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Winter Road Conditions and Traffic Accidents in Sweden and UK

Present and Future Climate Scenarios

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Abstract

This thesis investigates the distribution of slippery roads in Sweden and the UK for the present climate and how this may be affected by climate change for the rest of the century. It also addresses future scenarios for traffic accidents and winter road maintenance.

The purpose of this thesis is to get a better understanding of winter road conditions and relationships to motor vehicle accidents. A variety of scales are studied in this thesis ranging from nationwide studies in Sweden to smaller scale case studies in Sweden and the UK. The Swedish Road Weather Information System (RWIS) is one of the most extensive in the world with a total of 720 outstations. Air and road surface temperatures are measured at each outstation along with relative humidity, precipitation and wind.

In this thesis four different types of slipperiness are considered: Slippery conditions due to moderate hoarfrost (HR1), severe hoarfrost (HR2), road icing (HT) and rain or sleet on a cold road (HN). These four slipperiness types can be combined to form a winter index (WI). However, other types of precipitation are studied where appropriate.

Four papers are included in this thesis. The first aims of these papers include an analysis of the geographical distribution of different slipperiness types in Sweden and how these different types of slipperiness relate to traffic accidents. Further on the impact of climate change on road surface temperatures is also considered and in particular, what impact a changing climate would have on the number of traffic accidents, both in the Gothenburg area, Sweden and West Midlands, UK.

In Sweden, the frequency of occasions with road slipperiness increases towards the north, with the exception for the slipperiness type road icing (HT), which actually decrease towards the north. When a mild winter was compared to a winter with a temperature marginally warmer than the baseline winter (1961-1990), slippery roads caused more accidents in the mild winter where as snow was the cause of most accidents in the colder winter.

Climate change scenarios show that the number of days with temperatures below zero degrees will gradually decrease over the next century. By the 2080s (2070-2100), there will be a 22% reduction of the number of days in the Gothenburg area (Sweden) and a 48% reduction in the Birmingham area (UK). By using derived statistical relationships with traffic accidents, this translates to a theoretical reduction in the number of accidents occurring when the temperature is below zero degrees by 20% respectively 43%. Winter maintenance costs are likely to be reduced by at least 15% in the Gothenburg area until the 2080s. This can be compared with a decline of 38% *per* annum in the Birmingham area.

There may be a disadvantage with a warming climate at least when considering accidents. Since the temperature is rising the number of days with temperatures above zero degrees increases quite rapidly until 2080s. If the ratio between accidents and number of days at each degree will remain unchanged there will be an increase in the number of traffic accidents with as much as 88% at temperatures above zero degrees. Despite this great increase, the total amount of accidents will only increase by 2%.

Keywords: Winter road condition, Slipperiness, Traffic accident, Winter road maintenance, Climate change

Till Simon & Alva

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List of Publications

This thesis consists of a summary (Part I) of the four appended papers (Part II).

Paper I

Andersson A. K., Gustavsson T., Bogren J., Holmer B. 2007. Geographical Distribution of Road Slipperiness in Sweden on National, Regional and County Scales.
Meteorological Applications 14: 297-310.

Andersson did calculations, analysis and most of the writing. Gustavsson, Bogren and Holmer contributed with ideas during the planning and writing process.

Paper II

Andersson A. K., Chapman L. 2009. The use of a temporal analogue to predict future traffic accidents and winter road conditions in Sweden.
In Press Meteorological Applications.

Andersson did calculations, analysis and writing. Chapman contributed with ideas and contributed to a better language.

Paper III

Andersson A. K. 2010. A future perspective on traffic accidents in a warmer climate, a study in the Gothenburg area, Sweden.
Submitted to Climate Research.

Paper IV

Andersson A. K., Chapman L. 2009. The impact of climate change on winter road maintenance and traffic accidents in West Midlands, UK.
Resubmitted to Accident Analysis and Prevention after revision.

Andersson did calculations, analysis and some of the writing. Chapman contributed with writing and came up with the initial idea to the paper.

The papers are reprinted with permission from respective journal or authors.

Papers are referred to by their Roman numerals.

Conference proceedings

Andersson A.K., Gustavsson T., Bogren J. 2006. Variations in the Swedish winter road slipperiness. XIII International Road Weather Conference. Turin, Italy.

Andersson A.K., Gustavsson T., Bogren J. 2006. Distribution of winter road slipperiness in Sweden. 6th International Conference on Urban Climate. Gothenburg, Sweden.

Abbreviations

EARWIG	Environment Agency Rainfall and Weather Impacts Generator
ECHAM5	5th generation of the ECHAM general circulation model (EC short for ECMWF European Centre for Medium-Range Weather Forecasts HAM-Hamburg)
GCM	Global Climate Model
HN	Precipitation on a cold road
HR1	Moderate hoarfrost
HR2	Severe hoarfrost
HT	Road icing
IPCC	Intergovernmental Panel of Climate Change
IRWIN	Improved winter road index using historical observations from the RWIS networks in Sweden and Finland
ITS	Intelligent Transport System
MIPS	Slippery situation of at least one of the four slipperiness types (moderate hoarfrost, road ice, precipitation on a cold road and severe hoarfrost)
ONS	Office for National Statistics, UK
RSTdm	Daily minimum road surface temperature
RWIS	Road Weather Information System
SRA	Swedish Road Administration
SRES	IPCC Special Report on Emissions Scenarios
STA	Swedish Transport Agency
STATS-19	Road Accidents Statistics, UK
STRADA	Swedish Traffic Accident Data Acquisition
UKCIP	UK Climate Impacts Programme
WI	Winter Index

Contents

PART I SUMMARY

PART II PAPERS

Part I

Summary

“Don't knock the weather.
If it didn't change once in a while,
nine out of ten people couldn't start a conversation.”
Kin Hubbard (1868 - 1930)

1. Introduction

The first car crash was in 1771 when Nicolas-Joseph Cugnot collided with the Arsenal Wall in Paris. In the beginning of the last century, motor driven vehicles became more and more common (S.I.A, 2009). On the 31st August 1896, Mary Ward became the first person to be killed in a traffic accident, when she fell out of her cousins' car and was run over (IU, 2009).

Although Sweden has one of the world's lowest numbers of fatal traffic accidents, the Swedish parliament works towards a decrease in the number of accidents. Hence, in 1997 a treaty was ratified that there should be no fatalities or serious injuries in road traffic. One of the intermediate goals was to reduce traffic deaths by 50% by the year 2007 compared with 1996. In 2007 there were 471 persons killed, significantly over the target of 270 persons. In May 2009 new intermediate goals were set by the government. One goal is to reduce the number of persons killed in traffic by 50% from 2007 to 2020, so that in 2020 no more than 220 people would be killed. The number of seriously injured should also be reduced by 25% in the same time frame (VV, 2009).

The British government has a similar aim to reduce casualties (killed or seriously injured) on the roads in Great Britain by 40% in the year of 2010 compared with the average for 1994-1998, the aim for children casualties was a 50% reduction (Department for Transport, 2009a). When 2008 was analysed, the number of people seriously injured or killed was 40% less than the average in 1994-1998 and for children the reduction was 59% (Department for Transport, 2009b).

The difference between the two countries in achieving their aims can depend on many factors. For example, the nature of preventive measures before and during the campaign. The traffic density also differs between the two countries. Indeed, in 2007, 2946 people were killed in road traffic accidents in the UK compared to just 471 in Sweden (Department for Transport, 2009a).

There have been many previous studies on winter road conditions (e.g. Lindqvist, 1975; Bogren and Gustavsson, 1989; Thornes, 1991). There are also many studies linking traffic accidents and road conditions (e.g. Codling, 1974; Smith, 1982; Palutikof, 1991; Edwards, 1996). 40% of the traffic accidents in Edmonton, Canada, which occur during the winter months, are on roads with ice/snow or rain (Andrey and Olley, 1990). These accidents are often caused by a combination of precipitation and associated poor visibility which increases in winter (Fridström *et al.*, 1995; Edwards, 1999) and peaks in December (Asano and Hirasawa, 2003). Bad weather makes motorists drive more slowly (Hassan & Barker, 1999), as they reduce their speed, even though not by much, to adjust for worsening weather and conditions. For example, Kilpeläinen and Summala (2007) found that average traffic flow speed was reduced by 6.7% in bad weather. In wet and slushy conditions, the reduction can be as high as 25% (Martin *et al.*, 2000 cited in Koetse & Rietveld, 2009).

Lindqvist (1979) was one of the first to study the road climate in Sweden. He identified 24 types of slipperiness of varying severity, which were later reduced to ten (Norrman, 2000). Of the ten different types of slipperiness, precipitation on an already frozen surface had the highest accident risk. 52% of traffic accidents were caused by a reduction of road friction according to a study of Bogren *et al.* (2006).

Rain has been shown to be a major factor causing traffic accidents (Brodsky and Hakkert, 1988; Andrey and Yagar, 1993; Fridström *et al.*, 1995; Levine *et al.* 1995; Andreescu and Frost, 1998). Indeed, some studies show a doubling of the accident rate during rainfall (Bertness, 1980; Brodsky and Hakkert, 1988). There are also positive results, Andrey (2009) found that the rain-related traffic accidents have decreased with approximately 60% between 1984 and 2002 on the roads of Canadian cities.

Snow is often a cause of traffic chaos (e.g. Thornes, 2005; London Assembly, 2009). When there is snowfall, the risk for an accident is increased (Andreescu & Frost, 1998; Suggett, 1999; Norrman *et al.* 2000; Eisenberg and Warner, 2005). The impact varies considerably from study to study, Smith (1982) found an increase of just 2.2%, whilst other studies have found a doubling in the accident rate (Codling, 1974; Andreescu and Frost, 1998; Suggett, 1999). In the UK, 2.8% of all traffic accidents are caused by snow (Edwards 1999), but in some parts of the country it is higher with the highest percentage in northeast England (5.9%) (Edwards, 1996). Some studies also show that snow can contribute to a decrease in the amount of accidents (Fridström *et al.*, 1995) or at least diminish the outcome of the accidents (Koetse & Rietveld, 2009). In many cases, this can be explained by the effects of snow and ice influencing drivers behaviour. The results are postponed leisure trips as travel is restricted to essential journeys when driving conditions are poor (Smith, 1982; Palutikof, 1983; Parry, 2000; Kilpeläinen and Summala, 2007).

Road surfaces are the most slippery when the temperature is close to zero degrees (Moore, 1975). However, Campbell (1986) found that there were more accidents in Winnipeg, Canada, when the temperature was below -15°C than in the temperature range -15°C to 0°C. It is not only snow, ice, rainfall, wind, fog or low sun that can be a contributory factor for traffic accidents, even hot temperatures (>34°C) have shown to be a contributing factor in Saudi Arabia (Nofal and Saeed, 1997). Other factors can also affect driving, for instance sudden illnesses (Lam and Lam, 2005) or drink driving (Meyhew *et al.*, 1986; Horwood and Fergusson, 2000; Evans, 2004). Perhaps even superstition can play a role as the cause of an accident, Näyhä (2002) found that there was an increase in the amount of fatal accidents on Friday 13th for women by 1.63 compared with other Fridays, the corresponding number for men was 1.02. Fatal accidents among female drivers occurred most often in the temperature interval -3°C to 1°C that coincides when slippery roads occur.

The number of accidents on roads is reduced significantly by expensive winter road maintenance strategies. The most common ways to perform winter road maintenance are salting as a preventive measure or snow clearance by ploughing. The cost for winter maintenance varies from country to country. In Finland the annual cost is €100 million (Venäläinen and Kangas, 2003), where as in Sweden the total cost for 2005 was €207 million (VV, 2006). The UK spends £482 million (€538m 30/10/09) on the primary road network, plus a further £1069 million (€1193m 30/10/09) on local roads (Department for Transport, 2009). However, more efficient practices are greatly reducing the associated costs. For example, in the winter of 1993-1994 salt consumption in Sweden was 420 000 tonnes, this has been reduced and in the winter of 2007-2008 just 184 000 tonnes were used (VV, 1999; VV, 2009a). By comparison, the UK uses 2 million tonnes of rock salt in an average winter (Salt Union, 2009). These numbers are highly variable and depend on the severity of the winter season. For example, Changnon and Changnon (2005) found that in a mild winter the cost for ploughing and salting was reduced by 65–80% compared with a winter with normal conditions in USA. It is hypothesised that climate change will see such reductions become the norm. Indeed, an increasing focus on climate change is becoming evident with studies starting to appear documenting the impact of a changing climate on the winter road conditions (Venäläinen and Kangas, 2003; Carmichael *et al.*, 2004; Scottish Road Network, 2005).

Aim of the thesis

The overall aim of this thesis is to achieve a better understanding of current and future winter road conditions and associated relationships with traffic accidents. The first study is about the distribution of slipperiness on the Swedish winter roads in different scales, this was done to analyse if there were any differences in the slipperiness types across Sweden during five winters (Paper I). The second study continues the analysis of the winter road conditions in Sweden but in relation to traffic accidents. Two winters with fairly different weather is compared (Paper II). The third study also deals with traffic accidents in Sweden, but this study has a future aspect to it to analyse how a changing climate can affect winter road conditions and traffic accidents in the Gothenburg area (Paper III). The final paper is a study of the relationship between traffic accidents and air temperatures with respect to climate change in the West Midlands, UK (Paper IV).

The specific aims in this thesis are:

- Investigate if there are any particular geographical patterns in the distribution of slipperiness on the Swedish winter roads in three different scales, national, regional and county. (Paper I)

- Analyse how weather influences the traffic accidents on Swedish winter roads. (Paper II)

- Analyse the impact climate change have on road surface temperatures in the Gothenburg area, Sweden, and the effect it can have on traffic accidents. (Paper III)

- Study how traffic accidents across the West Midlands, UK, in the winter might change with climate change and to determine how the number of days requiring winter road maintenance may change in the future. (Paper IV)

2. Data and Methodology

Several sources of data have been used in this thesis, in this chapter the different sources will be presented and discussed.

2.1 Study areas

The majority of this thesis studies different parts in Sweden except for Paper IV that focuses on an area of the English Midlands.

Sweden

The study areas in Paper I, II and III are all in Sweden. Paper I, was a study of geographical patterns in Sweden divided into three different scales. The first scale was national where Sweden was divided into seven regions. Next, the paper focuses on a specific region (Region Väst) and finally looks in detail at one of the counties in the southern part of Region Väst, Halland (Figure 1). In paper II the same seven national regions were used, with a focus on the Region Skåne and the city of Stockholm (darker grey areas, Figure 1). Finally, Paper III analysed an area close to Gothenburg in the southwest of Sweden (area with larger dots, Figure 1). Sweden has a total areal of 449 964 km^2 whereof 410 934 km^2 are land.

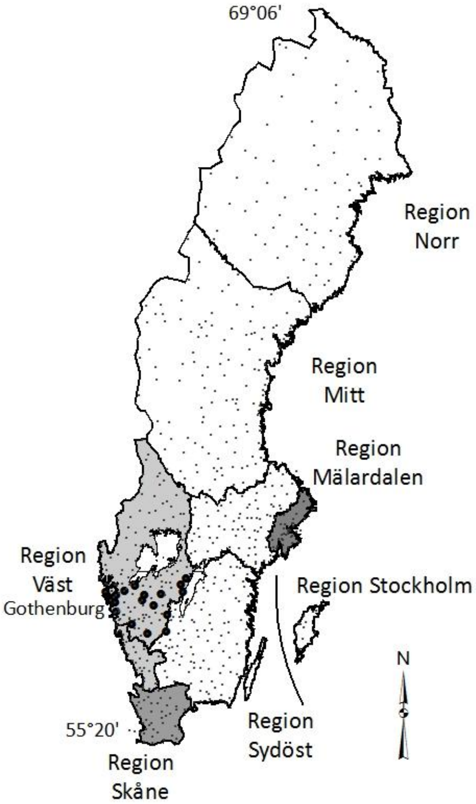


Figure 1. Map of Sweden, divided in seven regions. Region Väst (light grey) with Halland in the south, Region Skåne (grey), Stockholm (dark grey), RWIS outstations (small dots) and RWIS outstations in Gothenburg area (black dots).

West Midlands, UK

The second largest conurbation in United Kingdom, the county of West Midlands, was chosen as a study area in Paper IV (Figure 2). In the centre of this region lies the second largest city in England, Birmingham. The area of West Midlands is 902 km^2 England has a total areal 129 720 km^2.

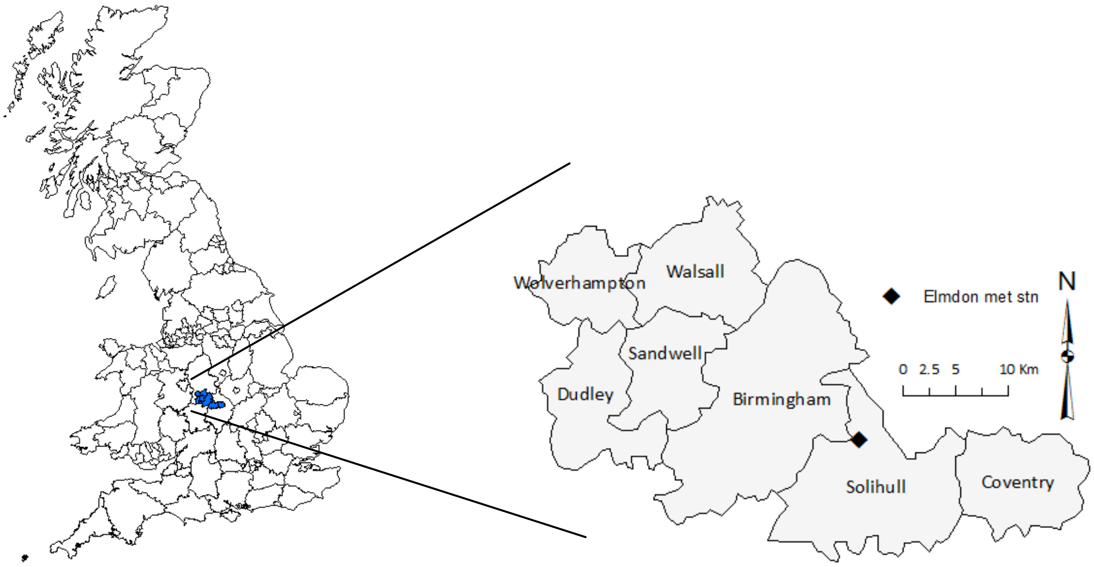


Figure 2. United Kingdom and in zoom West Midlands.

2.2 Road weather – RWIS

There are approximately 720 outstations in the Swedish Road Weather Information System (RWIS) (see Figure 1 for the RWIS locations). 200 outstations are equipped with cameras for monitoring the road surface. The outstations collect information about road surface temperature, air temperature, relative humidity, precipitation, and wind speed and wind direction. Additionally, dew-point is calculated from air temperature and relative humidity. Data are collected every 30 minutes during the winter months and stored in a database at the Swedish Road Administration (SRA). The weather data are used for winter maintenance decisions. Data have been collected in this way since the mid-1980s, and from 1992 is the information published on the internet. The main usage for the RWIS outstations is to monitor the road weather for the maintenance personnel. It is also more and more used in the intelligent transport system (ITS) (VV, 2009b).

2.3 Winter road conditions

Throughout this thesis there have been calculations of the slipperiness on winter roads. Four types of slipperiness have been focussed on, which are the four types originally developed by the Swedish Road Administration (Möller, 2002) to help them determine their need for maintenance activities.

The definitions for the four types of slipperiness are:

Slippery conditions due to moderate hoarfrost (HR1)

HR1 often occurs as a result of radiative cooling in the evening/night or turbulence induced mixing of an inversion layer in the morning. The road surface temperature should be between 0.5°C and 2.0°C lower than the dew-point temperature of the air.

Slippery conditions due to severe hoarfrost (HR2)

HR2 is, in general, the result of advecting warm and moist air. The road surface temperature should be at least 2.0°C lower than the dew-point temperature.

Slippery conditions due to road icing (HT)

For an HT situation, the road must first be moist/wet due to rain/sleet, melting snow or condensation of dew after which the temperature drops below +1.0°C which then results in a freezing road surface.

Slippery conditions due to rain or sleet on a cold road (HN)

A HN situation arises when rain or sleet falls onto a cold surface; a cold surface is defined as a road surface below +1.0°C.

In Paper I, the road surface temperature was set to be lower than +1.0°C for all four types of slipperiness, which followed SRAs definition for their decisions regarding winter maintenance activities, +1°C is used as a safety margin to account for any inaccuracy of the sensors. This was changed to 0°C in Paper II to get more real values for slipperiness.

A more complete definition of the four types can be read in Paper I or in Möller (2002).

Paper I used a winter index (WI) based on the number of occurrences of the four types of slipperiness.

$$\mathrm{WI} = \mathrm{HR1} + \mathrm{HR2} + \mathrm{HT} + \mathrm{HN} \qquad (1)$$

In Paper II, a slightly modified version of slipperiness types was used. When there was a situation with at least one of the four types it was referred to as MIPS (MIPS is an abbreviation of the four types of slipperiness, Moderate hoarfrost, road Ice, Precipitation on cold road and Severe hoarfrost). This study also considered other precipitations and road conditions: Rain, Freezing rain, Snow, Sleet or the combination of MIPS or Snow.

In Paper III and Paper IV the daily minimum road surface temperature and daily minimum air temperature was used instead of the different slipperiness types.

2.4 Future climate change

The eleven warmest years globally since the weather recording started (≈1850) were between 1995 and 2006. There has been a trend of changing precipitation patterns in many regions, the cyclonic activity in North Atlantic has increased and precipitation totals have now increased in northern Europe (IPCC, 2007). If greenhouse gases are not reduced, the global temperature is predicted to rise in the range of 1.1°C to 6.4°C during this century (IPCC, 2007). Over the same period, the Swedish winter air temperature is supposed to increase between 3.8°C and 5.5°C (Räisänen *et al.* 2003). In UK is the annual average temperature estimated to rise between 2°C to 5°C, with the warming expected to be more in summer than in winter (Met Office, 2009).

The IPCC Special Report on Emissions Scenarios (SRES, 2000) present different scenarios, depending on demographics, economics and technological development. In scenario A1 it is assumed that the world will have a population that peaks in the middle of the century, the economy is growing fast and that new and improved technology is introduced in a high pace. The A1 scenario is subdivided in three groups depending on the development in new technologies, if fossil energy is intensified (A1FI) or if it is going to be a non-fossil energy (A1T) or if it is going to be a balance across all sources (A1B).

In the A2 scenario the population will have a high growth rate and both economics and changes of technologies are slowly developed.

2.5 Weather generators

Weather generators are used to produce time series of stochastic weather data based on the baseline climate (Hutchinson, 1987). Paper III used a model for the calculations of the Swedish road surface temperatures in a future perspective. The model is called IRWIN (for further details Saarikivi *et al.* 2009) and uses an analogue model for statistical downscaling, which combines historical weather data from the RWIS outstation and the Global Climate Model (GCM) climate change scenario. The GCM is the ECHAM5 which is an atmospheric general circulation model from Max Planck Institute for Meteorology, Hamburg, Germany. To obtain road surface temperature the model takes the weather data in the scenario and compares it with historical data. The model is built on the emission scenario IPCC SRES A1B. IRWIN was used to obtain the road surface temperatures at baseline (November 1970-March 2000) and also for the three future time periods 2020s (N2010-M2040), 2050s (N2040-M2070) and 2080s (N2070-M2100).

EARWIG (Environment Agency Rainfall and Weather Impacts Generator), which is based on the UKCIP02 (UK Climate Impacts Programme) scenarios was used in Paper IV. EARWIG uses observed baseline (1961-1990) weather data from the UK Meteorological Office to produce daily weather records, which then can be used to generate probability distributions. EARWIG uses two stochastic models, first a simulation of rainfall, which is used in the second model, which is generating the other variables that are depending on rainfall (see Kilsby *et al.*, 2007 for a full description of the model and application). EARWIG used UKCIP02 medium-high emission scenario derived from the IPCC SRES A2 storyline (Hulme *et al.*, 2002). EARWIG was used to calculate temperature distributions for the baseline scenario and also for the three future time slices, 2020s (2011-2040), 2050s (2041-2070) and 2080s (2071-2100).

2.6 Traffic accidents

Swedish Transport Agency’s database, Swedish Traffic Accident Data Acquisition (STRADA), was used for the traffic accident analysis in Paper II & III. The database contains information about accidents obtained from both the police and the emergency units in hospitals. The number of participating hospitals has increased since the beginning in 2003. In June 2009, 71% of the hospitals were connected to STRADA (STA, 2009).

For the UK, the Department of Transports database, Road Accidents Statistics (STATS-19) was used in Paper IV. The British accidents are personal injury accidents with vehicles on public highways known to the police within 30 days. The statistics from personal road accidents has been recorded since 1909 and STATS-19 was introduced 1949 and is included on police accident report forms since 1969 (ONS, 2009).

3. Results

This chapter is subdivided into four subheadings to summarise the most important results of the four papers.

3.1 Distribution of slipperiness in different scales

The first study was to analyse if there were any differences in the amount of time with slipperiness depending on latitude and if there were differences between the different types of slipperiness in Sweden, this became Paper I. The distribution of different types of slipperiness was analysed at three different scales, national, regional and county (Figure 1). RWIS-data from five winters was compared, 1998-1999 to 2002-2003. The length of a winter is defined as the 7 months, October to April.

On a national scale the road slipperiness, the WI (Winter Index – number of occurrence of the four types of slipperiness), can be explained mostly by latitude (Figure 3) with a R^2 value of 0.96. If different types of slipperiness are considered, the two types of hoarfrost increase towards the north, where as the slippery conditions due to road icing (HT), increase towards the south, this is due to the temperature distribution since the HT situation occurs when the road is moist/wet and then freezes. The northern part of the country has an average temperature below zero degrees for a large part of the winter. Slippery conditions due to rain or sleet on a cold road (HN) is evenly distributed over the country with a small peak in the middle of the country.

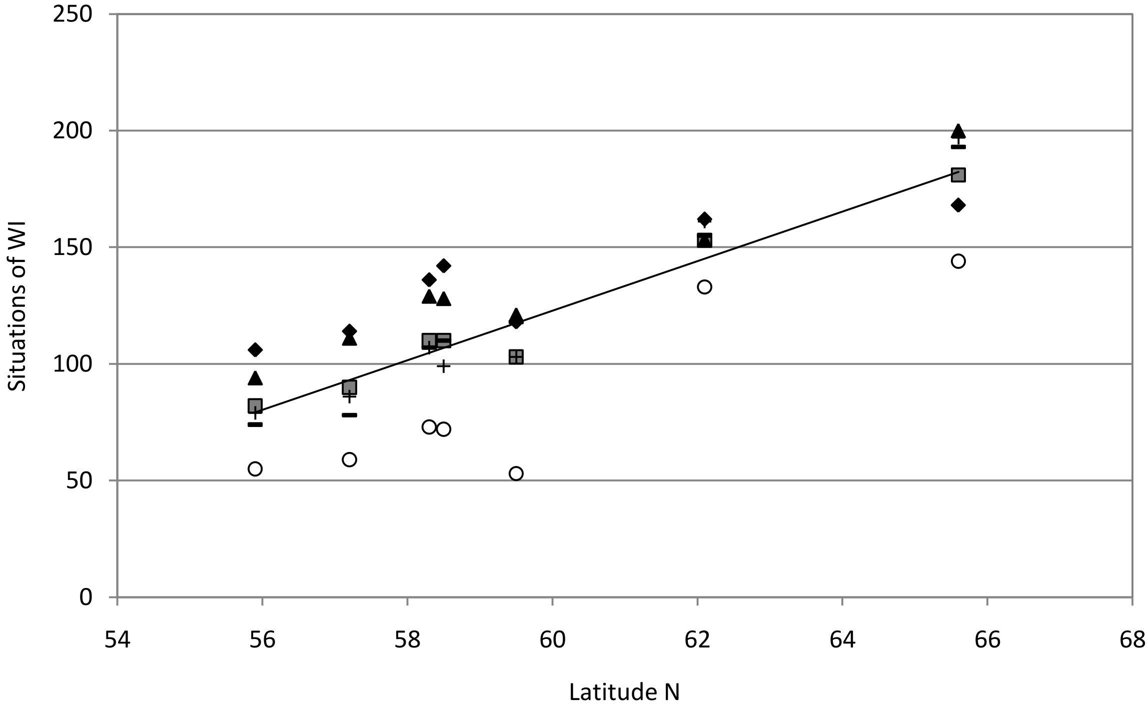


Figure 3. Relation between latitude and WI at the national scale. ■ 1998/2003, ◆ 1998-1999, ▲ 1999-2000, ○ 2000-2001, + 2001-2002, – 2002-2003.

At the regional scale, Region Väst was analysed in the same way as the national scale, producing similar results. However, road icing (HT) increased towards the east instead of towards the south and there were no particular pattern in the type “precipitation on a cold road” (HN).

Finally, at the county scale, Halland (the southernmost county in Region Väst consisting of seventeen RWIS outstations), there was no correlation between WI, latitude, distance from sea or altitude. No factors correlated with the WI. At this scale the local climate at each station seemed to have the highest impact on slipperiness.

The main aim of Paper I was to study if there were any geographical patterns in the distribution of slipperiness at these different scales. In the national and regional scales patterns were found that slipperiness increases towards north, but the county scale did not correlate with any of the geographical variables tested. It was also investigated how the distribution might change with future climate warming. It is likely that the number of hours with a road surface temperature below 0°C would decline if the winters get warmer. However, in the temperature range between -3°C and 0°C an increase might be possible, especially in the northern parts of the country, since there is a large amount of hours below -3°C and the temperatures are rising (Table I).

Table I. Road surface temperature (RST) by region as a mean for all winters (in percent).

Region	Latitude	RST below 0°C	RST −3 to 0	RST below −3
Skåne	55.9	25.1	17.4	7.7
Sydöst	57.2	37.9	23.0	15.0
Väst	58.3	38.9	21.5	17.4
Stockholm	58.5	41.0	25.2	15.8
Mälardalen	59.5	44.7	23.7	21.1
Mitt	62.1	64.1	24.4	39.8
Norr	65.6	75.8	19.9	55.8

The next section continues to study the different types of slipperiness and the connection to traffic accidents.

3.2 Traffic accidents and winter road conditions in Sweden

Paper II was an attempt to analyse in which way the weather influences traffic accidents in Sweden during the winter months. Two winters were used 2004-2005 and 2005-2006, and in this study the definition of a winter is the three months December to February. These winters were chosen because of their difference in weather, 2004-2005 was an unusually mild winter, where as 2005-2006 was more like the baseline winter (1961-1990). The study particularly focussed on the month of January as it had the largest contrast between the two years.

Figures 4a & 4c displays the amount of traffic accidents in the winter of 2004-2005 and 2005-2006 respectively. The accidents showed are the ones that have been reported both by police and hospitals and have a known accident site. The accidents shown in Figures 4b & 4d could potentially be caused by slippery roads. There is an evident reduction in traffic accidents in the metropolitan areas (Stockholm, Gothenburg and Malmö) which indicates that accidents due to slippery roads are less frequent close to urban areas. A comparison between the number of accidents and the traffic density was completed and showed that the highest ratio of accidents *per* vehicle was in the least trafficked areas in the northern part of Sweden. Conversely, the highly trafficked area of Stockholm (capital city) had the least accidents *per* vehicle.

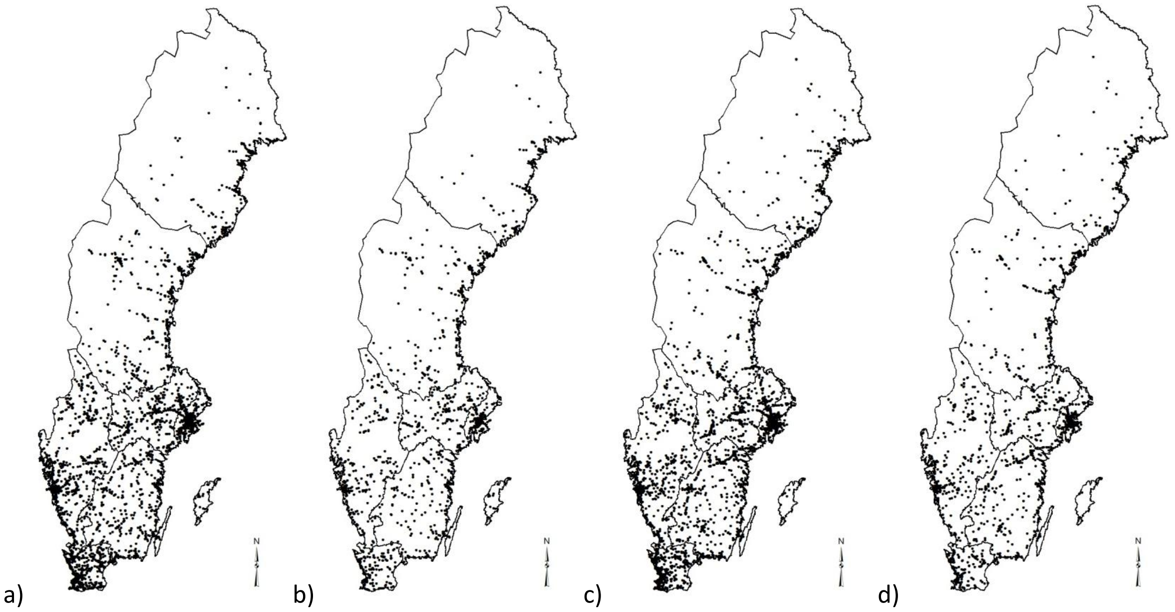


Figure 4. a) All traffic accidents in December 2004 to February 2005 b) accidents potentially caused by slipperiness 2004-2005 c) all accidents in 2005-2006 d) potentially caused by slipperiness 2005-2006.

The road conditions at the time for the accidents were compiled for the two winters. This was done to determine the road conditions preceding the time of the accident, and also to see which of the road conditions that was the most common when an accident occurred. The winter 2004-2005 had the largest amount of accidents when there was at least one of the four types of slipperiness (MIPS). In the winter of 2005-2006 the category Snow where the one with the most accidents.

MIPS or Snow occurred in 24.8% and 30.0% respectively of the three winter months. This difference in road condition is also shown in the percentage of accidents. 33.4% and 40.6% respectively of accidents were in this category (Table II).

Table II. Percentage of accidents in certain road condition and percentage of road conditions.

		HR1	HR2	HT	HN	MIPS	Rain	Freezing rain	Snow	Sleet	MIPS or Snow
Accidents	Jan 05	14.9	4.4	7.4	6.3	20.6	13.9	0.0	15.1	6.6	29.2
	Jan 06	11.1	3.2	3.1	2.9	15.4	3.3	0.4	25.4	2.2	37.8
	04-05	14.1	4.0	9.9	8.1	22.1	11.6	0.5	18.6	7.9	33.4
	05-06	11.3	3.2	4.8	4.5	16.7	5.4	0.9	30.3	3.3	40.6
Road conditions	Jan 05	9.1	4.9	3.3	1.8	15.9	5.6	0.1	7.9	1.5	22.1
	Jan 06	11.4	5.2	1.9	1.2	17.8	1.4	0.2	12.8	0.5	28.9
	04-05	10.4	4.9	3.7	2.2	17.8	3.9	0.1	9.7	1.8	24.8
	05-06	9.8	4.0	2.5	1.4	15.7	2.1	0.2	17.0	0.9	30.0

The same relationship was found when the area was downscaled to the metropolitan district of Stockholm, a very heavily trafficked area. Here, 27.2% of the accidents 2004−2005 occurred when there was a situation of MIPS or Snow compared with 34.3% in the colder winter of 2005-2006.

Figure 5 show the daily distribution of road accidents while there was a slippery situation (black bars – MIPS, Snow, Freezing rain or Sleet combined) in the colder winter when snow was more common (2005-2006). The histogram clearly shows that the majority of accidents occurred either when it was snowing or it had snowed within the preceding two hours (white bars). Actually 74% of the accidents in 2005-2006 occurred during or soon after a snowfall, this is also an indication for the prevailing weather this winter. There were only 54% of the accidents that occurred while snowing in the winter before, when the weather was milder.

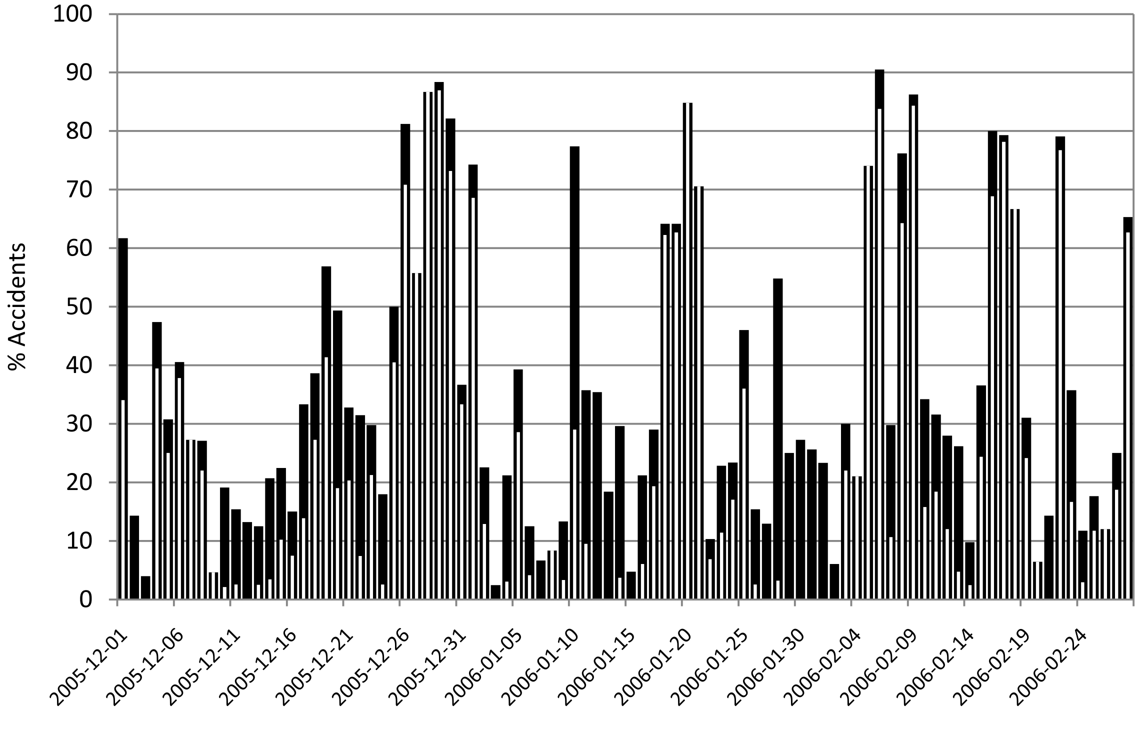


Figure 5. Percentage of the accidents with detected snowfall compared with accidents with slippery road conditions as a mean for Sweden in 2005-2006 ■ MIPS/Snow/Freezing rain/Sleet ☐ Snow.

The relationship between the total number of accidents and the number of accidents when there was a potential for slipperiness is plotted in Figure 6. 6 out of 10 traffic accidents in January 2005 (milder) compared to 9 out of 10 in January 2006 occurred when there was slippery conditions i.e. a situation of MIPS, Snow, Freezing rain or Sleet. This would indicate that when climate change makes the winters warmer than today, the number of accidents caused as a direct result of slipperiness will decrease in the future.

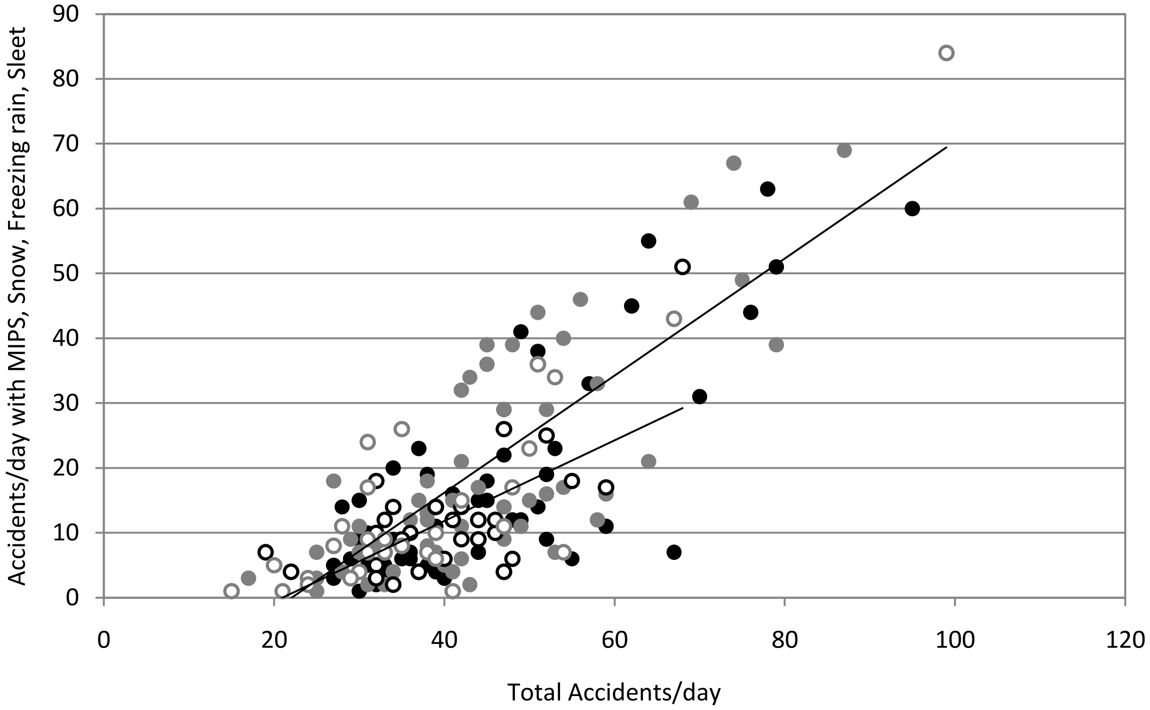


Figure 6. Accidents *per* day during MIPS/Snow/Freezing rain/Sleet vs. total amount of accidents *per* day ● 2004-2005, ○ Jan 2005 (short trend line), ● 2005-2006, ○ Jan 2006 (long trend line).

Finally, this study showed that traffic accidents are most prevalent when road surface temperatures are below -3°C or when there is a snowfall. This led to the question of how frequently this situation would be encountered in a warming winter climate. The next section analyse this.

3.3 Climate change impact on traffic accidents in Gothenburg, Sweden

19 RWIS outstations in the Gothenburg area were used in this investigation (Figure 1). Three winters 2006-2007, 2007-2008 and 2008-2009 were studied, where a winter is the five months between November and March. (*N.B.* Temperature is always the daily minimum road surface temperature (RSTdm) if not otherwise defined.)

During these three winters there were 1273 traffic accidents with a complete dataset for precipitation. There was no precipitation according to the nearest RWIS outstation in 79 % of the accidents. For the remaining accidents, it was raining in 12%, snowing in 8 % and freezing rain for 0.24% (Table I). To investigate which type of precipitation posed the largest risk for an accident, the following equation was used (Norrman, 2000):

$$\text{Accident risk}= \frac{1}{N}\sum_{m=\text{Nov 2006}}^{\text{Mar 2009}} A_{t,m}h_m\left(A_m h_{t,m}\right)^{-1} \qquad (1)$$

where

N – Number of months
$A_{t,m}$ – Number of accidents in month (m) in precipitation type (t)
h_m – Number of hours in month (m)
A_m – Number of accidents in month (m)
$h_{t,m}$ – Number of hours with precipitation type (t)

Norrman (2000) used it to estimate the risk of an accident at different road conditions. One assumption made in these calculations was that the accidents had an even distribution.

Although only 0.24% of the accidents occurred during *Freezing rain*, this precipitation type had the highest risk. There were 3 accidents recorded in the three winters in a total of 8 half-hours of *Freezing rain*. Hence, the risk for having an accident in this type of weather is high. The category of *No precipitation* had the risk of 1.0 which was the expected risk (Table III).

Table III. Accidents in 2006 – 2009 (NDJFM) in different type of precipitation and the risk of having an accident in different types of precipitation.

Type of precipitation	Number of accident (%)	Accident risk
No precipitation	79	1.0
Rain	12	1.1
Freezing rain	0.24	2.2
Snow	8	1.4
Sleet	1	1.6

Using the IRWIN scenarios, changes in average precipitation for the three time slices, 2020s, 2050s and 2080s was calculated for each of the three precipitation categories (*Snow*, *Rain* and *No precipitation*). To calculate the estimated number of accidents for the future the same statistical accident risks were applied to the average amount of precipitation in the future time periods. The distribution of the number of accidents became 11% for *Rain* and 9% for *Snow* while *No precipitation* was unchanged in the 2080s (the two missing categories, *Freezing rain* and *Sleet*, which were missing in the model since there was too few observations).

In 66% of the days November to March, 2006-2009, the daily minimum road surface temperature was equal or below zero degrees (Figure 7). The most common temperature during the three winters was -1°C. 67% of the traffic accidents occurred when the temperature was below zero degrees.

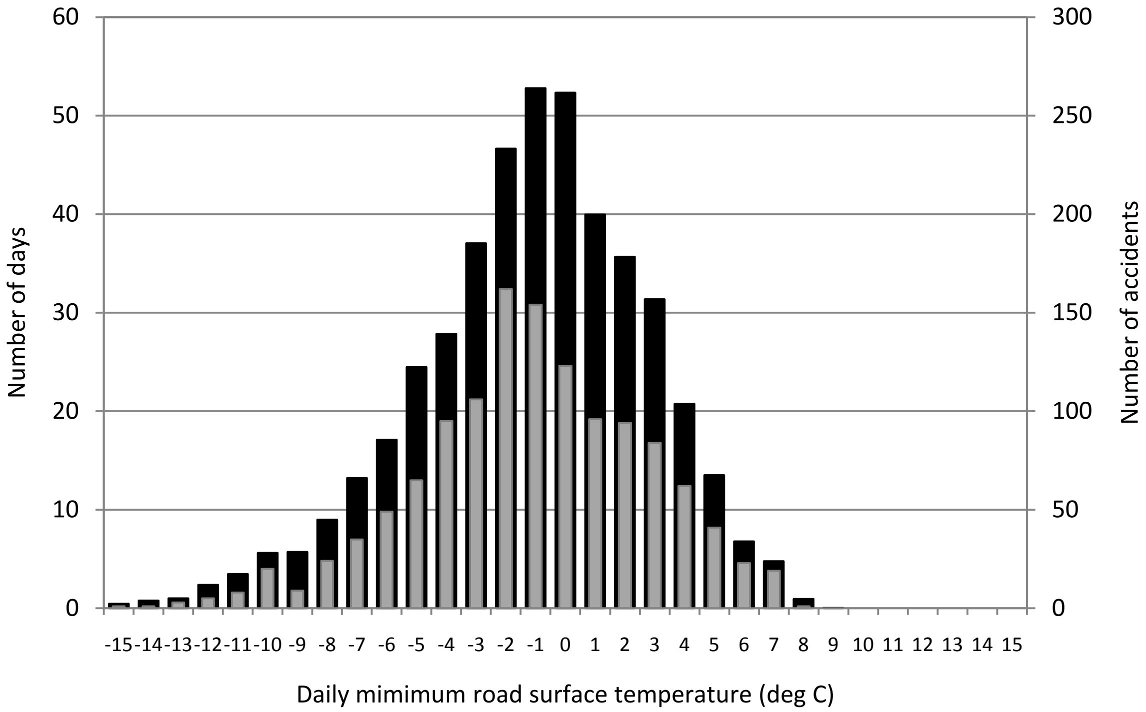


Figure 7. Number of days with daily minimum road surface temperature (°C) (black) and the number of accidents at the same daily minimum road surface temperature (grey) for the three studied winters 2006-2009.

The daily minimum road surface temperatures were compiled for the three future scenarios 2020s, 2050s and 2080s but also for the Baseline (1970-2000) and the number of days for each temperature degree was calculated. The number of days with temperatures ≤0°C decreased from the baseline winter to the 2080s from the original 79% of the days in the baseline winter to 62%.

The ratio between the number of traffic accidents and the number of days *per* winter for each temperature degree was then calculated.

$$\text{Number of accidents at RSTdm} / \text{Number of days per winter with RSTdm} \tag{2}$$

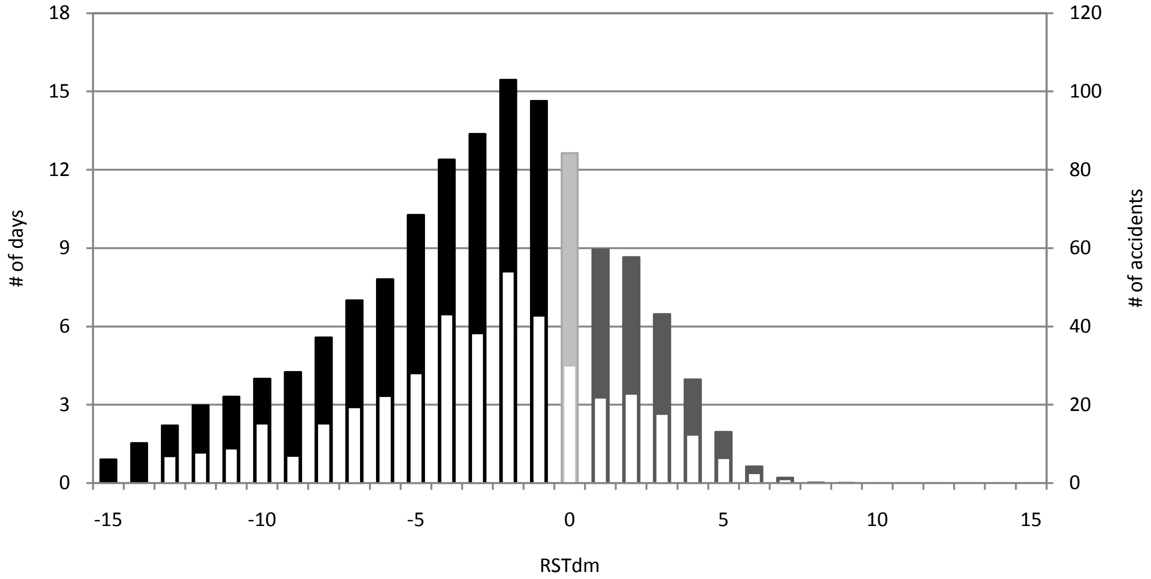
This ratio shows an increase of accidents/day if the temperature increases, this means that there are fewer accidents at lower temperatures, which can be an indication that drivers are more cautious at lower temperatures when there is a risk for slippery conditions.

$$\frac{\text{Number of accidents 2006-2009 at Temp X}}{\text{Number of days 2006-2009 at Temp X}} = \frac{\text{Number of accidents BL at Temp X}}{\text{Number of days BL at Temp X}} \tag{3}$$

The assumption was that the ratio is the same now and in the future (equation 3). This ratio was applied on the calculated number of days *per* winter at each temperature for the three future time slices 2020s, 2050s and 2080s. It turned out that there was a threshold in the daily minimum road surface temperatures at approximately -2°C for the number of days, i.e. below this temperature the number of days are decreasing and above the number of days increase. The number of days ≤0°C decreases by 22% between baseline and 2080s (Figure 8a-b) and the number of accidents show a decrease of 20% by the 2080s.

However, the number of days with temperatures above zero degrees will increase in the future from 31 days to 58, this lead to a large increase in the number of traffic accidents from 83 in the baseline period to 159 in 2080s, an increase of 88%. This great increase do not affect the total amount of accidents by much, the total number of accidents will increase by 2%.

a)



b)

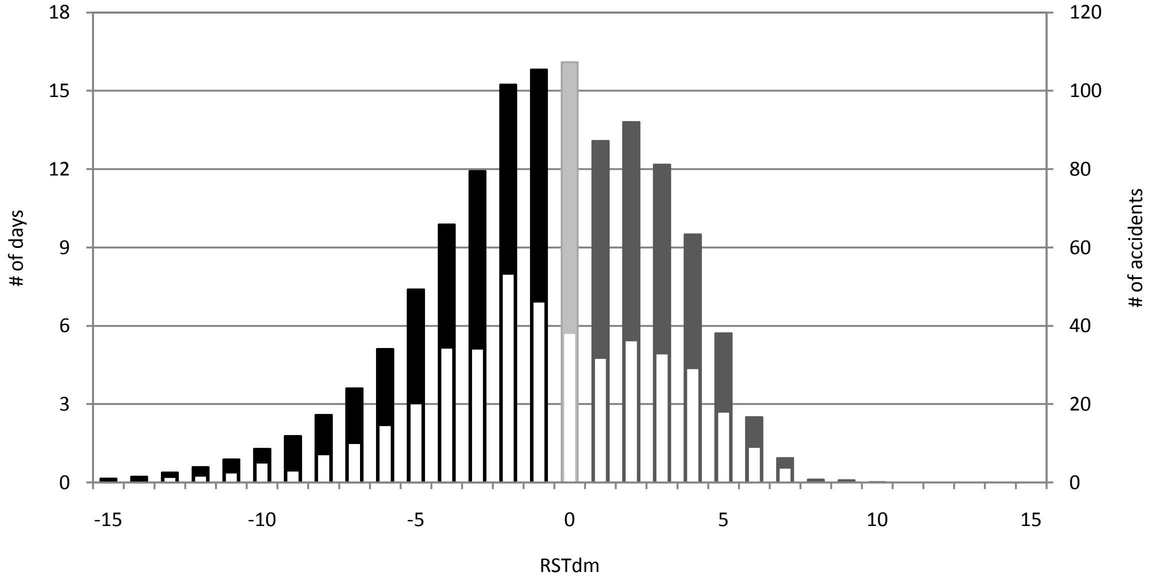


Figure 8. Number of days at daily minimum road surface temperature (°C) and number of accidents (White bar), <0°C (black bar), =0°C (light grey bar), >0°C (grey bar) a) Baseline b) 2080s.

The Swedish Government and the Swedish Road Administration have a long term aim to reduce the amount of salt used on the Swedish roads. In a baseline winter, there were 118 days with a daily minimum road surface temperature of ≤0°C, this is reduced by 22% to 93 by 2080s. When the Swedish road administration make decisions regarding winter maintenance activities they use an upper limit of +1°C instead of 0°C for the road surface temperatures to have a safety margin to account for any inaccuracy of the sensors (Möller, 2002). Taking this into account the number of days below ≤1°C is going to decrease by 17% by 2080. This translates into a decrease of at least 15% in the winter maintenance activities by the 2080s. If this is converted into salt, then up to 38 700 tonnes of salt could be saved in a future average winter.

The main conclusion in this paper was that the amount of winter traffic accidents in Sweden will decrease, at least when weather is considered. There are, however as mentioned in the introduction several other reasons why an accident may occur. Since the number of days with higher temperatures will increase there is a risk that the accidents at temperatures above zero degrees increase with as much as 88% in the winter months November to March.

So far traffic accidents with future scenarios have been studied in a small area in the south western part of Sweden, hence it was considered interesting to apply the same thought analysis somewhere else in Europe. The Birmingham (UK) area was chosen as both Gothenburg and Birmingham are the second largest cities in each country. The climate in the middle part of England is not dissimilar to the climate experience in south-west Sweden, but yet a few degrees warmer e.g. approx. 4°C difference in January. This means the area may provide a potential spatial analogue for climate change in Sweden.

3.4 Climate change impacts on winter maintenance and accidents in West Midlands, UK

The idea for Paper IV started with a visit to Birmingham University that provided data pertaining to traffic accidents statistics (STATS-19) and weather data from Elmdon (Birmingham airport) for the two winters December 2004 to February 2005 and December 2005 to February 2006. The aim was to analyse slipperiness and accidents in UK in the same way as done in Sweden. However, getting access to the road surface temperatures turned out to be impossible since it is not publically available so instead was air temperature data obtained from the World Meteorological Organisation weather station at Elmdon (Birmingham Airport) located centrally in the West Midlands analysed. Two consecutive years were chosen because they had differences in temperatures, the first winter had a mean temperature 1.3°C above baseline while the second winter were more close to the baseline winter. The weather generator, EARWIG (Kilsby *et al.*, 2007) was used for calculating the temperature distribution for a baseline scenario and for three future time slices, 2020 (2011-2040), 2050 (2041-2070) and 2080 (2071-2100). (*N.B.* Temperature is always the daily minimum air temperature if not otherwise defined.)

The number of days with an air temperature below zero degrees was calculated. For the baseline, there are 69 frost days *per* year decreasing with each time slice until the 2080s where 28 is left. The number of days *per* year for each temperature degree for baseline and for the three future time slices is plotted in Figure 9. In this figure, the temperature change is evident, with a 38% decrease of days *per* year with daily minimum temperature of five or less by the 2080s.

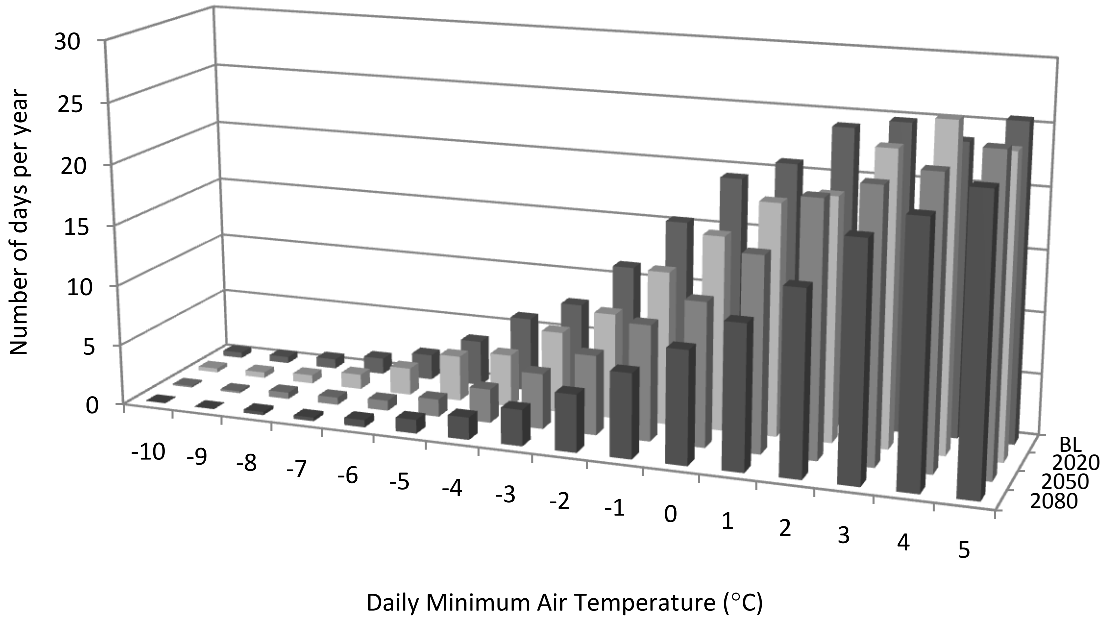


Figure 9. Number of days *per* year for each temperature degree ■ 2080 ■ 2050 ■ 2020 ■ BL.

Traffic accidents were analysed with respect to the actual air temperatures recorded at the time for the accident. To study how the number of traffic accidents in West Midlands might change with a future change of climate, a simple relationship was formed between the numbers of traffic accidents at baseline (DJF 2005-2006) and the climate at Elmdon for the same period of time:

$$\text{Number of accidents at Temp X} \big/ \text{Number of days per winter at daily minimum Temp X} \tag{4}$$

To calculate future accidents rates, the ratio in equation 4 was applied to the calculated number of days for three future time slices (Figure 10). As a validation of this method the ratio was also applied to the warmer winter (DJF 2004-2005) in which 2039 accidents were predicted. This is within 3% of the actual amount of traffic accidents in the database, so it gave confidence in the method. This methodology indiactes that there will be a decrease of 48% in the amount of days when the air temperature is below zero degrees. However, on the marginal nights with temperatures equal or below 5°C the traffic accidents will be reduced with 12%. For temperatures ≤0°C the predicted reduction of accidents is 43%.

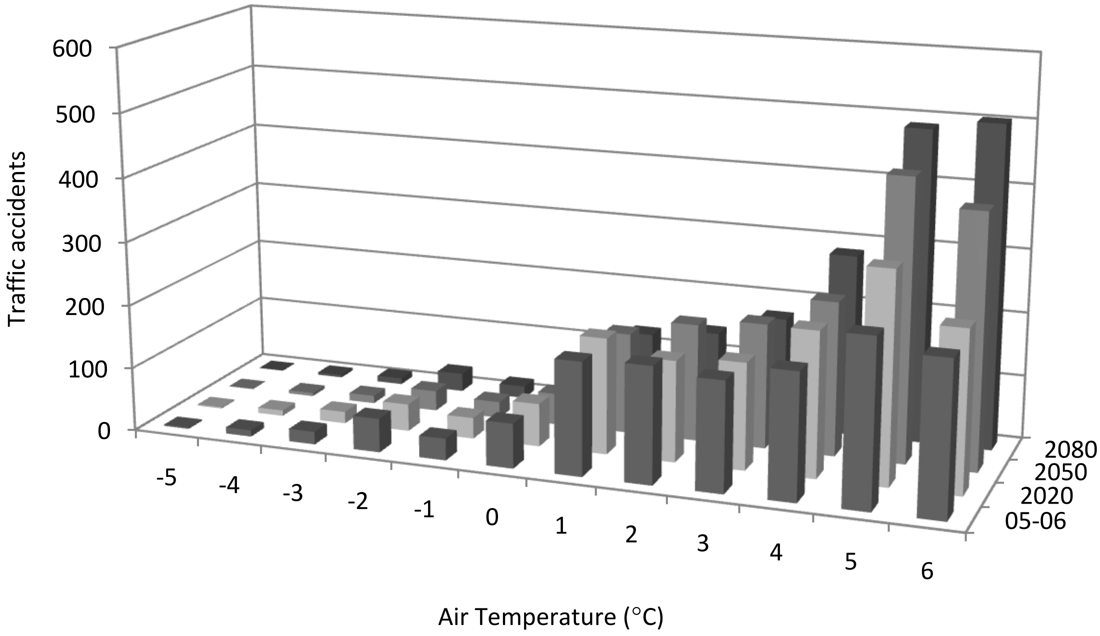


Figure 10. Amount of accidents in December to February for each temperature degree for the actual amount of accidents and for three future scenarios ■ 2005-2006 ■ 2020 ■ 2050 ■ 2080.

Hence, if the winters are to become shorter in line with climate change scenarios, will there be the same need for winter maintenance service? The answer is yes. Since the number of days below 5°C will remain in approximately 30% of the days in a year in the 2080s, they reduces with 21%, so there will continue to be many of the dangerous marginal nights that will need the winter maintenance service.

3.5 Summary of results

In general for the five winters that was examined in Paper I, the different types of slipperiness increased with increasing latitude, although this was not applicable for the category road icing (HT). A logical thought is that the traffic accidents also would increase towards the north. This is partly true since there is less traffic in the north and the relation between accidents and traffic density is considerably greater there than it is for an area with denser traffic. However, it was concluded in Paper II that the most accidents are occurring while it is snowing and not because of icy roads.

If the scenarios for the future climate are correct, then the number of days *per* year equal or below zero degrees will be reduced by 22% (Nov-Mar) in the Gothenburg area and 48% in the Birmingham area by the 2080s. This in turn should decrease the number of traffic accidents by 20% and 43% respectively. Winter maintenance costs should be reduced by milder winters. During the winter months, November to March, a 15% decrease would be possible in the Gothenburg area by the 2080s. For the Birmingham area, this could be as high as 38% (DJF).

The scenario for the number of days with daily minimum road surface temperature above zero degrees is increasing rapidly from 31 to 58 days between baseline and the 2080s. If the ratio between accidents and number of days is unchanged, the number of accidents will increase with 88% at these temperatures. Though, the total number of accidents will only increase with 2%.

4. Conclusions

This section is going to revisit the aims stated at the beginning of this thesis.

The overall aim with this thesis was to get a better understanding about winter road conditions and the relationship between slippery roads and traffic accidents.

Was there any particular geographical pattern in the distribution of slipperiness on the Swedish winter roads? The different types of slipperiness are to a great extent controlled by latitude. In the northern parts of the country it is more likely to be one of the two types of hoarfrost (HR1 & HR2, moderate and severe hoarfrost). Hoarfrost is established when the road surface temperature is at least 0.5°C below the dew-point temperature of the air. Hoarfrost contributes to a strong increase for the Winter Index (WI) towards the north. It is worth mentioning when talking about hoarfrost car drivers in the northern part of the country might not frequently experience this type of slipperiness since the roads usually are covered in snow and ice already and the frost just glitters on the surface. The slipperiness type, road icing (HT – moist or wet surface that freezes due to a temperature drop below zero) is more frequent in the southern parts of the country compared to the northern parts due to the fact that the temperature is more often around zero in the south.
This distribution was repeated at the regional scale. The only difference on the regional scale was that road icing (HT) had the highest amounts in the east, this might have been different if another region had been chosen instead. Finally, at the local scale, the county, the distribution of slipperiness appeared to have the largest influence from the local environment around the station.

In a mild winter there were more traffic accidents on the Swedish roads when it was slippery conditions. When the colder winter was studied, snow seemed to be the cause for the most accidents. This is the result of more occasions with snowfall in the colder winter and during the milder winter low temperature was more frequent at around zero degrees and thereby more opportunities of slipperiness.

The second main aim was to study what effect a warming climate might have on traffic accidents on wintery roads.

Winters will become warmer in the Gothenburg area and it will affect the road surface temperatures in the sense that the number of days below zero degrees will decrease by 22% until the 2080s. This in turn would reduce traffic accidents that occur at these temperatures by 20% over the same period. On the other hand a warmer climate leads to an increase in the number of days above zero degrees, which results in an 88% increase of the accidents during the five winter months studied. In total the accidents will increase with 2%.

Traffic accidents caused by slippery roads will also decline in the West Midlands, UK, because there will be fewer days with slipperiness when the winter climate becomes warmer. The number of accidents that occur when the air temperature is below zero degrees could be reduced with as much as 43% until the 2080s.

The number of days that need winter maintenance will be reduced until the end of this century in West Midlands, UK. If the days that have a daily minimum air temperature below 5 degrees are in need of winter maintenance, the days will decrease by 21%. But despite this, it is still 65 days left in the three winter months studied in this thesis with air temperatures below 5 degrees. So the need for winter maintenance will remain in the end of this century.

It seems inevitable that there will always be accidents on our roads. However, it seems like the number of accidents caused by slippery roads could be reduced in the future. Although long term accident trends and climate scenarios would indicate that accident rates should continue to fall. However, there are some factors that are contradictory to this. For example, if the roads are slippery less often, drivers might lack the skills of controlling a vehicle on slippery roads. However, both cars and roadways will be improved in the future and this will hopefully lead to less severe accidents and fewer personal injuries.

5. Reflections of future road climatology

Increased knowledge is the key to preventing accidents. If you know the road conditions before you travel, it could save you from having an accident.

Snow is easy to see and driving styles can be adjusted accordingly, however black ice on the road it is not as easy to spot. Black ice is the most dangerous form of slipperiness, because it is so difficult to detect, it is transparent with no lustre and is often mistaken for a wet road surface. It is formed on a wet or moist road when the road surface temperature is falling beneath zero degrees and over a short period of time, in the transition into ice, there is a release of latent heat that contributes of making a thin liquid film that freezes without any air bubbles. Black ice can in this thesis be compared with HT.

As concluded in Paper III & IV the number of dangerous marginal nights will not change drastically in the future. One possible scenario can be that the occasions with temperatures around zero degrees will even increase and as a consequence of this there will be more black ice. This will result in an increased number of traffic accidents and this is an area that needs more research.

To predict and understand more about the future road climate there is, among other things, a need to determine the distribution patterns of the different slipperiness types connected to the future climate. It is necessary to extend the mapping in this thesis to cover in detail larger areas. This will allow for changes in the pattern of slipperiness types to be fully identified.

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Before I start to thank people individually, I have to start by thanking everybody that feel concerned, so nobody is forgotten.

It has been a long and winding journey. It all started the 1st November 2002, and if I remember correctly it was a Friday and it consisted of a meeting with the others in the graduate school climate-mobility. After that I went home and began to think about what I just had started, this thought has been following me ever since for seven years, two others that have been following me, are my supervisors: Torbjörn Gustavsson and Jörgen Bogren. Thanks for giving me this opportunity to get a PhD degree. It has been a lot of fun and worthwhile.

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Ps. Don´t try to do translations on the internet,
väglag (road condition) translates to road teams.

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> When you are a Bear of Very Little Brain, and Think of Things, you find sometimes that a Thing which seemed very Thingish inside you is quite different when it gets out into the open and has other people looking at it.
>
> A. A. Milne (The House at Pooh Corner)

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Part II

Papers

Paper I

Geographical Distribution of Road Slipperiness in Sweden on National, Regional and County Scales.

Anna K. Andersson, Torbjörn Gustavsson, Jörgen Bogren and Björn Holmer

> "In the winter that road is treacherous.
> I was only going 20 mph when my accident occurred
> and once I hit the ice there was no way to stop."
> Andy Whyman quotes

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Geographical distribution of road slipperiness in Sweden, on national, regional and county scales

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ABSTRACT: The influence of latitude on the distribution of slipperiness of roads in Sweden was studied at three scales: national, regional and county. Data from 654 Road Weather Information System (RWIS) stations were compiled over five winter seasons, from 1998/1999 to 2002/2003. The aim of the study was to establish a basis on which to model how future climate changes might affect frequency of slipperiness and costs for maintenance in winter. Four types of slipperiness were studied (slippery conditions due to moderate (HR1) or severe (HR2) hoarfrost, moist/wet surface that freezes (HT), and rain or sleet falling on a cold road (HN)), all adding up to form the winter index (WI).

In Sweden, the distribution of slipperiness varies depending on the scale (national, regional or county). On the national and regional scales the mean temperatures give a general picture of the total slipperiness – i.e. dependence on latitude; different factors were tested and latitude proved to be the most correlated. Slipperiness caused by HR1 and HR2 hoarfrost tends to increase towards the north, while road icing (HT) decreases. On the county scale, neither latitude nor any other tested geographical variable, could explain much of the variance. Local climate and the directions of movement of individual weather systems may be more important. The regional scale is considered to be most suitable for future modelling of the influence of the effect of a changed climate on the slipperiness of the roads. Copyright © 2007 Royal Meteorological Society

KEY WORDS road climate; slipperiness; winter index; road icing; hoarfrost

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1. Introduction

Climate change and its impact on winter road conditions has been the central focus of a few studies during the last decade (Venäläinen and Kangas, 2003; Carmichael *et al*., 2004; Scottish Road Network, 2005). Some studies have concentrated on how much money can be saved on road maintenance in mild winters compared to winters with normal conditions. In the USA, in the winter of 2001–2002, the cost of snow ploughing and salting was reduced by 65–80% for the federal, state and local highway/street departments (Changnon and Changnon, 2005). In Finland, the costs for annual winter road maintenance amount to EUR 100 million (Venäläinen and Kangas, 2003). In Sweden, in 2005, the total cost for winter road maintenance amounted to approximately EUR 207 million (SRA, 2006).

Keeping roads free from ice and snow is a major part of winter road maintenance. If road maintenance is conducted properly the adverse effects of severe weather on society are reduced. Factors such as accidents and the costs of delays affect both individuals and society. Therefore, it is very important that winter maintenance is performed correctly and in a timely manner. To be able to do this, it is important to have a good understanding of the frequency and spatial distribution of slipperiness during the winter months. Knowing and understanding these conditions helps planning for future road maintenance activities in a changing climate. This study is intended to be part of a larger study of how climate change will affect winter road slipperiness in Sweden in the future, thereby influencing transportation. It can be of use in cost planning and the distribution of resources in winter road maintenance, with different types of slipperiness requiring different types of efforts.

The Intergovernmental Panel on Climate Change (IPCC) has predicted several different scenarios for future climate (IPCC, 2001). The scenario SRES A2 shows a very uniform world where local identities are preserved, there is a constant increase in world population, and economic growth is mainly regional and slower than in the other scenarios (IPCC, 2001). The annual mean temperature in Sweden is predicted to increase between 3.6 and 4.5 °C by the end of the twenty-first century, and between 3.8 and 5.5 °C in the winter months (December to February) (Räisänen *et al*., 2003). If this is the case for Sweden, it still does not indicate how this will affect severe weather and slipperiness. For example, if Gothenburg's mean January air temperature (1961–1990) (SMHI, 2005) increases 4 °C from −1.1 °C, this will, of course, change the potential slipperiness of the roads. For example, a road with a surface temperature of −1.7 °C

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and an air temperature of −0.3 °C might have a slippery situation of moderate hoarfrost (HR1), but if the future air temperature is changed to 3.7 °C the road surface temperature might change to 0.8 °C and the risk for slipperiness is over. If the mean temperature rises above zero there will be a decrease in the frequency of road slipperiness, but there will probably also be displacements in the proportions of the different types of slipperiness.

Today, winter indices are well-established tools for calculating the need for winter maintenance activities in relation to the climate (Hulme, 1982; Knudsen, 1994; Gustavsson, 1996; Heiberg Mahle and Rogstad, 2002; Strong and Shvetsov, 2006). The winter indices are climatological. Thus, they are not influenced by maintenance activities to prevent or reduce slipperiness.

To calculate variations in slipperiness, both in relation to today's climate and future climate scenarios, it is necessary to have detailed knowledge of the factors that give rise to slipperiness. Road slipperiness is mainly influenced by two factors: the prevailing weather and the local and micro-climate variations along stretches of road (for example, Gustavsson and Bogren, 1990; Knollhoff *et al*., 2003).

The interaction between atmospheric conditions and road surfaces can give rise to several types of slipperiness of varying severity. Lindqvist (1979) listed 24 types that were later reduced to10 (Norrman, 2000). Both, weather changes and stable weather can cause slipperiness. Slipperiness can also be associated with both, falling and rising temperatures. Of the ten different types of slipperiness proposed by Norrman (2000), four are used in the present study: moderate and severe hoarfrost, moist/wet surface that freezes and rain or sleet falling on a cold road. Some of the weather situations that can create problems on winter roads are described below.

Weather changes which result in precipitation on a frozen road surface will result in a slippery surface if it is not salted. During the winter, if the weather starts to clear up after rain has fallen on a surface which is above the freezing point, icy surfaces might occur due to radiational cooling of the road. Weather changes which advect warm air over a frozen surface might cause HR2. The warmer and more moist the air, the greater the risk for slipperiness due to sublimation (Bogren and Gustavsson, 1989). This is common during weather changes associated with warm fronts, even if the front itself does not produce active weather. Slipperiness can also occur without weather changes, due to the diurnal temperature cycle. Changes in combination with site-specific circumstances influence the risk of slipperiness. Such examples are:

- Rapid cooling of the surface – on clear and calm nights the road surface can be cooled by radiation to below the dew-point of the air. This will result in weak sublimation since the turbulence is weak due to the contemporaneous stabilization of the air (Lindqvist, 1975).
- Inversion above a cool surface – during clear and calm mornings with a cold road surface; the mixing of air due to turbulence by traffic, brings relatively warmer air down to the cold road surface causing risk of sublimation. At sunrise there is also a weakening of the inversion, and an increased turbulent transport of moisture towards the surface (Lindqvist, 1975).

Some of the events described above will occur over large areas (due to the presence of fronts and advection) while others are more site-specific. Differences in topography, nearby water bodies, vegetation, shading and thermal properties of the roadbed are all important factors that can differentiate the risk of slipperiness in an area. However, the distribution of slipperiness is also influenced by geographical factors such as latitude, altitude and distance from the sea, all of which affect temperature, humidity and wind in prevailing weather systems. In Sweden, Eriksson and Norrman (2001) also found that not only did altitude have some influence on an area from the Swedish west coast to 250 kilometres to the east, but also distance from the sea. However, the question arises as to whether the same geographical variables could explain the distribution of slipperiness if the area was much larger/smaller in size. Is there an optimal size to investigate geographical influences on the distribution of slipperiness?

The aim of this study was to investigate the particular geographical patterns in the distribution of slipperiness on Swedish winter roads, both for the total number of occurrences of slipperiness and for the four different types of slipperiness, and to see how these patterns depend on the size of the areas. Therefore, analyses were done on three different scales: national, regional and county. For the first two scales, the different types of slipperiness were related to latitude (since Sweden covers 15° of latitude). For the county scale, distance from the sea and altitude above sea level were investigated. The study is based on the Road Weather Information System (RWIS) in Sweden and was carried out over the period 1998–2003, with monitoring of the road conditions (i.e. temperature, precipitation and humidity) every half hour during the wintertime (defined as October to April).

2. Methods and Data

2.1. Study area

The Swedish Road Administration (SRA) uses both, regions and counties to divide the country into smaller administrative units. In total, there are 7 regions and 24 counties (Figure 1(a)). The regions are not similar in size, but the divisions are still useful, as they form areas with similar characteristics: these regions are used as a basis for the calculations of the extent of slipperiness. The reason for choosing the pre-defined regions used by the SRA is that the result of the analyses can be directly linked to such parameters as the cost of salt used for winter maintenance. Region Väst, in the western part of the country (Figure 1(b)), was selected for the analyses on the regional scale. One county in that region, Halland,

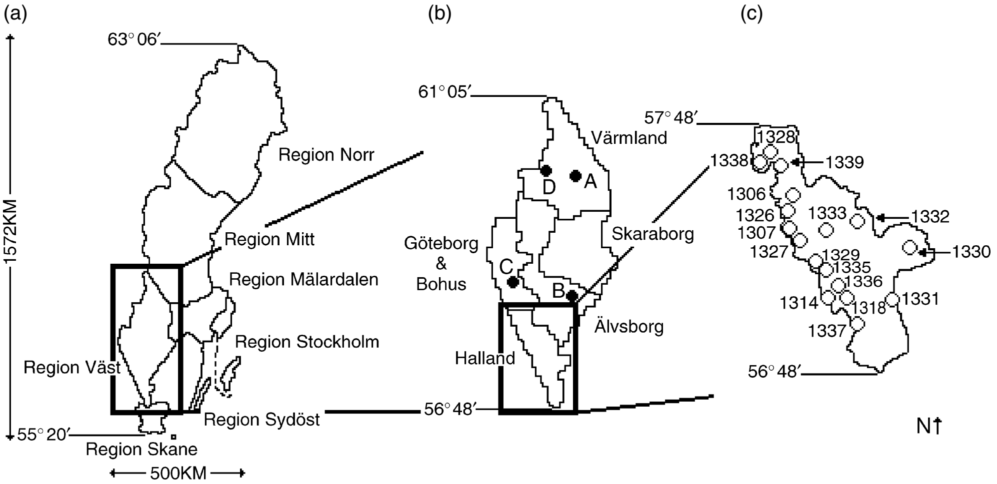

Figure 1. (a) The seven regions in Sweden (b) Counties in Region Väst with four marked stations (c) Stations in Halland.

was selected for a more detailed analysis (Figure 1(c)). All three areas have the same narrow stretch from north to south, which makes it easier to compare the different areas.

2.2. Swedish climate

The mean January temperature, between 1961 and 1990 (Figure 2), shows the typical pattern of decreasing temperatures with increasing latitude. The coldest mean annual temperature is found in the north in the areas east of the mountain range. Precipitation falls all year round, but the largest amount is in the summer and in the autumn, generally 500–800 mm year^{-1}, but in the mountain areas the yearly mean are 1500–2000 mm (SMHI, 2005). At that time of year, most of the low pressure comes in from the west or southwest, so most precipitation falls in the western part of Sweden. In the wintertime, most precipitation in the northern part of the country comes as snow. Temperatures are milder on the coasts than inland, the differences can be up to a couple of degrees (SMHI, 2005). Cold fronts most often come from the north.

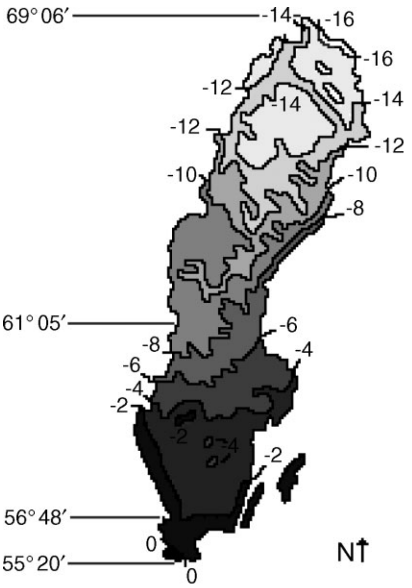

Figure 2. Mean air temperature in January 1961–1990, redrawn from SMHI (2005).

Since 1988, the annual mean temperatures in Sweden have been higher than the normal reference value, with the exception of 1996. On average, the mean annual temperature was about 1.3 °C higher than normal between 2000 and 2003 (SMHI, 2000–2003). During the five winter seasons studied, 2001 is closest to the mean value of the reference period 1961–1990 when the mean temperature was 0.7 °C higher than the normal reference temperature (SMHI, 2001). Here follows a short summary of the weather in the five winter seasons between 1998 and 2003 (SMHI, 1998–2003):

1998/1999: Early winter conditions in the northern part and in November 1998 winter prevailed in the whole country. The start of 1999 was mild in the south and cold in north, but winter conditions then returned with unexpected snowfalls during the end of the season.

1999/2000: Mild with several storms at the end of 1999, 2000 started relatively mild with much precipitation in the western and northern parts of the country. March and April were warm in the south, while March was cold in the north.

2000/2001: The end of 2000 was mild with a lot of precipitation; there were even some record precipitation amounts in the southern parts. The first month of 2001 was mostly mild with a short spell of colder weather and very little snow in the whole country.

2001/2002: The end of 2001 was very wet and mild, but there was some extremely cold weather at the end of December. Mild weather interspersed with some cold spells continued in 2002. April started with a lot of snow in the north, but then it became warm with record temperatures, while in the south there was a lot of rain.

2002/2003: In October and November 2002 there was very dry weather in the north and in the southeast there was a large amount of precipitation. January 2003 was

> cold in the north and warm in the south, February had the opposite relationship. March and April continued with mild weather and there was not much precipitation during these four months.

The area most exposed to frost is the northern part of Sweden, especially the areas with an altitude of 500 m above sea level and higher. The least frost-inclined areas are in the south, on the west coast and around the big lakes. Normally, slipperiness caused by frost starts at the beginning of October in the northern part of the country, and at the end of October in the southern part (SMHI, 2006); the border between north and south corresponds roughly to the southern border of Region Mitt (Figure 1(a)).

2.3. Road weather data

All information from RWIS stations in Sweden has been collected in a central database since the middle of the 1980s. Today the system consists of more than 710 stations situated along the major roads in the country. The stations monitor road surface temperature, air temperature, relative humidity, precipitation and wind speed. The dew-point is calculated from air temperature and relative humidity. Data are collected every 30 min during the winter months and stored in a database at the SRA. In this study, wintertime is defined as the period of 212 days between October and April.

Totally, data from 654 RWIS stations were used for the winter seasons of 1998/1999–2002/2003. All stations were checked for missing data. If any set of data had a gap lasting no more than 2 h in succession, then the missing data were replaced with data from the SRA. In situations where the interruption was over a longer period, the station in question was excluded from the analysis (for example, when the actual measuring process had an unknown start date, or when it was incomplete due to a missing or unknown end date). The number of stations varies between the different regions and years (Table I). Approximately 30% of the stations were excluded each year.

The mean value of the number of occasions on which slippery conditions developed was calculated for each type of slipperiness and each region in Sweden for the five winters. Slipperiness was compared in the different regions and in different winters. In Region Väst, further calculations of slipperiness were made for each county.

The first step in analysing the distribution of road slipperiness in Sweden on the national scale is comparing latitude with the winter index (WI). The latitude used at the national scale is a mean value of the stations' latitude for the region. The latitude is also used in Region Väst, but there the latitude for each station is used for downscaling. In the county of Halland, three different factors were analysed: latitude, distance from sea and altitude above sea level. The calculated WI and the individual types of slipperiness were investigated for each region and each winter season.

2.4. Winter index and classification of different slippery conditions

Combinations of monitored weather variables were used to calculate the possible occurrence of the four kinds of winter road slipperiness that the SRA considers most important for allocation of maintenance resources – that is, HR1, HR2, moist/wet surface that freezes, otherwise called road icing (HT) and HN.

By adding the number of occurrences of the four types of slipperiness the WI can be calculated.

$$\mathrm{WI} = \mathrm{HR1} + \mathrm{HR2} + \mathrm{HT} + \mathrm{HN}$$

All calculations of slipperiness are done in real-time and stored within the RWIS, and the information is used by the road maintenance personnel for making decisions on how to handle a situation of slipperiness.

The WI is a purely climatological index, so effects of maintenance actions, for example salting, are not included. No direct information is available about the actual road conditions (i.e. if there actually is a slippery road surface). RWIS data have the advantage of being collected close to roads, and they have a very high temporal and spatial resolution. These factors make it possible to perform detailed calculations with respect to both, what kind of slipperiness is actually possible on the road, and the duration of a specific occurrence.

For a weather event to be designated as slippery, a certain duration time has to be specified. The duration of an occurrence of slipperiness is determined in relation to length of time for which the salt is effective after it has been spread on the road, which is approximately

Table I. Number of road weather stations used in each region.

	Skåne	Sydöst	Väst	Stockholm	Mälardalen	Mitt	Norr
Latitude	55.9	57.2	58.3	58.5	59.5	62.1	65.6
98/99	33	52	87	26	36	107	72
99/00	35	52	88	26	37	111	72
00/01	36	53	95	30	38	118	76
01/02	36	53	95	30	38	117	76
02/03	36	53	94	31	38	117	76
Mean number of stations	35	53	92	29	37	114	74

4–6 h according to maintenance personnel. The required duration in the definitions below depends on the type of slipperiness and time of year. If the duration is shorter, the occurrence is not registered as being slippery.

Four classes of slippery conditions are defined by the SRA (Möller, 2002) to help determine their need for maintenance activities. These same definitions are used in this study and are given below. Common to all four classes is that the road surface temperature should be lower than +1.0 °C. The upper limit of the road surface temperature is specified as +1.0 °C, rather than 0 °C in order to have a safety margin for the maintenance personnel and to account for any inaccuracy of the sensors. The four definitions are:

- *Slippery conditions due to moderate hoarfrost (HR1)*
  HR1 often occurs as a result of radiative cooling in the evening/night, or turbulence-induced mixing of an inversion layer in the morning. In an HR1 situation, the road may be dry at the beginning but during sublimation it will become covered with crystals of hoarfrost. The road surface temperature should be between 0.5 and 2 °C lower than the dew-point temperature of the air. The upper limit is to ensure that there really are conditions for sublimation as opposed to a consequence of possible sensor error. HR1 has to have a minimum 6 h duration in October and a 5 h duration for the rest of the season in order to be counted as a slippery situation. If the durations are shorter it is not counted.

- *Slippery conditions due to severe hoarfrost (HR2)*
  HR2 is, in general, the result of advecting warm and moist air. The road surface temperature should be at least 2.0 °C lower than the dew-point temperature. HR2 has to have a minimum duration of 5 h in October and April, and 4 h from November to March in order to be counted.

- *Slippery conditions due to road icing (HT)*
  For an HT situation, the road must first be moist/wet due to rain/sleet, melting snow or condensation of dew, after which the temperature drops to below +1.0 °C, which then results in a freezing road surface. The definition for a moist road surface is that rain or sleet has fallen, or that condensation has occurred twice within the last 3 h. The reason for this rule is that one occurrence is not enough to know how moist the road is, and thus it is possible that the road surface would have dried up. However, if rain or sleet has fallen, or if there is presence of condensation twice within the last 3 h, there is a greater probability that the road surface is still wet or moist. The definition for condensation is that the road surface should be at least 0.5 °C lower than the dew-point temperature, and the road surface temperature should be above 0 °C at the time condensation occurs. HT has to have a minimum duration of 4 h in order to be counted.

- *Slippery conditions due to rain or sleet on a cold road (HN)*
  An HN situation arises when rain or sleet falls onto a cold surface; a cold surface is a road surface below +1.0 °C. HN has to have a minimum duration of 3 h in order to be counted.

The reason for the different duration times for HR1 and HR2, in comparison to HT and HN, is that they occur less often in October and April. The duration period is therefore extended by 1 h during these months.

Because the definitions are set as they are in this section, there are times when the system warns about slipperiness when there is no probability for slipperiness in practice. One example is when the road surface temperature is between 0 and +1 °C and the temperature does not sink below zero. Another situation is when the road surface becomes cold enough (approximately −10 °C) with the result of an increased surface friction. As a result, there will be some overestimation of the occurrence of slipperiness.

Other weather situations exist, namely, snowfall or snowdrift, as well as a combination of snow and wind that could lead to hazardous road conditions, but they are not considered here. However, if snow is melting, the road becomes moist and it could, for example, become an HT situation.

3. Results

3.1. Backgrounds

When considering road slipperiness the most dangerous temperatures are at 0 °C (Thornes, 1991) and a few degrees below. To obtain an idea of how the road surface temperatures differed between the different regions, the frequency of road surface temperature was calculated using two different temperature groups: road surface temperature 0 °C or below, and road surface temperature between −3 and 0 °C. As latitude increases, there was a distinct increase in the frequency of road surface temperatures below 0 °C. The southernmost region has road surface temperatures below 0 °C for 25% of the time as compared to the northernmost region, which was 75% of the time. However, the road surface temperatures between −3 and 0 °C are about the same throughout the country (Table II). Region Skåne and Region Norr have a slightly lower percentage compared to the rest in this category. This depends on two different effects, Region Skåne has the fewest occurrences of 0 °C or below, and therefore, the occurrence of temperatures between −3 and 0 °C will not be so great either, Region Norr has a large number of occurrences of road surface temperature below zero, but the majority are below −3 °C (Table II).

The decreasing mean air temperature in January relative to increasing latitude in Sweden is shown in Figure 2. During extreme temperatures some kinds of slipperiness become minimal, for example, the HN type, because it is too cold for this type of precipitation. However, the variability (standard deviation) of the mean air temperature in January is as much as 4 °C in the north and only 2 °C in the south (Ångström, 1974), which indicates a rather large variability in the weather that, in turn, can

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Table II. Percentage of road surface temperature (RST) by region as a mean for all winters, 1998–2003.

	Skåne	Sydöst	Väst	Stockholm	Mälardalen	Mitt	Norr
Latitude	55.9	57.2	58.3	58.5	59.5	62.1	65.6
Total RST below 0 °C	25.1	37.9	38.9	41.0	44.7	64.1	75.8
RST −3 to 0	17.4	23.0	21.5	25.2	23.7	24.4	19.9
RST below −3	7.7	15.0	17.4	15.8	21.1	39.8	55.8

lead to increased occurrences of slipperiness depending on advection. Earlier studies (for example, Gustavsson and Bogren, 1990) have shown that variations in temperature caused by a change of air masses often lead to hoarfrost. Therefore, temperature variations can be more interesting than mean temperatures.

Two stations were compared to show how slipperiness and changing road surface temperature are co-dependent. One station (station 2528, lat: 66°97′ long: 19°82′) was in the northern part of the country and the other in the southern part (station 1620, lat: 58°16′ long: 13°46′). The winter of 2002/2003 was studied to analyse when slipperiness warnings were issued. Two types of slipperiness were compared: HR2 and HT. All warnings for the two types of slipperiness were studied, and therefore, a period of slipperiness can last anywhere between half an hour to several hours.

HT did not occur at all between November and February in the northern part at station 2528, while HR2 was very common (Table III). This finding contradicts what was expected, and shows that there were more warnings for HR2 during mid-winter than in the beginning and end of winter. HR2 in the northern station in February occurred 21 times when the temperature was rising, and 10 times when the temperature fell. HT occurred only six times in the northern station; thrice in October, twice in March and once in April.

At the southern station (1620), both types of slipperiness are evenly distributed. One example is in January when both HR2 and HT occur seven times for both, rising and falling temperatures. HT is more common in the beginning and at the end of the winter at the southern station, which is probably due to temperature fluctuations around 0 °C during these months.

In total, there are more occurrences of slipperiness when the temperature is rising at the northern station, while at the southern station the relationship is more or less the same. The comparison of the two stations shows that there is a clear connection between the type of slipperiness, and where in the country it occurs (Table III)

Table III. Number of warnings for slippery situations with rising or falling road surface temperature. HR2 = Severe hoarfrost HT = Road icing.

Slippery type	Month	Station 2528		Station 1620	
		Rising	Falling	Rising	Falling
HR2	Oct	3	0	0	2
	Nov	7	5	1	0
	Dec	12	16	0	0
	Jan	20	10	7	7
	Feb	21	10	1	1
	Mar	6	2	0	0
	Apr	0	0	0	0
	$\sum$	69	43	9	10
HT	Oct	3	0	4	4
	Nov	0	0	7	12
	Dec	0	0	3	5
	Jan	0	0	7	7
	Feb	0	0	2	1
	Mar	2	0	0	2
	Apr	1	1	2	6
	$\sum$	6	1	25	37

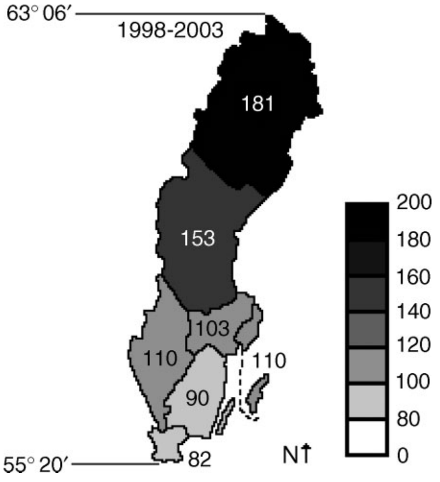

Figure 3. Mean value of the distribution of situations with slipperiness (WI) in Sweden for the period 1998–2003.

3.2. Distribution of road slipperiness on the national scale

3.2.1. Distribution of WI

The mean values of the total number of occurrences of slipperiness for the five studied winters 1998–2003 are shown in Figure 3. A clear distribution can be seen with the total number of occurrences increasing towards the north. There are approximately twice as many occurrences of road slipperiness in the northern parts of the country in comparison to the southern parts. One possible cause for this variation is that winter lasts longer in the north than in the south, that is, there is a gradual decrease in temperature with latitude. However, another factor can be the larger temperature variability in the north.

Figure 4 shows the relation between latitude and WI for each of the studied years, and in total for the entire period. The number of occurrences of slipperiness varied from year to year, but they all showed the same trend. The R^2 value, determination coefficient, was 0.96 for all winters from 1998 to 2003. The co-variations for the separate years are also very good (Table IV). On average, the WI increases by slightly more than 10 for each degree of change in latitude towards the north (Figure 4). The 1998/1999 winter had the highest amount of slipperiness in all regions except for Region Norr. This deviation is probably related to the different proportions of the types of slipperiness (Section 3.2.2).

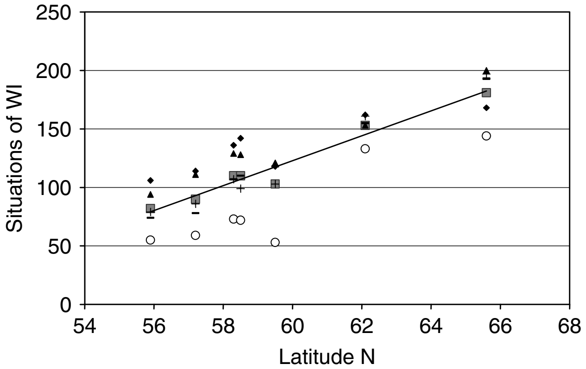

Figure 4. Relation between latitude and WI at the national scale. y = 10.63 × −514.83 R^2 is 0.96 for the 1998/2003 period. ■ 1998/2003, ◆ 1998/1999, ▲ 1999/2000, ○ 2000/2001, + 2001/2002, ▬ 2002/2003.

Table IV. Determination coefficients (R^2) between latitude and slipperiness during the different winter seasons (bold number over 0.50) WI = Winter index HR1 = Moderate hoarfrost HR2 = Severe hoarfrost HT = Road icing HN = Rain or sleet on a cold road.

Season	WI	HR1	HR2	HT	HN
98/03	0.96	0.83	0.96	0.78	0.05
98/99	0.78	0.54	0.93	0.87	0.60
99/00	0.96	0.52	0.95	0.67	0.02
00/01	0.82	0.79	0.91	0.08	0.47
01/02	0.96	0.86	0.93	0.77	0.87
02/03	0.98	0.93	0.99	0.65	0.12

The variations between the different years can, to some extent, be explained by the prevailing weather in that winter season. For example, the temperature of the 2000/2001 winter was very mild all season, and precipitation was above normal for the whole country. This winter season was the least slippery of all winters in the study. In contrast, the winter of 1998 came early, especially in the northern part, and by November had arrived over the whole country. The cold continued throughout the rest of the winter in the northern parts while the southern part of the country had mild temperatures with windy conditions in the beginning of 1999. Thus, both on the inter-annual basis and on the national scale, a mild and short winter gives a low WI.

3.2.2. *Distribution of different types of slipperiness*

The amounts for the different types of slipperiness in the seven regions are shown in Table V. The table clearly shows that the number of occurrences of the different types of slipperiness greatly varies between the different regions. In the two regions in the northern part of the country, the WI contains more than 80% hoarfrost, while in the south, Region Skåne, it is only 58%. The amount of WI due to HN slipperiness type varied between 9 and 18% in the different regions. The different types of slipperiness were investigated for co-variation with latitude in the same way as for the WI.

3.2.3. *Moderate hoarfrost (HR1)*

The amount of HR1 distinctly increases towards the north but levels out in the most northern part of the country (Figure 5). The determination coefficient for HR1 as a result of latitude varied from a value between 0.52 to 0.93, and the value for all winters between 1998 and 2003 was 0.83, which means that latitude can explain the distribution quite well.

On a yearly basis, 1998/1999 has the most occurrences of slipperiness with the exception of Region Norr; the highest value for that region was in the winter of 2002/2003. This region had a cold winter, and some months had very little precipitation as compared to the normal precipitation for the years between 1961 and 1990. The mild winter of 2000/2001 had the least occurrences of HR1 for all the regions.

Table V. Distribution of slippery conditions according to region, both in total (WI) and separately, for the different types of conditions as a mean for all winters, 1998–2003. WI = Winter index HR1 = Moderate hoarfrost HR2 = Severe hoarfrost HT = Road icing HN = Rain or sleet on a cold road.

	Skåne	Sydöst	Väst	Stockholm	Mälardalen	Mitt	Norr
Latitude	55.9	57.2	58.3	58.5	59.5	62.1	65.6
WI	82	90	110	110	103	153	181
HR1	37	44	50	53	51	68	70
HR2	11	15	27	26	23	55	85
HT	21	14	15	14	12	11	9
HN	13	16	19	17	17	18	16

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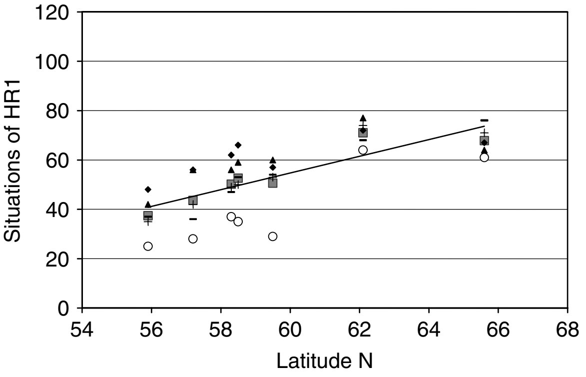

Figure 5. Relation between latitude and moderate hoarfrost (HR1) at the national scale. $y = 3.38 \times -148.14$ $R^2 = 0.83$. ■ 1998/2003, ◆ 1998/1999, ▲ 1999/2000, ○ 2000/2001, + 2001/2002, − 2002/2003.

3.2.4. *Severe hoarfrost (HR2)*

HR2 also occurs most frequently in the northern parts of Sweden (Figure 6). There is a clear increase towards the north. The R^2 values vary between 0.91 and 0.99, indicating a very strong relationship with latitudes. For all years, the determination coefficient was 0.96. This shows that variation in temperature has a noticeable effect in the northern part of Sweden. In the south, the number of HR2 occurrences is very low. For example, in the winter of 2000/2001, there were only six occurrences in Region Skåne.

The winter of 2002/2003 had the highest number of HR2 in Region Norr, and the 2000/2001 winter had the lowest, as was also the case for HR1. The distribution pattern of HR2 differs very little between the seasons in the south, and the spread between the years increases further north, with the largest range in Region Norr where the number of situations varies between 58 and 100.

Another difference is that HR2 reaches the highest frequency in the northernmost region, while HR1 has about the same in the adjacent region to the south. This is probably linked to relative humidity, which controls the dew-point temperature. The only difference between HR1 and HR2 is the difference between road surface temperature and dew-point temperature. HR2 must have a difference greater than 1.5 °C between the two temperatures. A reason for this is that the relative humidity is much lower in the northern parts of the country.

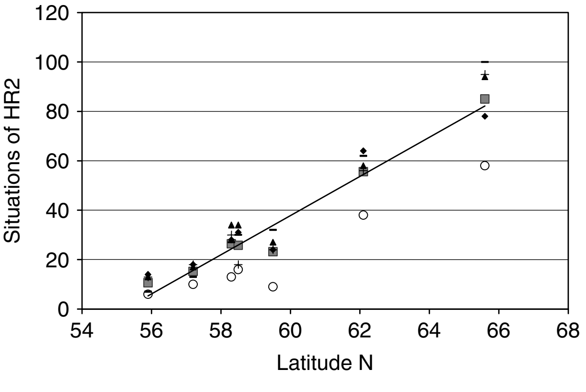

Figure 6. Relation between latitude and severe hoarfrost (HR2) at the national scale. $y = 7.92 \times -437.41$ $R^2 = 0.96$. ■ 1998/2003, ◆ 1998/1999, ▲ 1999/2000, ○ 2000/2001, + 2001/2001, − 2002/2003.

3.2.5. *Road icing (HT)*

HT (moist or wet roads that freeze) shows a decreasing number of occurrences towards the north (Figure 7), a pattern that is different to that found in slipperiness which is due to hoarfrost. This inverse relationship is also clearly seen in Table III, where the northern station has zero occurrences in the winter months. The R^2 value for HT as a function of latitude varies between 0.65 and 0.87 for the years studied. The R^2 value for all winters is 0.78. There is one exception, in the winter of 2000/2001, when it was only 0.08. For that year, the number of occurrences was almost the same in the seven regions maybe due to the mild winter. However, latitude generally is a good predictor of slipperiness due to HT.

3.2.6. *Rain or sleet on a cold road (HN)*

Slipperiness caused by HN does not show any relationship to latitude. In this case, HN increases in the first three regions but decreases further northwards (Figure 8). This

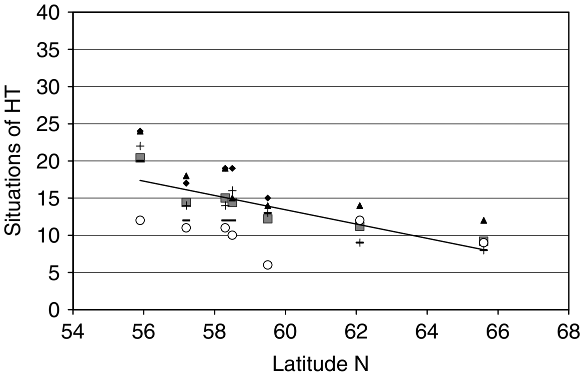

Figure 7. Relation between latitude and road icing (HT) at the national scale. $y = -0.96 \times +71.02$ $R^2 = 0.78$. ■ 1998/2003, ◆ 1998/1999, ▲ 1999/2000, ○ 2000/2001, + 2001/2001, − 2002/2003.

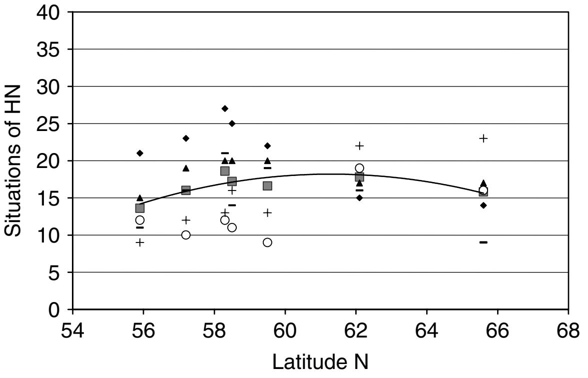

Figure 8. Relation between latitude and rain or sleet on a cold road (HN) at the national scale. $y = -0.14x^2 + 16.93 \times -500.64$ $R^2 = 0.71$. ■ 1998/2003, ◆ 1998/1999, ▲ 1999/2000, ○ 2000/2001, + 2001/2001, − 2002/2003.

type of slipperiness also commonly shows a variation between the seasons. In the winter seasons of 1998/1999, 1999/2000 and 2002/2003, Region Väst had the largest number of occurrences of slipperiness caused by HN. In one year, the amount was higher in the southern parts, while in the following year the highest values were found in the northern regions. Consequently, the slope of the regression line for a specific winter is either positive or negative. For a single winter, R^2 can be rather high (0.87 in 2001/2002), but when all winters are included it is very low. However, because there seems to be a curved trend for the relationship between HN and latitude, a second-degree equation was fitted to the trend line for all slipperiness in all the winters between 1998 and 2003. This second-degree curve gave a R^2 value of 0.71, which shows a better relationship between HN and latitude than the linear trend did (i.e. HN is most common in the middle of the country).

To summarize the results on the national scale, the latitude factor explains slipperiness quite well. However, its influence differs according to the type of slipperiness. WI increases towards the north as do also the two types of hoarfrost. HT, instead, decreases northwards, and precipitation on cold roads occurs mostly in the middle of the country, while further northward, the precipitation falls as snow, not rain or sleet.

3.3. Distribution of road slipperiness on the regional scale

3.3.1. Distribution of WI

As an example of the regional scale, Region Väst in southwestern Sweden was chosen (Figure 1). The distribution of WI follows the same pattern in Region Väst as it does on the national scale, with a strong increase to the north.

When Region Väst is studied year by year (Figure 9), considerable differences between the counties are seen. The slipperiness in Region Väst increased towards the northeast in the first three winter seasons, whereas in the last two seasons the increase was more northerly.

Regressions between latitude and WI were calculated in the same way as for the national scale. The slope of the regression line for all five winters was steeper than for Sweden as a whole (29 days for each degree of latitude, Figure 10), and R^2 was of the same magnitude (0.95). The winter with the lowest determination coefficient was 2000/2001 with 0.76. This winter was the mildest with the least number of occurrences in every county except for Skaraborg. The variation between the years increased towards the northern parts of the region. The northernmost county had a difference of 90 between the highest and the lowest number of occurrences, while Halland had 45.

The WI for the individual stations (average over the five winters) was also plotted against latitude, to get a more detailed view of the WI distribution. The latitudinal influence on WI is obvious when looking at individual stations. However, the larger variation of the WI for individual stations (Figure 11) caused the determination coefficient to decrease to 0.53. Some stations deviated more than others, one example being station A (Figure 1(b)), with almost 300 occurrences. An explanation for the large number could be that the station is located in an elevated, wooded area, and is thus more often exposed to colder temperatures. Station B, at lower latitude, with the highest amount of occurrences, is near a lake and exposed to winds from the south and southwest, but sheltered from all other wind directions. Station C is located on a high bridge and therefore, exposed to all wind directions. Station D, with the second highest WI

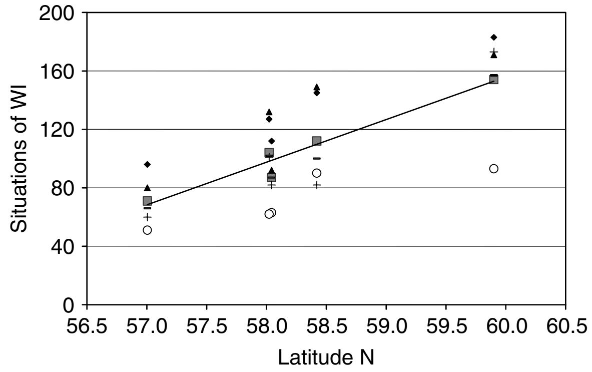

Figure 10. Relation between latitude and WI at the regional scale. R^2 is 0.95 for the 1998/2003 period. y = 29.19 × −1595.75. ■ 1998/2003, ♦ 1998/1999, ▲ 1999/2000, ○ 2000/2001, + 2001/2001, – 2002/2003.

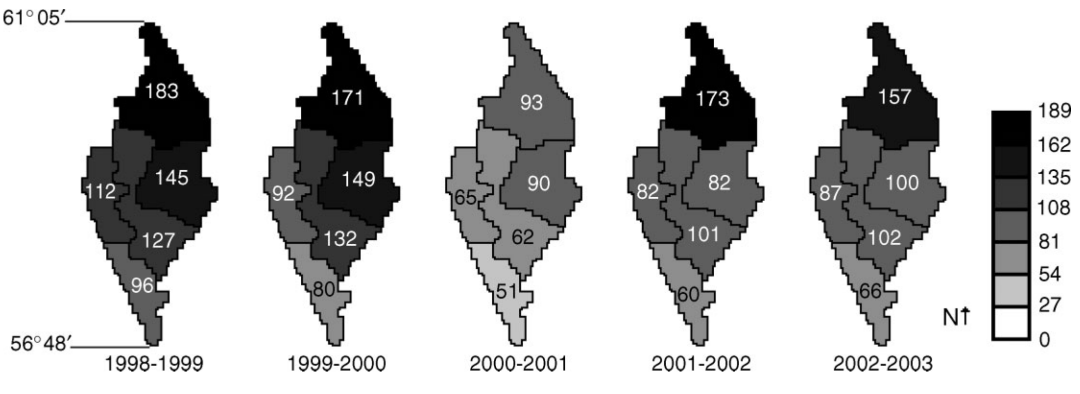

Figure 9. Distribution of slipperiness in total (WI) in Region Väst.

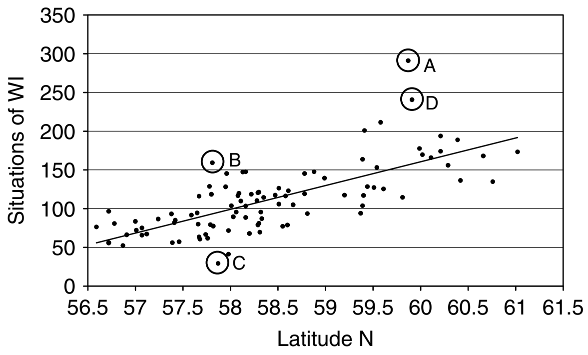

Figure 11. Relation between latitude and WI for the separate stations A–D, for the 1998/2003 period at the regional scale. $y = 30.69 \times +1680.68$ $R^2 = 0.53$.

number is located at a high, open place. In spite of this, the general trend is an increase with latitude.

As shown in Figure 2, January temperatures are higher in the coastal areas, so distance from the sea might influence the WI. However, latitude and distance from the sea were not as highly related as expected (R^2 value of 0.54), so, including distance from the sea in the regression hardly increases the explained variance.

3.3.2. Distribution of different types of slipperiness

Slipperiness that arises on account of both, HR1 and HR2, appears to have the same main pattern in Region Väst as for the national scale, with values increasing towards the north. However, HR1 has a northeasterly tendency (Figure 12) while HR2 has a more northerly direction (Figure 13). The R^2 values for the distribution of hoarfrost slipperiness as a mean value for all years are 0.90 for HR1 and 0.92 for severe.

Slipperiness due to HT, (Figure 14) or HN, (Figure 15) has a more diffuse pattern in Region Väst. HT has a slight tendency to increase towards the east. HN has the most irregular pattern. The precipitation appears to be spread evenly over the region. There is a weak trend showing an increasing degree of slipperiness towards the north for HN. For HT, the mean R^2 value for all years is close to zero and for HN the value is 0.48.

To summarize the results on the regional scale, the pattern of the distribution of slipperiness is the same for WI and hoarfrost as it was for the entire national scale, that is, a dependency on latitude. HT has a different pattern with increasing values towards the east compared to the national scale where it increased towards the south. The slipperiness type HN is evenly spread across the region while the national scale increases a little in the first three regions, thereafter there is a decrease in the values.

3.4. Distribution of road slipperiness on the county scale

3.4.1. Distribution of WI

The distribution of slipperiness at county scale was studied in Halland, the southernmost county in Region

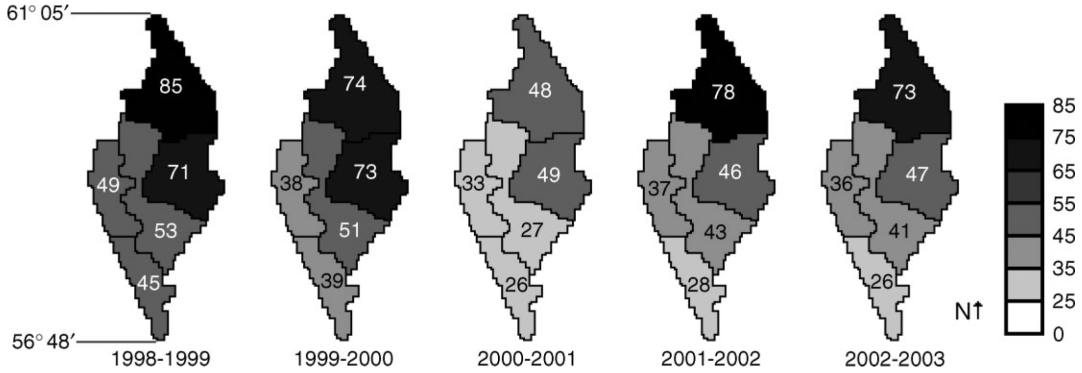

Figure 12. Distribution of moderate hoarfrost (HR1) in Region Väst.

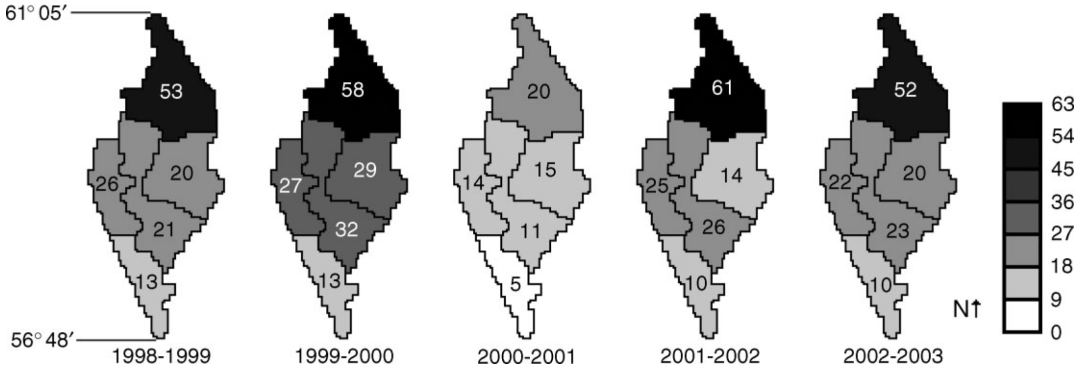

Figure 13. Distribution of severe hoarfrost (HR2) in Region Väst.

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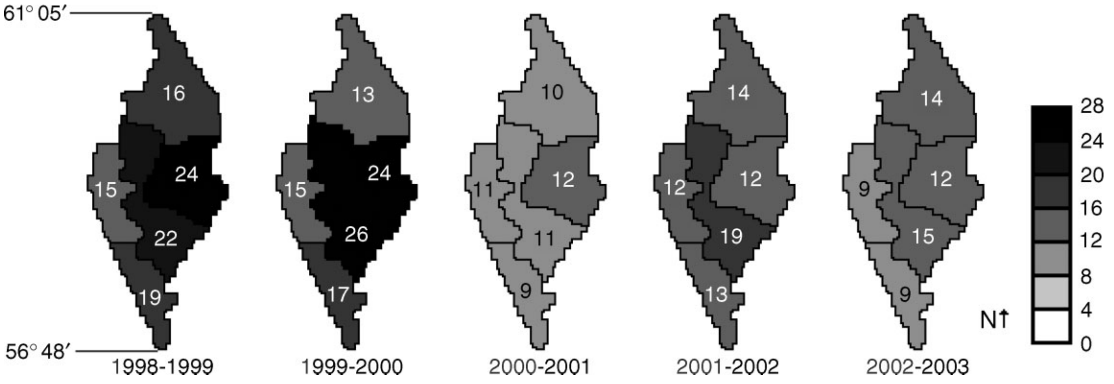

Figure 14. Distribution of road icing (HT) in Region Väst.

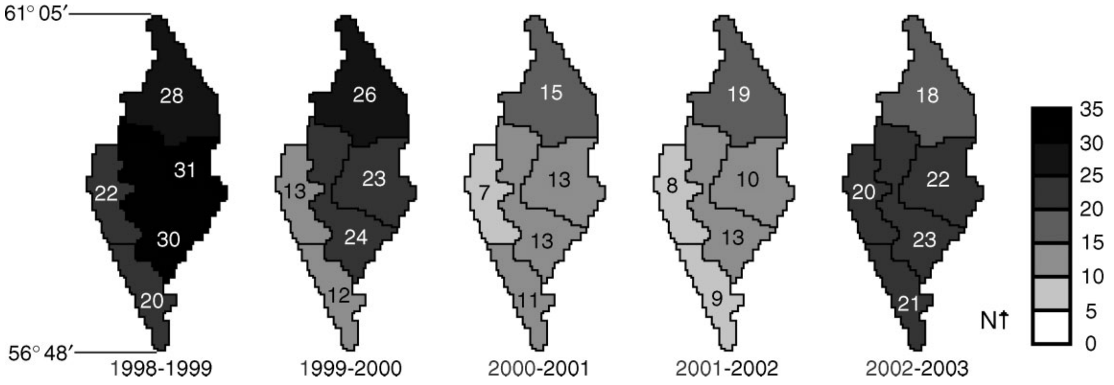

Figure 15. Distribution of slipperiness caused by rain or sleet on a cold road (HN) in Region Väst.

Väst. Seventeen stations are spread over the county (Figure 1(c)). On this scale, three factors were studied: latitude, distance from the sea and altitude above sea level.

In Figure 16, the latitude is plotted against the WI for each station. As seen, there is no correlation between WI and latitudes in Halland.

Distance from the sea was the next factor that was investigated (Figure 17). The results for this factor were as poor as they were for latitude. As the majority of the stations in Halland are placed on major roads along the coast, most stations are situated within 20 km from the coastline, with the exception of three stations (Figure 1(c) Station Nos: 1330, 1331 and 1332). The range in the number of occurrences of slipperiness is large between the different stations. The resulting correlation between distance from the sea and WI was zero.

The third factor that was studied was the altitude above sea level (Figure 18). The altitude above sea level does not differ much from station to station. Most of the stations are situated below 50 m above sea level. In this case, the determination coefficient was close to zero. The three stations with elevations above 100 metres are the same three stations that were furthest from the sea. These

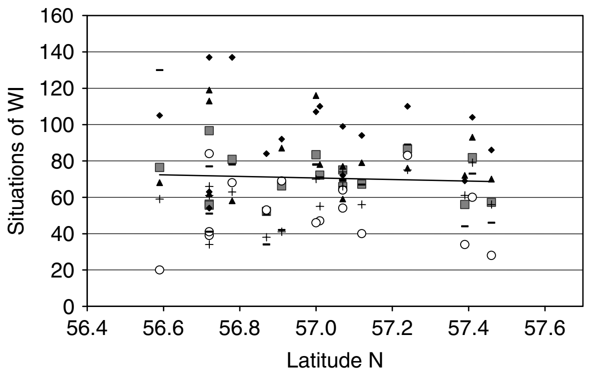

Figure 16. Relation between latitude and WI at the county scale. R^2 is 0.01 for the 1998/2003 period. y = −4.34 × +317.73. ■ 1998/2003, ♦ 1998/1999, ▲ 1999/2000, ○ 2000/2001, + 2001/2001, ‒ 2002/2003.

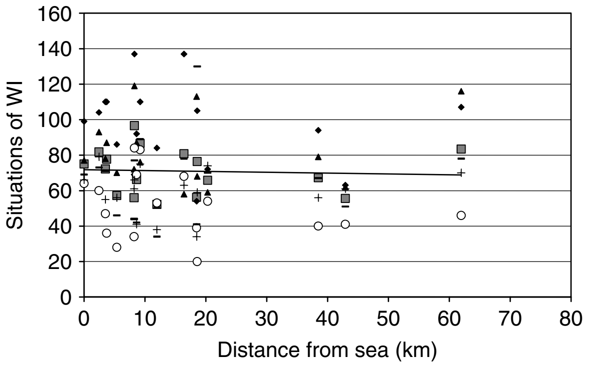

Figure 17. Relation between distance from sea and WI at the county scale. R^2 is 0.00 for the 1998/2003 period. y = −0.05 × +71.75. ■ 1998/2003, ♦ 1998/1999, ▲ 1999/2000, ○ 2000/2001, + 2001/2001, ‒ 2002/2003.

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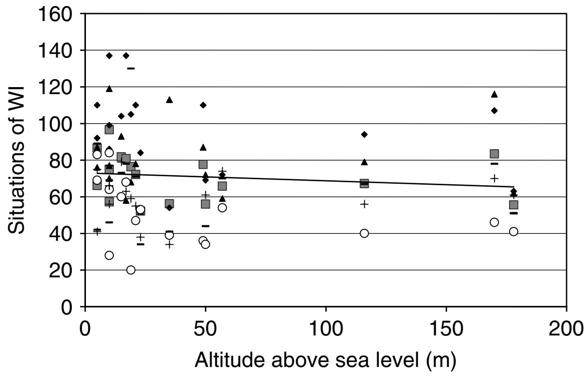

Figure 18. Relation between altitude above sea level and WI at the county scale. R^2 is 0.03 for the 1998/2003 period. y = −0.04 × +72.96. ■ 1998/2003, ◆ 1998/1999, ▲ 1999/2000, ○ 2000/2001, + 2001/2001, ▬ 2002/2003.

three stations are situated in the eastern part of Halland close to the border with the southern highlands.

In Figure 19, each station has an index relative to the mean value in all stations for each year. The index approach was chosen to make it easier to compare if there was any similarity in the relative frequency at the stations but it is not possible to find any patterns in Halland. One station with a high index one year has a low index the next year, and stations close to each other can have the opposite conditions.

3.4.2. *Distribution of different types of slipperiness*

In spite of the results in the previous section, where none of the tested factors could explain the distribution of WI, the different types of slipperiness were also studied in relation to the latitude at this scale. Table VI shows the determination coefficients for a linear trend of latitude and slipperiness in Halland.

HR1 increases slightly towards the north, and the increases are still larger for HR2, i.e. the same as the national scale. However, the determination coefficients are very low at this scale, so latitude cannot explain the distribution of slipperiness for the two types of hoarfrost. One explanation for this is the exposure of local climate at each station.

HT at the county scale tends to decrease with increased latitude. This is also the same at the national scale. The determination coefficient received the highest value (0.42) for any of the four types of slipperiness (Table VI).

Table VI. Determination coefficients (R^2) between latitude and slipperiness during the different winter seasons in Halland (bold number over 0.50) WI = Winter index HR1 = Moderate hoarfrost HR2 = Severe hoarfrost HT = Road icing HN = Rain or sleet on a cold road.

Season	WI	HR1	HR2	HT	HN
98/03	0.01	0.04	0.20	0.42	0.24
98/99	0.01	0.05	0.02	0.31	0.00
99/00	0.01	0.00	0.02	0.02	0.19
00/01	0.00	0.01	0.10	0.02	0.15
01/02	0.15	0.11	0.37	0.11	0.00
02/03	0.06	0.00	0.53	0.57	0.19

HN, had the second highest determination coefficient although it was only 0.24. There is a small trend for a decrease with latitude. This is a deviation from the other scales, where there were no particular trends for precipitation on cold roads.

To summarize the county scale: None of the three factors that were tested could explain the distribution of slipperiness well. In contrast to the WI for Halland, the different types of slipperiness showed that there are some trends in the distribution of slipperiness. Both HR1 and HR2 tended to slightly increase towards the north, while HT and HN tended to decrease. However, the determination coefficients were low, so the explanation for the distribution of slipperiness was not good at the county scale. There was also a comparison among the stations to see whether there was any similarity between them; for example, stations with the same type of location. This did not give any good co-variations either.

Studies at the county scale showed that there are too many differences in the locations of the stations, so the distribution of slipperiness at this scale cannot be easily explained. The factors that probably have the largest influence at this scale are the local climate at each station, the direction of the weather front and the weather types.

4. Discussion and Conclusions

A few studies have been undertaken on geographical factors influencing the climate in the winter months (Chapman and Thornes, 2006). Cornford and Thornes, (1996) used a modified Hulme index (Thornes, 1991)

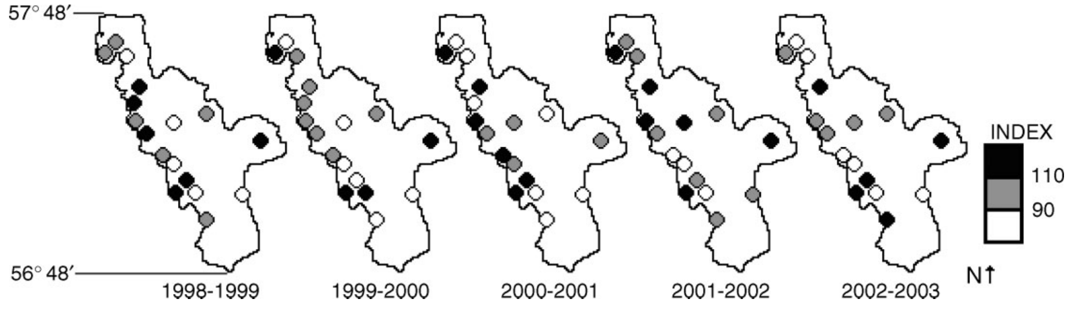

Figure 19. Each station's WI compared with the mean WI for every year in Halland (lat. 56° 48' to lat. 57° 48').

and found a strong relationship between altitude above sea level and the number of snowy days in Scotland. Eriksson and Norrman (2001) studied the influence of different types of slipperiness with distance from the sea in a rectangular area across southern Sweden. They showed an evident influence of distance to the east from the Swedish west coast. Both these studies are in the same order of magnitude as Region Väst; Scotland is approximately 25% larger and the rectangular area across southern Sweden is 25% smaller. However, the strongest relationship in Region Väst was with latitude. So why do these three regions differ with respect to which geographic variable that was most important to explain the distributions of slipperiness? In Scotland, the altitudes differed from sea level to 1300 m above sea level, while in the two Swedish areas altitudes were only slightly above 300 m. Thus, the range in temperature is much higher due to the differences in altitude in Scotland. The area used by Eriksson and Norrman (2001) is 2.5 times the length in west–east orientation than in south–north orientation. Distance from the sea (and diminishing temperature) has a larger range than latitude. Finally, in the present study, the elongated shape in south–north orientation of Region Väst favours latitude. So, the geographical variable with the largest range is the most important factor in explaining the distribution of slipperiness in these areas of regional size.

At the national and regional scales the two hoarfrost types (HR1 and HR2) are related to the decrease in temperature with latitude. Since the relationship between air and dew-point temperature is flattened out at low temperatures, low temperatures are not favourable for hoarfrost. However, low average temperatures often mean long winters, and thus more occasions when hoarfrost might develop. Furthermore, since the temperature variability is higher in the north due to the contrast of mild maritime air masses from the west, and cold continental air masses to the east, the number of hoarfrost occurrences can increase to the north. On the other hand, HT slipperiness decreases with latitude because of a more frequent variation of the temperature around zero degrees in the south. The HN slipperiness type is equally distributed throughout the whole country.

The largest deviation between the regional scale and the national scale is in the HT type of slipperiness, where the increase is to the east instead of a decrease towards the south. This is probably due to the difference in elevation, and therefore, a higher frequency of precipitation inland. Consequently, the roads become more moist, and the temperatures here are usually lower compared to the coast; therefore, ice can form.

At the county scale no particular pattern was found. On this scale, the characteristics of the location of the stations seems to be important. There are differences in the local climate at the stations; for example, whether the station is open or shaded, situated on a hill or in a depression, wind-exposed or close to water. The locations have to be examined more carefully so that they can be located at similar places to obtain a more reliable comparison between them. Studies have been conducted during clear, calm nights on road stretches where temperatures were measured and compared (for example, Gustavsson *et al.*, 1998; Karlsson, 2000) in order to examine the temperature differences between forests and adjacent open areas.

The aim in this study was to determine if there were particular geographical patterns in the distribution of slipperiness on Swedish winter roads at different scales for use in a model for a future study on winter road climate. The national scale has good correlations for latitude, but this scale can be too large an area to be used in a model. Factors such as distance from the sea or altitude above sea level might disappear because of the strength of the latitudinal influence at the national scale. At the county scale, no good correlations were found for any of the factors that were tested, so it is not suitable either. The study concludes that using the regional scale is best in a model for future winter road climate.

The strong correlation related to latitude implies that a calculation of the general increase in WI can be made using the equation in Figure 4. The slope of this relationship can be used to study the effect on a changing climate. As shown in Figure 10, it is possible to use this relationship for the regional scale.

If the climate changes to warmer winters the number of hours below 0 °C will be reduced but the number of hours between −3 and 0 °C will probably increase, especially in the northern parts of the country (Table II).

The variation in the distribution of different kinds of slippery conditions in Sweden means that the related costs vary accordingly. The results from this study give a broad picture of how slipperiness is distributed in different scales as a result of varying winter climates. These results can also form the basis of how a future climate change could influence the distribution of slippery conditions in Sweden. It will be possible to calculate the costs related to the changes needed for winter maintenance. In addition, it might be possible to establish the future costs of accidents related to winter roads, as well as other disturbances that are costly to society.

Acknowledgements

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Paper II

The use of a temporal analogue to predict future traffic accidents and winter road conditions in Sweden.

Anna K. Andersson and Lee Chapman

"Always have a plan, and believe in it. Nothing happens by accident."
Chuck Knox

The use of a temporal analogue to predict future traffic accidents and winter road conditions in Sweden

Anna K. Andersson & Lee Chapman

Abstract

Slippery roads due to ice and snow are a major cause of road traffic accidents in Sweden during the winter months. This paper investigates the hypothesis that as the climate becomes increasingly milder there will be a reduction in the number of accidents in winter. Two winters are compared in this analysis; one colder and drier than average, the other warmer and wetter than average. Despite the differences in weather between the two months, there was approximately the same number of accidents in both cases, although the exact cause of these accidents varied. It is concluded that using the warmer month as a temporal analogue, the accident rate in Sweden will not be reduced under current climate change scenarios. This result is attributed to the fact that drivers become more complacent in milder weather conditions where the risk of slippery roads is reduced.

Keywords: Road traffic accident, winter maintenance, slipperiness, climate change

1. Introduction

During the three year period 2003 to 2005, there were approximately 54,000 traffic accidents reported in Sweden where people were fatally or seriously injured (Swedish Institute for Transport and Communications Analysis: SIKA, 2006). There have been numerous studies into the effects of different weather conditions on traffic accidents in a variety of countries (e.g. Edwards, 1999; Keay and Simmonds, 2005; Andrey and Olley, 1990). In particular, rain has been shown to be a major factor (Andreescu and Frost, 1998; Fridström et al., 1995; Andrey and Yagar, 1993), with some studies showing a doubling in the baseline accident rate during rainfall (Brodsky and Hakkert, 1988; Bertness, 1980). Other than rainfall, wind, fog, low sun, snow, ice and even hot temperatures (e.g. Saudi Arabian summer >34°C) can be a contributory factor in road accidents (Nofal and Saeed, 1997). However, winter-time in Scandinavia, the major weather related cause of road accidents is snow and ice.

Despite Sweden, being well prepared for winter weather, some 45% of the total number of accidents reported during 2003 to 2005 occurred during the winter season (SIKA, 2006). This figure is in agreement with the work of Bogren et al. (2006) who established that 52% of road accidents occurring across two winter seasons in Sweden were caused by reduced road friction. Of the ten different types of slipperiness identified by Norrman et al. (2000), precipitation on an already frozen surface posed the highest risk, whereas hoarfrost or drifting snow the lowest risk. Similarly, Smith (1982) showed an increase of just 2.2% in the amount of traffic accidents on snowy days. These findings contradict other studies which have shown that snow could potentially double accident rates (e.g. Codling, 1974; Andreescu and Frost, 1998; Suggett, 1999; Nokhandan et al. 2008). With respect to ice, road surfaces are the most slippery at temperature of zero degrees (Moore, 1975). However, Campbell (1986) studied the effect of temperatures on traffic accidents in Winnipeg, Canada and found that there were more accidents when the temperature was below -15°C than in the temperature range -15°C to 0°C. Overall, it appears that the effects of snow and ice appear to be mitigated by driver behaviour, with motorists postponing their leisure trips by car when driving conditions are poor (Palutikof, 1983; Kilpeläinen and Summala, 2007).

The overall aim of this study is to analyse the way in which the weather influences traffic accidents in Sweden during the winter months over two consecutive winters DJF 2004-2005 and DJF 2005-2006 (Figure 1). A specific objective of this paper is to contrast accident rates in months of different prevailing weather. For this reason, this study will focus in some parts on the month of January, as although accident totals are not highest in January, there was a large difference in the weather experienced in the two Januarys over the study period. January 2006 was a cold and dry month where as January 2005 was warmer than average with increased precipitation. This methodology was chosen for two reasons. Firstly, it is hypothesised that there will be fewer traffic accidents caused by slippery roads in the milder month when compared with the cold January 2006. Secondly, January 2005 could potentially be used as a temporal analogue to provide an indication of how climate change could influence future road conditions and thus road accidents.

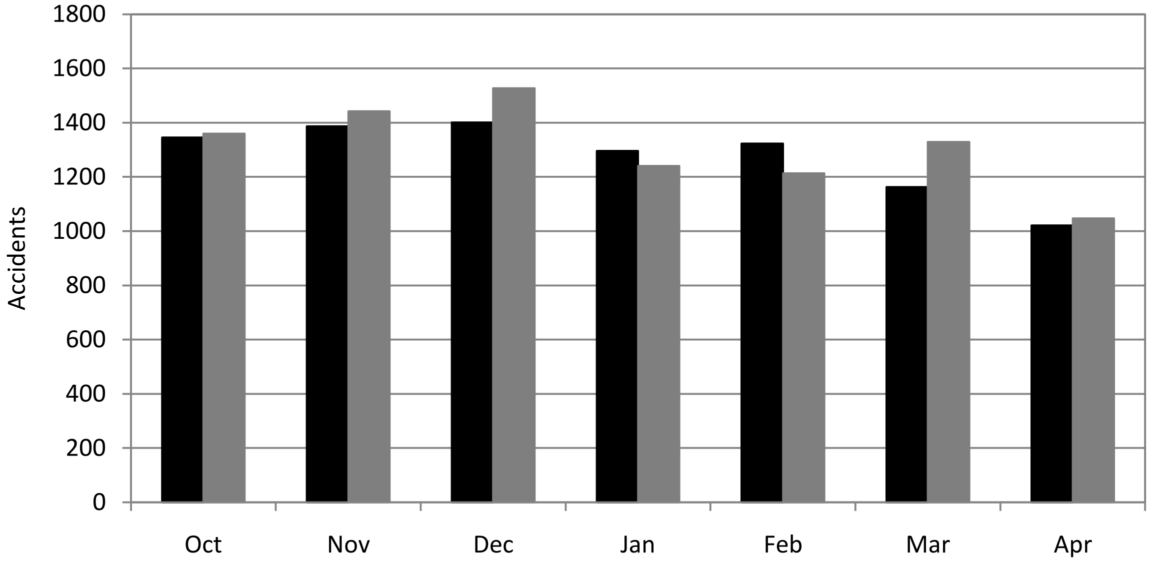


Figure 1. Traffic accidents in Sweden during the winters of ■ 2004-2005 and ■ 2005-2006.

2. Methodology

2.1 Area of Study and Data

Although the area of study covers all of Sweden, there is a particular focus on the smaller areas of Region Skåne and Stockholm (Figure 2). Accident statistics involving just motor vehicles were compiled from the Swedish Road Administration (SRA) database (Swedish Traffic Accident Data Acquisition: STRADA) which has been the official record of Swedish road traffic accidents since 2003. The database contains information obtained from both the police and the emergency units in hospitals.

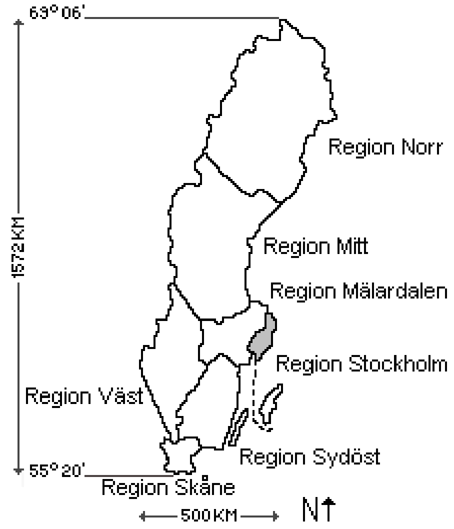


Figure 2. Map of Sweden divided in seven regions. Area of Stockholm (grey).

All climate data used in this study is obtained directly from outstations of the Swedish Road Weather Information System (RWIS). The system presently consists of approximately 720 stations situated along the major roads in the country. Each outstation routinely collects information about road surface temperature, air temperature, relative humidity, precipitation and wind speed and direction. Data are collected every 30 minutes during the winter months and stored in a central database at the SRA. Data have been collected in this way since the mid-1980s, but a recent development has seen the inclusion of a camera at around 200 of the outstations to aid monitoring of the surface state of the road.

In this study, each recorded accident is spatially joined in a Geographical Information System (GIS) to the nearest RWIS outstation. By using this approach, the prevailing weather and conditions (type of slipperiness) at the time of the accident can be determined. A decision was taken to analyse the prevailing weather for the previous two hours to determine the cause of the accident as this was considered to be more representative than a simple snapshot of the weather at the time of the accident. Furthermore, it is hypothesised that often the cause of the accident would be a sudden change in the weather. This would then be captured in the two hour time interval. There are some limitations with this approach. Firstly, due to the 30 minute time interval used by outstations, the nearest time interval to the accident time needs to be used. Secondly, there is also the potential for error due to the location of the RWIS outstation often being several kilometres away from the scene of the accident and therefore potentially experiencing different local weather.

2.2 Different types of slipperiness

For this study, road slipperiness has been subdivided into four types in which the road surface temperature should be lower than 0°C. These four categories are the same as used by Andersson et al. (2007), with a minor change to the +1°C threshold to 0°C and are based on the scheme used by the SRA in their decision−making for maintenance activities i.e. salting or ploughing (Möller, 2002). The different slipperiness types have the following definitions (for further details see Andersson et al. 2007):

Slippery conditions due to moderate hoarfrost (HR1)
The road surface temperature should be 0.5°C to 2°C lower than the dew−point temperature.

Slippery conditions due to severe hoarfrost (HR2)
The road surface temperature should be at least 2°C lower than the dew−point temperature.

Slippery conditions due to road icing (HT)
Moist/wet road surface due to rain/sleet, melting snow or condensation of dew and a temperature drop below 0°C.

Slippery conditions due to rain or sleet on a cold road (HN)
Rain or sleet falls onto a road surface below 0°C.

Where there has been a situation of at least one of these four types it is referred to as MIPS (MIPS is an abbreviation for the four types of slipperiness, Moderate hoarfrost, road Ice, Precipitation and Severe hoarfrost). However, there are also three types of precipitation (snow, freezing rain and sleet) that can contribute to a slippery road. These are also taken into account and are used in the comparisons of how the different road conditions influence the amount of traffic accidents. The different precipitation types Snow, Freezing rain and Sleet is obtained from the RWIS−stations precipitation sensors, which measure both the amount and type of precipitation.

3. Baseline Weather Conditions

The two winters used in this study can be described as mild and above average (2004−2005) and one (2005−2006) more like baseline average (1961−1990). Both winters experienced similar weather in December and February. However, there was a large contrast in the weather experienced in January. For this reason, the study focuses on the two January months.

The average January mean temperature in Sweden (Figure 3a) has a range from zero in the south to below −16°C in the north (SMHI, 2005a) with an overall average of −6.5°C (SMHI, 2006a). The average precipitation range is from below 40 mm in the northern part of the country (Figure 3b) to over 100 mm in some of the mountain areas (north-west), the whole country has an average of 46 mm of precipitation in January (SMHI, 2006a).

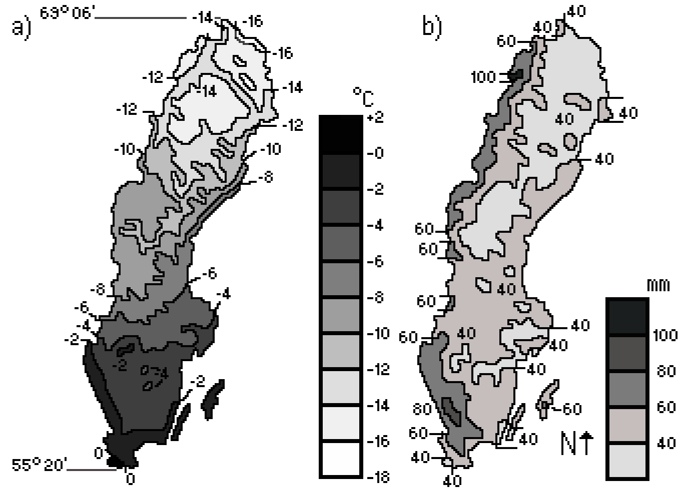


Figure 3. a) Average mean air temperature b) average precipitation in January 1961−1990 redrawn from SMHI (2005a) and SMHI (2007a)

<u>January 2005</u>
Most of the month had mild winds from the west with frequent precipitation. It was particularly windy in the south of Sweden and in mountainous areas. The month started with temperatures well above average, although during the later part of the month the temperatures were more normal. Overall, temperatures in the northern and middle part of the country were 5−8°C above average and

the southern part 3−5°C degrees above average (Figure 4a). With the exception of the south of the country, precipitation was also above average in many parts of the country. This was falling often as rain, even in the north of the country (SMHI, 2005).

January 2006

Although, the north of the country had a mild month, locally 6°C above average, further south, temperatures were average, with the southernmost parts of the country up to 2°C below average. Precipitation was also below average, with the exception being mountainous areas where it was locally up to double the normal amount. In the south parts and along the east coast the precipitation was half of the average amounts (Figure 4d) (SMHI, 2006).

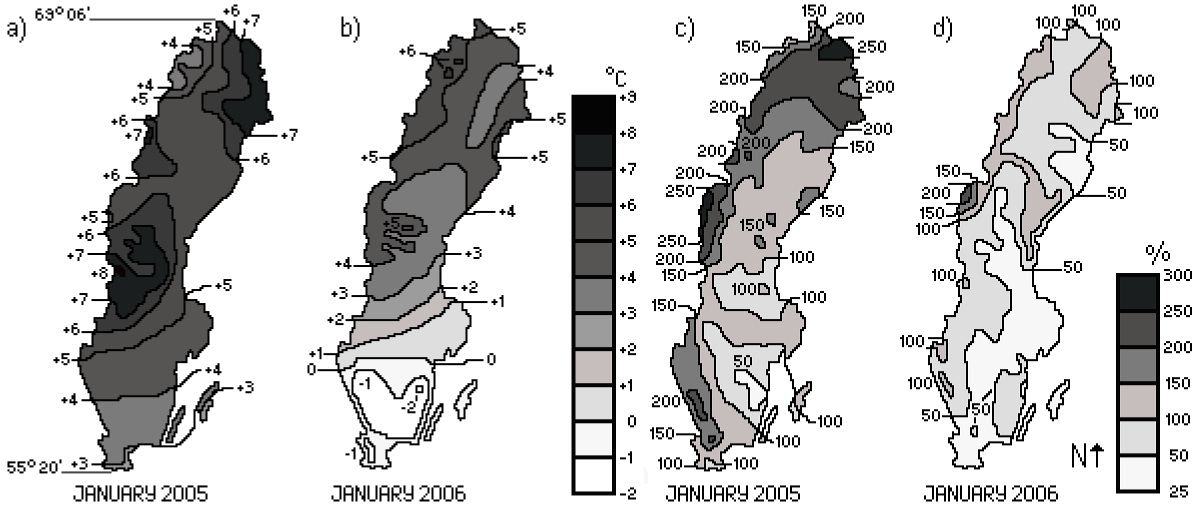


Figure 4. a) Deviation from normal mean air temperature in January 1961−1990 in January 2005 and b) 2006 c) percentage of precipitation compared with normal mean precipitation in January 1961−1990 in January 2005 and d) 2006 redrawn from SMHI (2007).

3.1 Road surface temperatures

Typical road surface temperatures for the January months of the study period are shown in Figure 5.

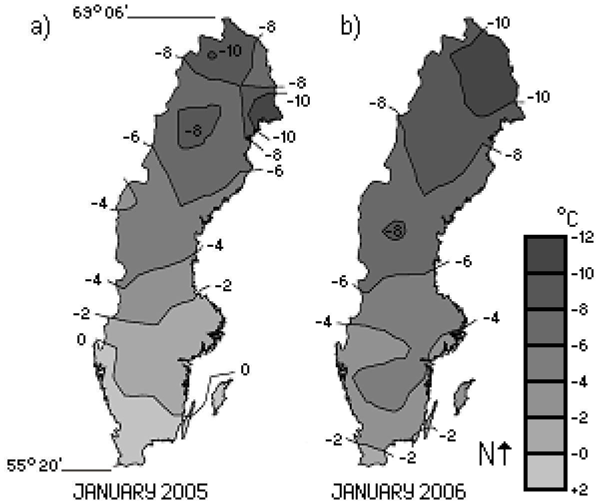


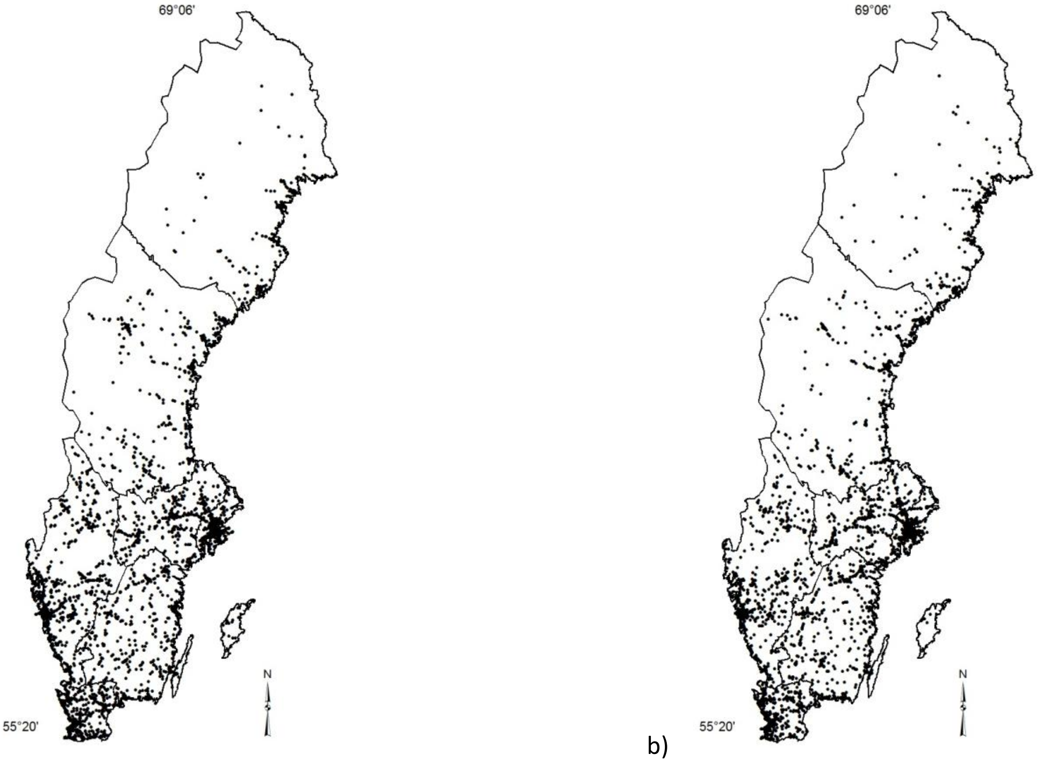
Figure 5. Road surface temperatures in a) January 2005 and b) January 2006

The temperatures are taken from the RWIS outstations and calculated to a mean value for each month before being spatially interpolated. (NB: The accuracy of the interpolations is increasingly accurate in the south of the country due to the denser network of outstations in these regions). Figure 5 shows that the overall pattern for the two months is as expected with road surface temperature reducing with latitude. However, there is a clear difference in the magnitude of temperatures between the two months, especially in the southern parts of the country, with January 2005 being typically 2-4°C warmer than January 2006. Notably, the southernmost part of the country had a mean temperature above 0°C.

4. Results & Discussion

4.1 Accident Distribution

There were 3987 traffic accidents in December 2004 to February 2005 (3897 with available position data), the following winter (2005−2006) had 3922 traffic accidents whereof 3803 with available position data. In January 2005, there were a total of 1253 accidents compared with 1179 in January 2006. The distribution of these accidents is shown in Figure 6 and is indicative of the general pattern of an increased number of accidents located at major urban centres and highways.



a) b)

Figure 6. Accident positions in a) 2004-2005 and b) 2005-2006

4.2 Temperature Distribution

Using the RWIS outstation data, the mean air temperature in January 2005 was −0.19°C compared with −4.03°C in January 2006. Air temperatures were below 0°C for just 53% of the time in January 2005 compared to 81% in January 2006. With respect to MIPS or Snow (i.e. the percentage of the presence of at least one slipperiness type or snow) this stands at 22.1% and 28.9% for January 2005 and 2006 respectively.

As a first step to ascertain whether there are fewer weather related accidents in the milder month of January 2005, the number of accident was plotted as a cumulative percentage for each degree of the road surface temperature at the time of the accidents (Figure 7).

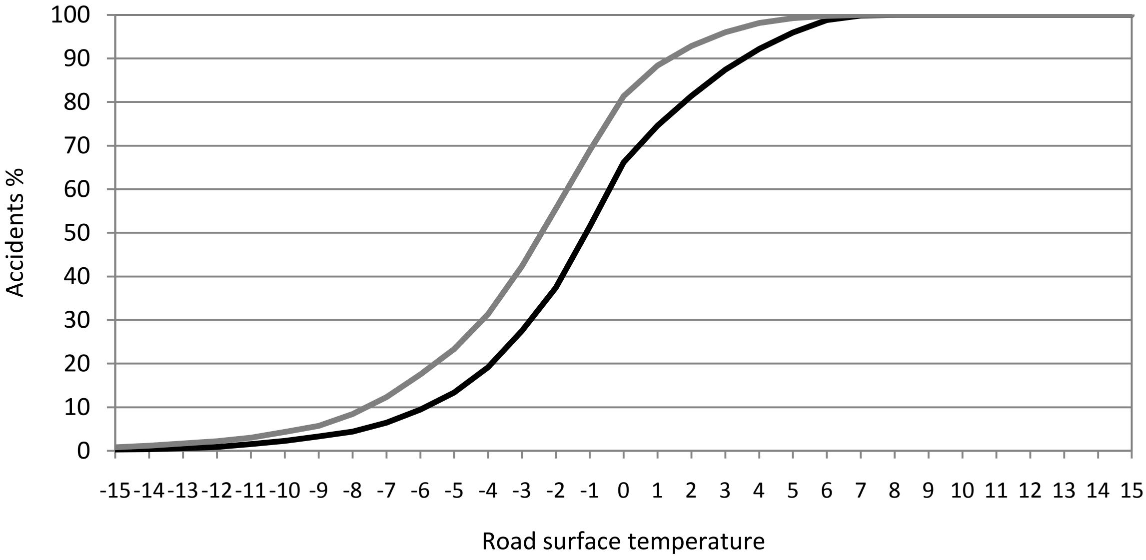


Figure 7. Road surface temperatures when the accidents occurred in cumulative percentage ■ 2004-2005 ■ 2005-2006

Although there are other factors to take into account when deducing the slipperiness of the road, this simple analysis of surface temperature provides a basic comparison between the two years. Ultimately, road surface temperature is the most important prerequisite in order to get a slippery road surface, since a road cannot become slippery if the surface temperature is over 0°C. Figure 7 shows that 66% of the accidents in 2004−2005 were caused when the surface temperatures was below 0°C compared to 81% in 2005−2006. The difference in surface temperature between the two years is clear and shows that the road surface temperatures were generally higher when an accident occurred in 2004−2005 than in 2005−2006. If the months of January is excerpted the percentage is in the same range as it were for the three months (64% resp. 88%).

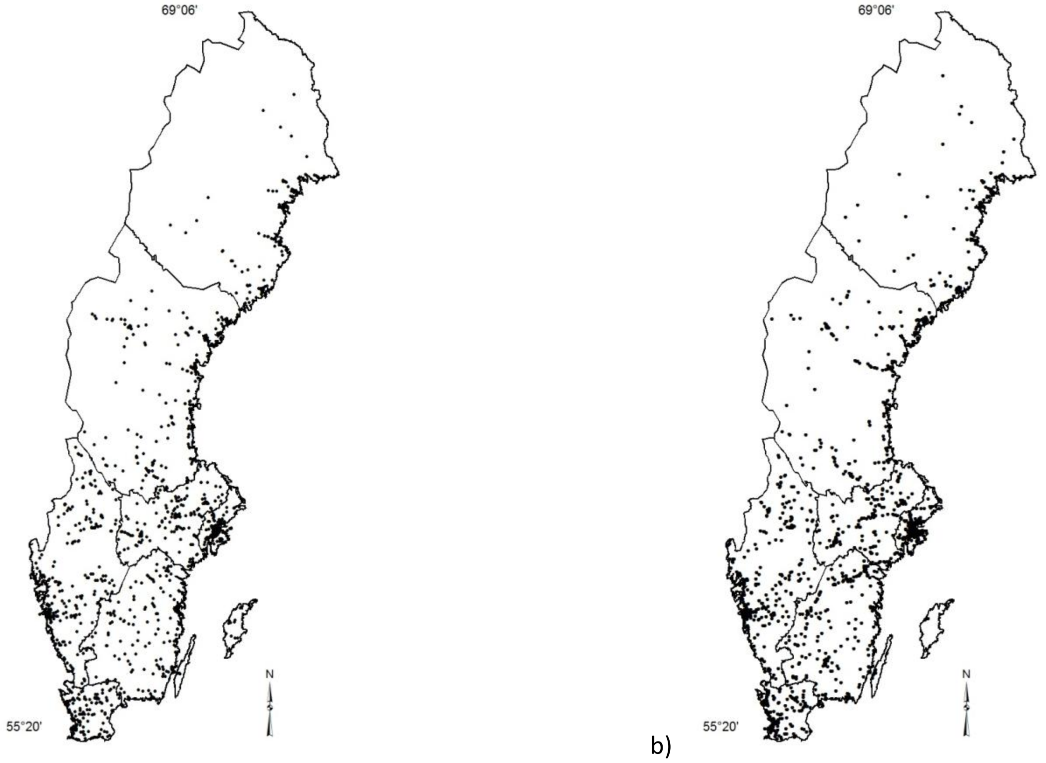
It is accepted that the most dangerous temperature when it comes to slippery roads is when the road surface is around or just below 0°C (Thornes, 1991). The distribution of traffic accidents at various thresholds is shown in Table I. There is actually little difference between the two years for temperatures between 0 and -3°C (when ice is most slippery: Moore, 1975). Only when the interval is increased further do the differences become more apparent.

Table I. Road surface temperature (RST) while traffic accident (in percent).

	RST below 0°C	RST −3 to 0	RST −5 to 0
Jan 2005	63.7	34.9	46.1
Jan 2006	87.7	35.3	54.6
2004-2005	56.6	34.8	45.8
2005-2006	75.2	39.2	55.1

4.3 Distribution of slipperiness

In order to analyse if the amount of accidents increased or decreased in different parts of the country from 2004−2005 to 2005−2006, Sweden was subdivided into the seven SRA regions (administrative units) (Figure 1). Figure 8 shows the distribution of road accidents across these regions where a risk of road slipperiness has been identified.



a) b)

Figure 8. Accidents potentially caused by slipperiness a) 2004-2005 and b) 2005-2006

Whilst the amount of accidents in the three of four of the southernmost regions of Sweden increased from 2004−2005 to 2005−2006 (Table II), there was a decrease in the other regions. However, if the months of January are compared it is the three southernmost regions that increased. Comparing these results with the respective temperature data for January (Figures 3 and 4) demonstrates that the regions with an increase in accidents in 2006 had a noticeable decrease in mean temperature from 2005 to 2006. Further north, this difference becomes less apparent, with mean temperatures for both months falling below 0°C.

Table II. Percentage of accidents in each region and the difference between 2004-2005 and 2005-2006.

	Region Skåne	Region Sydöst	Region Väst	Region Stockholm	Region Mälardalen	Region Mitt	Region Norr
Latitude	55.9	57.2	58.3	58.5	59.5	62.1	65.6
Jan 2005	9.9	8.0	20.3	18.9	12.8	16.3	13.9
Jan 2006	14.8	15.2	22.0	17.7	9.9	11.2	9.2
Increase/decrease	50.0	90.6	8.6	-6.4	-22.9	-31.1	-33.7
2004-2005	14.3	12.1	22.0	13.7	12.5	62.1	10.5
2005-2006	13.4	14.0	24.5	15.5	12.0	12.7	7.9
Increase/decrease	-5.9	15.4	11.5	12.9	-3.8	-14.8	-25.1

4.4 Traffic Density

A common problem in studies of this nature is the difficulties involved in taking into account the influence of traffic density. For example, Figure 6 clearly shows the clustering of accidents in the major urban areas of Sweden and is acutely evident in the Stockholm region. To account for this the total number of accidents was corrected by taking into account the 2002 traffic flow of each region (VV, 2003).

Figure 9 shows that although Stockholm is the region with a highest proportion of accidents, the accident rate per number of vehicles are actually the lowest in Sweden. This is due to the high amount of vehicles in this region compared to other regions. Instead, Regions Norr and Mitt, the least trafficked regions in the north and also Region Väst in the west of the country have the highest ratio of accidents per vehicle in the study period.

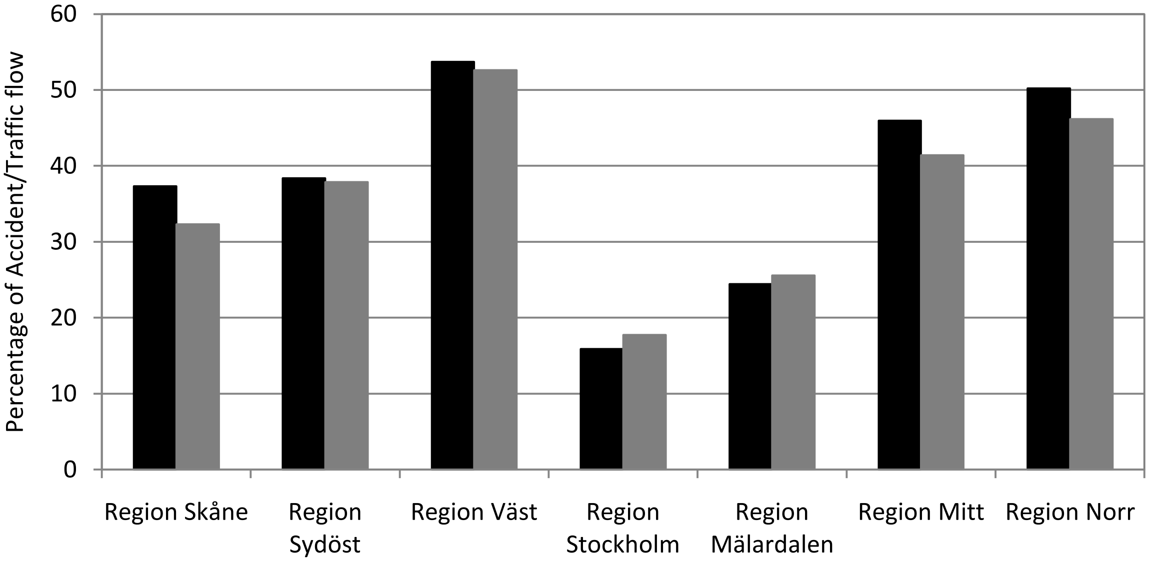


Figure 9. Percentage of accidents per traffic flow in Sweden's seven regions ■ January 2005 ■ January 2006

4.5 Influence of Road Condition

The condition of the road at the time of the accident was also examined in order to analyse if there are differences in the type of weather at the time of the accident (i.e. the slipperiness and precipitation type). It is hypothesised that January 2005, as the warmer of the two months, could prove to be a useful indicator of typical road conditions under future climate change scenarios.

Table III provides a breakdown of the percentage of accident types for the two whole winters as well as for both the two months. The winter 2004−2005 had a higher proportion of accidents that occurred while there was at least one of the slipperiness types, HR1, HR2, HT and HN and therefore MIPS, compared with 2005−2006. This is also reflected in the months of January which had the same relationship. The largest difference was for the accidents that occurred while there was snowfall, representing 18.6% of the total number of accidents that occurred in 2004−2005 compared to 30.3% in 2005−2006.

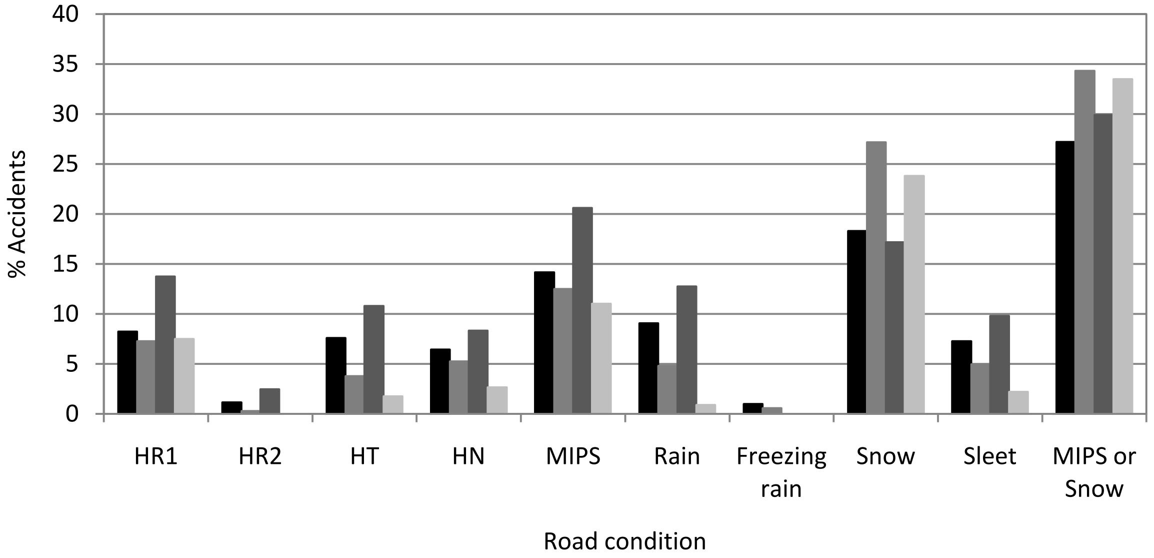
Table III. Percentage of accidents in certain road condition and percentage of road conditions. Slippery conditions due to moderate hoarfrost (HR1), severe hoarfrost (HR2), road icing (HT), rain or sleet on a cold road (HN), a situation of at least one of these four types (MIPS).

		HR1	HR2	HT	HN	MIPS	Rain	Freezing rain	Snow	Sleet	MIPS or Snow
Accidents	Jan 05	14.9	4.4	7.4	6.3	20.6	13.9	0.0	15.1	6.6	29.2
	Jan 06	11.1	3.2	3.1	2.9	15.4	3.3	0.4	25.4	2.2	37.8
	04-05	14.1	4.0	9.9	8.1	22.1	11.6	0.5	18.6	7.9	33.4
	05-06	11.3	3.2	4.8	4.5	16.7	5.4	0.9	30.3	3.3	40.6
Road conditions	Jan 05	9.1	4.9	3.3	1.8	15.9	5.6	0.1	7.9	1.5	22.1
	Jan 06	11.4	5.2	1.9	1.2	17.8	1.4	0.2	12.8	0.5	28.9
	04-05	10.4	4.9	3.7	2.2	17.8	3.9	0.1	9.7	1.8	24.8
	05-06	9.8	4.0	2.5	1.4	15.7	2.1	0.2	17.0	0.9	30.0

A similar pattern is exhibited for MIPS or Snow of 33.4% and 40.6% respectively. Table III also provides information pertaining to the actual frequency of the slipperiness types. The general trend appears to mirror the distribution of accidents in each class, with MIPS or Snow being the primary cause of road traffic accidents.

Stepping down from the national picture of Sweden, the analysis was repeated at a smaller scale for the heavily trafficked area of Stockholm (Figure 10a). Interestingly, the results were comparable to those obtained for the whole of Sweden, with snow accounting for 18.3% of accidents in 2004−2005 (17.2% January 2005) compared with 27.2% in 2005−2006 (23.8% January 2006). For the category MIPS or Snow it was 27.2% and 34.3% for respectively winter. Region Skåne (in the more marginal south of Sweden) presents a similar picture (Figure 10b).

a)



b)

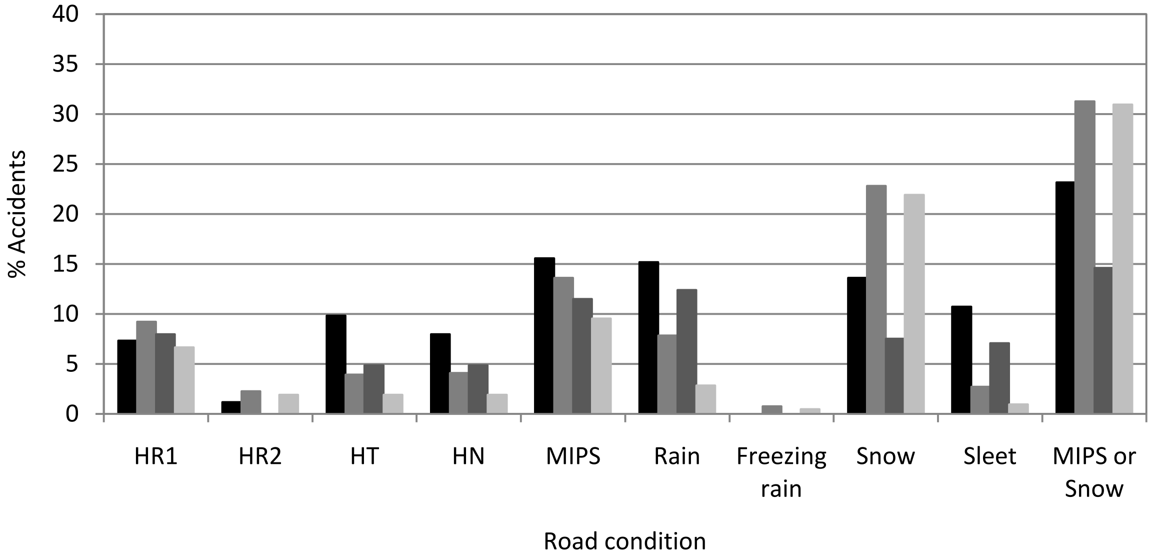


Figure 10. Percentage of accidents in different road conditions in a) Stockholm and b) Region Skåne ■ 2004-2005 ■ 2005-2006 ■ January 2005 ■ January 2006

4.6 Daily Distribution of Accidents

The relationship between MIPS or Snow and road traffic accidents can be more easily clarified by looking at the daily distribution of road accidents (Figure 11). Figure 11b, in particular, shows that the majority of road traffic accidents in 2005−2006 occurred either when it was snowing or it had snowed within the two hours preceding the accident. For example, there is a significant cluster of accidents in the snowy period 17th to 25th January 2006. Furthermore, in both Januaries, the 20th January saw the heaviest snowfalls and it is on this day that the highest number of accidents was recorded in the winter of 2005-2006. Of all the accidents in 2004−2005 where the weather was conducive to slipperiness, 54% of accidents occurred during or after snowfall. In 2005−2006, this figure was 74% and indicative of the prevailing weather producing more precipitation in the form of snow than the previous year.

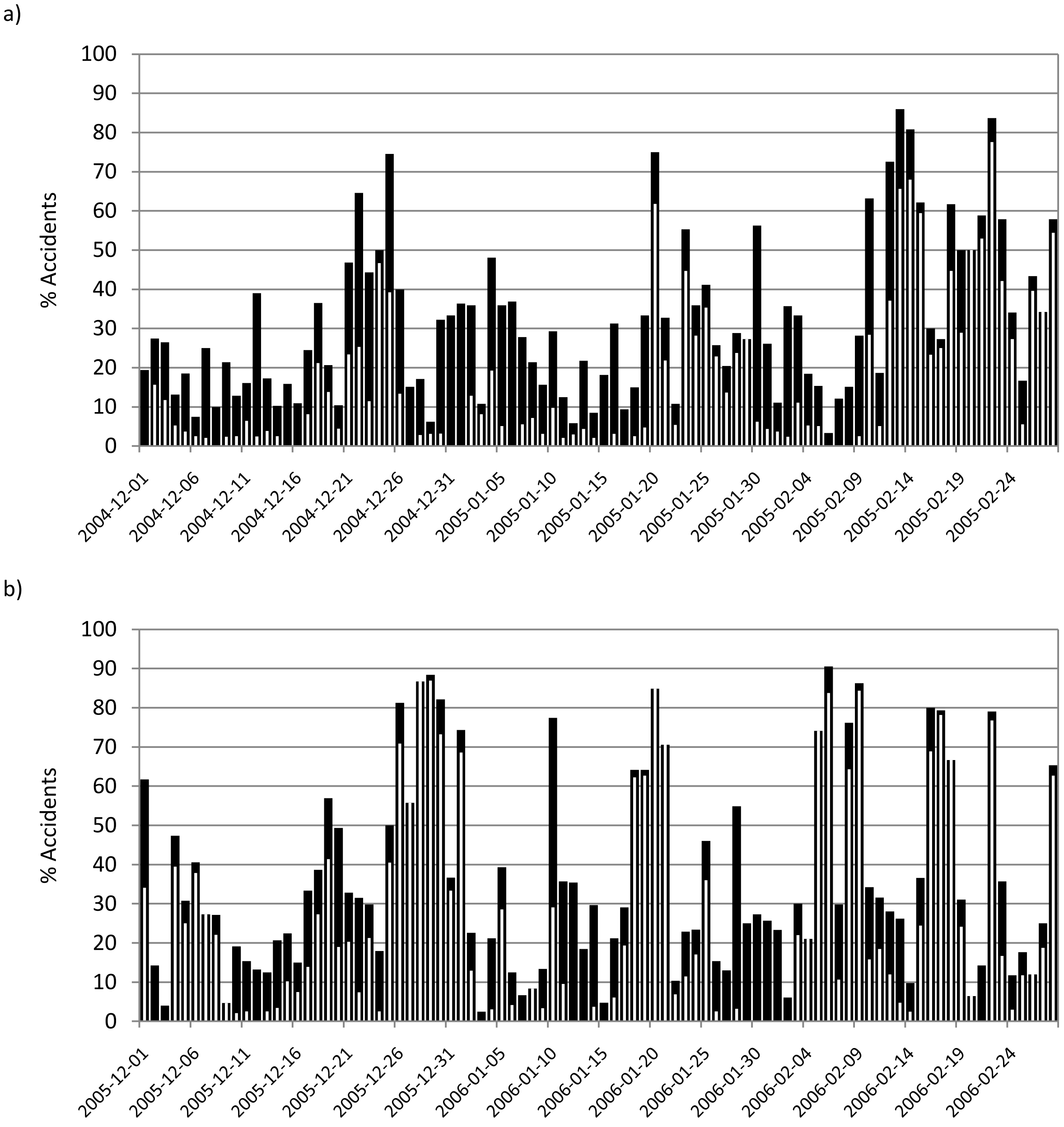


Figure 11. Percentage of the accidents with detected snowfall compared with accidents with slippery road conditions as a mean for Sweden in a) 2004-2005 and b) 2005-2006 ■ MIPS/Snow/Freezing rain/Sleet ☐ Snow

Figure 12 shows the relationship between the total number of accidents and the amount of accidents caused due to slipperiness. A clear distinction can be seen between the years. A greater proportion of accidents can be attributed to slipperiness in 2005−2006. For every 10 accidents in 2005−2006, 9 are due to slipperiness compared to 8 out of every 10 in the milder 2004−2005. If only the month of January is studied, the differences will become even clearer with 9 out of 10 in January 2006 and 6 out of 10 in January 2005. The implications of this with respect to climate change, with a warming climate and thereby warmer and rainier winters, would suggest that accidents caused as a direct result of slipperiness will decrease in the future. However, this is only by using January 2005 as a temporal analogue. As ice is more slippery at 0°C (Moore, 1975), there is a danger that climate change may cause more marginal nights in Sweden and hence actually increase the risk.

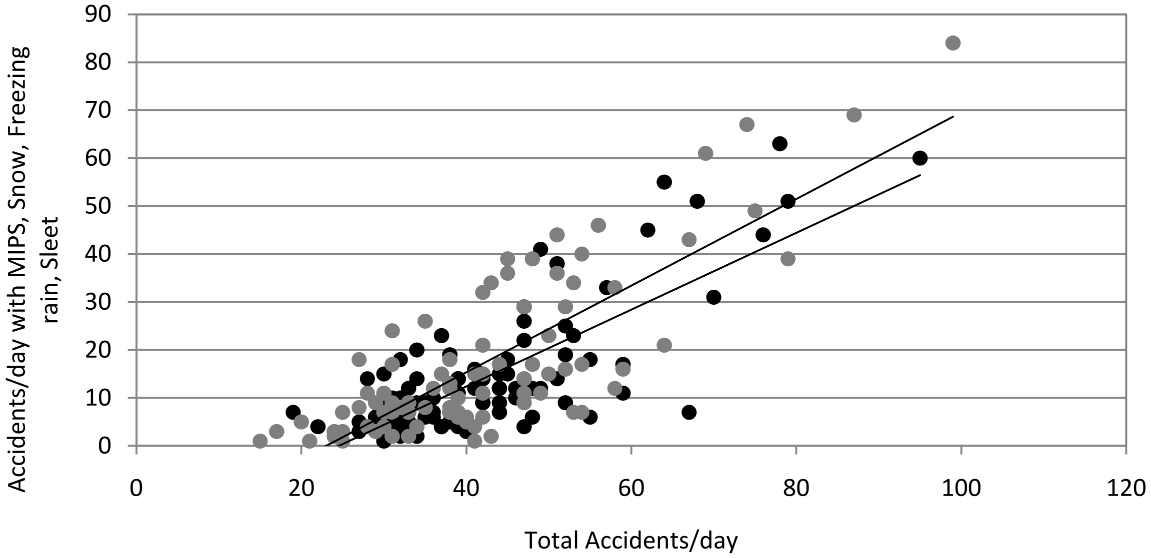


Figure 12. Accidents per day during MIPS/Snow/Freezing rain/Sleet vs. total amount of accidents per day ● 2004-2005 (y=0.80x-19.65 R^2=0.60; Jan 2005 y=0.62x-13.04 R^2=0.44) ● 2005-2006 (y=0.90x-20.78 R^2=0.64; Jan 2006 y=0.90x-19.94 R^2=0.74)

5. Conclusions

Of all accidents recorded during the mild winter 2004−2005, 18.6% of them were related to snow of which 57.0% occurred in February 2005. For the cold winter 2005−2006, snow was more common and accounted for 30.3% of the total number accidents, of which 29.1% occurred in February 2006.

Of all accidents recorded during the mild winter 2004−2005, 7.9% of them were related to snow of which 11.5% occurred in January according to the accident reports. For the cold winter 2005−2006, snow was more common and accounted for 11.2% of the total number accidents, of which 21.9% occurred in January. This agrees with the work of Norrman et al. (2000) who demonstrated that slipperiness of the form “precipitation (snow) on a frozen road surface” induced the most accidents.

It has been shown that the amount of traffic accidents should increase in poor weather conditions (Andreescu and Frost, 1998; Andrey et al. 2003), however the results of this study would suggest that this is not always the case. Despite the different weather conditions experienced in the two January months used in this study, the total number of road accidents recorded across Sweden remained similar. It would seem logical to hypothesise that the number of road accidents would increase under colder conditions, but the statistics fail to take into account more minor accidents, such as vehicles gently slipping of the road or the fact that motorists will adopt a more cautious driving style in poor conditions. For example, Edwards (1999a) saw that the average speed was reduced 4.4% when it was rain compared with when it was fine weather. This is perhaps demonstrated by the fact that there was 5.2% more accidents caused by slippery roads in the milder January 2005 compared with the same month in 2006. Alternatively, this may simply be a consequence of the increased marginality of the weather in January 2005.

With respect to slipperiness, although the most dangerous road surface temperature has been shown to be 0°C, this study shows that it is actually temperatures below -3°C where accidents are more prevalent. Putting this in a future perspective, assuming increased winter air temperatures of 3.8 to 5.5°C in Sweden over the next century (Räisänen et al. 2003), the number of accidents due to slipperiness should actually decrease. This will be a direct consequence of reduced snowfall, and higher overall temperatures. Indeed, accidents related to slipperiness could become quite uncommon in the south of Sweden as the climate becomes increasingly marginal. In this instance, a spatial analogue could be useful to make a first approximation of the future situation in Sweden. In the marginal climate of the UK, 2.8% of all traffic accidents are attributed to snow, with 25-40% of them occurring in the month of January (Edwards, 1999). The highest proportion recorded in the UK occurs in County Durham, in NE England where 5.9% of all accidents are attributed to snow (Edwards, 1996). These figures are small when compared to Sweden. Even in the mild January of 2005, 15.1% of accidents were attributed to snow (in 2006 it was 25.4%). There is some potential to maybe study the winter climate of the UK as a spatial analogue for climate change in Sweden.

In summary, although the number of severe accidents attributed to slipperiness will reduce in a warming climate, this does not automatically mean that the total number of accidents will decline. Using January 2005 as a temporal analogue clearly shows that this is not the case. Furthermore, a large number of accidents can not be explained due to the prevailing weather. In the two winters used in this study, 65.3% respective 58.8% of accidents could not be explained by the weather. Overall, climate change should reduce the number of accidents related to slipperiness and will may reduce the burden of winter road maintenance by reducing the number of frost days. However, it is highly likely that the number of problematic marginal nights (where ice is most slippery) will remain the same. Whilst studies indicate that motorists modify their driving to compensate for conditions today, the motorists of the future may grow complacent and lack the skills to cope with extreme events which will still occur, even in a milder climate.

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Paper III

A future perspective on traffic accidents in a warmer climate, a study in the Gothenburg area, Sweden.

Anna K. Andersson

“In the spring, I have counted 136 different kinds of weather inside of 24 hours.”
Mark Twain

A future perspective on traffic accidents in a warmer climate, a study in the Gothenburg area, Sweden

Anna K. Andersson

Abstract

This study examines the effects climate change can have on winter road conditions and the frequency of traffic accidents that occur during wintertime. All traffic accidents over three winters in the Gothenburg area (~20 000 km^2), in the south-west of Sweden, were assigned to the nearest outstation in the Swedish Road Weather Information System (RWIS). This was done to obtain the daily minimum road surface temperature on the same day as the traffic accident occurred.

Future climate scenarios for the 2020s, 2050s and 2080s were modelled and a ratio between the number of traffic accidents and the daily minimum road surface temperature was calculated. This study suggests that the percentage of traffic accidents for temperatures equal to or below zero degrees might be reduced by 20% by the 2080s compared to the total amount of accidents. Winter maintenance, such as salt scattering, can be reduced by at least 15% by the 2080s, due to a reduction in the amount of days with risk of slippery roads in this part of Sweden. However, in temperatures above zero degrees the number of accidents involving motor vehicles will increase noticeably due to more days at these temperatures.

Keywords: climate change, traffic accident, RWIS, road maintenance, road climate

1. Introduction

An annual average of 425 traffic accidents were reported to the Swedish Road Administration’s database during the three winters (November – March) 2006-2007 to 2008-2009 in coastal south-western Sweden (county of Västra Götaland). Positions of these accidents were registered and known by police and hospitals. Approximately 40% of annual traffic accidents occur in these five winter months.

The reasons why accidents occur can vary. While there have been studies of traffic accidents and poor road conditions (Fridström *et al.* 1995; Edwards 1996), others have focussed their studies on connecting accidents to different types of precipitation, e.g. snow (Codling, 1974; Andreescu and Frost, 1998; Eisenberg and Warner, 2005) and rain (Brodsky and Hakkert, 1988; Levine *et al.* 1995). The linkage between traffic accidents and slippery roads has been studied by others (e.g. Lindqvist, 1979; Gustavsson and Bogren, 1990; Norrman, 2000). Other reasons for accidents include drink driving (e.g. Meyhew *et al.* 1986; Horwood and Fergusson 2000; Evans, 2004) or sudden illnesses (Lam and Lam 2005). Studies of speed reduction in adverse weather also exist. Edwards (1999) found average speeds were reduced by 4.4% in rain compared to fine weather. Andrey (2009) concluded that rain-related traffic accidents decreased by approximately 60% on the roads of Canadian cities over two decades. However, in snow this trend was not noticeable.

Andersson & Chapman (2009) studied the influences of weather on traffic accidents in Sweden. One conclusion was that traffic accidents were more prevalent at road surface temperatures below -3°C, a common winter temperature in Sweden. With the future scenario of temperature changes (3.8 to 5.5°C in Sweden over the next century (Räisänen *et al.* 2003)), the number of traffic accidents due to slippery roads might decrease.

There are few studies that state the impact climate change can have on winter road conditions, and thereby the impact it has on traffic accidents. Therefore, the focus of this paper is to analyse the impact climate change may have on the road surface temperatures and thus its effects on traffic accidents. Changes to winter road maintenance in the future are also discussed. This paper expressly addresses the following questions:

- If the winters are getting warmer, and thus the number of days with slippery roads is decreasing, will the frequency of traffic accidents on roads with low temperatures (≤0°C) also decrease?
- If there is a decrease in the amount of accidents at low temperatures, is the total amount of accidents during the winter months also likely to decrease?

This paper is a study of winter roads and traffic accidents using weather data from outstations in the Swedish Road Weather Information System (RWIS), three future time scenarios of road weather and calculated estimations of the number of traffic accidents for the rest of this century. Parameters such as fewer roads with oncoming traffic, increases/decreases in traffic, the usage of studded tyres during the winter months in Sweden or improvements to cars (i.e. anti-lock braking systems) are not taken into account in this study. Studded tyres are commonly seen on vehicles in Sweden; their usage is debated and even prohibited on some roads. Möller and Öberg (2009) analysed the effects of a reduction in the usage of studded tyres in Sweden and concluded that annually the estimated number of police-reported injury accidents would increase by 56 and the people killed would increase by 1.8 if usage reduced from 70% to 50%.

2. Methodology

2.1 Area of Study and Weather Data

The area studied in this paper lies near Gothenburg, south-west Sweden (Figure 1), and is approximately 20 000 km^2. There are 19 outstations from the Swedish Road Weather Information System (RWIS) that have been used in this area for the collection of weather condition data. This area was chosen because future climate scenarios were available for the 19 RWIS outstations, as they are part of the IRWIN project (for further description see Saarikivi *et al.* 2009), and because they had reliable data with few errors. Each traffic accident has also been connected to the nearest RWIS outstation to provide estimations about the prevailing road weather at the time of the accident.

Traffic accidents and weather data in this study are from three winters 2006-2007, 2007-2008 and 2008-2009. A winter is defined as the five months from November to March.

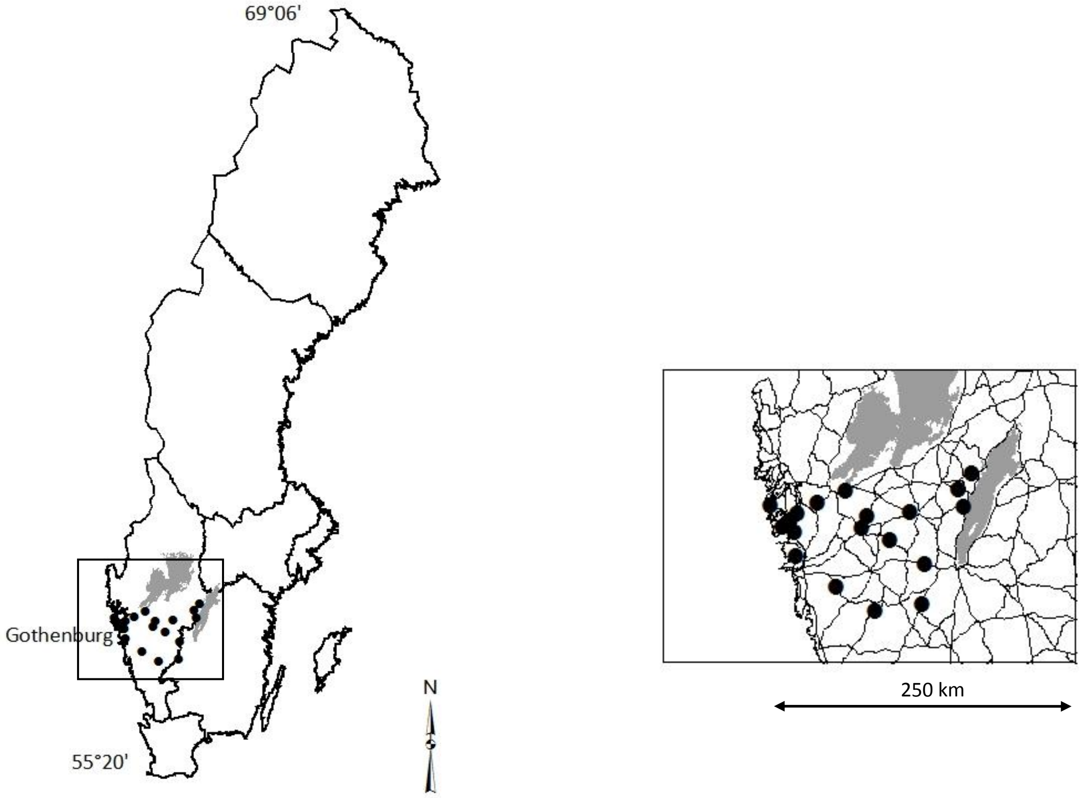


Figure 1. Location of RWIS outstations in the Gothenburg area, Sweden

2.2 Road weather - RWIS

Climate data for the winters 2006-2007, 2007-2008 and 2008-2009 were taken from the Swedish Road Weather Information System (RWIS). There are today about 720 outstations in Sweden and 200 of them also have cameras installed for monitoring the road surface. The outstations collect information about road surface temperature, air temperature, relative humidity, precipitation and wind speed and direction. Data is sampled every 30 minutes during the winter months. This data has been collected in a central database at the Swedish Road Administration (SRA) since the mid-1980s. RWIS outstations are primarily used to monitor road surface conditions for winter maintenance decision-makers. It is also used more and more in the Intelligent Transport System (ITS) (VV, 2009).

2.3 Traffic accidents - STRADA

The Swedish Road Administration's database, STRADA (Swedish Traffic Accident Data Acquisition), has been used to obtain data about traffic accidents. STRADA has been the official record of Swedish road traffic accidents since 2003. The database contains information obtained from both the police and the emergency units in hospitals. Although there were initially only a few hospitals with emergency rooms connected to STRADA, thus not all accidents have been reported in the database, the coverage during recent years has been increasing. In June 2009 71% of hospitals were connected to STRADA (Swedish Transport Agency, 2009).

The criteria for the accidents analysed in this paper were that they had to be known by both the police and a hospital, and only at a known and confirmed position within the study are. The accidents consist of six different types of traffic accident, they all involve motor vehicles, and the accidents are: single, oncoming, overtaking, catching up, turning off, or crossing accidents. While there were many other accidents reported, they did not have exact positions or involved, for instance, pedestrians,

cyclists, tractors or animals. The exact reasons why an accident has occurred are not known in STRADA.
There are, however, many accidents that never get reported at all to STRADA. One example is from January 5, 2008, when the following was reported in a Swedish newspaper: "The entire southern Skåne was plagued by treacherous icy conditions on Saturday because of freezing rain and strong winds. Between 10am and 5pm there were about 80 traffic accidents reported to the police department in Skåne." (Aftonbladet, 2008). Only eight accidents were reported in STRADA during the entire day in Region Skåne. This indicates that there are many accidents missing in the statistics, and it must be clarified that the accidents used as statistics in this paper are the more severe ones.

The traffic accidents were time corrected to the nearest half hour and then connected to the nearest RWIS outstation. This was done to get an idea of the weather at the time of the accident. The accidents were also connected to the daily minimum road surface temperature, allowing comparisons to the number of days with the same daily minimum road surface temperature. In this study, an accident has occurred in winter road conditions if there are theoretical conditions for it i.e. the nearest RWIS outstation shows a surface temperature of zero degrees or below.

2.4 Climate change – future road surface temperatures

The future road weather dataset is generated as a part of the IRWIN project, funded by the ERA NET ROAD (for further description see Saarikivi *et al.* 2009). IRWIN scenarios are based on Global Climate Models (GCM). To make the climate change predictions, IRWIN uses the analogue model for statistical downscaling to combine the historical RWIS outstation weather data and GCM climate change scenarios. To obtain road surface temperatures, the model takes the weather data in the scenario and compares it to historical data.

The model is built on the atmospheric general circulation model ECHAM5 and also IPCC emission scenario A1B, which is defined by a rapid growing economy and a global population that peaks in the middle of the century and then declines. The scenario assumes also that new and more efficient technologies are rapidly introduced (IPCC, 2002).

The modelled data is divided into four time slices; November to March for Baseline (BL) 1970 – 2000, 2020s (2010 – 2040), 2050s (2040 – 2070) and 2080s (2070 – 2100); and is calculated for each RWIS outstation.

2.5 Traffic accidents – future scenario

Andersson and Chapman (2009a) used a temporal analogue to predict the change in the number of traffic accidents in a future perspective; the same analogue is used in this paper. The relationship ratio is calculated as the difference between the number of accidents at each temperature degree and the number of days *per* winter at the same daily minimum road surface temperature (RSTdm).

$$\text{Number of accidents at RSTdm} \Big/ \text{Number of days per winter with RSTdm} \qquad (1)$$

The assumption is that the ratio is the same in the three future time slices (2020s, 2050s and 2080s) as the ratio is in the winters of 2006-2009 (equation 2).

$$\frac{\text{Number of accidents 2006-2009 at Temp X}}{\text{Number of days 2006-2009 at Temp X}} = \frac{\text{Number of accidents BL at Temp X}}{\text{Number of days BL at Temp X}} \qquad (2)$$

This ratio between accidents and number of days is used to calculate an estimated number of traffic accidents for the three future time periods.

3. Results

3.1 Daily minimum road surface temperature

There were 1280 traffic accidents during the three winters in the study area. Some of the accidents, when linked to the RWIS outstations, were missing the road surface temperature and/or precipitation at the time of the accident. Therefore the daily minimum road surface temperature is used instead of the road surface temperature at the time for the accident.

In order to study how climate change might affect the amount of winter related traffic accidents and the need for winter road maintenance, it is essential to identify the impact today's climate has on accidents and maintenance. Climate scenarios for the future will essentially provide insight into how much the temperature will increase, and for this reason the variation in the road surface temperature is plotted together with the number of accidents for the winter 2007-2008 (Figure 2). This graph does not show any obvious pattern between the number of accidents and temperature. For instance, days with the most accidents have a daily minimum road surface temperature that varies between -3.8°C and 2.2°C. There is no particular trend for which day of the week the accidents occurred, though there is a small reduction in the number of accidents on Saturdays and Sundays, which probably depends more on the sparse traffic than the lower temperatures.

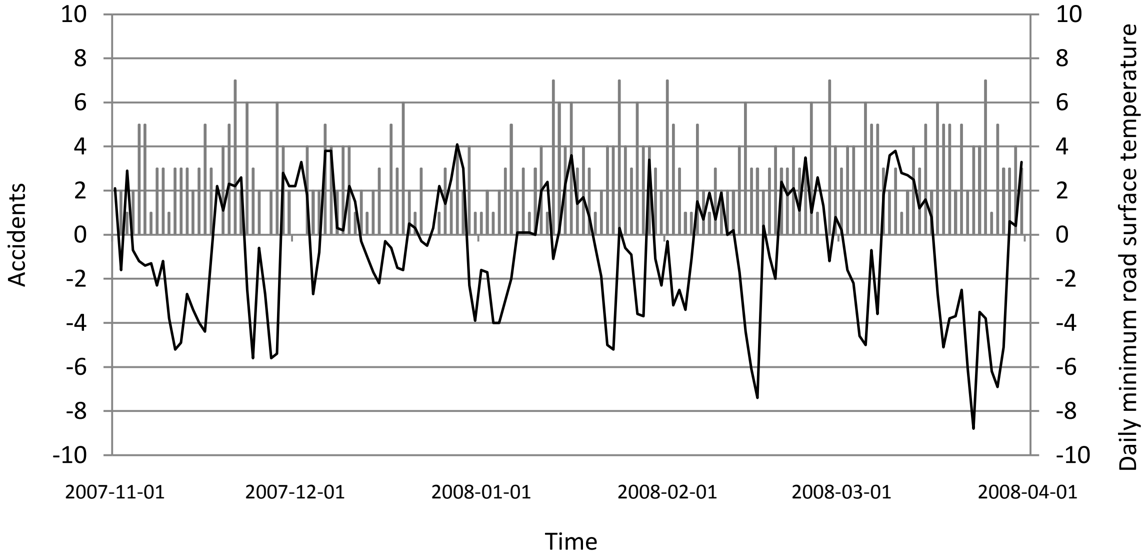


Figure 2. Number of accidents and daily minimum road surface temperature per day in the winter 2007-2008.

To continue to see how traffic accidents are influenced by different kinds of weather, the accident risks in different precipitation will be discussed in the next section.

3.2 Precipitation

There were 1273 traffic accidents with a complete dataset for precipitation during these three winters and 79% of these accidents occurred while there was no precipitation, according to the nearest RWIS outstation. Of the remaining 21% of accidents, 12% occurred while raining and 8% had snowfall (Table I). There was no precipitation at the 19 RWIS outstations over 82.8% of the time. However, even though there was no precipitation at the time of an accident, the road surface could have been slippery due to earlier precipitation.

Norrman *et al.* (2000) calculated the risk of having an accident in different types of slippery road conditions, and found that, of the 10 types of slipperiness in the expert system developed by Norrman (2000), precipitation (rain/sleet) on a frozen road surface had the highest risk.

The same equation used by Norrman *et al.* (2000) for calculating accident risk in different road conditions is used here to determine the accident risk in different precipitation types.

$$\text{Accident risk} = \frac{1}{\mathrm{N}} \sum_{\mathrm{m=Nov\ 2006}}^{\mathrm{Mar\ 2009}} \mathrm{A_{t,m} h_m} \left(\mathrm{A_m h_{t,m}}\right)^{-1} \tag{3}$$

where

N – Number of months
$A_{t,m}$ – Number of accidents in month (m) in precipitation type (t)
h_m – Number of hours in month (m)
A_m – Number of accidents in month (m)
$h_{t,m}$ – Number of hours with precipitation type (t)

The assumptions that the accidents were evenly distributed and not affected by road conditions were made in these calculations.

Table I. Accidents in 2006 – 2009 (NDJFM) in different type of precipitation and the risk of having an accident in different types of precipitation.

Type of precipitation	Number of accident (%)	Accident risk
No precipitation	79	1.0
Rain	12	1.1
Freezing rain	0.24	2.2
Snow	8	1.4
Sleet	1	1.6

The greatest risk for an accident to occur was during *Freezing rain*, even if these accidents were very few. There were a total of three accidents during the three winters, but during the same time only eight half-hours were registered at the RWIS outstation indicating *Freezing rain*, suggesting the risk of being involved in an accident is really high while it is *Freezing rain*, even though it does not occur very often. The category *No precipitation* had the risk of 1.0, meaning that there were as many accidents as expected. If the accident risk is larger than 1.0, there have been more accidents than expected at an even distribution. The precipitation type *Snow* had an accident risk of 1.4, i.e. there is a higher risk of being involved in an accident while it is snowing.

3.3 Distribution of future precipitation

This study is mostly concerned with road surface temperatures, since the precipitation in the IRWIN model only calculated precipitation for the future divided into two categories, *Rain* and *Snow* (the two categories *Freezing rain* and *Sleet* had too few observed occasions in the measured data to be of use in the model). The distribution for accidents in Table I was for the winters 2006-2009; three winters warmer than average. To compare the accident risks to a future perspective the same accident risk used in Table I was used for the calculated precipitation in the three time slices.

Based on the IRWIN model, the precipitation was compiled as an average for the Baseline and the three time slices 2020s, 2050s and 2080s. Using this calculation, the level of No precipitation is likely to remain constant over the rest of this century. However, the two categories Rain and Snow will alter. There is an increase in the Rain hours between the baseline years (BL) and 2080s by 71% and over the same time Snow will decrease by 35%. This change will result in a change of the number of accidents by the same percentage (Table II).

Table II. Percentage of precipitation in Baseline (BL) and in three future time slices 2020s, 2050s and 2080s (NDJFM) across different types of precipitation and the risk of being involved in an accident in different types of precipitation.

Type of precipitation	BL (%)	2020s (%)	2050s (%)	2080s (%)	Accident risk	Accident BL (%)	Accident 20s (%)	Accident 50s (%)	Accident 80s (%)
No precipitation	83.5	82.9	83.4	83.1	1.0	80.7	80.1	80.6	80.3
Rain	5.8	8.0	8.6	9.9	1.1	6.5	8.9	9.6	11.1
Snow	10.6	9.2	8.0	6.9	1.4	14.5	12.4	10.9	9.4

3.4 Temperatures and accidents during three winters

In chapter 3.1, the daily minimum road surface temperature and the number of accidents *per* day were plotted and no particular patterns were found. In order to analyse this in more detail, all accidents were connected to the nearest RWIS outstation and the daily minimum road surface temperature (RSTdm) for each accident was compiled. These temperatures were then compared to the number of days this daily minimum road surface temperature had occurred during the three winters, to see if the temperatures were connected to the accidents, as Figure 2 showed a low correlation between accident and temperature. The number of days each road surface temperature occurred during the three winters is plotted in Figure 3 together with the number of accidents at each road surface temperature.

Some 66% of days were below zero degrees, while 67% of accidents occurred at these temperatures. The most common daily minimum road surface temperature was -1°C, while accidents peaked at -2°C.

The relationship between traffic accidents and the number of days for different temperatures in Figure 3 are not the same for the different daily minimum road surface temperatures. However, there are some intervals that have similarities if the percentage is compared. In the intervals between 0°C and 3°C and for temperatures below -5°C there are fewer accidents in percentage compared to days, while more accidents occur at temperatures between -4°C and -1°C and above 4°C. The interval with the highest number of accidents was from -4°C to -1°C, with 40% of the total amount of accidents. The majority of days had temperatures between -4°C to 3°C (Table III).

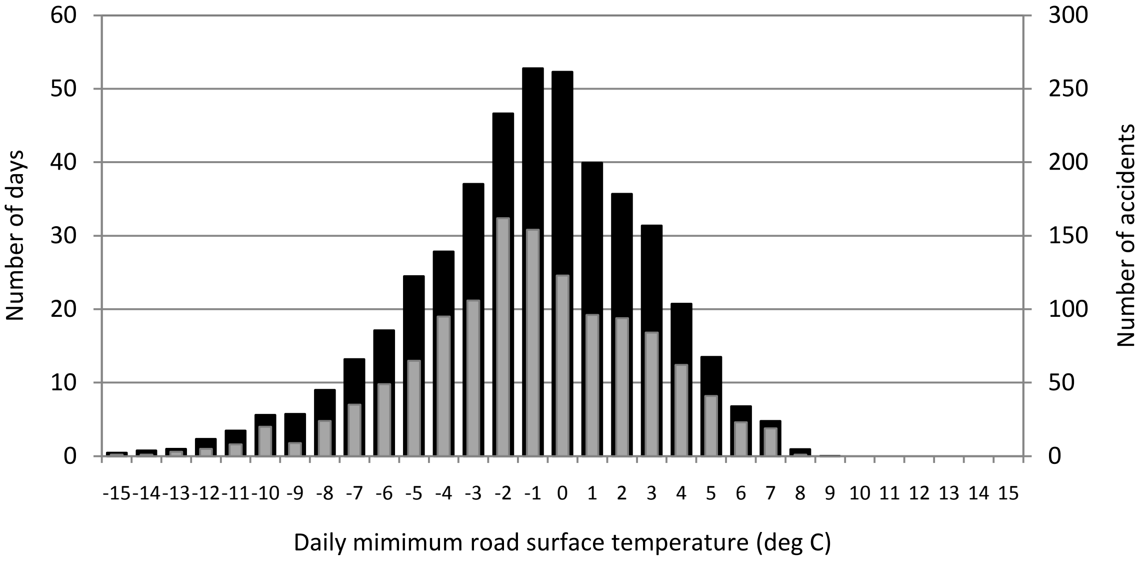


Figure 3. Number of days with daily minimum road surface temperature (°C) (black) and the number of accidents at the same daily minimum road surface temperature (°C) (grey) for the three studied winters 2006-2009.

From Table III it can be concluded that there is a connection between temperature/slipperiness and accident risk and therefore there is an interest to know how the future change in temperature will influence the risk for accidents.

Table III. Distribution of accidents and number of days with different daily minimum road surface temperature in 2006 – 2009 (NDJFM).

Temperature Range	Number of Accidents (%)	Number of days (%)
≥ 4°C	11.4	10.3
0°C – 3°C	31.0	35.1
-4°C – -1°C	40.4	36.2
≤ -5°C	17.2	18.4

The same relationship as mentioned above is equal to that in equation 1. Figure 4 display the ratio between the number of accidents and the number of days at the same daily minimum road surface temperature in order to study the change in temperature on the number of accidents *per* day.

The trend line plotted in Figure 4 indicates that there is an increase with a magnitude of one accident/day if the daily minimum road surface temperature increases with 20 degrees. There are fewer accidents at lower temperatures. This can be an indication that drivers are more cautious at lower temperatures, when there is a risk for slippery conditions.

Two general conclusions can be drawn in section 3.4.

1) There is an increase in accidents at temperature close to 0°C.
2) There is a general increase in temperature with increasing road surface temperature.

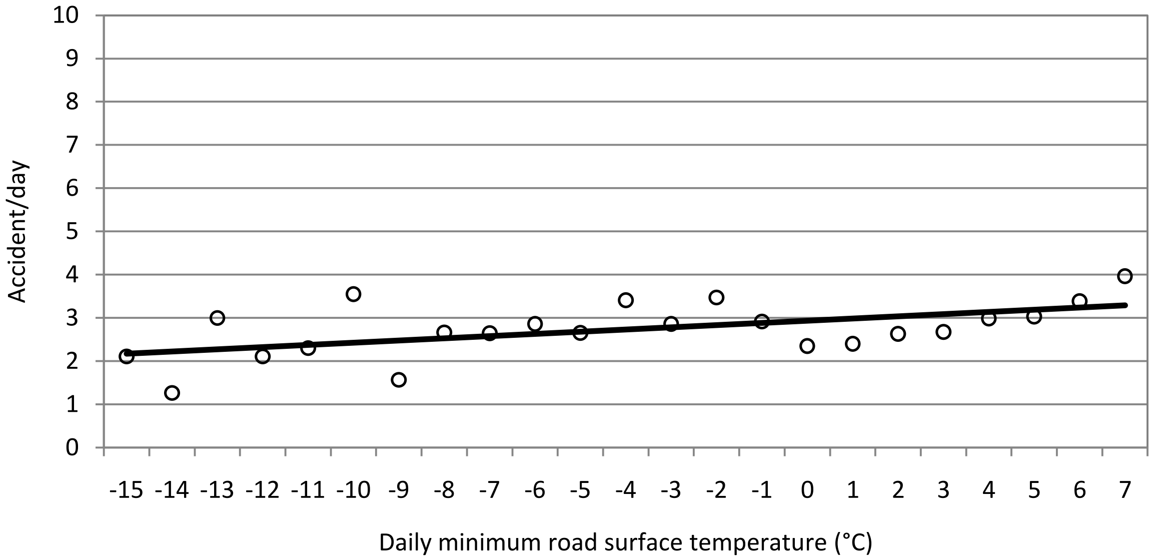


Figure 4. Number of accidents per number of days with the same daily minimum road surface temperatures. Trend line y = 0.05x +2.13 R^2 = 0.30.

To predict future scenarios, some assumptions had to be made. One assumption was that traffic remains the same as today (e.g. the traffic density, road construction and speed limits are the same). Another assumption was that the same number of accidents occurs at the same daily minimum road surface temperatures (equation 1 and Figure 4).

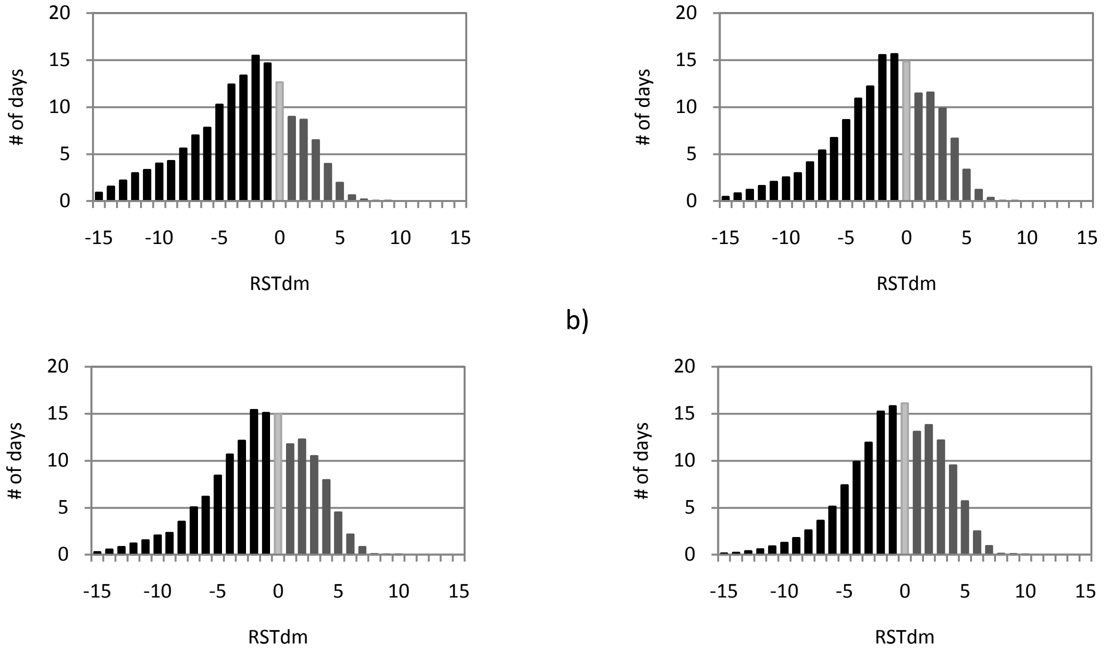
The ratio (equation 1) between accidents and temperature was applied to the number of days for the three future time slices 2020s, 2050s and 2080s. This ratio was also applied to the number of days for the baseline, since the three studied winters were warmer than the baseline years and therefore the comparisons between the three recent years and the future periods are not appropriate. The future time slices are therefore compared to the baseline.

3.5 Road surface temperatures and traffic accidents in 2020s, 2050s and 2080s

Road surface temperatures were calculated for the three future scenarios 2020s, 2050s and 2080s and also for a baseline period (1970-2000). The daily minimum road surface temperatures were thereafter selected and compiled for each road surface temperature and are plotted in Figure 5.

If the number of days at baseline (Figure 5a) is compared to the actual number of days in the three recent winters (Figure 3), the main differences are that there were a more widespread number of days in the baseline period and the most common daily minimum road surface temperature is at -2°C rather than -1°C. There are also more days at colder temperatures. The three latest winters have been warmer than the 30 years' average baseline winters, at least if the daily minimum road surface temperatures are compared.

During the five studied winter months, 79% of the days with daily minimum road surface temperatures were equal to or below zero degrees at baseline. In the scenario for the 2080s, the amount of days has changed to 62% (Figure 5a & 5d).



a)

b)

c)

d)

Figure 5. Number of days with daily minimum road surface temperature (°C) a) Baseline b) 2020s c) 2050s d) 2080s. <0°C (black bar), =0°C (light grey bar), >0°C (grey bar).

In both Figure 5 and Table IV the change throughout this century is evident for the number of days at different daily minimum road surface temperatures. For temperatures equal to or below zero degrees, the number of days will be decreased by 20%, and for temperatures above zero the increase is 87%. There is a threshold at -2°C; below this the number of days is decreasing and above increasing.

To compare the changes in time, the same temperature intervals are used for the actual temperatures in Table III. In the temperature range between 0°C and 3°C the increase of days will be 50% during the 100 years between Baseline and 2080s (37 days to 55), while in the range between -4°C and -1°C there is a decrease of 3 days from 56, and for temperatures below five degrees will be reduced from 50 days at Baseline to 24, a 52% decrease (Table IV).

Table IV. Percentage of days with daily minimum road surface temperature at Baseline, 2020s, 2050s and 2080s at different temperature ranges

Temperature Range	BL (%)	2020 (%)	2050 (%)	2080 (%)
≥ 4°C	4.6	7.7	10.4	12.5
0°C – 3°C	24.6	31.8	32.9	36.6
-4°C – -1°C	37.4	36.2	35.4	35.0
≤ -5°C	33.4	24.3	21.3	15.9

The ratio between number of traffic accidents and number of days (equation 1) was applied to the calculated number of days *per* winter in the three future scenarios, 2020s, 2050s and 2080s to estimate the number of accidents at each daily minimum road surface temperature. This was also done to the baseline period to make comparisons with today, instead of the winters 2006-2009, which was warmer than the average baseline.

The calculated number of accidents is plotted in Figure 6. There is a small increase in the total amount of traffic accidents between baseline and 2080s, with 10 accidents or 2%. The decrease in the number of days below -2°C is reflected in the number of accidents; there is a 22% decrease in the accidents equal to or below zero degrees from today to the 2080s. However, the large difference is in the temperatures above zero, where the accidents will be increased by 88% over the same time, from 83 to 159.

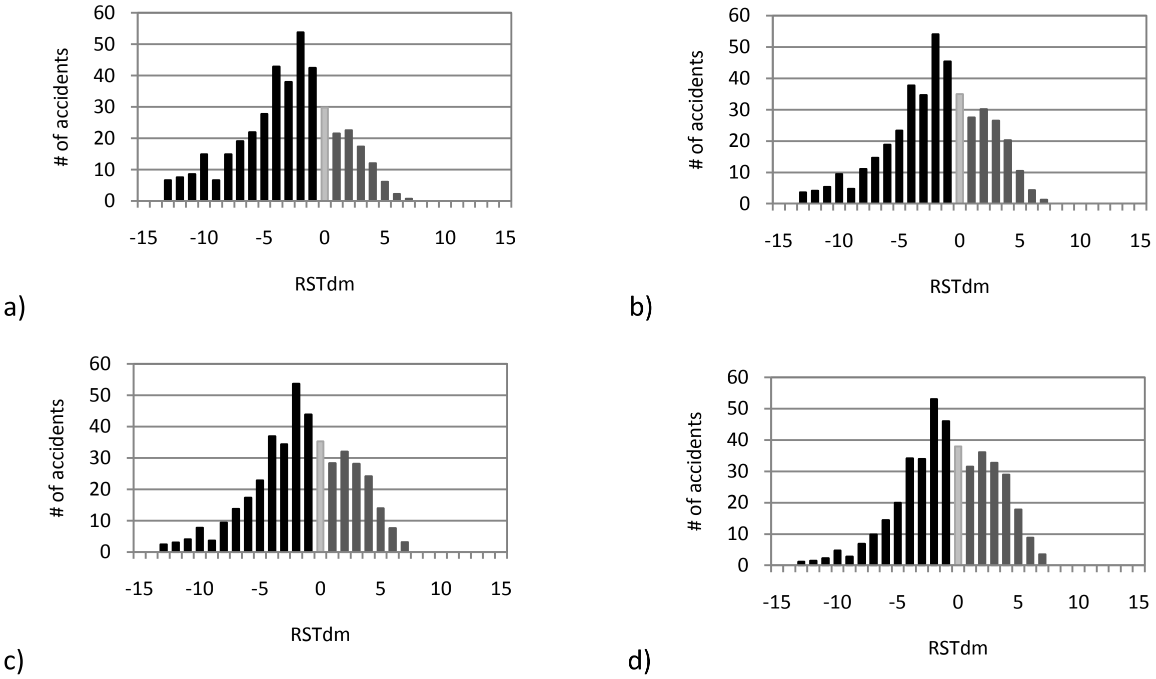


Figure 6. Number of accidents at daily minimum road surface temperatures (°C) a) 2006-2009 b) 2020s c) 2050s d) 2080s. <0°C (black bar), =0°C (light grey bar), >0°C (grey bar).

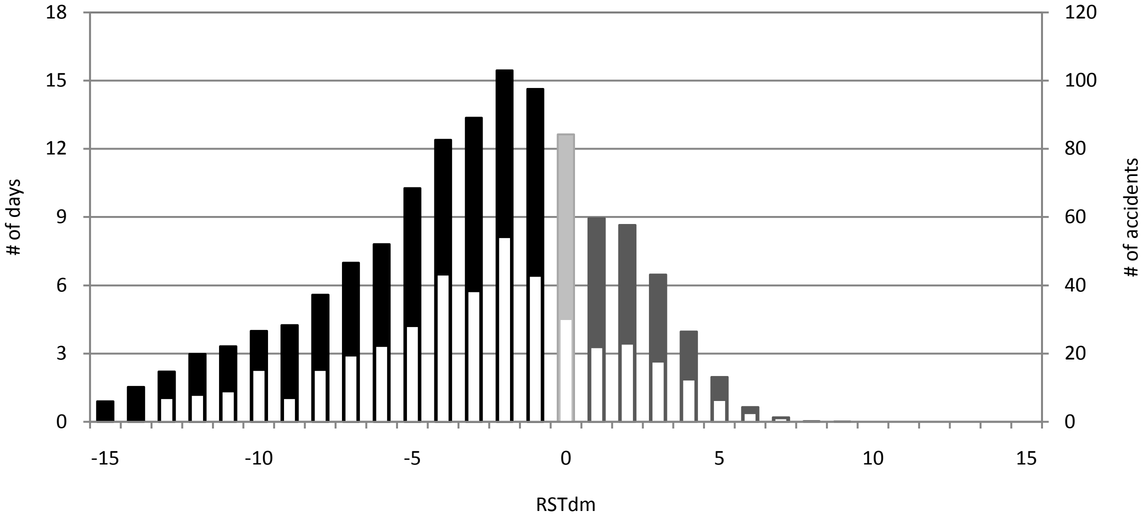
The distribution of accidents at the same temperature intervals as previously used is compiled in Table V. Most accidents occur at the interval between -4°C and -1°C and this temperature interval continues to have the most accidents in the 2080s. However, in the range from 0°C to 3°C the increase is 48%. This is a temperature range where there is high potential for slipperiness at exposed locations, e.g. bridges and valleys.

Table V. Percentage of accidents at daily minimum road surface temperatures at Baseline, 2020s, 2050s and 2080s across different temperature ranges.

Temperature Range	BL (%)	2020 (%)	2050 (%)	2080 (%)
≥ 4°C	5.1	8.6	11.5	13.8
0°C – 3°C	21.9	28.2	29.1	32.3
-4°C – -1°C	42.4	40.7	39.6	39.0
≤ -5°C	30.7	22.5	19.8	14.9

To see the changes in both the number of days at different temperatures and the number of accidents throughout this century, Figure 7 was plotted. Comparing the two graphs, the daily minimum road surface temperatures seem to be less widespread in the 2080s compared to baseline and more concentrated in the temperature range between -4°C and 4°C. In the 2080s, 118 of the 151 days in the five months are in this temperature range, compared to 97 days at baseline (+22%). The number of accidents will increase by 19% in this temperature interval.

a)



b)

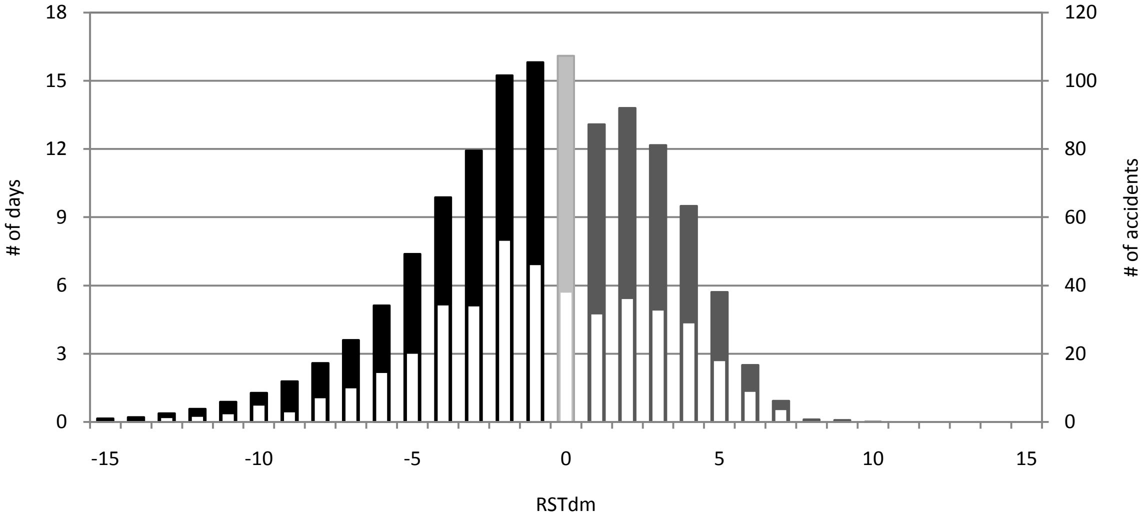


Figure 7. Number of days at daily minimum road surface temperatures (°C) and number of accidents (White bar) a) Baseline b) 2080s. <0°C (black bar), =0°C (light grey bar), >0°C (grey bar).

4. Discussion and conclusion

Although the calculations in this paper are limited spatially to a smaller area, it is possible to get an idea about the distribution of future scenarios for road surface temperatures. It can also paint a picture of the number of traffic accidents expected at the end of this century. One of the aims of this paper was to analyse the impact of a warming climate on the daily minimum road surface temperature. The number of days at each daily minimum temperature will shift in the future, to fewer days with lower temperatures. There will be a turning point at -2°C degrees, i.e. the number of days in the temperature range below -2°C will decline and at temperatures above this the number of days will increase.

As well as road conditions, there are many other factors that can affect drivers. Even though the number of traffic accidents increase at road surface temperatures above -2°C, it does not necessarily have anything to do with slippery roads, but the risk of accidents is increased since roads are more slippery when the road surface temperature is close to 0°C (Moore, 1975). In the temperature range when the road is the most slippery, the trend is decreasing in the number of days with daily minimum road surface temperatures equal to or below zero. This in turn can lead to a decrease in the amount of traffic accidents caused by slippery road conditions. This study has shown that the percentage of traffic accidents for temperatures equal to or below zero degrees will be reduced by 20% by the 2080s. However, the total number of accidents will not decrease. Instead there will be a small increase of the total number of accidents (+2%).

When the climate is getting warmer the number of days for temperatures above zero degrees is increasing. This, in turn, results in an increase of traffic accidents equal to or above zero degrees by 88%. This increase may be the result of high velocity, since the driver thinks that there is no risk of slippery conditions.

Andersson & Chapman (2009) concluded that traffic accidents were more prevalent at temperatures equal to or below -3°C, which is a temperature common in the Swedish winter months. It has been shown in this study that there will be a decrease in the number of days with cold road surface temperatures by the 2080s, and that traffic accidents can therefore be assumed to decrease. However, if the number of occasions with slippery roads is strongly reduced the awareness of the driver is reduced and the skills to control a sliding vehicle might also be lost. This could instead lead to an increase in the amount of accidents on days with slippery conditions.

In the baseline months (Nov-Mar) there were 118 days that had a daily minimum road surface temperature of zero or below. By 2080 these days are reduced to 93; a reduction of 22%. This reduction could lead to a diminished need for winter road maintenance. However, the Swedish Road Administration uses the upper limit of +1°C for road surface temperatures, instead of 0°C, to allow a safety margin to account for any inaccuracy of the sensors (Möller, 2002). The number of days with temperatures equal to or below 1°C will decline by 17% by the 2080s. This might lead to a possible reduction of winter maintenance by at least 15% in the Gothenburg area, Sweden.

The Swedish Government and the Swedish Road Administration's goal is to reduce the amount of salt on the Swedish roads. In the winter of 1993-1994 the salt consumption was 420 000 tonnes. This amount was reduced 50% by 1996-1997. The reduction has continued and, for the winter 2007-2008, consumption was 184 000 tonnes (VV, 1999; VV, 2009a). During the last ten winters there has been an average salt consumption of 258 000 tonnes *per* winter. If this is reduced by 15% there will be a saving of 38 700 tonnes. Assuming that one tonne of salt costs 580 SEK (Ihs and Möller, 2004), this will save 22 446 000 SEK (€2 096 700; 06/11/09) *per* year in today's monetary value. The amount of salt can probably be reduced even more in the future and techniques for salt scattering can probably be further improved. If the low consumption in the winter 2007-2008 is lessened by 15%, 27 600 tonnes of salt can be saved.

The conclusions in this paper are that the number of accidents increases with increasing temperature at present time. The largest number of accidents is at temperatures just below zero degrees, indicating that slipperiness and poor road conditions affect the frequency of accidents and the need for winter road maintenance is high at these temperatures.

The conclusions about the future is that due to a reduction in the number of days with winter road conditions will lead to a decrease in the traffic accidents involving motor vehicles by the end of this century and the need for winter maintenance will not be as large as today. However, in the temperature range around zero degrees the change will not be as great as at lower temperatures but the total need for winter maintenance will be reduced. There will be a large increase in the number of accidents occurring in the temperatures above zero degrees, perhaps as a result of more careless driving at these temperatures where the drivers perceive the risk of slippery conditions as low.

Acknowledgements

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Paper IV

The impact of climate change on winter road maintenance and traffic accidents in West Midlands, UK.

Anna K. Andersson and Lee Chapman

> "The English winter; ending in July, to recommence in August."
> Lord Byron (1788-1824)

The impact of climate change on winter road maintenance and traffic accidents in West Midlands, UK

Andersson Anna K. & Chapman Lee

Abstract

Winter weather can be a significant cause of road traffic accidents. This paper uses UKCIP climate change scenarios and a temporal analogue to investigate the relationship between temperature and severe road accidents in the West Midlands, UK. This approach also allows quantification of the changes in the severity of the winter season over the next century in the region. It is demonstrated that the predicted reduction in the number of frost days should in turn reduce the number of road accidents caused due to slipperiness by approximately 50%. However, the paper concludes by warning against complacency in winter maintenance regimes. A warmer climate may result in budget cuts for highway maintenance which in turn may well reverse declining accident trends.

Keywords: road surface temperature, road traffic accident, winter road maintenance, climate change, temporal analogue, weather generator

1. Introduction

The British government has a long term aim to reduce the number of casualties on UK roads by 40 % in the year 2010 compared with the average for 1994-98 (Department for Transport, 2009). There have been numerous studies into the influence of weather conditions as a cause of traffic accidents (e.g. Codling, 1974; Palutikof, 1991; Edwards, 1996). However, precipitation, and associated poor visibility, is the main cause of many weather related incidents (Keay & Simmonds, 2006; Songchitruksa & Balke, 2006; Koetse & Rietveld, 2009) and is a problem which becomes particularly acute in winter (Fridström et al., 1995; Edwards, 1999). Indeed, there is often a pronounced peak in accidents in the month of December (Asano & Hirasawa, 2003), where the problems of winter weather are compounded with reduced daylight hours. In colder climates, the risk of an accident increases if the precipitation is falling as snow (Andreescu & Frost, 1998; Suggett, 1999). Andrey & Olley (1990) found that 40% of the total number of winter accidents occurred on roads with ice/snow or rain. In particular, Norrman et al. (2000) identified that the largest amount of accidents occurred when snow was falling on a frozen road surface. However, these relationships are not universal. Some countries are well prepared for winter weather and the onset of snow can actually mean a decrease in the number of accidents (Fridström et al., 1995) or at the very least, the severity of incidents (Koetse & Rietveld, 2009). Drivers respond to the conditions by restricting travel to essential journeys (Parry, 2000; Smith, 1982) and by driving more slowly (Hassan & Barker, 1999). For example, Kilpeläinen & Summala (2007) showed that average traffic flow speed reduced by 6.7% in bad weather. Similarly, in wet and slushy conditions, speed reductions can be as high as 25% (Martin et al., 2000 cited in Koetse & Rietveld, 2009)

The UK does not have a particularly snowy climate, but the appearance of snow is often the cause of traffic chaos (e.g. Thornes, 2005; London Assembly, 2009). To some extent, this represents complacency in the winter maintenance regime. Although a duty of care exists to protect the motorist (as per section 42 of the UK Railways and Transport Safety Act, 2003), it is clearly not reasonable for every responsible party to maintain a stockpile of specialist equipment to deal with snowy conditions which may only occur once or twice per annum. Instead, the problem which is the focus of attention in the UK is the formation of ice on roads. On many winter nights, the forecast is straightforward and the roads are treated if necessary. However, marginal nights, where temperatures are close to freezing, are more problematic. This paper studies traffic accidents across the West Midlands during the winter months December to February with the aim of applying UKCIP (UK Climate Impacts Programme) climate change scenarios to determine how the number of days requiring winter road maintenance may change in the future and how this subsequently may affect road traffic accident statistics.

2. Methodology

2.1 Area of Study & Weather Data

The focus of this study is the county of the West Midlands (Figure 1) which is the second largest conurbation in the UK. This study makes use of weather data obtained from the World Meteorological Organisation weather station located centrally in the region at Elmdon (Birmingham Airport).

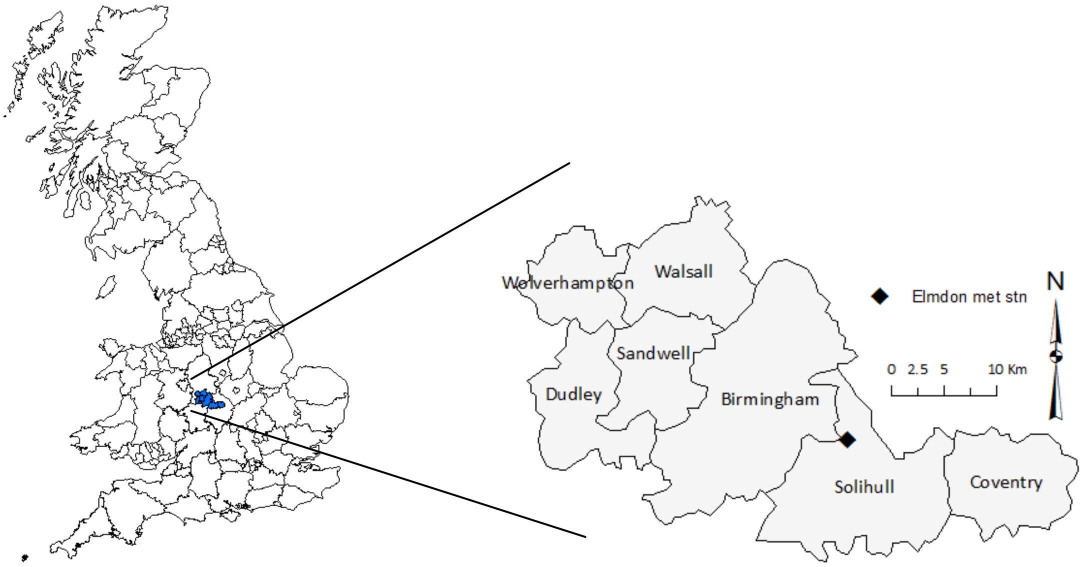


Figure 1. Area of interest, Showing the location of the West Midlands and Elmdon weather station.

2.2 STATS-19 Data

In the UK, the recording of the weather as a factor in road accidents has been undertaken on police accident report forms (STATS-19) since 1969. All road accidents which involve a fatality or personal injury are recorded on the form, which is filled in at the site of the accident by an attending police officer. However, 'damage-only' or 'minor injury' accidents are not recorded. This means that true accident data are likely to be under-reported. Furthermore, although weather conditions are recorded in the database, it is important to appreciate that road accidents are caused by a combination of factors and that weather may not be the principal cause.

Figure 2 provides an overview of winter (DJF) traffic accidents numbers that have occurred in the West Midlands over the last 10 years. To put this into context, the accident rates are plotted against the winter mean temperature. Since DJF 1999-2000, there has been a general downward trend in the number of accidents recorded each year. This is in common with other studies and is attributed to be a consequence of improvements in vehicle technology (Edwards, 1996). However, over this time period there is no overall warming trend evident in the mean winter temperatures. Indeed there is a limited relationship between mean temperature and long term accident rates, although the coldest year (DJF 2000-2001) did produce the second highest number of accidents. In order to improve understanding of the impact of temperature on road accidents, much more detailed analysis of individual years are required.

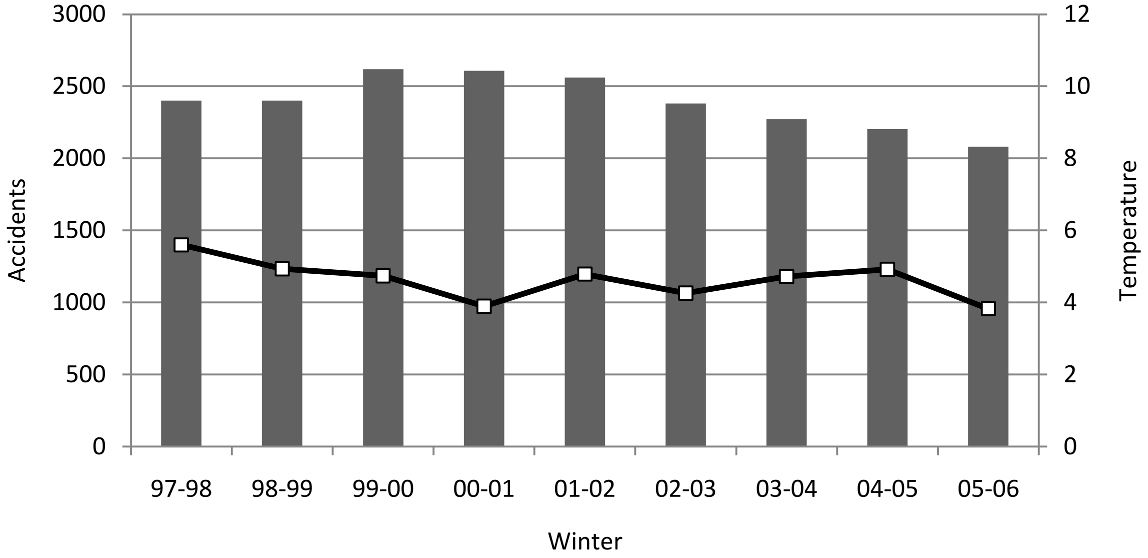


Figure 2 Accidents in the West Midlands plotted against mean winter temperatures. Accidents (grey bars), mean temperature ☐.

This study contrasts the last two years of data shown in Figure 2 (DJF 2004-2005 and DJF 2005-2006). DJF 2004-2005 was chosen as this was a warm winter (although not exceptional for the last 10 years) with mean temperatures of 1.3°C above the 1961-1990 baseline (UK Met Office, 2009). As a result, it may represent a temporal analogue of future average weather conditions (e.g. Feenstra et al., 1998). For comparison, DJF 2005-2006 was selected for a more detailed analysis as this was more an 'average' year being marginally warmer than the baseline conditions. Consecutive years were chosen so as to remove the impact of long-term trends on the accident data, for example, increasing traffic numbers or improvements in technology such as anti-lock brakes (Edwards, 1996).

In the West Midlands, there were 2204 traffic accidents in DJF 2004-2005 (although only 2102 had a full record suitable for analysis). In DJF 2005-2006 the amount of accidents was similar totalling 2081 (2070 with a full record). These accidents are plotted in Figure 3 against the air temperature value measured at Elmdon when the accident occurred. Surprisingly, considering the difference in average temperature recorded in each of the two seasons, the total number of accidents in each of the years is very similar.

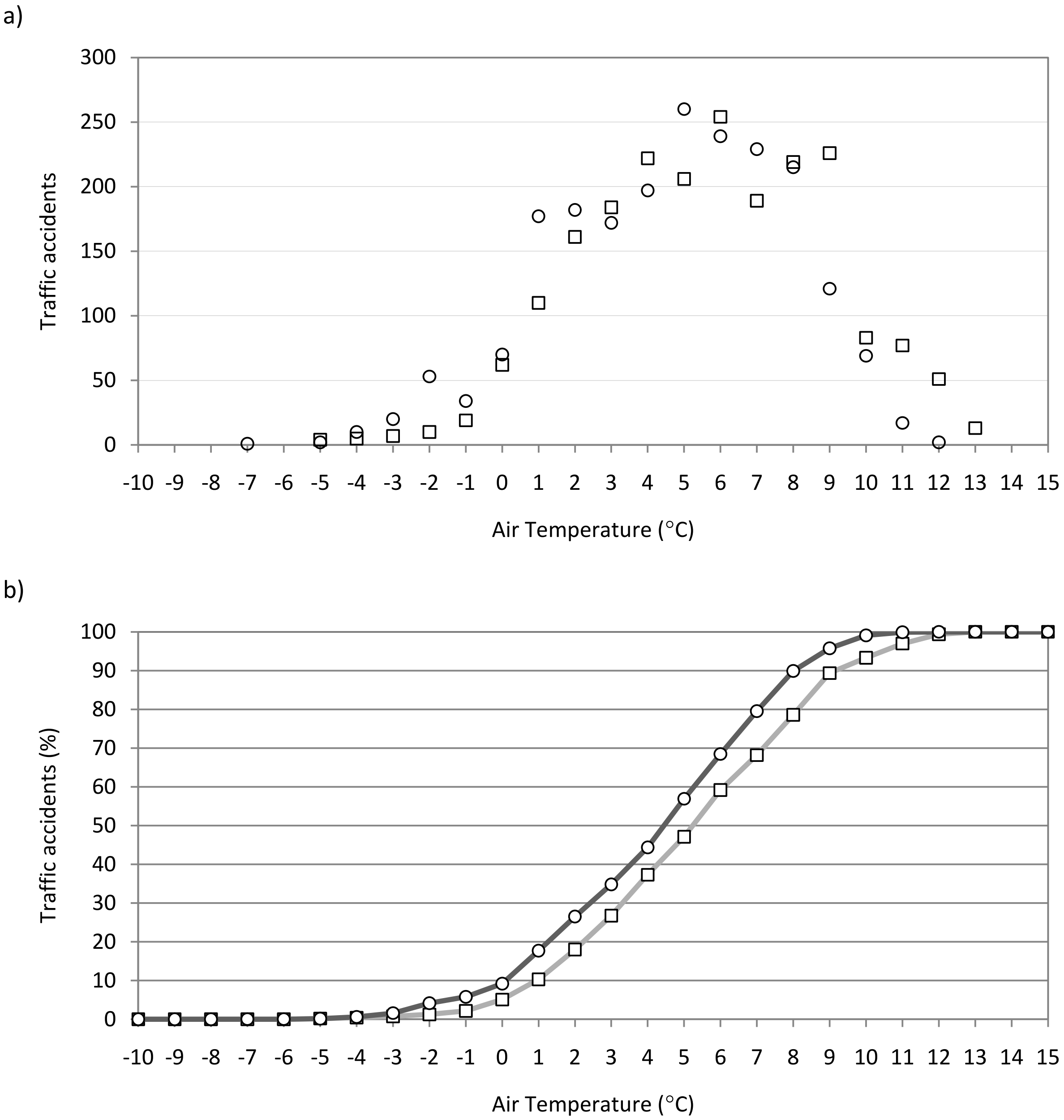


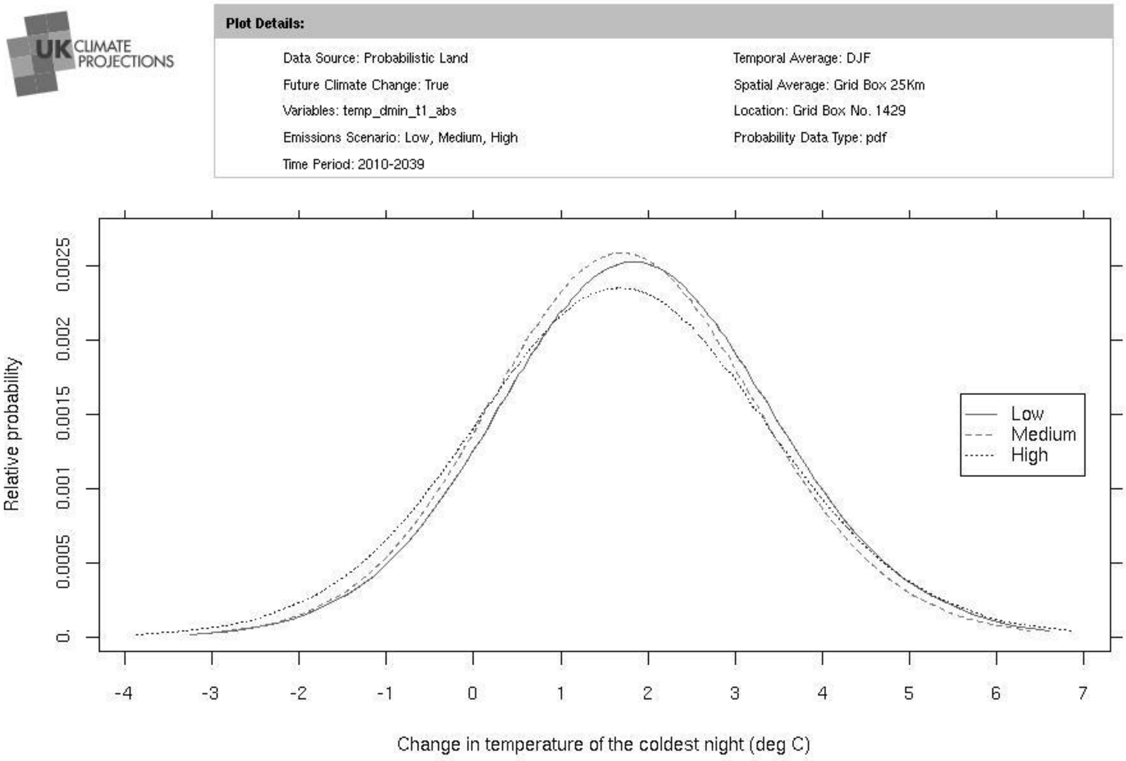
Figure 3. Road accidents in the West Midlands. a) Amount of accidents in December to February 2004-2005 & 2005-2006, ☐ 2004-2005 ○ 2005-2006, and b) cumulative percentage plot.

Figure 3b shows a cumulative percentage graph for accident numbers at different air temperatures. Here the difference between the two winters can be more clearly identified with a greater percentage of accidents occurring below the 0°C threshold in DJF 2005-2006. In terms of winter maintenance, 0°C is a critical threshold as ice is most slippery at 0°C when in a semi-frozen state (Moore, 1975). However, this is based on road temperature and not air temperature. Although the two are related, there is no rule of thumb measurement to translate between the two. During the winter months, it is not unusual for road surface temperatures to be several degrees below air temperature (Bogren & Gustavsson, 1991; Thornes, 1991), but this is very much dependent on the local geography (Chapman et al., 2001). For example road surface temperatures during a clear and calm evening change more rapidly in valleys and depressions than at more exposed locations (Gustavsson et al., 1998). This can be seen in Figure 3a as the accident rate peaks at air temperatures around 4-6°C (therefore, road temperatures could theoretically be below freezing). This could be a consequence of the increased frequency of temperatures in this range but could also be caused by drivers adjusting their behaviour to icy conditions (Koetse & Rietveld, 2008). For these reasons, this study will use 5°C as an upper threshold for marginal nights (these are the most difficult nights to forecast correctly in winter as the road surface may or may not fall below freezing).

2.3 Probabilistic Climate Change Scenario Data

The climate change scenario data used in this study is taken from the UK Climate Impacts Programme (UKCIP). UKCIP co-ordinate the UK based climate change prediction models derived from the Intergovernmental Panel on Climate Change (IPCC). 2009 saw the launch of the UKCP09 probabilistic scenarios summarising the latest information on current and projected climate change. UKCP09 is based around three IPCC CO2 emission scenarios, namely A1FI (High); A1B (Medium) and B1 (Low). It is also subdivided into several future scenario periods although the most commonly used are the 30-year periods centred on the decades 2020s (i.e. 2011-2040), 2050s (2041-2070) and 2080s (2071-2100) (Hulme et al., 2002). Figure 4 shows example output from UKCP09 detailing the change in temperature of the coldest night for a range of scenarios. All scenarios demonstrate a general warming trend, and since the highest relative probability for the temperature change of the coldest nights in the medium emission scenario is approximately +2.5°C in the winter months December to February. This can therefore be an indication for a reduced need of winter road maintenance in the future. Indeed, based on this evidence, it can be concluded that noticeable warming will occur over the next decade and that the winter DJF 2004-2005 may well represent a temporal analogue of the situation to be encountered in the 2020's.

a)



Plot Details:

Data Source: Probabilistic Land
Future Climate Change: True
Variables: temp_dmin_t1_abs
Emissions Scenario: Low, Medium, High
Time Period: 2010-2039
Temporal Average: DJF
Spatial Average: Grid Box 25Km
Location: Grid Box No. 1429
Probability Data Type: pdf

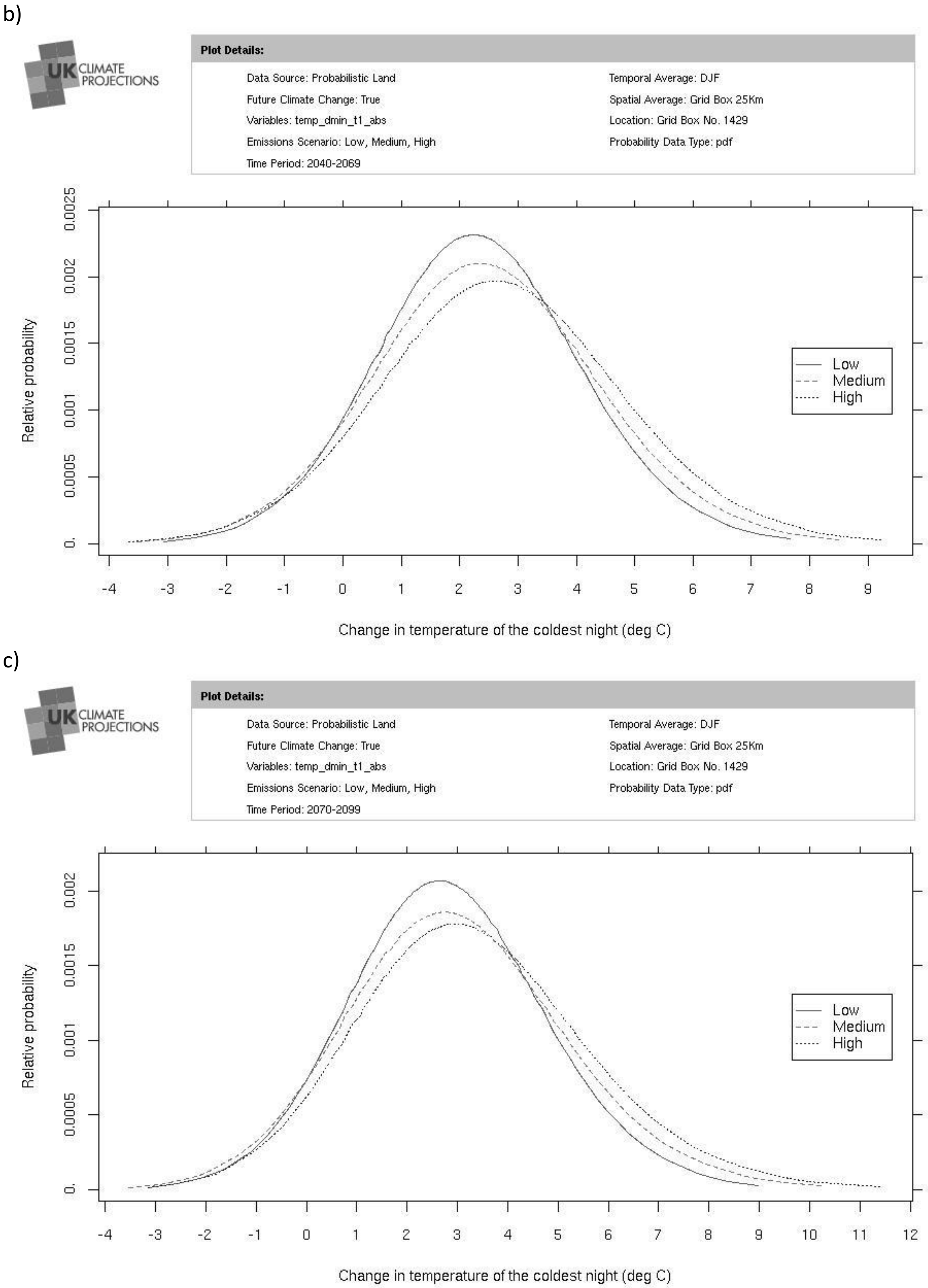


Figure 4. Change in temperature of the coldest night from UKCP09 climate change predictions for a) 2020's b) 2050's and c) 2080's.

2.4 Weather Generators

Weather generators are used to produce time series' of stochastic weather data based on the baseline climate (Hutchinson, 1987), however they have recently been adapted to account for climate change scenarios (e.g. Semenov & Barrow, 1997). Before the launch of the UKCP09 scenarios, weather generators were needed to produce probabilistic output. The increased information available from UKCP09 now means that the use of a weather generator is not necessary for many studies, but the functionality has been included to allow for studies at a daily time-scale. However, at the time of writing, the UKCP09 and associated threshold detector was still in development and hence for the purpose of the study, EARWIG (Environment Agency Rainfall and Weather Impacts Generator), which is based on the earlier UKCIP02 scenarios is used. EARWIG uses observed baseline (1961-2000) weather data from the UK Meteorological Office to produce daily weather records which can then be used to generate probability distributions. EARWIG uses two stochastic models, first a simulation of rainfall that is used in the second model that is generating the other variables that is depending on rainfall. Although EARWIG was originally developed for use in the climate impact assessments of agricultural and water system management (see Kilsby et al., 2007 for a full description of the model and application), it has since been used in other climate change impact assessments. For example, Dobney et al. (2009) used the technique to study the impact of climate change on railway buckling in the southeast UK.

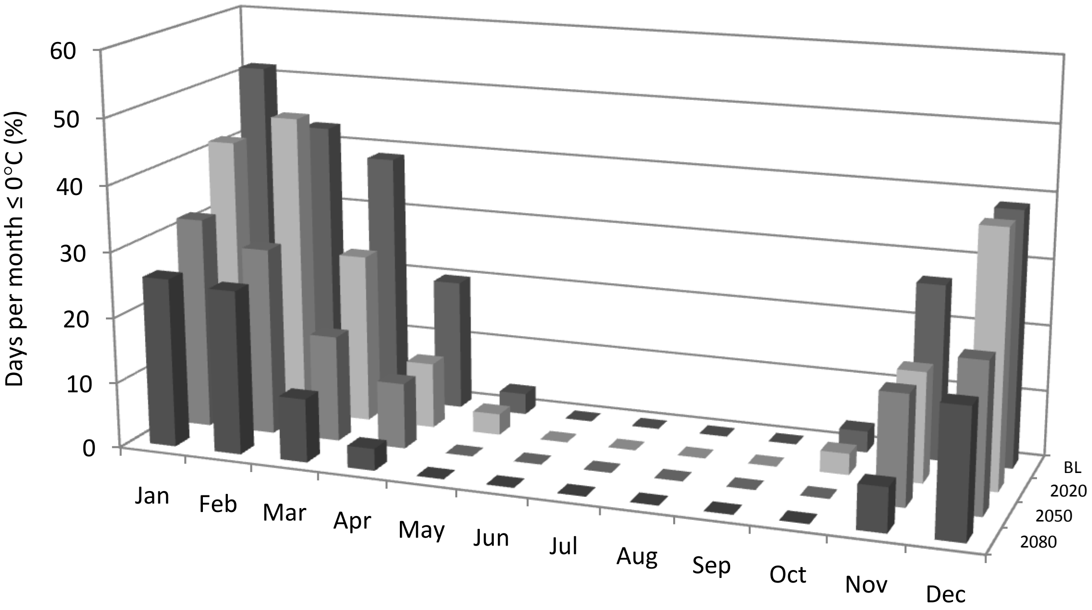
In this study, EARWIG was used to calculate temperature distributions for the baseline scenario and also for the three future time slices, 2020, 2050 and 2080. In the interests of conciseness, only the UKCIP02 medium-high emission scenario derived from the IPCC SRES A2 storyline is used (Hulme et al., 2002).

3. Results

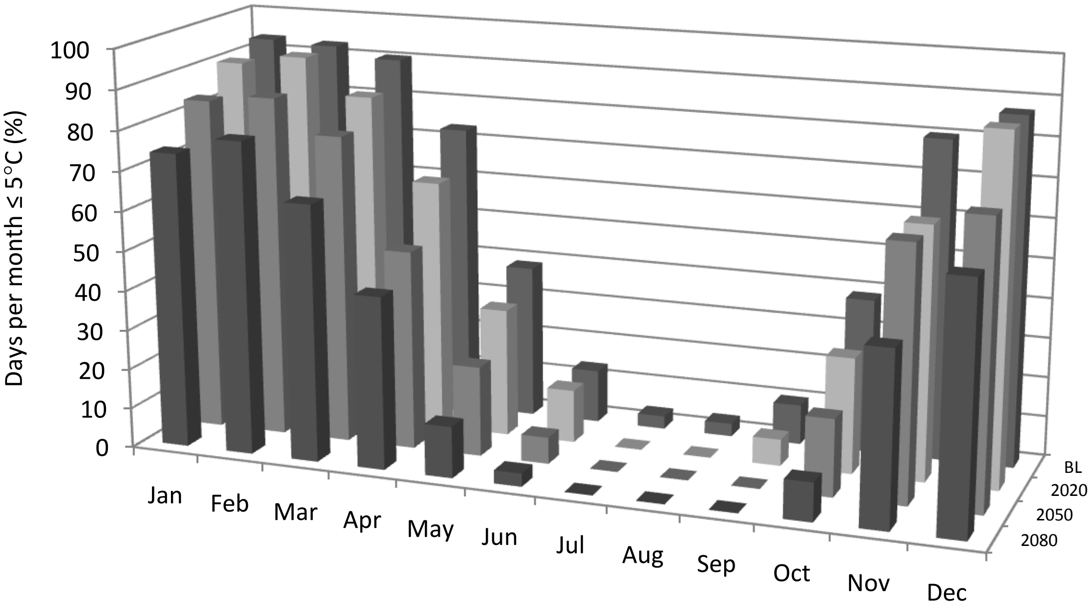
3.1 Future climate scenarios

Using EARWIG, the percentage of days per month with air temperatures equal or below the two thresholds of 0°C and 5°C were calculated (Figure 5a,b). As expected, in line with the UKCP09 scenarios, there is a general trend of increasing temperatures over time. This in turn translates into a decrease in the number of frost days and length of the winter season. At the moment, 69 frost days can be expected in the region every year, but this is predicted to shorten to 28 by 2080 (Figure 5a). A similar trend can also be seen using the upper threshold of 5°C (Figure 5b), a reduction of 38%. The frequency of each minimum temperature over the course of a year is summarised in Figure 5c.

a)


Days per month ≤ 0°C (%)
0
10
20
30
40
50
60
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
BL
2020
2050
2080

b)


Days per month ≤ 5°C (%)
0
10
20
30
40
50
60
70
80
90
100
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
BL
2020
2050
2080

c)

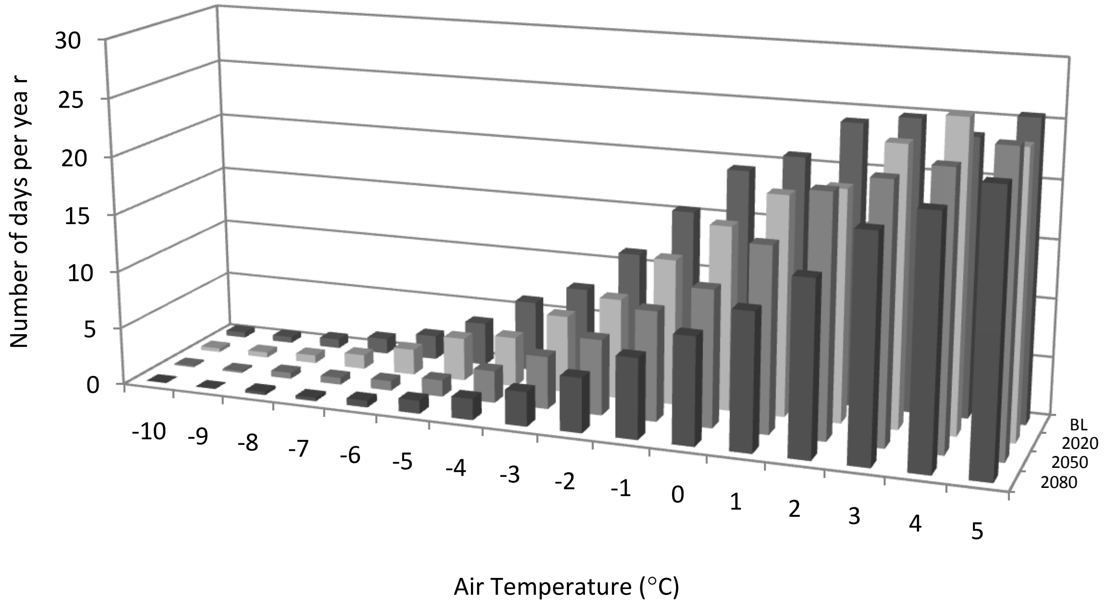


Figure 5. a) Percentage of number of days per month with air temperatures a) ≤0°C , b) ≤5°C and c) Number of days per year for each temperature degree ■ BL ■ 2020 ■ 2050 ■ 2080.

3.2 Future traffic accidents

In order to investigate how future accident numbers will change under the various climate scenarios, a simple theoretical relationship between the climate at Elmdon (DJF 2005-2006) and baseline accidents (DJF 2005-2006) was derived based on the ratio:

$$\text{Number of accidents at Temp X} \Big/ \text{Number of days per winter at daily minimum Temp X} \tag{1}$$

The result is produced for each temperature degree interval which can then be applied to the future climate scenarios to predict future accident numbers (Figure 6). Using this methodology, 2039 accidents would be predicted for the temporal analogue year DJF 2004-2005 which is close to the 2102 total recorded in the STATS-19 database.

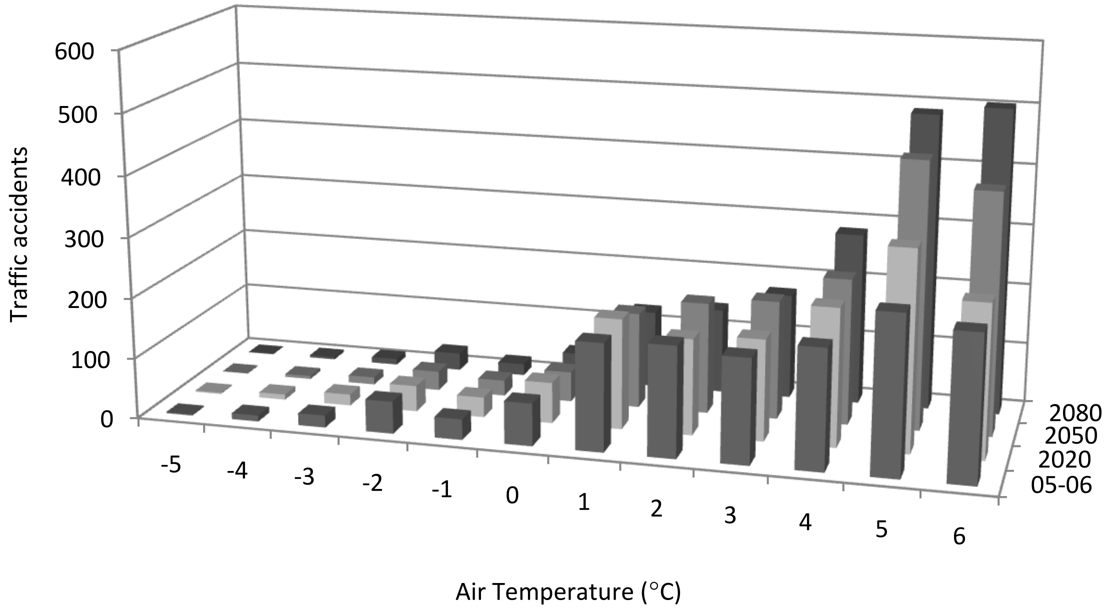


Figure 6. Amount of accidents in December to February for each temperature degree for actual amount of accidents and for three future scenarios ■ 2005-2006 ■ 2020 ■ 2050 ■ 2080.

Based on this analysis, the reduction in the number of days below the 5°C threshold will lead to a reduction in the number of traffic accidents by 12%, that otherwise might have been caused by slippery winter roads. However, care must be taken when performing a projection of this nature as a major assumption is being made that the rate of accidents will remain constant over time. This is highly unlikely as improvements in vehicle technology and road safety are highly likely to continue to reduce accident numbers (Edwards, 1996). Indeed, to take this into account requires a far more sophisticated climate change impacts analysis (e.g. Jaroszweski et al., 2009). Furthermore, the projections made in this paper are highly subjective due to the uncertainty surrounding STATS-19 data and the climate models used by UKCIP. For these reasons, the 43% reduction in the number of accidents ≤0°C by 2080 predicted in this paper is more than likely a conservative estimate (Figure 6).

4. Discussion

This study has identified that under UKCIP climate change scenarios there will be a significant change to the winters experienced in the West Midlands. Low freezing temperatures will become far less common and the winter season will be shorter. Using the methodology in this paper, it is hypothesised that this will in turn result in reduced numbers of road traffic accidents and also, in theory, the cost of winter maintenance.

Each year, the UK spends £482m on the winter road maintenance of the primary road network, plus a further £1069m on local roads (Department for Transport, 2009). Approximately 30% of the road network in UK is treated on a regular basis (Handa et al., 2006), which in an average winter uses up 2 million tonnes of rock salt (Salt Union, 2009). The seven unitary authorities who comprise the West Midlands treat over 3700km on a night by night basis which equates to a total of 270 tonnes per treatment. Hence, based upon the analysis in this paper, a significant saving could be made on salting operations in the West Midlands by 2080. Since the authorities make preventive maintenance, and the number of days below five degrees (marginal nights with risk for slippery roads) is reduced with 38% the reduction of salt can be in the same range.

However, an environment of continual cost cutting currently exists. Local authorities seek to achieve 'best-value' for the local taxpayers by reducing costs on services wherever possible. After a number of mild years in the UK (Figure 2), there has been the temptation to gradually reduce stockpiles of salt as a cost-saving measure. An initial run of mild winters had proven this to be a prudent measure, there was serious shortcomings over the winter season 2008-2009 where many councils ran out of salt. The result was that many roads across the country went untreated leading to widespread disruption reported across the media. Such complacency is not new in the UK. The country is frequently underprepared for snow-related problems (e.g. Thornes, 2005; London Assembly, 2009), and the danger is that a similar situation is now starting to occur with icy roads.

Whilst lessons will have been learned from the winter season 2008-2009, talk of climate change will always make winter road maintenance an easy target for decision makers when setting annual budgets. An argument could be made that if freezing temperatures are rarely experienced in the future, it may not be appropriate to operate a winter maintenance service (at least not at the level accustomed to). However, as this paper has shown, it is not the coldest of nights which cause the problems (≤0°C), it is the marginal nights (≤5°C). Indeed, the number of marginal nights will not change significantly over the next century. In the Baseline DJF there were 82 marginal nights with a minimum temperature of 5°C or under. By 2080 this reduces to 65, a reduction of 21%. However, this still means that a winter maintenance service will be required in the future to secure the roads and thereby reduce road accidents under the most dangerous of situations where surface temperatures hover above 0°C. To some extent this is also demonstrated by the use of DJF 2004-2005 as a temporal analogue where the increased temperatures experienced in that year made only a minor difference to accident numbers when compared with a baseline year (Figure 2a). In effect, accident numbers were greater than predicted which underlines the need for caution when using temporal analogues to infer future climate change (e.g. Andersson and Chapman, 2009)

5. Conclusion

In summary, the number of frost days (≤0°C) and the length of the winter season will reduce in the West Midlands. This will theoretically result in a 43% reduction in the number of accidents caused due to slipperiness (days with frost). It can also lead to a reduction in the quantity of salt required to treat the roads. However, as the number of dangerous marginal nights (≤5°C) still remain in approximately 30% of the days in a year (Figure 5c), it will remain essential to maintain a winter maintenance service over the next 80 years to prevent a significant increase in accident numbers due to winter weather.

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