was performed for conditions where the railway experienced most problems because of the heat. In this case meteorological station of Cabauw was selected as closest for the comparison of historical data about weather conditions and railway performance.

Figure 13 shows the Probability Density Functions (PDF's) for maximum temperature for the baseline situation (BL) and the four climate scenarios in an 11-year period from 2045 to 2055. It is clear from this graph that the temperature is about to rise in all four scenarios. This will have a significant effect on the number of failures as well. In the worst case they may increase from 50 to just over 90 per 11 year period, as it can be seen in Figure 14.

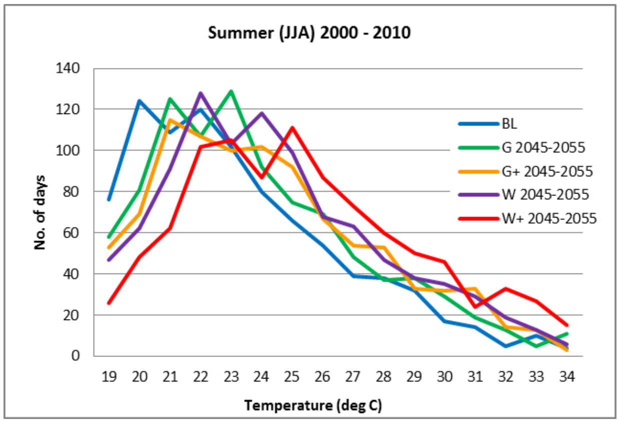

Figure 13: Frequency distribution of temperature for baseline and the KNMI climate scnearios for Cabauw

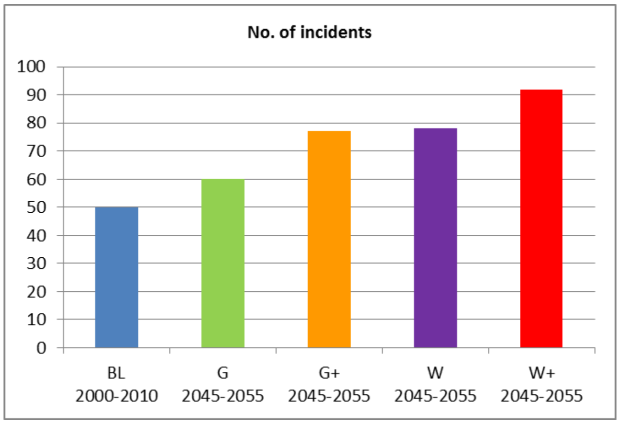

Figure 14: Projected number of failures for period 2045-2055 based on KNMI climate scenarios and compared with the baseline (2000-2010)

ADAPTATION MEASURES

Based on risk priorities adaptation strategies can be developed, supporting decision-making about future maintenance, rehabilitation and repair planning. One of the means to make decisions is to evaluate the economic effectiveness of proposed adaptation measures. In order to perform that decision makers need access to figures that represent the net costs of climate change, which is usually very difficult to collect and separate from other costs and effects.

Furthermore gaps in knowledge and capacity to understand potential effects of climate change may act as barriers to implement effective adaptation, for example (Gardiner et al. 2009):

- uncertainty in regional climate change projections, combined effects of different weather phenomena
- a lack of strategic direction from legislation and policy to drive adaptation
- a lack of sector-specific information sources and methodologies to assess how effective adaptation responses could be.

Adaptation responses to reduce the vulnerability of railway infrastructure from climate change should be assessed based on the following considerations:

- the magnitude and rate of climate change: adaptation is more feasible when climate change is moderate and gradual than when change is abrupt;
- clear identification or establishment of where responsibility for adaptation options may lie, plus any influence on these options;
- where existing risk management responses can accommodate climate change considerations; and
- where adaptation actions can be effective in achieving specific (and other) goals, acknowledging that adaptation responses can have unintended consequences.

Generally the robustness of assets should be increased, in order to change the current strategy of much reliance on operating restrictions, which equals to less reliable performance, into less operating restrictions strategy and more reliable performance.

CONCLUSIONS

In this paper the historical data analysis, identification of risks and climate vulnerability assessment of railway infrastructure are presented. Correlations of past failures on two busiest railway tracks in the Netherlands with the related temperature and precipitation conditions have been established. The analyses of total number of failures related to the weather effects indicated that the most critical weather events are high temperatures, snowfall and low temperatures. Probabilities of occurrence of certain risks under certain weather conditions have been calculated.

For the prediction of future railway failures (failures of performance) four KNMI climate scenarios were used (KNMI 2009). For the two railway tracks under investigation the temperature rise for the period 2045 to 2055 means an opposite effect on the expected number of failures. In wintertime the number of failures will decrease with an increase in winter temperature and probable decrease in snowfall. However, the analysis has also indicated that most problems occurred during first snowfall in the season. That suggests that the effect of low temperature and amount of snowfall is moderated by the preparedness of the agency. In summertime the number failures may double. Higher temperatures due to climate change seem to have a significant impact on the rail network. Research work, related to the precipitation and flooding risk prediction, is currently under progress.

Based on the analyzed cases the weather condition thresholds have been determined as well as related components of the system which might be under risk. The probability of failures, as a consequence of certain weather conditions is then used for the prediction of future vulnerability under changed climate conditions. Based on the vulnerability assessment risk maps will be developed, depending on the different climate scenarios. Risk mapping should be then used as a support tool for decision-makers enabling a development of sustainable adaptation strategies for climate change impact. The proposed methodology for risk assessment of climate change impact on railway infrastructure based on the temperature and precipitation predictions can be further extended to other weather impacts and failure / risk scenarios. With this methodology it is aimed to support infrastructure managers to decide on the appropriate intervention strategies and measures, and to ensure climate robust infrastructure.

Based on the performed case study following lessons may be learned:

- the improvement of the data collection about the failures is necessary; data should be structured;
- only local effects are stored – there are often effects on other components (next level effects) and long-term effects; no consistent information about costs, delays and safety;
- database should be in accordance with the final objective – development of maintenance and / or adaptation measures;
- infrastructure managers need quick answers which are very difficult to be given without clear image what has happened in the past
- better integration of climate change considerations into current asset management plans;
- adaptation strategies involve also users mind-set adaptation.

Climate change is a continuous process. As a result, the issue is not how to adapt to a “new” climate, but how and at what price to adapt our society to a constantly evolving climate. Adaptation must be therefore understood as a permanent transition policy on the very long-term.

ACKNOWLEDGMENT

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