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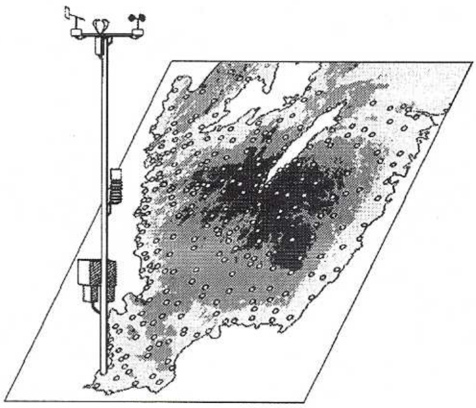
WINTER ROAD CLIMATE INVESTIGATIONS USING GIS



Marie Eriksson

Department of Physical Geography
GÖTEBORG 2001

- Marie Eriksson -

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Akademisk avhandling

Som för avläggande av Filosofie Doktorsexamen vid Institutionen för Geovetenskaper, Naturgeografi, Göteborgs Universitet, kommer att offentligen försvaras torsdagen den 7 juni, kl 10:00 i Stora hörsalen, Geovetarcentrum, Göteborgs Universitet.

Fakultetsopponent: Professor Reinhold Steinacker, Institut für Meteorologie und Geophysik, Universität Wien, Österreich.

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ABSTRACT

Problems with transportation due to adverse weather conditions affect many areas of the society. The goal with road climate research is to understand the spatial and temporal variations in road conditions and what processes that interact to create these conditions. This knowledge can be used to improve forecasts, make actions against problematic conditions more efficient and when planning new road sections.

This thesis mainly deals with the applications of climate knowledge to winter road conditions. The advantages of using GIS (geographical information systems) in spatial analysis and description are shown. Each specific geographical environment creates its own climate with characteristic spatial and temporal patterns. The relationships on different scales were investigated and the effect of adverse road conditions on road safety was also studied. Data from the Swedish road weather information system (RWIS) was used to define road conditions. Digital elevation and landuse data was used for terrain descriptions.

A method is presented that makes it possible to follow formation of road slipperiness during a weather change. Data from the RWIS has high spatial and temporal resolution suitable for studying road conditions during front passages. The distribution of specific slipperiness types can be studied if slipperiness is defined from meteorological variables measured at the stations. The hazardous situation when rain or sleet falls on a frozen road surface was studied. The approach enabled dynamic studies and gave an increased understanding of the interactions between synoptic and road conditions. Comparisons between spatial patterns and terrain data can be made with GIS.

The relationship between spatial variations in road slipperiness and geographical parameters was investigated. It was shown how this knowledge could be used to further evaluate the locations of RWIS stations. A station could then be optimally equipped based on the prevalence of specific slipperiness types. The selected site-specific parameters explained a considerable amount of the variations in road slipperiness. Latitude and elevation explained most of the variation in southern Sweden. Sky view photographs could also contribute to objective station descriptions. A new method for calculating sky view factors from digital images was developed.

Results also showed that there was an increased risk for accidents during slippery road conditions. Twenty percent of the accidents were verified as occurring during slippery conditions both by RWIS data and accident reports. At the time of the accidents during the two road conditions with highest accident risk ("rain or sleet on a frozen road surface" and "snowfall together with hoarfrost") there was 100% maintenance activity. It suggests that in order to reduce the number of accidents during these situations, public awareness must be increased. It can be accomplished by providing information about road conditions to drivers and by further studies of road climate variations.

Keywords:
Road climate, slipperiness, GIS, RWIS, traffic accidents, sky view factor, winter road maintenance

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Front cover illustration: The image shows the topography in southern Sweden and locations of road weather information stations.

"Efter stort snöfall eller utwäder, åligger närmaste Allmoge å landet och Städernas Inwånare at ofördröjeligen skotta de allmänne Landswäger och Gator der så stora Snödrifwor finnas, att the resande ej kunna begwämligen fortkomma, Borgmästare och Råd I städerna samt Cronobetienterna på landet böra noga tilse at sådant icke försummas".

Ur 1734 års gästgivareordning,
Vägverkets historiska samlingar

ABSTRACT

Problems with transportation due to adverse weather conditions affect many areas of the society. The goal with road climate research is to understand the spatial and temporal variations in road conditions and what processes that interact to create these conditions. This knowledge can be used to improve forecasts, make actions against problematic conditions more efficient and when planning new road sections.

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PREFACE

This thesis includes the following papers:

I Gustavsson, T., Bogren, J. & Eriksson M. (1998). *GIS as a tool for planning new road stretches in respect of climatological factors.* Theoretical and Applied Climatology 60(1-4): 179-190.

II Eriksson, M., Halley, V. & Nunez, M. (2001). *Frost prevention and prediction of temperature variations and cooling rates using GIS.* Submitted to Agricultural and Forest Meteorology.

III Eriksson, M. & Norrman, J. (2001). *Analysis of station locations in a road weather information system.* Accepted for publication in Meteorological Applications.

IV Holmer, B., Postgård, U. & Eriksson, M. (2001). *Sky view factors in forest canopies calculated with IDRISI.* Theoretical and Applied Climatology 68 (1-2): 33-40.

V Eriksson, M. (2001). *Regional influence on road slipperiness occurrence during winter precipitation events.* Submitted to Meteorological Applications.

VI Norrman, J., Eriksson, M. & Lindqvist, S. (2000). *Relationships between road slipperiness, traffic accident risk and winter road maintenance activity.* Climate Research 15(3): 185-193.

The papers are referred to in the text by their roman numbers. Much of the work has been conducted in collaboration with my colleagues. Model construction, analysis and writing were performed by myself in Paper I and II, through continuous discussions with the co-authors. Vanessa Halley constructed the instrument set-up and planned the measurements in Paper II, while Associate Professor Manuel Nunez contributed with valuable discussions and comments. The work in Papers III, IV and VI was performed jointly by the authors.

INTRODUCTION

Road climatology is the knowledge of interactions between climate processes and the road environment. It is an important subject since problems with transportation due to climate and weather affect many areas of the society. The most problematic situations in northern countries occur in winter when roads become slippery or difficult to drive on. The common goal with road climate research is to understand the spatial and temporal variations in road conditions and what processes that interact to create these conditions. This knowledge can be used to improve forecasts and make actions against problematic conditions more efficient. The results presented in this thesis lead one step further towards this goal.

Background

Winter roads were very important to transports in northern Sweden a few hundred years ago. Much of the heavy transports of coal and ore depended on straight roads across frozen lakes and wetlands. The first time winter road maintenance was mentioned in any type of statute was 1687. According to that text, county governors were to clear and maintain roads and bridges also during winters if necessary. In the early 1900's, the arrival of motorised traffic experienced the first real problems with winter road conditions, which resulted in a change in the law stating the requirements of winter road maintenance. In the beginning, sand was used to increase friction and in the 1960's salt was used more widely on main roads (Swedish National Road Administration, SNRA, 2001).

The most important task for winter maintenance is to work for a sufficient friction on the road. Any weather condition that reduces the skid-resistance can have a negative effect on road safety. This will be the definition of road slipperiness in this thesis. Other factors influencing the point at which cohesion between the tyre and the road surface is lost are the condition of the tyres, the speed of the vehicle, the skill of the driver and the road surface material. Most important of all is likely to be the state of the road surface (Perry & Symons, 1991).

Roads become most slippery just below zero degrees when water can coexist with snow or ice (Kari, 1976). For example, ice crystals are harder at lower temperatures and snow does not stick as easily to the surface, which make roads less slippery. Road conditions can form during one weather situation and remain for several days. Therefore, it is important to have a deeper understanding of road conditions in relation to a changing weather and climate on a local- and micro-scale. It is also necessary to study the interaction of air and road surface temperature, humidity, wind etc. in the formation of slippery conditions.

Road climate variations

Climate act on different scales and the interactions between these scales are important to understand for coming discussions. The text in this section describes climate variations that occur on different scales, from large- to small-scale variations.

The regional climate in an area naturally determines the extent of wintertime transportation problems. Monthly or seasonal characteristics of road climate can be described with a winter index. Several indices have been developed mainly to compare regions with different maintenance requirements (Knudsen, 1994; Cornford & Thornes, 1996; Johns, 1996 and Harrison & Harrison, 1996). Another example is the GAB-index adapted for Swedish conditions. It was described and evaluated by Gustavsson (1996) and consists of a summation of occasions with snow, frost and black ice. In the summation, these events could be weighted according to the costs they generate.

Traffic problems vary between countries because of climate variations. Internationally, Sweden has had a relatively long tradition of studying road climate because of its cool winter climate. Compared to Sweden, winters are generally milder in Great Britain and icy roads are more likely to result from the abrupt arrival of a cold air mass with associating clearing skies than from warm fronts (Wood & Clark, 1999). Based on the contents of research reports, there seem to be more problems with drifting snow and fog in England than in Sweden. In Japan, the greatest problem is large amounts of snow. Research deals with how to prevent traffic chaos during sudden heavy snowfalls and development of snow removal technology. Japan banned studded tyres 1990, which increased the importance of further research on slipperiness prevention (Masuda, 1998).

Climate on a local scale is largely governed by topography and the type of landuse, for example, forests or open fields. The characteristic temperature patterns could be generalised according to prevailing weather. One approach (used in the first part of this thesis) is to distinguish three characteristic situations: Cloudy and windy weather, clear days and clear and calm nights. During cloudy and windy weather there are small spatial variations because of the well-mixed atmosphere. The variations that do occur depend mainly on differences in elevation (due to the lapse-rate). The influence of cloudiness on air and road surface temperature has been studied by e.g. Bogren & Gustavsson (1991), Wood & Clark (1999) and Bogren et al. (2000a). Temperature distribution during a clear day is governed by incoming solar radiation. Screening objects, like trees and road cuts become very important for the resulting road condition (Bogren, 1991; Shao & Lister, 1995 & Bogren et al., 2000b). On clear and calm nights, there can be an inverse relationship with elevation. Air stability and local shelter effects lead to cold air flows and pooling in low lying areas (e.g. Tabony, 1985; Kalma et al. 1986; Bogren & Gustavsson, 1991; Blennow, 1998; Gustavsson et al., 1998). Large and complex temperature variations in short distances are typical (Gustavsson et al., 1998). It increases the need for further studies of these small-scale variations and especially how they can be modelled.

Road construction affects the small-scale meteorological processes acting near the road surface. Road-bed materials have specific thermal properties, for example heat capacity or thermal conductivity, and thus react differently to a weather change. Road surface temperature is especially sensitive to the material used (Gustafson, 1981 and Gustavsson & Bogren, 1991). Bridges usually have lower surface temperatures than adjoining roads (Gustavsson & Bogren, 1991) because of their construction. They lack a compensating heat flow from the ground during night and usually have a high sky view and a large loss of long-wave radiation. When a bridge crosses water, there is moisture available that can freeze onto the road and cause slipperiness. Takle (1990) reported that frost was more often observed on bridges than on roadways.

Factors like road construction and variations in traffic flow are not further discussed in this thesis, even though they affect the road condition. IR technique is one method that can be used to investigate the effect of these factors on the road surface temperature (Lindqvist, 1987 and Gustavsson & Bogren, 1991). Traffic also has an effect on the road condition when slipperiness has developed. Vehicles change the structure of ice and snow by mechanical work and increased temperature (caused by friction and engine heat etc.). The influence from traffic on the road condition is seldom as large as variations caused by topography or landuse.

Maps of spatial variations in near-surface temperature have a wide range of applications other than that of road climate. Many crops are sensitive to low temperatures and local frost risk maps can be constructed from known terrain-temperature relationships. (Davis, 1978; Laughlin & Kalma, 1990; Blennow & Persson, 1998). Traditionally, local climate mapping was performed by manual analysis of aerial photographs and maps, often followed by extensive field measurements (Bogren & Gustavsson, 1986 and Lindqvist, 1991). The recent fast development of GIS (geographical information systems) enables computer-based terrain mapping and analysis. A GIS provides a powerful set of tools for collecting, storing, retrieving, transforming and displaying geographical data for a particular purpose (Burrough, 1986). The benefits of using GIS for road climate studies will be shown in this thesis. Digital elevation and landuse data is now available for large parts of the world. Many of the important geographical factors determining climate variations can be derived from digital terrain models. These factors can be used in models describing spatial variation in areas where no observations are available. Derived relationships can be applied to, or created specifically for, road climate, which is a new approach. More research is also needed on how to predict climate on different scales.

Road weather monitoring

Many countries have constructed a Road Weather Information System (RWIS) for real time monitoring of road conditions. About 6500 road weather stations are installed in 27 countries around the world, as of March 2001 (SIRWEC, 2001). In addition to most European countries, the United States, Japan, Canada and Australia also have a RWIS. Sweden has about 660 automated stations that continuously register a number of meteorological parameters (described in the data and methods section). Data is collected every 30 minutes and stored in a central database at the Swedish National Road Administration. It is a source of information with high spatial and temporal resolution that enables investigations of road climate variations. The Swedish RWIS also includes weather satellites, radar stations and forecast models. The information is used by traffic information centrals and maintenance offices to decide when and where actions should be taken.

To improve the decision making, RWIS stations are usually sited where an early warning of slipperiness can be obtained. Early registrations occur in different environments depending on weather conditions, time of year and time of day. Consequently, the stations are placed in different local and regional environments to cover a wide range of situations. For example, it is useful to place stations at a wide range of elevations to monitor temperature during unstable conditions. Regional or local environments could be described by parameters derived from a digital terrain model.

The common methods used to locate stations include thermal mapping, knowledge of the regional climate and discussions with local maintenance personnel. Continuous mapping of road surface temperature is performed with infrared sensors, usually mounted on vehicles (Smith, 1988; Thornes, 1991 and Shao et al., 1997) but also airborne (Beaumont et al., 1987 and Lindqvist, 1987). Thermal mapping in Sweden includes measurements of air temperature at two levels. Three main factors determining the road surface temperature can be distinguished from a thermal mapping: road-bed material, radiation balance at the surface and advection and stagnation of cold air (Gustavsson, 1999).

If an objective and quantitative description of station locations existed, it would be possible to further optimise the RWIS in terms of instrumentation and relocation of stations. Instead of describing stations as being e.g. "exposed" or "screened" as today, fish-eye photographs could give the sky view and thus exposure to winds. The sky view factor (SVF) also influences the radiation balance at the surface. Bärring et al. (1985) showed that variations in SVF were related to variations in road surface temperature.

Effects of adverse road weather

Both extreme events and small climate fluctuations affect road transport statistics (Palutikof, 1983). In order to minimize disruption and maximize safety more research on interactions between transport and weather is needed. Many studies of weather and road accidents have concentrated on the risk increase during wet road conditions, e.g. Brodsky & Hakkert (1988) and Andrey & Yagar (1993). More countries are affected by adverse road conditions caused by rain than slippery roads resulting from ice. It is generally accepted that wet road friction is always less than that for the least skid-resistant dry road surface (Andrey & Olley, 1990). Less is known about accident risk during snowfall. It is usually found higher than during "fine" weather (Schandersson, 1988 and Andreescu & Frost, 1998) but accidents are generally less severe (Codling, 1974). Many studies group rain, snow, fog, ice etc. to "adverse" weather conditions and compare with dry conditions (Fridstrøm et al., 1995; Khattak et al., 1998; Edwards, 1999 and Híjar et al., 2000). It would be useful to know the effect of different road conditions formed during different weather situations (Figure 1). Winter road maintenance could then be optimised to prioritise the worst situations and some RWIS stations could be equipped to monitor these situations specifically. A standardised description of road conditions is also needed.

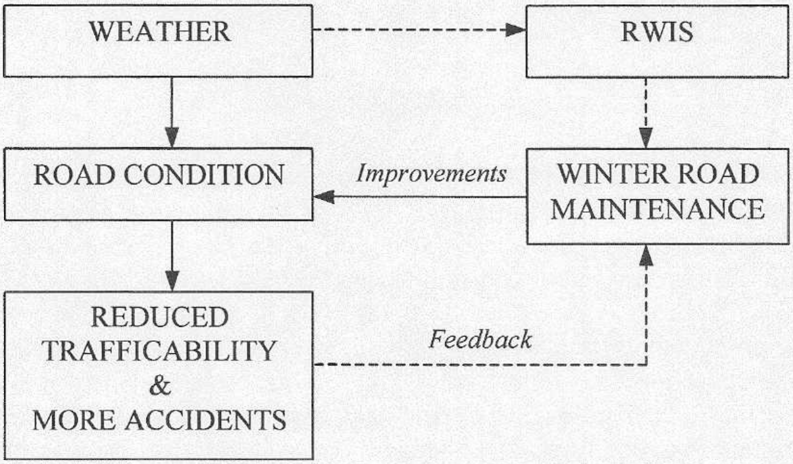


Figure 1. *The flow chart shows the interactions between weather and transport.*

Lovell (1966) published one of the first studies describing how the choices between road route alternatives and road designs were decided on the basis of climate. When comparing a number of routes for a new road, the ones exposed to the worst local climate conditions may be expected to take significantly less traffic and have an unacceptable high accident rate (Musk, 1991). Cornford & Thornes (1996) showed significant relationships between winter maintenance expenditure and three different indices representing winter severity. Thus, by considering local climate factors and the seasonal variations already at the road planning stage, many problems and costs can be avoided. These types of evaluations and climate mappings can benefit from using GIS. Different sources of information, like known relationships between climate and accident risks, maintenance costs etc., could be integrated in a GIS to evaluate the road climate in an area.

Objectives

This thesis deals with the applications of climate to winter road conditions. The advantages of using GIS (geographical information systems) in spatial analysis and description are explored. Each specific geographical environment creates its own climate with characteristic spatial and temporal patterns. These relationships on different scales are investigated by using GIS to create descriptive environmental parameters. The knowledge can be used to plan road weather monitoring and winter road maintenance in any area where digital data is available. The effect of adverse road conditions on road safety in a region of southern Sweden is also studied.

A first pilot study (Paper I) explored the idea of using GIS to create a model describing relative variations in road climate based on topography, landuse and general climate data. A vision evolved of further developing a road climate model with the purpose of including a range of information sources like accident and maintenance data. It requires several lines of research to examine the relationships between the influencing factors.

The main objectives of this thesis have been to:

- Find objective and quantitative parameters that can be used to describe RWIS station locations and variations in road climate on different scales. Investigations of the relationships between local terrain parameters and road conditions are required to find suitable parameters (Paper II, III, IV).

- Develop a method for evaluating road climate in an area using GIS. One of the central questions in road climatology is the relationships between road slipperiness, traffic accident risk and winter road maintenance. These relationships give information on how to compile information in a layered GIS model (Paper I, VI).

- Develop a method for monitoring road conditions during weather changes and study how synoptic conditions influence road conditions. Road condition is defined by the interaction of several meteorological variables. The method is tested on warm front passages and the topographic influence on the occurrence of road slipperiness is investigated. The benefits of using GIS for presentation and analysis will be examined (Paper V).

These objectives have had the common intention of contributing to optimised station locations and equipment, optimised winter road maintenance and a climate input in the planning of new road sections. It can be achieved by integrating different data sources in a GIS with climate in focus.

STUDY AREA

Data and applications for most of the work in this thesis were performed in southern Sweden, in the area shown in Figure 2. From a road climatological perspective, this area is interesting because it has a great variability in winter road conditions and more traffic than northern Sweden. Frequent temperature fluctuations around zero degrees require accurate forecasts and larger maintenance efforts. Slipperiness forms during a range of weather conditions in the whole winter season. The northern part of Sweden has a colder climate with long periods of homogenous road conditions. Drivers in these areas become more used to driving on winter roads. There is also a more dense network of road weather stations in the southern part of the country. It is necessary to have as high spatial coverage as possible to enable studies of small-scale variations in road weather.

The regional climate of southern Sweden is strongly influenced by the westerlies. According to data from 1873 to 1995, presented by Chen (2000), westerly and south-westerly circulation types occurred between 30-45 percent of the time during winter (a total of 27 circulation types were investigated). Elevation (Figure 2) is the other major climate determinant. The southern part of the Scandinavian mountain range has lower temperatures than surrounding areas and results in less precipitation eastwards. The south Swedish highland has elevations around 200-300 m (south of the two large lakes in Figure 2). The sharp rise in topography on the west side of the highland causes orographic uplift and an increase in cloudiness and precipitation. The west coast has a precipitation of about 300 mm during the winter from November to April. Further inland it exceeds 500 mm during the same period. The increase of yearly precipitation with elevation can be up to 150-200 mm/100 m in this area. Average temperature varies in approximately the same way with a more maritime influence along the coasts to a more continental influence in the highlands where there are larger temperature amplitudes during the year. The two large lakes also have a dampening effect on temperature, but their influence is smaller than that from the sea.

Lowest temperatures are reached in February with a monthly average of about -5 to 0°C in southern Sweden and -5 to -10°C further north. Distributions of temperature and precipitation are reflected in the number of days with snow cover, which varies from less than 50 days at the west coast to about 100 days on the south Swedish highland. The data described here is based on the climatological normals from 1961-90 presented in the National Atlas of Sweden (1995).

Norrman (2000a) described the spatial variations of road slipperiness in southern Sweden using data from two winter seasons (1996-97 and 1997-98). Road conditions were analysed by defining a set of slipperiness types that could be classified from RWIS data. The most common types of road slipperiness in this area were hoarfrost and snowfall on a cold road surface (<0°C). They accounted for about 60 percent of the slippery time these winters. Generally, the amount of registered slipperiness increased with latitude and elevation.

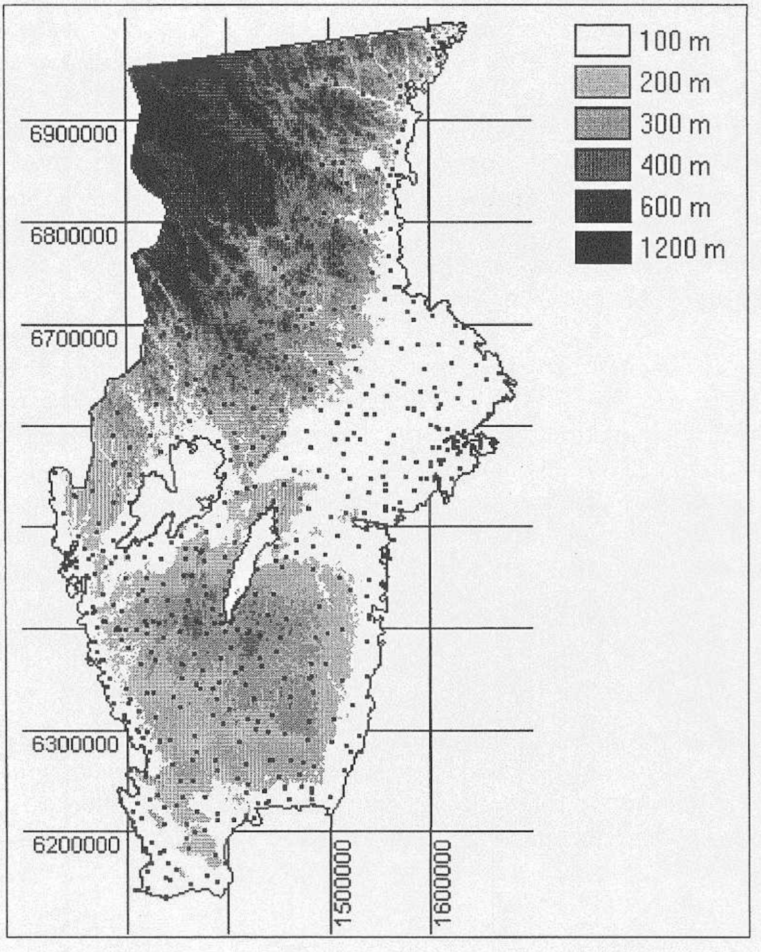
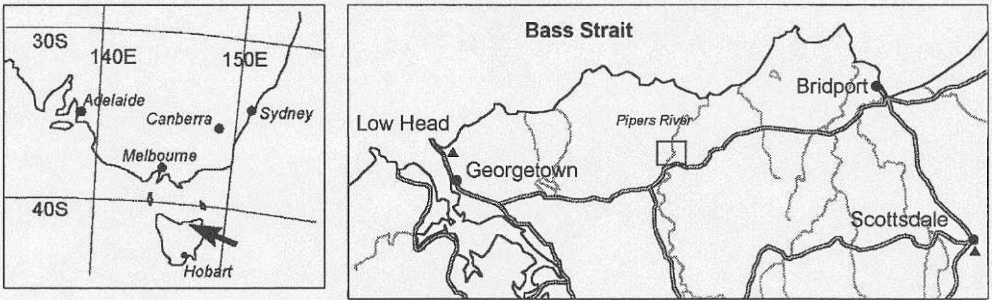


Figure 2. *Elevations in the southern part of the Swedish mainland. Note that the scale does not have equal intervals. The black dots are RWIS stations (a total of 576) and the grid is the Swedish national grid in km. The Swedish west coast lies south of 6550000 and Norway borders Sweden further north on the west side.*

Tasmania

Measurements and modelling of radiation frosts in Paper II were conducted in the north-eastern part of Tasmania, Australia (Figure 3). The area has experienced an increase in frost frequency during the last years (Anders, 1998), which has resulted in crop damages, in this case on vines. The landscape in this part of Tasmania consists of mostly open and hilly grazing land with scattered trees (Figure 4). The surveyed property is about 0.5 km^2 and elevations vary between 24 and 60 meters above sea level (Figure 5). The vineyard is located on the slopes of the Pipers River. There is a knoll in the central part of the study area, from where the land is gently sloping to the sides. The south-eastern slope is the steepest and has the lowest elevations.



(a) (b)

Figure 3. *The surveyed area is situated in the north-eastern part of Tasmania shown by the black arrow (a). Figure 3b shows the northern coast of Tasmania. The small square marks the location of the study area*

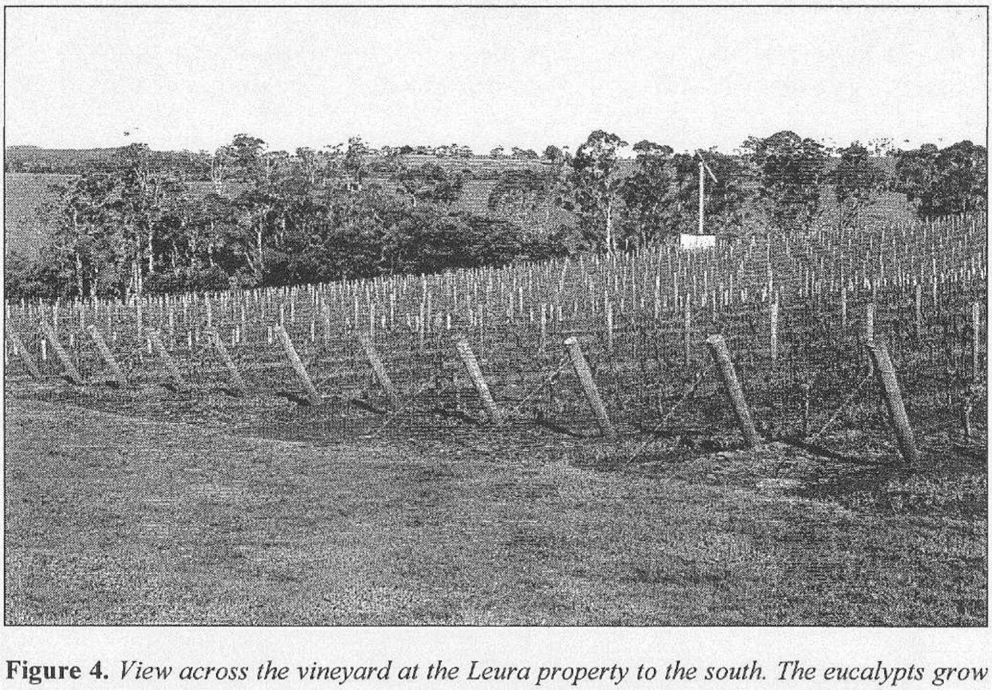


Figure 4. *View across the vineyard at the Leura property to the south. The eucalypts grow along the small Pipers River valley. A wind machine used for frost protection is seen in the upper right part of the photo.*

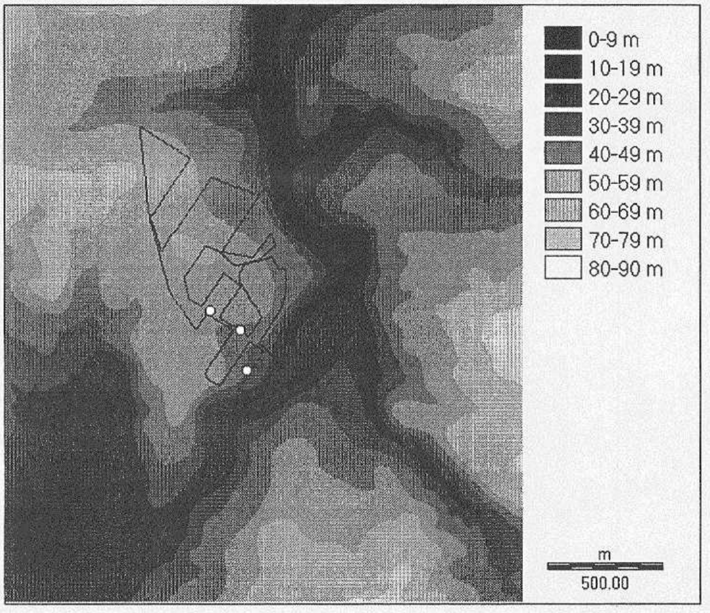


Figure 5. *Elevations in Leura vineyard are shown in 10 m intervals. The measurement transect is black and positions of wind machines used for frost protection are shown as white dots.*

DATA AND METHODS

Data from several sources was used for the investigations in this thesis. In this chapter they will be described to give a background to the results and discussion.

Climate data

Road weather stations

The Swedish National Road Administration currently has a network of about 660 road weather stations. Data from the Swedish RWIS (Figure 2) was used in Papers III, V and VI. The stations register meteorological information two times an hour, thus producing climate information with both high temporal and spatial resolution. Each station is equipped with sensors measuring air temperature at 2 m height, relative humidity and road surface temperature. Surface temperature is registered by a probe about two millimetres below the asphalt surface. Both air and road surface temperature is measured with an accuracy of ±0.3°C. Some stations also register wind speed, wind direction and the amount and type of precipitation using an optical precipitation sensor. Wind and precipitation is measured at a height of 5 m. The dewpoint temperature is automatically derived from air temperature and relative humidity. Each value for air and road surface temperature is an average of six measurements every five seconds during 30 seconds. Stations with more than 96 (two days) of erroneous registrations during one month were excluded from all analyses.

A road slipperiness classification (Norrman, 2000b) was used for studying road climate variations (Paper III and VI). It is an expert system developed for automatic and consistent analysis of large amounts of data from the RWIS. Ten different types of slipperiness are distinguished (Table 1). Conditions like freezing rain and snow compacted by traffic cannot be detected with the RWIS and are therefore not included in the classification and analysis.

Table 1. *The ten types of road slipperiness that can be distinguished in the classification of RWIS data. The necessary variables are P (amount or type of precipitation), T_{air} (air temperature), T_{road} (road surface temperature), T_{dew} (dewpoint temperature), Rh (relative humidity) and U (wind speed).*

Type of slipperiness	Precipitation	Variables
1. Rain or sleet on a frozen road surface.	Yes	P T_{air} T_{road}
2. Snowfall on a frozen road surface.	Yes	P T_{air} T_{road}
3. Snowfall or sleet on a warm road surface.	Yes	P T_{air} T_{road}
4. Snowfall together with hoarfrost	Yes	P T_{air} T_{road} T_{dew}
5. Hoarfrost and low visibility	No	T_{road} T_{dew} Rh
6. Freezing dew followed by hoarfrost	No	T_{road} T_{dew}
7. Strong formation of hoarfrost	No	T_{road} T_{dew} Rh U
8. Weak formation of hoarfrost	No	T_{road} T_{dew} Rh U
9. Drifting snow	Yes	P T_{air} Rh U
10. Watercover which freezes	Yes	P T_{air} T_{dew} T_{road} Rh

Mobile measurements

Mobile temperature measurements from a 4WD motorcycle were performed for studies of small-scale temperature variations during radiation frosts (Paper II). A mast with seven copper-constantan thermocouples (0.56 mm in diameter) mounted in radiation shields was attached to the front. The top sensor had a height of 2.2 m and the lowest 0.3 m above ground. It was ensured that a good flow of air reached the sensors and that they were not affected by heat from the engine etc. A transect through the vineyard (Figure 5) was planned to encompass different elevations and ground covers. Temperatures were collected five times each night: Just after sunset and every tree hours until just before sunset (around 18, 21, 00, 03, and 06). Each run took 20-25 minutes and a Campbell Scientific CR10 logger recorded the temperature every second. The maximum potential error of the thermocouple measurements was ±0.14°C. Three nights were considered suitable for the modelling by being calm and clear: 12, 26 August and 20 September 1998.

Temperature data was corrected for the time it took to drive one transect. At several occasions, temperature differed more than one degree between start and finish. A linear correction was used and corrections were applied to each run and sensor, since cooling rates differed during the night and between levels.

Geoinformation

A Digital Elevation Model (DEM) with 50 m regular grid size was used for creating a road climate model (Paper I). According to the National Land Survey of Sweden the average error in elevations is less than ±2.5 m. Digitising of some features in this paper was made from a topographical map on the scale of 1:50 000.

A DEM with 10-m contours was used for the radiation frost modelling (Paper II). The contours were interpolated to a grid with 5 m resolution in the GIS ArcInfo using a discretised thin plate spline technique, the *interpol* command. The method was specially designed for creating hydrologically correct DEM:s. Slopes and aspects of the area were calculated from the DEM.

The freely accessible elevation model GTOPO30 was used to create terrain variables describing the locations of road weather stations in Paper III. GTOPO30 is a global DEM with a spatial resolution of 30-arc seconds (8.33×10^{-3} degrees), which is approximately 1 km. Elevations are in metres above mean sea level and have a vertical root mean squared error of 18 m. The latitude/longitude grid was transformed to the Swedish national grid system (RT90) by recalculating each coordinate with the software Maptrans (MAPTRANS, 1996). RT90 is a datum with Cartesian coordinates. Northing is defined as the north-south variation in the Swedish national grid system (Figure 2) and easting as the east-west coordinate.

A landuse database is available from *GRID-Arendal* on the Internet and it has the same resolution as the DEM, 1 km. It is a combination of data from the Digital chart of the world and the European Space Agency remote sensing forest map of Europe. This data also had to be converted to the Swedish national grid. It was done by resampling the image in the GIS Idrisi (Clark University, 1999), which gave a RMSE in the positions of 560 m, i.e. about half a pixel. Idrisi is the GIS software mainly used in this study and it is a grid-based system. The term digital terrain model (DTM) refers to any type of terrain data in this thesis, e.g. both elevation and landuse. DEM only refers to elevation data.

Accident reports

The relationship between road slipperiness, accidents and winter road maintenance activity was investigated for an area in south-western Sweden (Paper VI). Traffic accident data was obtained from police reports compiled by the Swedish National Road Administration. The data set included all accidents, except those involving wildlife, on state roads, i.e. not local streets in towns and cities since they are a municipal responsibility. The reason for choosing police reports to base this study on, is that the exact time and place of each accident is given. The information is needed to connect the accident data to other data sets. There are other sources of accident data, which could perhaps provide a more complete picture of accident occurrence, e.g. from insurance companies. There are a number of accidents, mostly less severe vehicle damages, which people find unnecessary to report to the police. However, almost all accidents involving serious personal injuries are reported to the police, i.e. included in the study. The number of reported traffic accidents in the study area during winter was 67 in 1991/92, 84 in 1993/94 and 95 in 1995/96.

Maintenance reports

The Swedish road network is divided into areas, each of which has one contractor responsible for winter road maintenance (WRM). The contractors report every occasion that they have been out on the roads. In the report, they note the time, place and type of action etc.

A time generalisation was needed to compare accident and WRM data. Since maintenance action can take several hours, a day was divided into four different periods: morning, day, evening and night (Paper VI). If there had been any maintenance performed during the period in which the accident occurred, the road condition was considered to be improved. Each working area archives their own maintenance reports on paper and maintenance data can therefore be difficult to access and interpret. Reports from two seasons, 1993-94 and 1995-96, were used for WRM analyses.

RESULTS

Road climate variations modelled with GIS

Features of the landscape that influence climate variations, like topography and landuse, can be described or modelled with GIS from digital terrain models. The relationships between several of these geographical parameters and climate have been studied in this thesis.

Latitude and longitude of an area determines its general climate. Coordinates are basic parameters in all geographical information systems. They are needed for georeferencing the data, i.e. determine its position in a defined coordinate system. When studying larger regions they need to be included in a climate model. A large part of the variation in road slipperiness in southern Sweden could be explained by using only northing and easting as independent parameters in a multiple regression model (Paper III). The resolution of the model was one kilometre. Up to 60 percent of the spatial variation in slipperiness was explained during the winter season

1997-98 (Figure 6). In this context, slipperiness was the monthly sum of the ten types described in Table 1. That is, the dependent parameter was the number of RWIS registrations (half hours) classified as slippery.

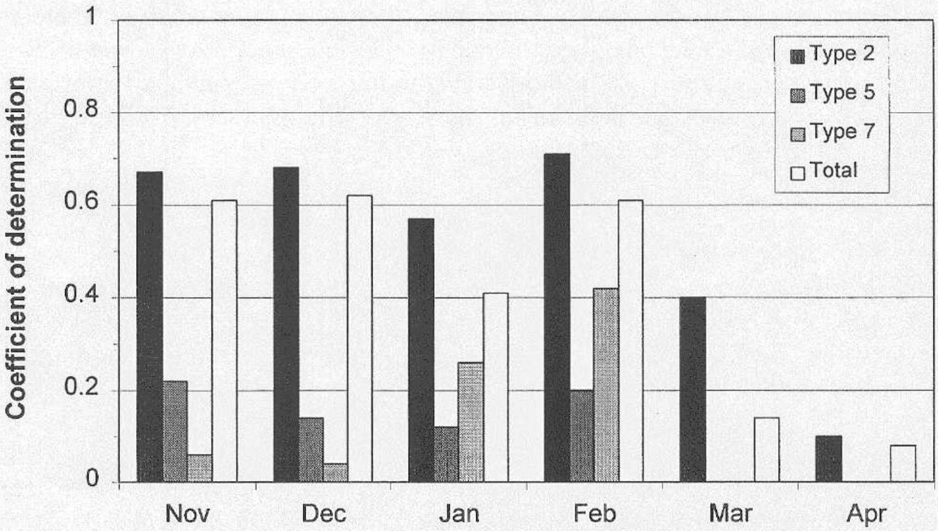


Figure 6. *Coefficient of determination, R^2, when using northing and easting as independent variables in a regression model describing spatial variations in road slipperiness. The analysis is based on data from one winter season in southern Sweden. Type 2 is snowfall on a frozen road surface, Type 5 is hoarfrost and low visibility, Type 7 is strong formation of hoarfrost and Total is the sum of all 10 Types.*

The specific type "snowfall on a frozen road surface" (Type 2), had an even higher correlation with northing and easting than "Total" (Figure 6). It is a slipperiness type that develops regionally, since snowfall usually affects large areas. The degree of explanation was highest between November and February and lower in the end of the season. It could be explained by higher surface temperatures in the end of the winter season, which could lead to a more scattered appearance of this slipperiness type, since the selection criteria require road surface temperatures below zero. Two types of slipperiness that form more locally were also modelled: "Hoarfrost and low visibility" (Type 5) and "strong formation of hoarfrost" (Type 7). They showed very small correlations with position, only around 0.2-0.3. Largest part of the variation in slipperiness was explained by northing even when more descriptive parameters were included in the multiple regression.

Northing can represent variations in the available amount of solar energy, which is an important variable in the surface energy balance. On a smaller scale, spatial variations in incoming solar energy are caused by topographical variations. Direct incoming radiation on a surface during a clear day can be modelled from slope and aspect derived from a digital elevation model. An example was shown in Paper I, where sunny and shaded slopes were mapped for a day in February. A relative measure of total solar energy received during the day before a radiation frost was related to temperatures during the night (Paper II). The received energy helped explaining some of the variations in temperature during the following clear and calm night. Higher energy receipt generally resulted in higher temperatures.

Another parameter related to topography and solar radiation is the time of local sunset. Radiative cooling during clear weather begins before the sun sets and the exact time will vary with slope and aspect. Time of local sunset was also included in the small-scale temperature model (Paper II). It helped explaining the spatial variations during a clear and calm night. As expected, it was most important for the resulting temperature in the beginning of the night. Generally, it had a smaller influence than the received energy.

Elevation is a commonly used parameter to describe climate variations. It was the main determinant in the above-mentioned small-scale models (Paper II). Elevation has different effects on climate on different scales and during different weather situations. Elevation intervals were included in a road climate model where it described lapse rate during neutral conditions (Paper I). The model described the relative risk for low temperatures during specific weather situations; cloudy and windy, clear day and clear and calm night. The influence from elevation was not studied separately, but in the way the model was constructed, elevation was a necessary parameter. The influence of elevation on the distribution of winter road slipperiness in southern Sweden was studied (Paper III). Elevation had a significant influence during the whole season except for March. This month generally had low coefficients of determination (R^2). One explanation could be that the sun can create large differences between sun exposed and shaded ground, which leads to a high small-scale variability in road surface temperature and thus slipperiness. It means that the low R^2:s could be a result of the model resolution (1 km).

A detailed study of slipperiness Type 1 (rain or sleet falling on a frozen road surface) was made in Paper V. The criteria for this type are precipitation, air temperature above zero and road surface temperature below zero degrees. When rain or sleet falls on a frozen road surface there is a high risk for road icing. Two warm front passages across southern Sweden were examined to study the influence from e.g. elevation on the spatial distribution and occurrence of this type. A high risk for road icing was found in the higher areas of the south Swedish highland (Figure 7). Road surface temperatures were lowest here before the warm front arrived and the warming rates were not high enough to reach above zero. Air temperatures were above zero for the stations shown in Figure 7. The other front passage was preceded by lower temperatures (around -10°C). Air temperatures in the higher elevations were never above freezing. On this occasion, only lower lying areas experienced this type of slipperiness. Higher elevations probably had snow, which is a more obvious risk to the drivers than rain that could form an ice layer on the frozen road surface. A more obvious risk for slipperiness should lead to a more careful driving behaviour.

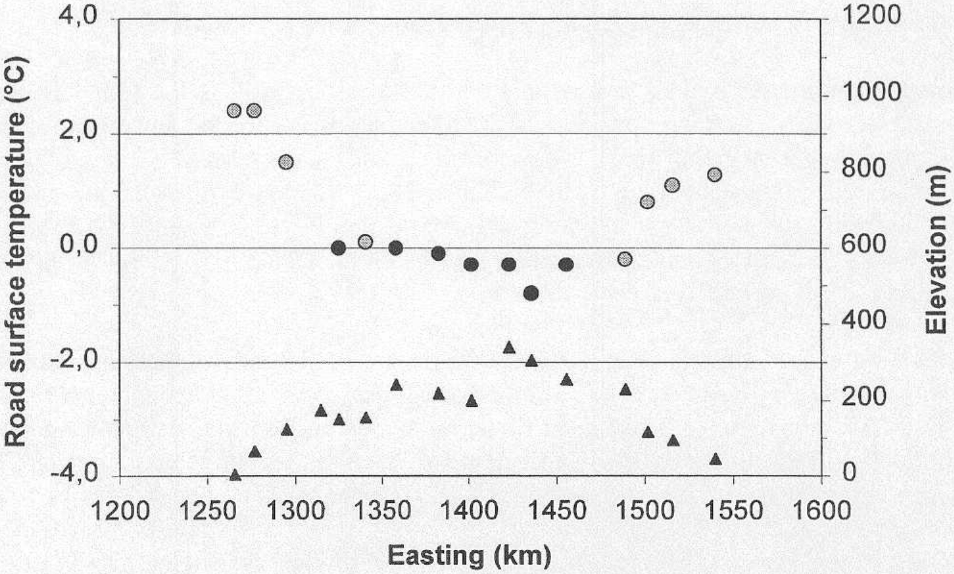


Figure 7. *A profile of 16 RWIS stations from the east to west coast across the south Swedish highland. Road surface temperature registrations (dots) in ℃ at midnight on the 15th of February 1999 are shown. Stations marked with black dots fulfil the criteria for rain or sleet on a frozen road surface. Elevation for each station is marked as triangles for comparison.*

The sea does have an influence on climate and it can be a useful parameter in climate modelling. Distance to the coast helped explaining the variation in number of slippery half-hour registrations at the RWIS stations during some months (Paper III). It was calculated for all stations in Figure 2. A smaller distance from the coast had a positive correlation with slipperiness occurrence, which could be explained by the presence of more humid air. Available water in some form is needed for the formation of slipperiness.

Relative topography also had an influence on slipperiness in the same study. It was calculated from a digital elevation model as a difference in elevation between each point and the points (i.e. heights) at a specific radius. The radii 1, 3, 5 and 10 km were tested as a measure of exposure. The relative topography calculated on a scale of 1 and 3 km had significant correlations with slipperiness. Concave land had more slipperiness than convex. Best correlation was received in January and February. It could indicate that these months had many occasions with low temperatures in valleys and depressions. Besides topography, shelter is provided by vegetation. Forests and open areas (mostly agricultural land) have different climates. During front passages, for example, air and road surface temperatures react faster to a weather change at exposed locations (Paper V). The difference in temperature depends on previous and prevailing weather.

It was tested if a landuse description in addition to topographical parameters would improve the explanation of spatial variations in slipperiness (Paper III). Stations were divided into those located in forest, open land or land close to water (lakes, rivers or the coast) in both categories. The multiple regressions were then performed on each group instead of on the entire dataset (all stations in Figure 2). The hypothesis was that observations made in similar environments would have less scatter around trends in the relationships to site-specific parameters. The model performance improved but the difference was not large. It improved most for stations located in an open environment and hardly at all for forest environments. The difference could be explained by a larger probability for variations within forests on a smaller scale than 1 km, which was the model resolution. The definitions of some of the slipperiness types are very sensitive to small changes in, for example, road surface temperature. In this case, the forest structure could influence the occurrence of slipperiness.

Landuse was also included in the model describing risk for low temperatures (Paper I). It included a division of forest, open areas and open concave areas (likely to have stagnation of cold air during clear and calm nights). Urban land was also distinguished, but the specific influence of each land group was not investigated.

Road weather monitoring

Field stations in the RWIS must be carefully located and equipped with suitable instruments for optimal detection of slipperiness. Knowledge of the spatial and temporal distribution of different types of slipperiness is needed to achieve these goals. Standardised descriptions of station locations would facilitate comparisons and evaluations of the station network. Such descriptions could be created from digital terrain models describing topography and landuse. Fish-eye photographs of the sky hemisphere could be used for the detailed description of local vegetation structure, shading etc.

Most of the geographical parameters described in the previous chapter were shown to have an influence on the distribution of road slipperiness in southern Sweden. They could be calculated for any area using GIS. Significant relationships (with 95% statistical significance) were received even though a resolution of one kilometre was used. Station descriptions would be even more useful with a finer resolution. When using finer resolutions it is still impossible to include the effects of shading from vegetation. The structure of a forest and how dense it is influence e.g. road surface temperature and exposure to winds in different directions. A new method for calculating sky view factors (SVF) was developed (Paper IV). It was based on digital fish-eye images and the calculations were performed in a GIS. The method was tested in forest environments and had a precision range of around 0.05. Minimisation of the errors requires a manual control of the limit between sky and canopy pixels. Difficulties in identifying this limit arise from gleaming at the canopy edges caused by reflecting sunlight. Sensitivity was largest in the central parts of the image up to about 70 percent of the radius. Resolution of the image had surprisingly little effect on the precision. Only small random differences in SVF of 0.01-0.04 occurred with a change in resolution from over 2000 to less than 100 image pixels in diameter.

With quantified descriptions, it is possible to study spatial variations in road climate. Practical examples of how this information can be used for an optimal location and instrumentation of stations were shown (Paper III). In Figure 8, local environments along a road are compared to station locations. The road consists of 208 pixels in the grid model and 19 stations are available for road weather monitoring along it. It was shown that in this example, road environments were well represented by the stations. However, at some places, the road passes close to water (group FW and OW) but none of the stations is located near water at present. It could be a disadvantage when monitoring road conditions, since many of the slipperiness types are influenced by the presence of moisture, for example the formation of hoarfrost.

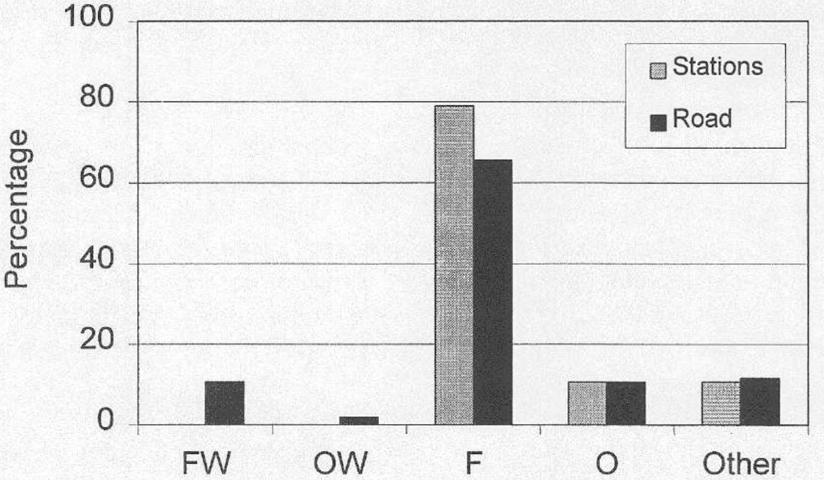


Figure 8. *Station locations compared to the road environment expressed in percent of the total number of stations and the total number of pixels along the road respectively for different land groups. FW = forest and near water, OW = open land and near water, F = forest and not near water and O = open and not near water. The category Other includes e.g. urban land.*

Temporal variations in road slipperiness are just as important as optimising the road weather information system. Real-time monitoring of road conditions is necessary to plan preventive actions. Local parameters could be continuously plotted against any measured climate variable to predict slipperiness. Another way is real-time interpolation of data (as suggested in Paper III).

A method for increasing the knowledge of the road weather characteristics in an area was shown (Paper V). The knowledge is important for the winter road maintenance personnel who needs to take proper actions against potential hazards. Road conditions continuously change during front passages. Spatial and temporal patterns will be not be the same from one area to another because of landscape characteristics. It is also of great importance to study the interaction of meteorological variables that results in specific road conditions. It was shown that a complex pattern of slipperiness occurred in southern Sweden during winter precipitation events. The warm front passages affected a large region but still resulted in much spatial variation in slipperiness.

Data from almost all road weather stations in an area was classified to show the distribution of rain or sleet on a frozen road surface. The front passage 15-16 February 1999, across southern Sweden, lasted about 17 hours. A maximum of 37 percent of the stations was affected by road icing at the same time. Images for each half hour during the first seven hours of this slipperiness event are shown in Figure 9. The discontinuous pattern is caused by variation in local and regional environments that affect air and road surface temperatures at the stations. The midnight image (00:00) can be compared to Figure 7, which shows a profile across the image in an east-westerly direction.

There were 32 half-hour registrations during the first three hours of rain or sleet on a frozen road surface, of which 17 were at stations situated in forest and 8 in road cuts. Sheltered locations will react slower to a warming, which favours low road surface temperatures and a risk of road icing. Stations closest to the west coast did not register a risk for road icing this time, which could be a result of low elevations or local environments favouring slightly higher road surface temperatures. Many stations along the west coast are exposed and situated in an open environment.

The complexity of road slipperiness with interaction between many meteorological variables must be emphasised. It requires dynamical studies at high resolution, both spatially and temporally. The advantage of the presented method of following the advance of a front (Paper V) is that it can be used with any definitions of road conditions as long as the meteorological data is available.

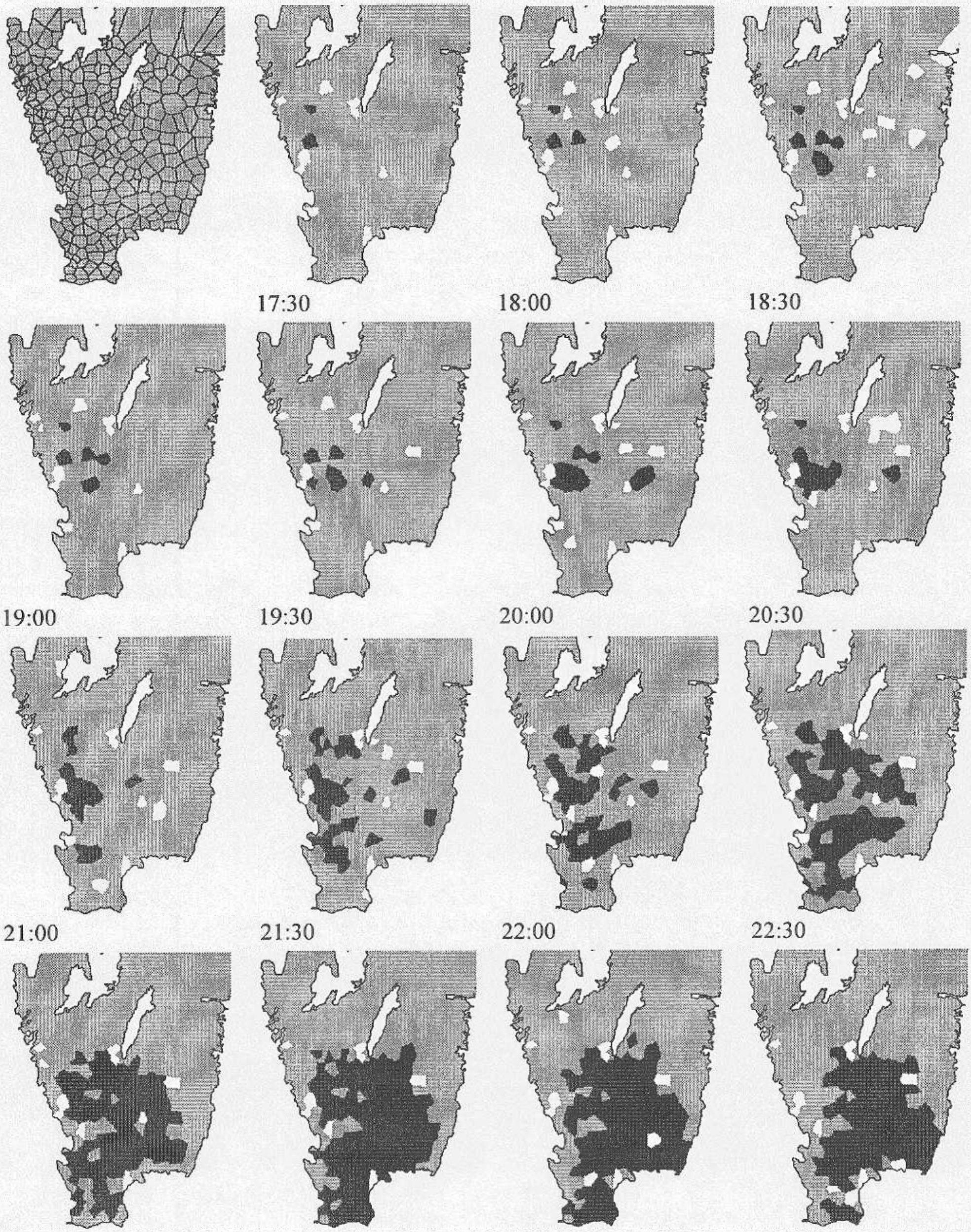


Figure 9. *The top left image shows the Thiessen polygons created around every station (totally 265) for display purpose. Areas affected by a risk for road icing by rain or sleet on a frozen road surface on 15 February are dark grey and malfunctioning stations are white.*

When knowing the regional influence on slipperiness in a specific area through map sequences, a great deal of information is obtained. Previous studies have been made on separate variables and few stations or in limited areas. With these map sequences, it is possible to get an overview of the whole event and thereby improve forecasts and slipperiness prevention. A GIS provides a useful tool for compiling this type of information with tables of data linked to flexible spatial displays and analysis functions.

Effects of adverse road weather

Adverse road conditions affect transportation in different ways. The distribution of accidents between different slipperiness types was investigated (Paper VI). The distribution was compared to maintenance activity to show a method for optimising slipperiness prevention. The essence of this reasoning was shown in Figure 1 in the introduction.

Classified data from two RWIS stations in the county of Halland, south-western Sweden, was matched in time with the accidents occurring on roads nearby. The results are based on data from three winter seasons with different climate characteristics. Accident rate for each slipperiness type was calculated as the ratio of the number of traffic accidents during that type and the duration of that type. To calculate a risk, there has to be a comparison with some reference situation, e.g. not slippery conditions or the amount of traffic not affected by accidents. The assumption that accidents are randomly distributed during a month and not affected by road condition is made in this study (Paper VI). The accident rate was divided by the expected number of accidents to derive an accident risk. If this risk was higher than one, more accidents occurred than expected if they had been evenly distributed.

The data in Table 2 is based on analysis of 246 accidents. Of the 83 accidents occurring on slippery roads according to the classification of RWIS data, most accidents (36%) happened during snowfall on a frozen road surface. This slipperiness type did not have the highest accident risk, probably because this road condition was rather frequent. Rain or sleet on a frozen road surface had the highest accident risk, which indicates that it is a hazardous situation. Slipperiness can be difficult to anticipate if it is raining and air temperature is above zero. A layer of ice can form quickly and lead to low friction.

The Poisson test was used to examine whether the number of accidents during a specific road condition was significantly different from the expected number of accidents during that time. All conditions except Type 5, 6 and 10 was statistically significant on the 95% level. It could be explained by the few accidents occurring during these conditions (Table 2). The Poisson test was inapplicable to non-slippery conditions, since there were too many accidents during the longer periods. The test was designed for "rare events". However, the total number of accidents for all slippery conditions was compared to the non-slippery conditions with the Chi square test. The test showed a statistically significant difference between observed and expected number of accidents on the 99% level for both road conditions.

Table 2. *Accident distribution on slippery road conditions and accident risk for each type of slipperiness. *** indicates that with 99% statistical significance, the number of accidents during that slippery road condition is higher than the expected number. ** is 95% and * 90%. Calculated accident risk for non-slippery conditions is included for comparison.*

Road condition	Accident distribution (%)	Accident risk
1. Rain or sleet on a frozen road surface	13	11.6 ***
2. Snowfall on a frozen road surface	36	6.1 ***
3. Snowfall or sleet on a warm road surface	6	3.4 ***
4. Snowfall together with hoarfrost	6	6.4 ***
5. Hoarfrost and low visibility	8	1.5 *
6. Freezing dew followed by hoarfrost	2	3.2
7. Strong formation of hoarfrost	12	2.5 **
8. Weak formation of hoarfrost	11	4.5 ***
9. Drifting snow	5	1.5 **
10. Watercover that freezes	1	2.6
Non-slippery		0.7

At the times of the accidents during the two types with highest accident risk, Type 1 and 4, there was 100% maintenance. That is, even with full maintenance activity, traffic accidents still happened during these road conditions. It indicates that other measures must be taken, for example to increase public awareness with information about road conditions. For accidents during snowfall on a frozen road surface, there was 65% activity, an indication that the maintenance performance could be increased.

Of the 246 accidents, 50% were related to slippery conditions either in the accident reports or by the classification. Simultaneous verification from these two data sets occurred for 20% of the accidents, i.e. both sources noted slippery road conditions for the same accident. Benefits of applying a standardised slipperiness classification to all sources for road safety information were demonstrated: RWIS, accident reports and winter road maintenance reports (Paper VI).

Climatological factors should be considered when planning the layout of new road sections since both winter road maintenance and accidents are affected by adverse weather. A GIS model of relative variations in local climate is presented in Paper I.

The basic approach was to use three distinct weather types, each being characterised by local climate features. Geographical features with a risk for low temperatures were identified for each weather type. The frequency of each weather type in the study area was used to weigh the maps together. This GIS model for low temperatures proved to be comparable to a manual mapping performed for different road alternatives.

CONCLUSIONS AND DISCUSSION

Road slipperiness is very frequent in southern Sweden, which shows the importance of studying spatial and temporal variations in road climate. Many different types of slipperiness can form through interactions between several meteorological variables. GIS is a very useful tool for analysing spatial variations, presentation and integration of different sources of information, but it is little used within road climatology at present. This thesis has pointed out some of the many fields within road climatology, winter maintenance and traffic planning where GIS methodology can be an asset. The focus has been to implement knowledge about spatial and temporal variations in climate when evaluating road climate and road weather.

Figure 10 shows an approach that may be used when evaluating road climate in an area using GIS. The results presented in this thesis can be used for this purpose. The first requirement for a spatial analysis of road conditions is standardised and quantitative descriptions of RWIS station locations. The second requirement is a standardised description of road conditions. The descriptions not only need to be applied to RWIS data, but also to accident or WRM analysis.

Spatial variations in road slipperiness can be modelled by deriving information about topography and landuse using a GIS. Information with varying resolution is needed to understand variations caused by the regional and local environment. Different site-specific parameters are needed to describe small- and large-scale variations. The method of objective mapping, that combines statistical and GIS techniques, can contribute to an optimal siting of RWIS stations for a good slipperiness detection. Optimal choice of sensors could also be made with knowledge of which road conditions are frequent in an area. Relative costs or other measures of importance (e.g. accident risks) could be associated with each road condition (Figure 10). The last step in the road climate evaluation is implementation of the climate knowledge. The discussion below will follow Figure 10, starting with the descriptive landscape parameters in the same order as in the results section. The section dealing with station descriptions ends with a discussion on data quality. The last sections concern the applications of winter maintenance and road planning, ending with suggestions for further investigations.

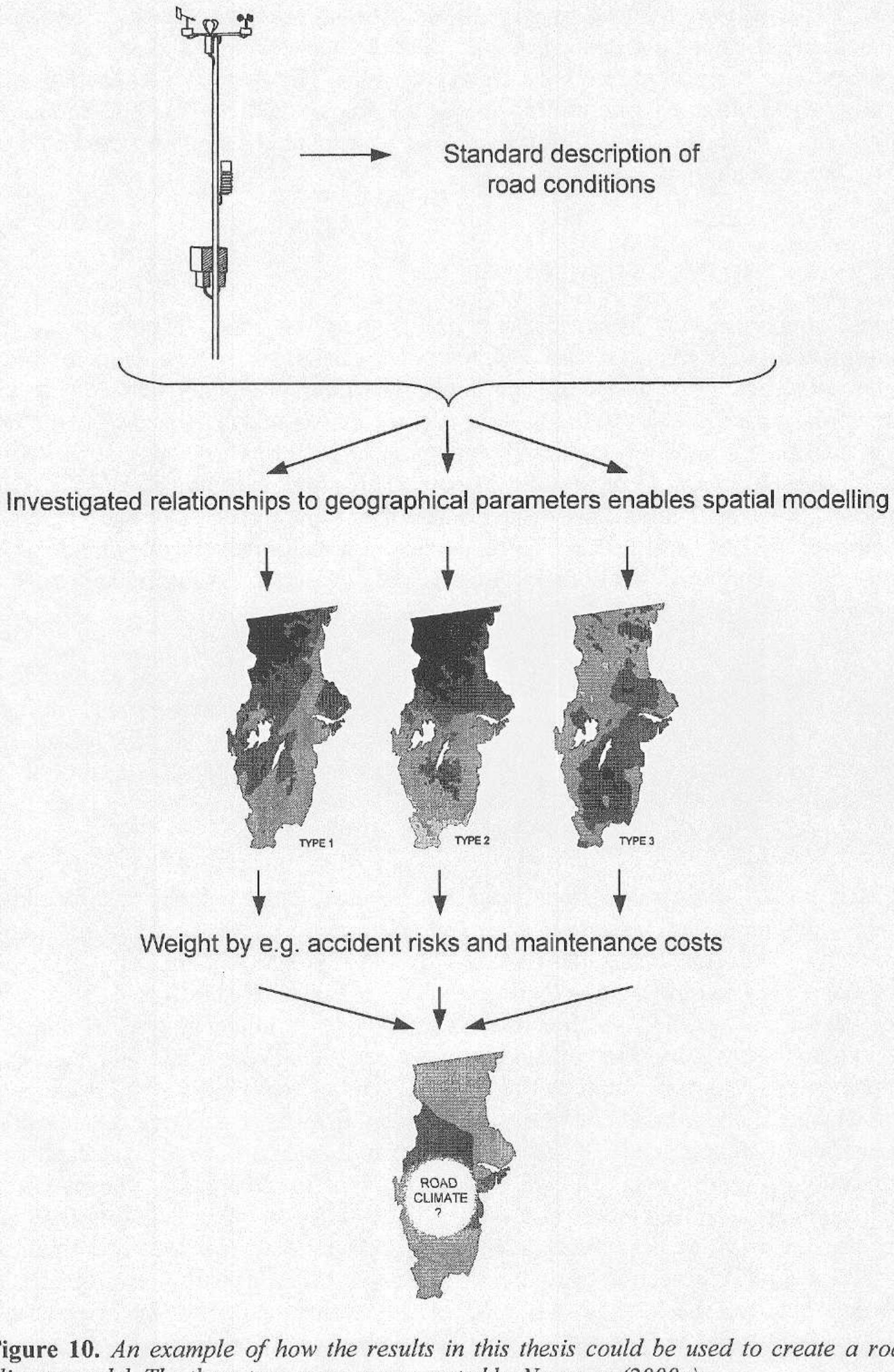


Figure 10. *An example of how the results in this thesis could be used to create a road climate model. The three type-maps were created by Norrman (2000a).*

Describing and optimising stations in the RWIS

It is necessary with a standardised description of station locations to be able to investigate the spatial distribution of road slipperiness, as previously described. There is usually a description of the surroundings for each station in Sweden but these can sometimes be subjective and difficult to quantify for use in statistical analysis or interpolations. A station location could, e.g. be described as "exposed" or "sunny low-point in forest". Digital terrain models and GIS can be used to derive quantifiable local parameters. Lapen and Martz (1996) point to the importance of automated techniques for objectively measuring topographic parameters from DEM:s and using the variables to define the terrain features in a quantitative way. Automated techniques also increase the possibility to reproduce the method for other datasets.

The work in this thesis has shown that many local parameters can be derived from DTM:s and be successfully used in road climate modelling. The results have increased the understanding of which parameters that influence formation of different types of slipperiness. The most useful descriptions were position and elevation of a site. They proved to explain much of the variation in road conditions. Interpretations of physical relationships are clear for these parameters. Areas at a higher elevation or further north generally have lower temperatures and a larger fraction of the precipitation falling as snow relative to rain. The explained variation of around 60% is expected to increase with data from more winters and a model with higher resolution. Most importantly, each month and each slipperiness type should be modelled separately. For example, snowfall on a frozen road surface (Type 2) had a higher degree of explanation that the slipperiness total (Figure 6). Norrman (2000a) also found that separate types and months were more successfully modelled than the total slipperiness occurrence.

Some road conditions, for example hoarfrost, form very locally. For describing these variations, relevant topographical parameters have to be included and at a high resolution. The results presented in Figure 6 indicate that the 1 km resolution used in Paper III is too coarse to describe such variations. The results from the detailed temperature mapping during radiation frosts (Paper II) also show much small-scale variability. In a study of minimum temperatures, Blennow and Lindkvist (2000) also found that variations on a local scale were overshadowed by variability at the micro-scale. Amount of incoming direct solar radiation and the time of local sunset due to topography can be used to model small-scale temperature variations (Paper II).

Relative relief or shelter can be successfully included for the modelling of road climate variations on different scales (Paper III). Several other authors have found high correlations between relative relief and temperatures (e.g. Tabony, 1985 and Carrega, 1995). Relationships with precipitation was found by Basist et al. (1994), who used exposure in specific directions and it proved to be most important during winter. From the examples presented in this thesis, it can be concluded that the exact method for calculation of a shelter parameter is not so important as long as it is represented and that the scale is adapted for each purpose.

The important effect of shading or sheltering from trees can never be fully represented even if digital terrain data can have a high resolution. SVF has been correlated to road surface temperatures by e.g. Bärring et al. (1985), Gustavsson (1999) and Karlsson (2000). A sky view description for each RWIS station can be retrieved by using the new method presented in Paper IV. Quality of the fish-eye image is important, depending not so much on the resolution as the brightness difference between sky and non-sky areas. The photos should therefore be captured on overcast days. It would be very useful with such a description and not too labour intensive compared to earlier methods. If the northerly direction was indicated in each image, it would be possible to calculate wind shelter, shading or incoming direct radiation at any time. Some additional method has to be implemented to enable interpolation along a road. For example, the continuous methods of measuring SVF presented by Postgård & Nunez (2000) or Chapman (2000). Thermal mapping, which measures the effects of sky view, is the conventional method that also could be used.

A generalised model of sky view could be achieved by adding the vegetation height to a digital elevation model (Blennow & Persson, 1998). SVF for the road can then be calculated from the DEM according to Dozier & Frew (1990). Accuracy of the results depends on the accuracy of the vegetation heights. Blennow & Persson (1998) measured vegetation height along a road with an inclinometer and a tape measure, which is not feasible for larger areas. Kawashima et al. (2000) correlated surface air temperature with NDVI (normalised difference vegetation index) obtained from satellite imagery. NDVI describes the vegetation density and could therefore be used as a general measure of shelter. For road weather purposes, i.e. nowcasting and forecasting, the most detailed methods are needed, like fish-eye images.

Ninyerola et al. (2000) modelled temperature and precipitation separately with a similar GIS model to that presented in Paper III. The parameters altitude, latitude, continentality (distance to coast), solar radiation and cloudiness were included and gave high coefficients of determination, up to 0.9. A combination of parameters, like the classified slipperiness used in this thesis, seems to be more difficult to model. However, it is crucial to road climate studies, since a specific road condition form through the interaction of weather variables (as discussed in Paper V).

Road weather data used as model input needs to be of high quality. For data analysis purposes, it can be problematic that stations are placed in a wide range of environments. An objective station description would give more control on road climate studies utilising RWIS data. In Paper III, stations placed on bridges were excluded from the analysis to minimise erroneous influence from stations in extreme environments. Homogeneity tests of the station network would be useful for future analysis.

Good quality data is also required to enable classification of different slipperiness types. An important and often used criterion in road weather analysis is 0°C, both for air and road surface temperatures. Further investigation and sensitivity analysis is needed considering sensor accuracy and other errors that may occur, for example variations in placement of the road surface temperature probes (Bogren et al., 2000). A critical examination of the road slipperiness classification into ten different types is found in Norrman (2000a & b).

One important issue that has not been taken into account, when defining road conditions, is salt on the road surface. Salt is used in many areas to improve (i.e. to change) road conditions. Meteorological definitions of slipperiness would then have to be modified, since the freezing point is changed. Unfortunately, this information is not available from the RWIS at present.

Optimising winter road maintenance

Planning of winter road maintenance can be optimised with knowledge about which road conditions are most common in different areas. Duaas et al. (1994) stated that a methodology for distributing funds for winter maintenance must acknowledge and fully compensate for the great variation in winter conditions. The maps and information presented in this thesis can be useful in this context. Different types of slipperiness require different types of action. Slipperiness maps showing spatial variation could be grouped into new maps according to maintenance methods. They could also be grouped or weighted against each other depending on how much it costs to perform a required action (Figure 10).

Another application of detailed road climate maps, is routeing of winter gritting vehicles. Eglese (1994) presents a mathematical model for finding the best route. Climate is represented as the expected number of days in the year when gritting is required. It is important to evaluate the effect of maintenance continuously, since reducing the number of accidents is one aim for the road administration, (Paper VI).

The advantage with the presented accident analysis is the time resolution. Data was synchronised so that we know that the accident actually occurred during a specific weather condition. Andreescu & Frost (1998) did not correlate data in this way and noted that it was a disadvantage in their study. They used monthly data and longer periods. One constraint with the method presented in this thesis, however, is the small-scale variability. Road condition at the accident site might not correspond exactly to the condition registered at the RWIS station. On the other hand, there is a large random component in accident occurrence (Andrey & Olley, 1990; Fridstrøm et al., 1995 and others), so data from nearby stations should be accurate enough for these purposes.

GIS a tool in road climate

A general map of road climate and its effects in an area have many applications. Winter indices can describe the severity of winter climate. Even if they describe events that affect e.g. maintenance costs, they do not provide a complete road weather evaluation. A more relevant investigation could be performed by classifying data into different slipperiness types that could develop. Together with standardised descriptions of station locations, GIS enables a combination of other factors like road accidents and WRM costs (Figure 10). A highway safety information system database in the U.S.A. is currently being integrated with GIS (Smith et al., 2001). It contains many types of data connected to roads, for example accident locations and road-bed material. In a GIS, each road segment can be associated with any desired information, also on climate. The authors describe the benefits of using GIS in road safety analysis compared with traditional methods.

Climate should also be a more important factor when planning new road stretches, considering the costs associated with future accident risks and maintenance requirements. It has been shown that accident risks varied considerably between ten different slipperiness types (Paper VI). Since different types have a different impact on the road climate, they should be weighted accordingly in a road climate evaluation. It is important to concentrate efforts on the most hazardous situations. For example, each accident risk can be multiplied with slipperiness maps showing the distribution of that specific type. The separate maps could then be summarised to a final map that can be used as decision support in the planning process (Figure 10). Maintenance costs could also be included in the same way. The most maintenance requiring road conditions could be assigned higher weights. By being aware of the most problematic conditions, the most accident-prone and maintenance requiring areas can be avoided beforehand. The environment could also benefit from climate considerations when planning maintenance routes and routing alternatives for new roads. It is now a common goal to reduce the amounts of salt used for de-icing.

Development of road slipperiness is a complex subject with interactions between several meteorological processes. Dynamical studies at high resolution, both spatially and temporally, are needed to understand variations caused by regional and local environment. This thesis emphasises the importance of studying the combined effect of meteorological variables on road conditions. Previous studies have been made on separate variables and few stations or in limited areas. With map sequences presented in a GIS, it is possible to follow weather changes, e.g. front passages, and thereby improve forecasts and slipperiness prevention.

Future research

Further investigations of relationships between weather and road conditions could improve forecasts and the general understanding of slipperiness formation. The synoptic situation could be classified with e.g. cluster analysis and then compared with the road condition. This method would make the interpretation of relationships between topography and climate much easier. GIS is a tool that could be used in such studies to display slipperiness distributions. Climate change discussions can be applied to road conditions if the synoptic- and local- scale interactions are more thoroughly understood.

Thermal mappings are available for many roads in Sweden. This data could be integrated in investigations of site-specific parameters and road slipperiness. The present interpolation methods lack information about micro-scale variations.

Homogenity tests of the data from the RWIS would improve the quality and enable analysis of longer time series. Data from more winters are needed to verify the strength of the relationships shown in this thesis. It is also necessary when making models operational or to make useful evaluations of road climate in an area. It is important to consider sensor accuracy and consistency, especially when classifying data into different road conditions. The defined road conditions would need to be tested against observations for verification. To investigate how slippery they are, friction measurements could be performed.

Neural networks could be used in road climate research. For example, it could be trained to recognise spatial patterns of specific slipperiness types in a region. This type of study could also be integrated with knowledge about synoptic situation and local patterns.

For the purpose of planning winter maintenance or the layout of new road stretches it would be useful to co-operate with economists. The approach would enable analyses to see the actual cost-benefit of considering climate.

Information and guidance about prevailing road condition to the public could lead to a change in driver behaviour. Research on this subject is already progressing with tests on variable message signs and recommended speed limits. Road weather information could also, to a larger extent, be broadcasted via radio (RDS: Radio data system) or mobile telephones. More research on road weather is needed to make this information correct and reliable.

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