

THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

ENERGY EFFICIENCY IN WINTER ROAD MAINTENANCE  
A ROAD CLIMATOLOGICAL PERSPECTIVE

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“Driving in the ice isn’t so bad...  
the problem I have is more with the stopping”

*Maxine*



## ABSTRACT

Practices in winter road maintenance are dependent on the climate and weather impacting roads and the road users' requirements. As in many other fields of transportation, it is of interest to investigate fuel efficiency potentials in the different aspects of the road maintenance area. The main focus of this thesis was on investigating energy use in winter road maintenance activities in southern Sweden. It is crucial to understand which parameters are of the largest significance in slipperiness, as well as to investigate the weather information that the operations are based on, since the climate is the reason for requiring winter road maintenance in the first place. The original energy use needs to be set, to be able to know whether efficiencies are made. In this thesis, two approaches were taken to understand if existing fuel consumption models for heavy-duty vehicles could be applied within winter road maintenance or whether in-vehicle fuel data such as data from vehicle manufacturers should be used instead. Finally efficiency potentials were explored with the use of a route optimisation programme for winter road maintenance practices.

The climate data analyses showed that frost warnings are the most common type of slipperiness in the southern parts of Sweden. If such warnings were to be under- or overestimated, it could have a large impact on the energy used, since unnecessary slipperiness treatments could be performed. Furthermore, the mobile water depth measurements indicated that it is possible to detect differences in water depth along roads and that exit ramps could be interesting in terms of changed treatments, since the water depths were quite large on those ramps. From the use of the fuel consumption model included in the Swedish National Road and Transport Research Institute, or VTI, winter model, it was concluded that anti-icing would not be energy efficient in terms of traffic energy use, since drivers tend to drive at higher speeds on salted roads. Snow density and amount would however, impact fuel consumption, which is why the removal of snow could save traffic energy use.

The best method to evaluate energy use during winter road maintenance was the use of in-vehicle data. The existing fuel consumption model used in this thesis, underestimated the fuel use, which implied that the energy use in winter road maintenance practices depends on other aspects than what was stated in the model calculations. Such other aspects seemed to be the weather and way of work that in turn demand significant changes in speed. Changes in speed was also regarded as a potential efficiency measure, as the velocities of the heavy-duty vehicles seemed on average to be below what was estimated as the most fuel-efficient speed for this type of vehicle. Using the route optimisation programme further put a way for evaluating efficiency potentials. It was shown that installing underground heating systems or road surface-installed salt spreaders at strategic locations could save fuel use, as would changing operations from sanding to salting, as well as adding extra materials depots during the sanding operations. The analysis also indicated that additional materials depots for anti-icing measures would not result in any change in fuel use.

The thesis has contributed to finding ways to evaluate energy use and efficiency potentials within the field of winter road maintenance, where the main issues to consider are what energy road maintenance vehicles use and how road maintenance practices are planned. New measuring techniques and improved accuracy in the weather information system can contribute to reducing the use of both vehicles and fuel.

Keywords: Road climate, RWIS, frost, snow, fuel consumption, heavy-duty vehicles, route optimisation programme, energy efficiency, winter road maintenance

## PREFACE

This doctoral thesis is based on the following appended papers which are referred to in the text by Roman numerals.

- I. Riehm, M., & Nordin, L. (2012). Optimization of winter road maintenance energy costs in Sweden: a critique of site specific frost warning techniques. *Meteorological Applications*, 19(4), 443-453. doi: 10.1002/met.275. *Reprinted with permission from the journal. L. Nordin participated in the planning, data analysis, discussions and writing of the paper.*
- II. Nordin, L., Riehm, M., Gustavsson, T., & Bogren, J. (2013). Road Surface Wetness Variations: Measurements and Effects for Winter Road Maintenance. *Journal of Transportation Engineering*, 139(8), 787-796. doi:10.1061/(ASCE)TE.1943-5436.0000546. *Reprinted with permission from ASCE. L. Nordin participated in the planning, did most of the writing, performed data analysis and some of the field work.*
- III. Nordin, L., & Arvidsson, A. K. (2014). Are winter road maintenance practices energy efficient? A geographical analysis in terms of traffic energy use. *Journal of Transport Geography*, 41(0), 163-174. doi: <http://dx.doi.org/10.1016/j.jtrangeo.2014.09.004>. *Reprinted with permission from the journal. L. Nordin initiated the paper, did most of the writing and data analysis.*
- IV. Nordin, L. (2015). Can fuel consumption during anti-icing or snow removal activities be realistically modelled using an existing model for heavy-duty vehicles? Submitted to *Transportation research Part B: Methodological*.
- V. Nordin, L., Blomlöf, L. (2015). Using a route optimisation programme to estimate efficiency potentials in winter road maintenance. *Submitted to International journal of environmental Science and Technology. L. Nordin initiated the paper, did climate analysis and the writing of the paper.*

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Nordin, L., Gustavsson, T., Bogren, J., Chen, D., Li, H., & Tian, H. (2011). ChiWi - a road weather index for China. *International Journal of Climatology*. doi: 10.1002/joc.1870

Conference proceedings and abstracts

Nordin, L., 2010, Method for understanding where winter maintenance could be more energy efficient, Proceedings of 15<sup>th</sup> International Road Weather Conference, SIRWEC, Quebec City, Canada.

Nordin, L., 2012, Energy use within winter road maintenance operations, 16<sup>th</sup> International Road Weather Conference, 23-25 may, 2012, SIRWEC, Helsinki, Finland.

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## **2. PAPERS I-V**



## Summary

“When you’re curious, you find lots  
of interesting things to do”  
*Walt Disney*

## INTRODUCTION

### AWARENESS OF THE ENVIRONMENT

Humans have always interacted with the environment surrounding them. For survival, it has been necessary to use the resources the environment can give. Throughout our history, we have been good at using these resources, learning about our environment and about ways to extract as much from it as possible. By using our environment, we have changed it; we have altered the landscape and have been affected by and have had to adapt to the natural changes it has thrown upon us. We have used its resources and investigated how it works, to create tools and build houses and cities, which has altered the surrounding landscape and natural processes around us. We have built roads for people, wagons and cars, and even more cars and cargo. We have used fossil fuel to fuel our cars and build our equipment, and we have started to overuse the resources in our environment. It is clear that since the 1970s, we have been using more oil than we have been discovering (Smil, 2005), and as reviewed by Bardi (2009), some scientists have suggested that we have already passed the peak in production of crude oil. Also, de Almeida and Silva (2009) predicted that peak oil would happen sometime between 2008 and 2012. They further compared their results to those of the best-known experts in the field, most of whom proposed a peak date between 2010 and 2015. During the oil crisis in the 1970s, it became clear that the oil resources would not last forever. In only a few months, oil prices quadrupled, which affected the economy by decreasing oil use and increasing capital stock and the marginal cost of production (Murphy and Hall, 2011). However, after this first decline in the use of oil, consumption soon increased again (Murphy and Hall, 2011; Smil, 2005). This awakening to the finiteness of the oil reserves became the start of a search for more energy-efficient ways to use energy. The years between 1950 and 1970 had also been a time of some huge environmental disasters, such as the great London smog, the Love Canal disaster and the DDT threat (Scholz, 2011), which opened people's eyes and launched the environmental movement. People became aware of how their actions could affect the environment, and the quest instead became to find ways to interact with the environment at a more sustainable pace.

This thesis was conducted in the field of *physical geography*, a field of study that includes all parts of the natural sciences concerning the Earth's life layer (i.e. the shallow zone of land and oceans that contains most of organic life; (Strahler and Strahler, 1992). Physical geography is the glue that connects the atmosphere, the lithosphere and the hydrosphere in relation to the biosphere, which means that physical geographers are interested in factors that affect the habitability of the life layer. They consider patterns of human interactions with such natural sciences as meteorology, climatology, oceanography, geology, geomorphology and plant ecology. Physical geography is an environmental science that is needed to understand how humans are affecting the environment around them, and climate change is therefore a large area of interest within physical geography.

To understand the ongoing interactions, changes and activities of the Earth's system, it is important to think in terms of flow of energy and matter, starting with the sun and the exchange of energy through the Earth and atmospheric layers. The system is a complex one in which the atmosphere plays an important part, not only as a reflector of harmful rays of ultraviolet (UV) light and space debris, but also as an absorber of heat. Through its atmosphere, the Earth absorbs about 70% of the solar radiation, while it reflects the remaining 30% of the radiation back into space. The atmosphere absorbs heat at different levels, with 3% being absorbed in the stratosphere and 17% in the troposphere; about 50% of the solar radiation reaches the surface where it is absorbed by plants, oceans or soil. The Earth's surface then re-emits the long-wave radiation back into the atmosphere, where some of it is absorbed in the clouds and some is emitted back towards the Earth's surface, while a percentage is re-

emitted out into space (Hartmann, 1994). Depending on the Earth's rotation, oceans and landmass distribution, the climate varies over the year at different latitudes and altitudes.

Describing the climate is done at different scales: the macro-scale for the climate in a region or a country, the meso-scale for the local climate in a city, forest or valley, and the micro-scale for a much smaller area, such as for a few metres close to or on the Earth's surface (Ahrens, 2009). At every level, climate change affects us and we affect it. The latest Intergovernmental Panel on Climate Change (IPCC) assessment report shows that humans are influencing the climate by the use of fossil fuels and by greenhouse gases emissions (IPCC, 2013). It is also clear that the changed climate will affect us, with more rain in some areas and drought in other areas, and with higher temperatures, melting ice caps and sea-level rises. We need to not only adapt to the changed climate, but also mitigate the use of fossil fuels; one such action is pursuing energy efficiency measures.

### TRANSDISCIPLINARITY OF THE THESIS

Collaboration between science and society has proven to be of value when seeking to understand changes in the human–environment system (HES) described by Scholz (2011). This way of working is referred to as *transdisciplinarity*. Scholtz described transdisciplinarity processes as collaborations involving industry, government, administration, other stakeholder groups and the public at large. Transdisciplinary processes are used, for example, when considering adaptation to and mitigation of climate change. This type of process provides society with the knowledge of how a new technique or the natural environment works at their interaction with society. It is also a way of lessening the gap between researchers and the general public, since transdisciplinarity helps put science into practice from the beginning. An ideal transdisciplinary process, according to Scholtz, involves scientists, decision makers (e.g. government) and stakeholder groups (e.g. representatives from the industry).

This thesis has in many ways been a transdisciplinary project, with *scientists* from the Road Climate Group at the University of Gothenburg meeting the *decision makers* from the Swedish Transport Administration and the *stakeholders* of the road maintenance contractor Skanska. It began with an open guiding question about how to find energy efficiency measures within a road maintenance contract area. As the project evolved and the parties met to discuss the case, it became clear that the project needed to be more limited. Since winter road maintenance is such a crucial part for traffic safety but also such a large part in the overall maintenance budget the project was narrowed down to only consider the winter road maintenance (WRM) aspects. So the new guiding question and hence the title of this thesis became: “*Energy Efficiency Potentials in Winter Road Maintenance – A Road Climatological Perspective*”

Following the steps proposed by Scholz (2011) in the HES framework, it was important to know the system boundaries and the interactions between the involved parties. The following section looks at the system known as the *road maintenance contract area*.

### ROAD MAINTENANCE CONTRACT AREA

To describe the system of winter road maintenance, let us start with the road users. They are the ones demanding safe and passable roads, which in winter means being snow- and ice-free and not slippery. The authority with overall responsibility for the national roads is the Swedish Transport Administration (STA). The STA works within the current political decision-making structure, since the Swedish Parliament decides on the goals that the STA should strive to achieve. Many of the goals are drawn from different policies, directives and influences from such international coalitions as the European Union (EU) and the United Nations (UN). Among its policies, the STA has an environmental policy that is aimed at reducing the impacts of the road transportation system on the

environment (STA, 2012). The primary target areas of this policy are greenhouse gases, air quality, noise and water catchment.

The roads are divided into contract areas containing approximately 1,000 km of roads of different sizes and variations in annual average daily traffic (AADT). Each of these contract areas is outsourced via a public procurement process. The STA sets up the contract concerning the rules and regulations for how the maintenance in each area should proceed. The contracts are also a way for the STA to control such environmental aspects as restrictions in the use of different chemicals, oils and other fuels, and the types of tires used (STA, 2012), all in line with the primary target areas.

## THE CONTRACT

A contract containing information on how the maintenance area should be kept and what is required to keep the roads open and safe is set up between the winning contractor and the STA. Most contracts run for a period of 6 years. Within each contract, a special chapter on winter road maintenance describes the demands and the time limits, as well as the start criteria for the snow removal and anti-icing activities (STA, 2014). Awareness of the environment is also included in the contract, since the amounts of chemicals and sand used in winter maintenance need to be reported to the STA every month. All winter maintenance vehicles should have GPS-oriented equipment that regularly sends information on the maintenance activities, as well as the amount of salt spread and the start and stop times for a specific maintenance activity. The STA has also decided on a salt strategy prompted by the general willingness to reduce salt usage, as well as from the EU directive on water (Ölander, 2004). In its strategy, the STA strives to reduce the salt used on the roads in a number of ways; however, salting is still the most effective and economical way to keep the roads clear and safe.

## WINTER ROAD MAINTENANCE

The road standards are set according to the AADT, where the largest roads have more than 16,000 vehicle passes every day and the smallest have fewer than 500. There are five road classes within the winter road maintenance regulations, with class 1 roads such as motorways being the largest and most heavily trafficked. Class 1 to 3 roads should be clear of snow and ice at all times during winter, but with slightly fewer time constraints for class 3. To be able to keep roads clear of snow and ice, salt is used in a preventive manner, meaning that dissolved salt (brine) in a solution of 77% water and 23% NaCl is spread when early warnings of freezing are received. This type of action is generally called *anti-icing*, since it entails spreading the brine to lower the freezing point of the road surface by a few degrees and thereby prevent ice from bonding to the surface. It takes less energy to lower the road surface's freezing point than it does to break an existing bond of ice (Boselly, 2001). Breaking such bonds between the ice and the surface demands much more chemicals and is called *de-icing*. More about these concepts is given in Papers I and II.

During snowfall events, the larger roads are treated with a practice that combines snow removal (ploughing) with de-icing. Hence, the vehicle is equipped with one or more ploughing blades as well as salt solution canisters. The smaller class 4 and 5 roads, are however, only ploughed during snow events, and in the case of slipperiness are sanded instead of being anti-iced or de-iced. Sanding a road surface at temperatures close to zero normally yields a sand spray-off time of approximately 200 vehicle passes (VTI, 2014). In practice, this would mean that after about 200 vehicle passes, more sand needs to be applied. In the northern parts of Sweden, the temperatures in wintertime are significantly below freezing, and keeping such roads clear of snow and ice would demand too much salt. Studies have shown that it is possible to use salt for temperatures down to -15°C (Ljungberg, 2001). However, the STA indicates that even though it would be possible to use salt for melting snow

down to  $-18^{\circ}\text{C}$ , it would demand too much salt; hence a limit of  $-6^{\circ}\text{C}$  is set for Swedish practices. According to the Salt Institute in the United States, salt brine could be used down to temperatures of about  $-9^{\circ}\text{C}$  (SafeWinterRoads, 2015). Roads in the northern and mountainous parts of Sweden are kept “winter white”, meaning that snow and ice are packed on the road surface, building up the surface itself. To sand on such a surface with a method called *hot-sanding* would increase the number of vehicle passes before the sand is sprayed off, since the heated sand melts into the packed snow. However, no such area was investigated for this thesis, and this method is not discussed further.

As the anti-icing is performed before slipperiness occurs, it requires personnel round-the-clock from October 1 until April 30. Since maintenance during the rest of the year demands far fewer personnel, most contractors hire subcontractors to handle maintenance activities, especially during winter. The subcontractor is also part of the system as they are the ones actually performing the activity which is the result of a maintenance decision taken by the contractor. Should it be decided that drivers need to drive in a more eco-friendly manner, they would be the ones who would be most directly affected by such a decision and would have to change their way of working. Subcontractors are often very aware of their work environment – in other words, the road – and know exactly which parts of the road are likely already frozen if they are called out too late. They are also the ones who would be aware of a change in fuel use resulting from a shift in practice, and if so, would be spurred on to save more money with less fuel use. In the end, their performance is what will ensure the roads are safe and passable. This leads us back to the road users and hence completes the system description. The next part of understanding the HES is an analysis of the environment that sets the limits for and regulates the whole concept of WRM: the road climate.

## ROAD CLIMATE

### *FROST AND ICE*

Frost is the road weather parameter that is of largest concern in this thesis. It is also the most common cause of road slipperiness in southern Sweden (Eriksson, 2001; Norrman et al., 2001; Riehm and Nordin, 2012). It is formed at temperatures below freezing, when the road surface temperature falls below its dew point temperature, which usually happens during cold, clear nights when the road is cooled by emitted infrared radiation.

The larger the difference between surface temperatures and the dew point temperature, the larger the amount of frost (Karlsson, 2001). Frost is hence dependent on surface temperature and the net flux of water vapour onto the surface. These two parameters are also dependent on wind speed (Hewson and Gait, 1992). If the turbulence it brings is not too strong, the wind can help by mixing the air layers right above the road surface with more humid air from layers higher up. This way, more frost can form; however, if the turbulence is too strong, the air layers might be too mixed, leading to increased temperatures above the dew point temperature (Jordan and Smith, 1994). In the same manner, traffic flow may influence the frost formation indirectly, since turbulence from traffic may warm the road surface by mixing the air with warmer, overlying air layers, as well as by producing friction (Thornes, 1991) and traffic heat fluxes (Chapman and Thornes, 2005). As frost is formed when heat is emitted through long wave radiation, objects that are colder than the air can freeze even though the air temperature is above freezing.

Ice form at temperatures below freezing when there is water on the road. It seems to be the most slippery around temperatures close to  $0^{\circ}\text{C}$  (Chapman et al., 2001). Knowing where there is water on the road is crucial when determining where roads might freeze.

### *ROAD SURFACE WETNESS*

Road surface wetness is another important parameter when it comes to slipperiness of the roads. A wet road stretch is usually also colder than a drier road owing to increased loss of latent heat (Chapman and Thornes, 2011). This makes it crucial within winter road maintenance to know about road surface wetness, since this parameter indicates where the road might freeze. It is also crucial to know how much salt would be needed to lower the freezing point to the required temperature, since the water might dilute the salt applied. Road surface wetness is a dynamic parameter that depends on the volume of splashing from the passing traffic, as well as on the weather, in terms of not only precipitation, but also dewfall, evaporation and snow melt. Vehicles might also contribute by leaking water from exhaust pipes and by carrying moisture for several hundred metres as they pass (Chapman and Thornes, 2011). Other factors influencing the wetness of a road are the road surface characteristics, such as macro- and micro-textures and material porosity where water can accumulate. Jansson et al. (2006) also specified the road surface heat balance as a factor, which would include influences from the surrounding landscape and topography.

### *SNOW*

Snow falls when air temperatures are around freezing and below. Temperatures, amount and densities of the snow will have various types of impact on the traffic. Accident risks increase during a snowfall. Andrey and Mills (2003) showed that the risk of accidents increased by 100% during a snowfall, but these accidents are usually less severe. The colder the snow, the more suspendable by wind the snowflakes are because of their smaller sizes and less branching structures (Perry and Symons, 1991). This could lead to snow drifting, which in some areas could become quite troublesome. The snowfall will affect the traffic speed, as shown in a study by Sabir et al. (2008) in which speeds were reduced by 7%. The intensity of the snowfall reduces the travelling speed by between 4% and 13%, as indicated by Maze et al. (2005) and Tsapakis et al. (2013) found that of the various types of weather they studied, snowfall would cause the largest time delays.

### *ROAD WEATHER INFORMATION SYSTEM*

The contractor uses information from the Road Weather Information System (RWIS), together with weather forecasts and their own observations. The most substantial information comes from the RWIS with its close to 800 outstations in Sweden. The system was first introduced in the 1980s. It consists of weather stations positioned at the roadside to measure surface and air temperature, precipitation in amount and type, humidity and wind. Some stations also have a remote sensor of some kind, often a surface sensor, which is installed on a nearby bridge or in a shaded area, for instance. The common idea with the system was to position these weather stations at locations that would freeze first (Gustavsson and Bogren, 2007). Such locations include shaded areas where the road surface can be many degrees colder than surrounding sunlit areas; in addition, proximity to water can bring humidity to the road, thus causing it to freeze. Bridges are usually close to water and are cooled not only from above but also from beneath, which makes them more prone to freezing. Cold pools are other typical areas that after sundown can decrease in temperature more rapidly than surrounding high lands as a result of cold, dense air flowing downwards following the topography.

### *ENERGY OF THE WINTER ROAD MAINTENANCE SYSTEM*

For this thesis, the energy use within the road maintenance contract area was limited to mainly considering the energy use of maintenance vehicles, since they are the ones performing the operations. Some consideration was also given to ordinary traffic, since road users are the ones demanding maintenance activities to start with. Other types of energy use such as in street lighting or in roadside construction were not considered, since such aspects do not concern the actual maintenance activities.

As the efficiency potentials examined for the thesis were focused on maintenance vehicles and their use, it is the contractor and the subcontractor who might be the ones looking to save on energy use and perhaps labour and costs.

## OBJECTIVES OF THE THESIS

The overall objective of the thesis was to find ways to realise energy efficiencies of winter road maintenance. To be able to do this it was important to understand which factors that decides about when maintenance operations should occur. The first part of the thesis will consider the understanding of the weather information that is used in the system. The second part will consider the energy use and the third part will suggest potential efficiencies. The specific objectives are described here.

### PART I – UNDERSTANDING THE WEATHER INFORMATION SYSTEM

The road weather information system is the most crucial tool for planning when to perform winter road maintenance. It is therefore important to know how the system works because by knowing this it is possible to realise potential inaccuracies that might lead to false warnings. Even though the system is good at detecting early frost warnings there is still a gap of information of what happens in between stations. The first two specific objectives are presented here.

- To understand how the information system works and realise how inaccuracies can affect the efficiency of winter road maintenance. Paper I
- How could new measuring techniques add to increased information and potential efficiency? Paper II

### PART II – THE ENERGY USE OF THE WINTER ROAD MAINTENANCE SYSTEM

- How could weather parameters influence the fuel consumption of traffic and winter road maintenance? Paper III and IV
- How should energy use within a maintenance area best be regarded – using measurements or by modelling? Paper IV

### PART III – ENERGY EFFICIENCIES IN THE WINTER ROAD MAINTENANCE SYSTEM

- To suggest energy efficiency potentials (Papers I, III, and IV) and to propose a method for evaluating possible efficiencies within winter road maintenance (Paper V).



## STUDY AREAS

The investigated study areas in Papers I, II, IV and V of this thesis, are located in the southern parts of Sweden, as shown in Figure 1. Paper I addressed frost warnings in the entire Västra Götaland region. Paper II concerned the maintenance area of Västerås, marked with a black box, while maintenance area Trollhättan, within the green box in Figure 1, was used in both Papers IV and V. The Linderödsåsen route, in the maintenance area with the same name, is marked with a blue box furthest to the south, and was also a focus for Paper IV. Paper III looked at different overall regions of Sweden based on the model used in the study and therefore is not shown in Figure 1.

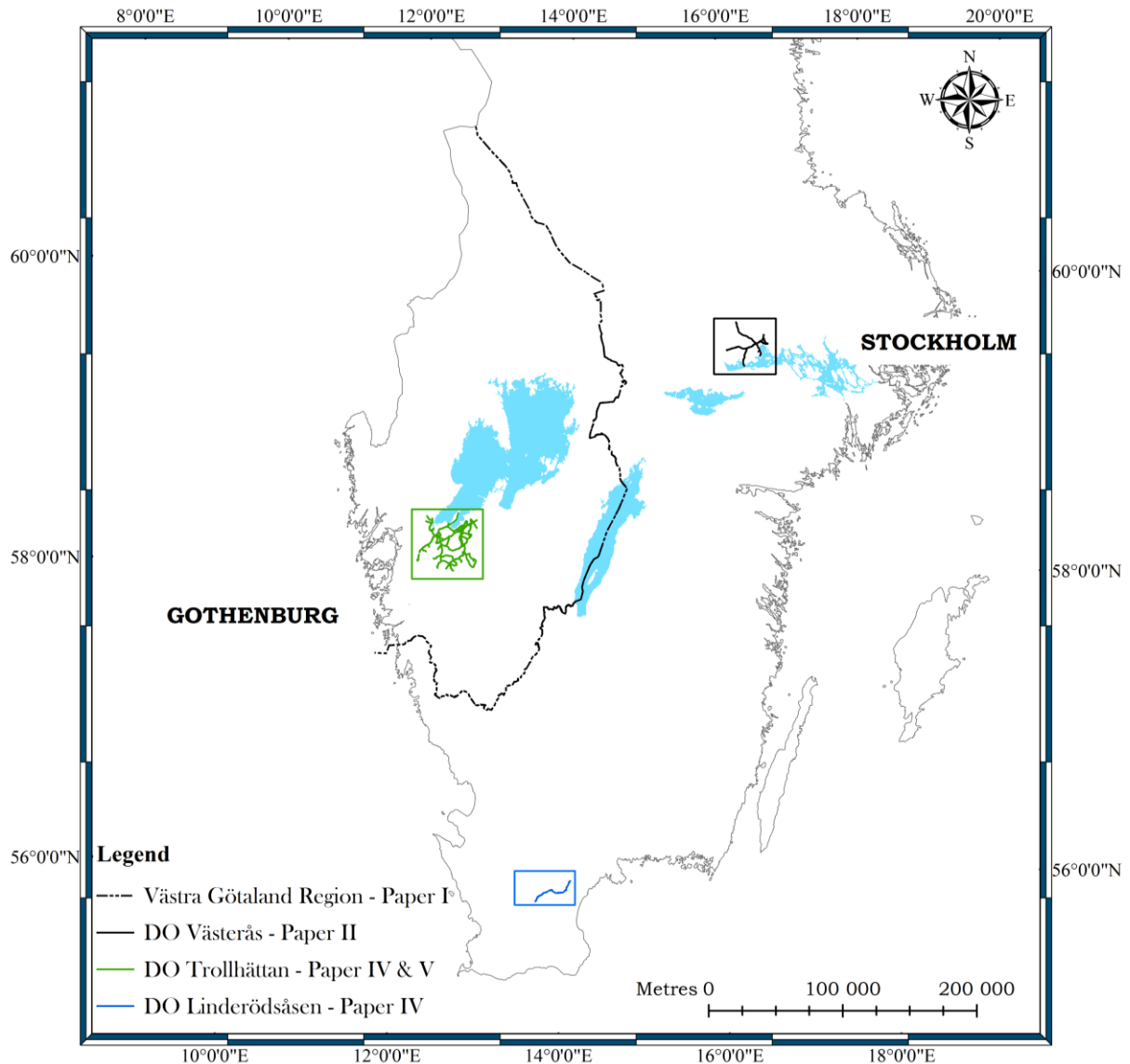
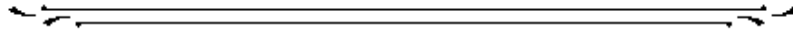


Figure 1. The study areas of the different papers are shown in the figure. The legend indicates which area is presented in which paper.

The subsequent parts of this thesis are structured according to the objectives, with the first part considering the understanding of the weather information system regarding filling the gaps in aspects that concern energy use. The second part examines aspects of how to measure the energy use in the system, in terms of both traffic energy use and a maintenance vehicle perspective. The third and final part concerns different efficiency measures that have been discussed in the papers included in the thesis.



## PART I – UNDERSTANDING THE ROAD WEATHER INFORMATION SYSTEM

Road surface slipperiness depends on temperatures and the presence of water or humidity on the roads. This section will describe different ways of detecting these parameters and discuss how the tools used could be affecting the winter road maintenance in terms of fuel consumption.

### FROST WARNINGS

Indications from other studies as well as previous analysis of the RWIS data from some stations were that the RWIS, even though fairly dense station-wise, did have some difficulties in reporting data accurately. What would the implications be if the measurements were erroneous, since the RWIS is used at so many different levels of practice? Paper I gives an overview of the system and an analysis of one of the most common parameters when it comes to slipperiness: the frost warnings.

### ROAD WETNESS

The second issue explored for this thesis concerned the wetness of the roads. This is a crucial factor when it comes to road slipperiness and WRM, since the salt spread on the roads will be diluted by the amount of water on the road surface. Since road wetness is also such a dynamic parameter, measuring it at the different RWIS stations is of little value, plus the factor is too difficult to model. However, with the new types of sensors connected to GPS systems, it is much easier to install sensors on the maintenance vehicles, to measure such parameters as they travel. The research described in Paper II offered the opportunity to test one such sensor and investigate whether such information would be useful in adapting the salting rates to fit the amount of water on the road surface. This way, it would be possible to gain a more uniform freezing point of the road and in the long run possibly save salt and mitigate the effects on the environment.

## METHODS – PART I

There are different methods to apply in seeking to understand the slipperiness of the system. Much has already been investigated, from the micro-heat and humidity fluxes that control frost formation described by, for example, Chen et al. (1999); Karlsson (1999), Almkvist et al. (2005) and Baad and Brodersen (2010), to regional thermal mapping that indicates the temperature variations along a road (Thornes, 1991). The RWIS has been in use in Sweden and Europe since the 1980s. In Sweden, it is frequently used both by practitioners in deciding when to take action against slipperiness and by authorities in regulating financial compensation for contractors. Scientists also regularly use the system for research. Even though sensors have been upgraded or replaced and more stations have been installed, the system's way of operating has remained the same, permitting a good historical database,

from which it is easy to obtain data and get a general overview of a region's climate. In Paper I, frost warnings from the system were analysed in terms of accuracy.

### FROST WARNINGS – DATA ANALYSES

The system sends frost warnings when the road surface temperature is less than +1°C and at least 0.5°C less than the dew point temperature, which is, in turn, automatically generated from the air temperature and relative humidity. Frost information from 166 RWIS stations for the three winters between October 2007 and April 2010 were analysed in Paper I, based on what impacts erroneous information would have on the accuracy of the system's ability to predict frost. First, the overall frost distribution was analysed to detect anomalies between stations in the 23,500 km<sup>2</sup> large region of Västra Götaland in the southwest of Sweden. Second, stations with an additional temperature sensor were analysed to investigate if there were differences in frost warnings between using the standard installed sensor and using the additional sensor. The effects of possible missed warnings as well as false warnings were then evaluated.

### ROAD WETNESS – MOBILE MEASUREMENTS

The RWIS has long been used as a tool for understanding the road conditions. However, a new increasingly common approach in winter road maintenance and research is to measure along the roads using mobile measuring tools. Haavasoja et al. (2012) tested a road condition–monitoring sensor on a car, to detect road conditions along the roads. New on-vehicle sensors measure road conditions such as dry, moist, wet, icy, frosty and snowy (Juga et al., 2012). Since the sensors often are connected via GPS, it is possible to detect exactly where on the road the various conditions appear, as was tested by Casselgren et al. (2012).

Road surface wetness was measured in Paper II, using a spectroscopy sensor (Infralytic GmbH, Marburg, Germany) mounted underneath a winter maintenance vehicle. The sensor was connected to a GPS system and a GSM phone modem. The maintenance vehicle operated on two major roads in the winter road maintenance district of Västerås, 90 km west of Stockholm, Sweden. Two field studies were performed, one along the highway E18 (26,000-46,000 AADT) running east to west through the city of Västerås. The other field study was conducted along road RV66 (9,000 AADT), which runs in a northwesterly direction from Västerås towards Surhammar. The field studies were conducted when the RWIS was warning of slipperiness. The aim of the studies was to determine whether water depth variations along the roads were large enough to be measured.

## RESULTS – PART I

### FROST WARNINGS – DATA ANALYSES

The frost distribution analyses performed in the study described in Paper I showed an interesting deviation in the data from the investigated stations. The number of warnings per station varied from 10 to 2,931 in the same region, where the mean is 608 warnings. The considerably lower number of warnings on some stations and the particularly high number of warnings on others indicated that information from such stations should be treated with care. The information, or lack thereof, might mean that there are no frost occasions at the station with 10 warnings, but more likely that there are some errors and hence some missing frost warnings. The station that showed substantially more warnings could either be prone to frost or be erroneous. There was no possibility of investigating each station for errors, but further investigations showed that 42 of the 166 stations had an additional temperature sensor. An additional sensor is often installed at a station that is considered more prone to

slippery conditions. The sensor may be installed in another lane or even a few hundred metres away in a shaded area or on a bridge. When the frost warnings are calculated, the worst case scenario is used, meaning that whichever temperature is the lowest will automatically be used in the calculations but with the same humidity for both cases. Figure 2 shows the distribution of the differences in temperature between the standard installed sensor and the additional sensor. The variations ranged from 15°C above the temperatures of the standard sensor to 5°C below.

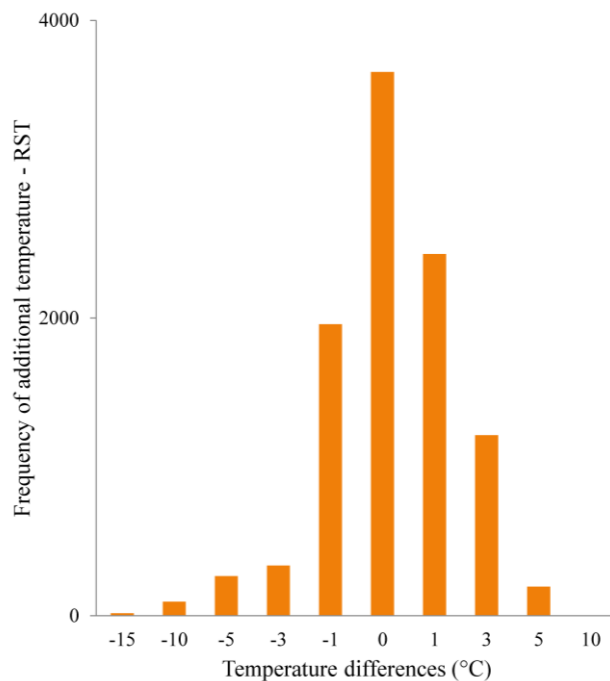


Figure 2. Distribution of the differences in half-hour temperature readings between the additional temperature sensor and the standard temperature sensor.

Figure 3 shows the differences in the number of frost warnings using the standard sensor compared with frost warnings using the additional sensor for each of the 42 RWIS stations with additional sensor. Most of the analysed stations showed discrepancies, both positive and negative. Such discrepancies strengthens the implications that the temperature can vary over very short distances and furthermore indicates that caution should be taken when considering frost warnings at stations with additional sensors. As shown in Figure 4, two of the stations gave more than 1,000 more warnings with the additional sensor, which implies some form of measuring error at these stations. If used in the maintenance operations, such errors could result in unnecessary treatment events.

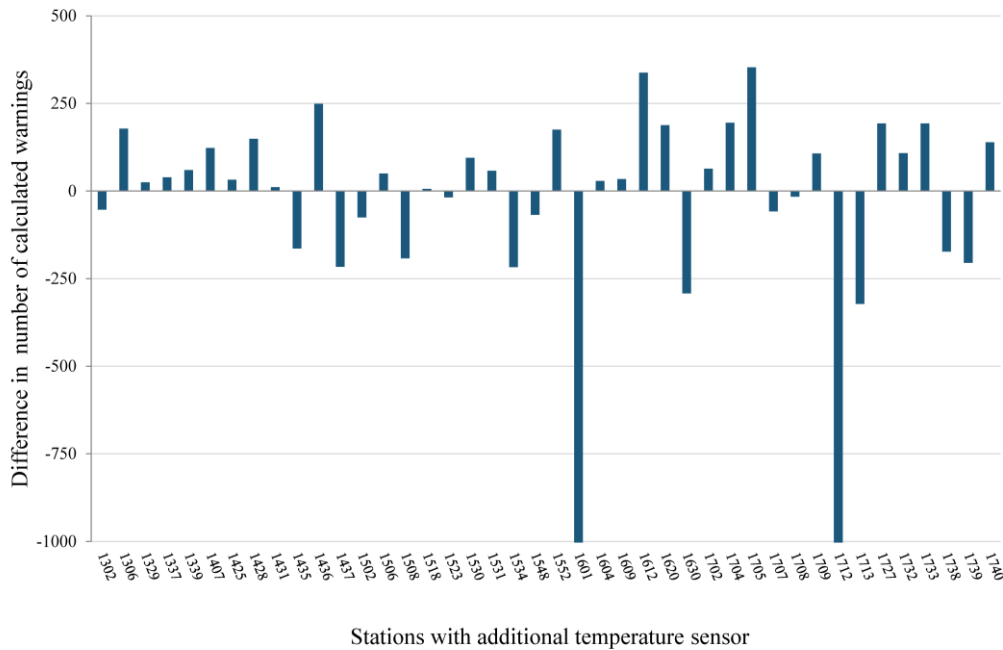


Figure 3. Differences in calculated frost warnings using the additional temperature sensor data versus the standard temperature sensor data.

As described earlier, the frost warnings are calculated as the difference between road surface temperature (RST) and the dew point temperature (DP) and have to be at least  $0.5^{\circ}\text{C}$ . When looking at these differences, it was clear that differences larger than  $4^{\circ}\text{C}$  were rare and most common were the differences of between  $0.5^{\circ}\text{C}$  and  $1^{\circ}\text{C}$ . The larger the difference, the more dew or frost was deposited. Considering that there could be up to a  $2^{\circ}\text{C}$  difference between the dew point temperature 10 cm above the road surface and the dew point temperature 2.5 metres above the road, as described by Almkvist et al. (2005); Baad and Brodersen (2010); Karlsson (1999), many of the frost warning differences from  $2^{\circ}\text{C}$  and up, as shown in Figure 4, might have been overestimated. If the limits for the DP-RST difference in the frost calculations were changed from  $0.5^{\circ}\text{C}$  to  $0.6^{\circ}\text{C}$ , about 10.3% fewer warnings would be given. If this difference had been exaggerated, with  $1.5^{\circ}\text{C}$  resulting from measuring errors, about 78% of the frost warnings would have been unnecessary.

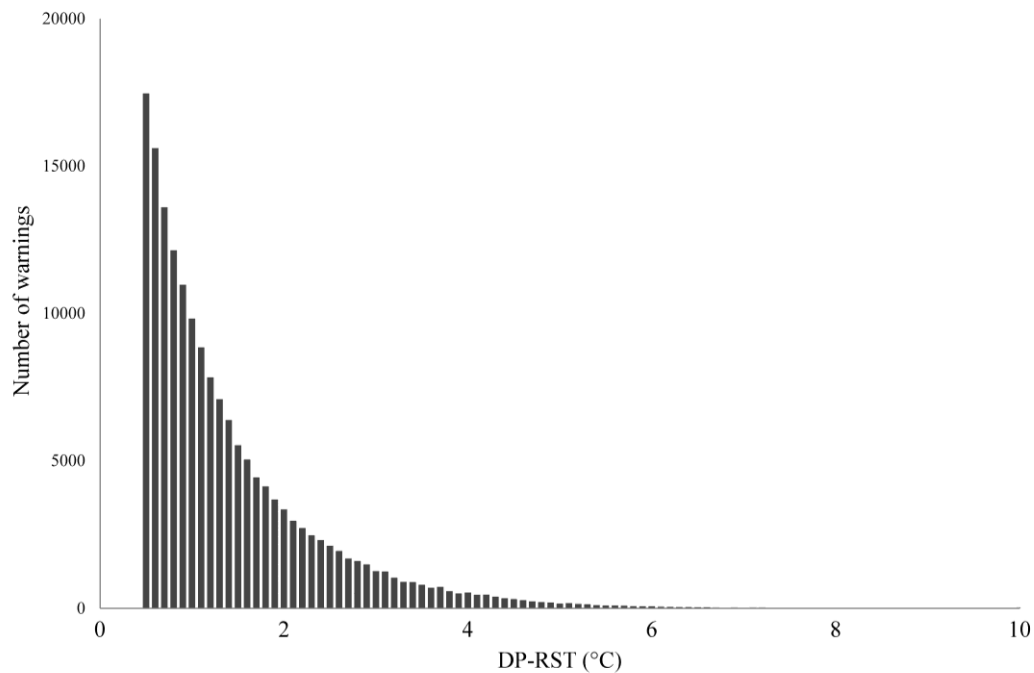


Figure 4. DP-RST during 178,547 frost warnings in western Sweden during 2007-2010.

#### ROAD WETNESS – MOBILE MEASUREMENTS

The mobile measurements in Paper II, showed that it is possible to measure road surface wetness and that such measures can optimise the salt usage. The measurements indicated that there were substantial variations of wetness at different spatial scales along the road, as well as between lanes. The wetness varied depending on the type of road. The larger, more frequently travelled road with a higher road standard had more uniform wetness, than the smaller road, however, with some marked wet patches. The ramps off the highway were found to be the wettest sections and so would need more salt during the spreading. The ramps are critical, as they are less frequently travelled than the road in general and so are exposed to less heat from engine exhaust or friction; hence, they are more prone to slipperiness. In addition, the ramps are often curved and require a quick reduction in a vehicle's speed, which possibly increases the risk of accidents in slippery road conditions. If the salt spread was to be applied in accordance with the road surface wetness, the study showed that the variations of water depth of 1.4 mm could save up to 42% of the salt usage on smaller roads. The wetness of the highway was much more uniform in character, only varying between 0.5 mm and 0.6 mm; nevertheless, up to 22% of the salt use on highways could potentially be saved.

## PART II – THE ENERGY USE OF THE WINTER ROAD MAINTENANCE SYSTEM

### INFLUENCE OF WEATHER PARAMETERS ON TRAFFIC ENERGY USE

In Paper III, The Swedish National Road and Transport Research Institute (VTI) Winter model was used to analyse the effects that snow density and amount would have on traffic and specifically on its energy use. The fuel consumption part of the Winter model, was used for the study. The model is based on actual measurements and observations of different road conditions alongside traffic flow measurements (Wallman, 2001; Wallman, 2005). For more information on the background of the model, please see Paper III. Snow amount and density were varied, from 0.2 to 1.2 cm for the densities 100 kg/m<sup>3</sup> and 400 kg/m<sup>3</sup>. The road length was set to 100 km, as this would represent the total length of an anti-icing route, and the time aspect was set to one day. The model was run for dry, bare roads and then the data were compared with data on slushy/snowy roads with different snow densities and amounts. For anti-icing, data on dry, bare roads were compared with data on wet roads and also icy roads.

The results of Paper III showed that there are differences in fuel consumption depending on the density of the snow. Driving at speeds up to 70 km/h in snow with a density of 100 kg/m<sup>3</sup> would require more energy than driving on bare roads. However, if the speed is increased, the fuel consumption would depend more on the higher speed than on the resistance from the snow, unless there is more than 1 cm of snow on a road with a speed limit of 90 km/h. Increasing the speed even more requires there to be at least 2.5 cm of snow for its removal to be energy efficient in terms of traffic energy use. For heavier snow of 400 kg/m<sup>3</sup>, the boundaries are much lower. It would in essence be enough with 0.5 cm of snow for removal to be energy efficient, at any speed up to 115 km/h. The larger the roads, the more energy efficient it is to remove the snow, hence areas with a lot of large roads would benefit the most from winter road maintenance operations. The fuel consumption from driving on dry, bare roads was always higher than from driving in moist, wet or icy conditions, meaning that it would not be energy efficient to perform anti-icing. However, it is such a crucial practice in terms of safety and effective road maintenance that reducing or even removing the practice would most certainly result in a large increase in the number of fatal accidents.

### ENERGY USE OF WINTER ROAD MAINTENANCE – MEASURE OR MODEL

The second aspect, the energy use of winter road maintenance is the main focus of part II of this thesis.

Before it is possible to reflect on energy efficiency, it is necessary to understand how much energy or fuel consumption maintenance vehicles use. It is common to use models for fuel consumption of traffic – one example is the VTI's fuel consumption model used in Paper III. Models for heavier vehicles are also common and are often included in route optimisation models for such areas as waste and cargo (Delorme et al., 2010; Tavares et al., 2009). Using models is one aspect of gaining knowledge of energy and fuel consumption; the other is to use in-vehicle data that are obtainable from vehicle manufacturers. Some of the largest of heavy duty vehicle's manufacturers have agreed on what is referred to as the Fleet Management System standard interface (FMS-Standard, 2014). This system connects an on-board computer containing driver logs, messaging services, positioning, tracking and so on with a portal in the office (Pettersson, 2008). The Fleet Management System is intended to assist

hauliers to get a better overview of their transport management; however, the system has also been proven to be useful in investigating energy use in winter road maintenance.

## METHODS – PART II

For the study in Paper IV, raw data from four maintenance vehicles were downloaded from the Scania Fleet Management Portal. Data on time, position, distance travelled, total fuel consumption, number of hard brakes and hard accelerations, speed and idling, among several other parameters, were recorded approximately every 10 minutes from November 2013 to March 2014. Two maintenance areas were included in the study. The northernmost area is the road maintenance contract area of Trollhättan. The large lake of Vänern influences the winter climate of the region from the northeast. The roads run across fairly flat terrain, although the land is used in a variety of ways. The other area is the road maintenance contract area of Linderödsåsen, which also is the name of a somewhat marked ridge in the area. The road maintenance route covering the road that runs across this ridge has slopes varying from 3% to 6%. In addition, this area is influenced in the east, by the waters of Hanö Bay in the Baltic Sea.

This study entailed two concepts. The first concept was to use an already existing model to calculate fuel consumption based on equations from Ntziachristos and Samaras (2000) and Tavares et al. (2009) which include speed, road gradient and loading, whereas the second concept was using measured values from the Scania Fleet Management data. More detailed descriptions of the methods and equations can be found in Paper IV. The two different concepts were compared and the aspects of eco-driving and the influence of different types of maintenance operations and different types of snow were also considered.

The mean values of speed and fuel consumption were calculated based on odometer readings (giving the distance travelled) and the total fuel data. The data were later sorted into different speed levels, to investigate at which speed the fuel consumption is at its optimum. Fuel consumption differences between uphill and downhill travel, as well as between a full load at the beginning of an anti-icing activity and a less full load at the end, were investigated and tested for significance.

As for the application of the VTI's Winter model in Paper III where it was shown that snow densities would influence fuel consumption, it was interesting to investigate whether this aspect also held true for heavier vehicles equipped with one or more ploughing blades weighing a few extra tonnes. Snowfall events were sorted into different temperatures to simulate various snow densities. Snow at temperatures of between -4°C and -10°C was referred to by Roebber et al. (2003) as the lightest type of snowflakes. Snowfall events at temperatures of less than -4°C were hence, defined as light snow, while snow events at temperatures of between -1°C and 1°C were defined as heavy snow. Weather information from MESAN, an analytical meteorological model based on observations of weather interpolated in 11\*11 km grids and provided by the Swedish Meteorological and Hydrological Institute (SMHI), was connected to each vehicle data point. This could be done because each point had a global position that could be related to the MESAN's specific grid data for the particular area.



## RESULTS – PART II

The fuel consumption of the maintenance vehicles in the study was higher at low speeds, as can be seen in Figure 5, where the black line represents data from all vehicles no matter what type of activity. At 60 km/h, there is a low point, meaning that this point would be the optimum speed limit for using as little fuel as possible. The fuel consumption in the anti-icing activities follows the same pattern, but with lower initial fuel consumption at the lowest speeds.

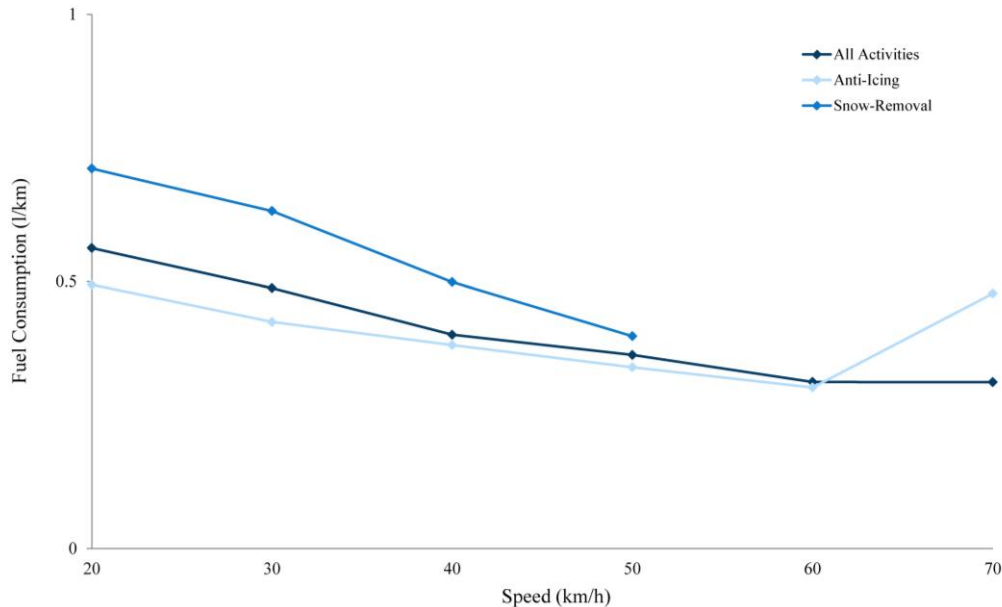


Figure 5. Fuel consumption for all vehicles in the study at all times, as well as for those vehicles performing anti-icing and snow removal.

Snow removal is the activity with the largest fuel consumption at lower speeds, but the consumption decreases quickly to reach a minimum at 50 km/h. There were no winter maintenance data on average speeds above 50 km/h. Looking at the speeds between different vehicles and for different type of activity reveals that anti-icing is performed on average about 10 km/h faster than snow removal. T-tests with a significance level of 0.001 showed that fuel consumption is higher when driving uphill than when driving downhill, as it is for driving with a full load at the beginning of a route than for driving with a reduced load at the end.

### COMPARISONS WITH THE MODEL CALCULATIONS

Road slopes of 3% and 6% were used in the equations below to calculate the gradient correction factor (GrCF) of the model equations. The loading was set to different levels of load in the Load correction factor (LCF) and different velocities in the FCS (Fuel Consumption as a function of only speed) equation, to permit comparison with the measured values.

$$\text{GrCF} = 0.41e^{0.18 \cdot \text{slope percentage}}$$

$$\text{LCF} = 1 + 0.36(\text{Load percentage} - 50)/100$$

$$\text{FCS} = 1595.1 \cdot \text{speed}^{-0.4744}$$

These factors were then multiplied to give the total fuel consumption

**Total Fuel Consumption = FCS\*LCF\*GrCF** at different speed levels.

To be able to visualise the differences in measured values, the model calculations were plotted against the measured values, as shown in Figure 6. The dashed lines are the model calculations, which appear to follow those of the overall measurements as well as the anti-icing, although they also appear to either underestimate or overestimate the fuel consumption. The equations used in the model were representing heavy-duty vehicles of > 16 tonnes.

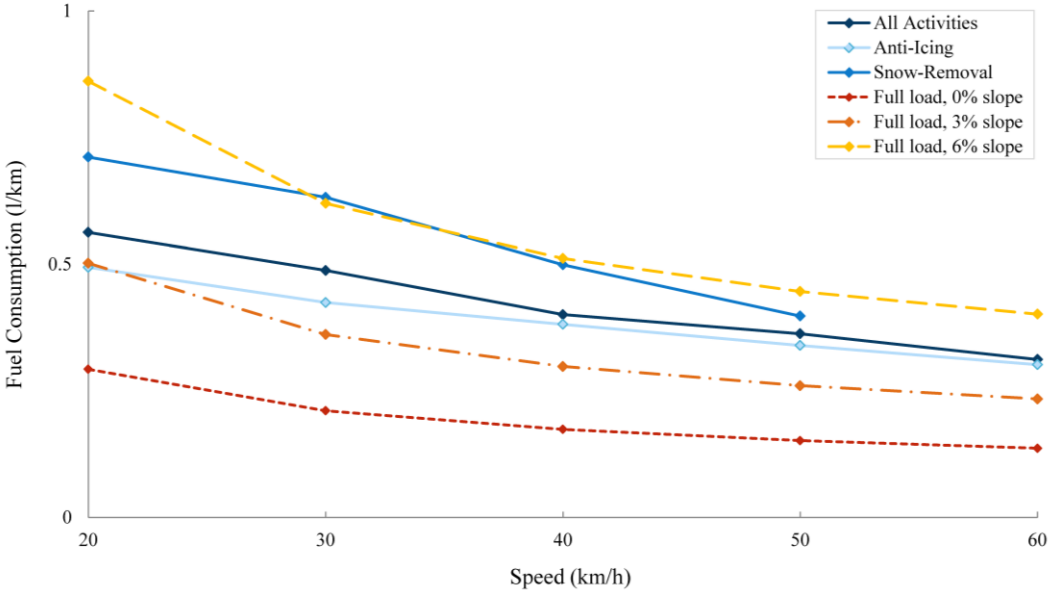


Figure 6. Fuel consumption for all vehicles in the study compared with the model calculations.

Implementing the model calculations into each road segment of the routes yielded an average per route of 37.6 litres compared with the real vehicle data of 47.0 litres for the same area. When analysing the lines in Figure 6, it might seem that model calculations with a slope somewhere between 3% and 6% could fit the “all activity” and “anti-icing” curves. Such a comparison is made with slopes of 5% in Figure 7.

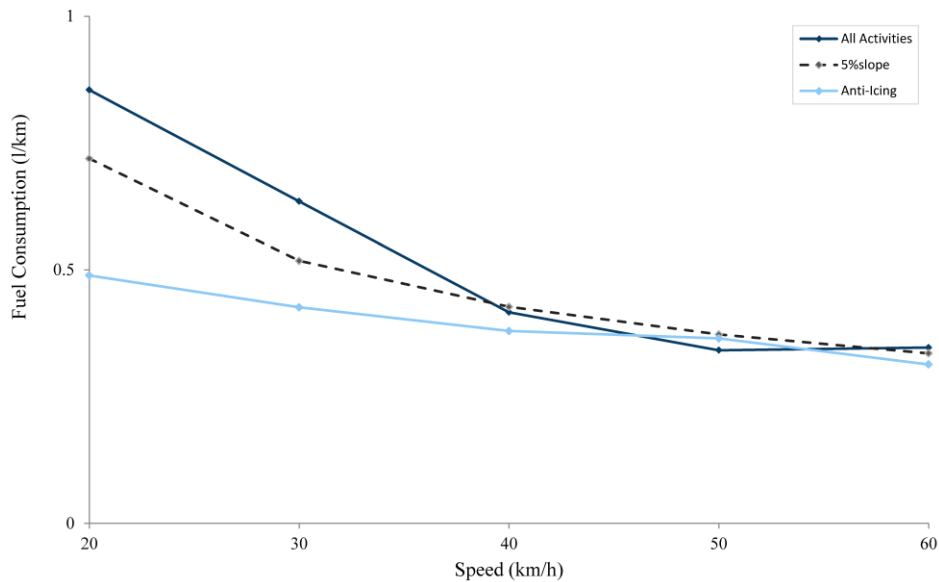
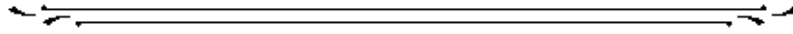


Figure 7. Fuel consumption from all activities and anti-icing compared with model calculations for a full load and a 5% road gradient.

The comparison does however show that the curves will differ quite a lot at low speeds. This and the previously described fuel consumption calculations per road segment implied that other parameters than road gradient and loading could be affecting the results, possibly the influence of different types of snow. It was significantly stated in Paper IV that warmer snow would use more fuel than dry cold snow.

When comparing the idling and hard braking and accelerations of the vehicles in the study with other studies, it seemed that drivers were quite good at eco-driving. However, there could be some potential to save fuel by, for instance, reducing the idling time. These potential savings are discussed in the next part of the thesis.



## PART III – FINDING ENERGY EFFICIENCY

This part of the thesis addresses the potentials for energy efficiency, starting with an improved RWIS (**Paper I**), moving on to changes in start criterion for snow removal in terms of traffic energy use (**Paper III**), and then on to changes in driver behaviour of maintenance vehicles (**Paper IV**). Part III ends with a case study using a route optimisation programme to investigate some suggested efficiency measures (**Paper V**).

### EFFICIENCIES REGARDING THE ROAD WEATHER INFORMATION SYSTEM (PAPER I)

The frost warnings from the system are used to decide on when to take action but also for financial compensation. The contractor knows this and will hence try to get as good compensation as possible. If he does not treat the roads he might in the worst case be fined if slipperiness did occur; conversely, if they treat the roads but no frost happens, they may not be paid in full. All is regulated by information from the RWIS. If any part of the system fails or if the system sends too many warnings, unnecessary treatments may result.

The findings of the study described in Paper I showed that due to different types of errors in estimating and measuring dew point and road surface temperatures in the RWIS, false warnings could be generated by the system. A 0.1°C error in the difference between the dew point temperature and the road surface temperature could yield 10.3% unnecessary warnings. As the uncertainty of the road surface sensor is  $\pm 0.3^\circ\text{C}$ , it is quite possible that the system is either missing warnings or giving false warnings. An error resulting from the sensor being installed at an unrepresentative height could amount to up to 2°C, as Baad and Brodersen (2010) and other researchers have described. About 78% of all warnings could have been unnecessary if the difference between the dew point temperature and the road surface temperature had been exaggerated, with 1.5°C due to measuring errors. Furthermore, the accuracy uncertainties of the sensors  $\pm 0.3^\circ\text{C}$ ; this alone could most likely yield the -0.1°C error in the DP-RST difference shown in the first row of Table 1. These potential errors were put into an energy context in the Paper I study by the use of two methods. The first method entailed using the estimations for snow removal vehicles made by Stripple (2001), where an energy value of 17.1 MJ/km of a 13 m-wide road was upscaled for the 20,816 km roads of the investigated region. The second method entailed using NTMCalc (NTM, 2015), an Internet-based calculation programme that draws on European emission and fuel consumption models. These two methods concurred quite well, and an average established between them was used later for energy savings calculations that took account of the presumed errors in frost warnings (Table 1).

Table 1. Energy and fuel cost related to unnecessary frost warnings due to errors in frost warnings where the dew point temperature is overestimated.

Error in DP-RST (°C)	Percentage of unnecessary warnings	Number of unnecessary warnings in an operations area	Number of unnecessary activities in an operations area	Energy related to those activities (kWh)
-0.1	10.3	52	3	287,499
-0.5	41.4	207	10	958,331
-1.0	65.0	325	16	1,533,329
-1.5	78.0	390	20	1,916,661
-2.0	86.5	433	22	2,108,327

### SAVINGS IN TRAFFIC ENERGY USE (PAPER III)

As described in the section on the impact of snow density and amount, it was found that performing anti-icing was not energy efficient. However, some potential savings could be made by changing the start criterion for snow removal, which is dependent on snow depth on the road. For class 1-3 roads, the start criterion is set to 1 cm and for class 4 roads to 2 cm. Hence, these are the limits to consider, as they are already used in winter road measures. Driving at speeds of 70 km/h in 2 cm snow would yield traffic fuel consumption/100 km (a maintenance area) of 14,200 litres. If this snow were removed, the fuel consumption would decrease by 15.5%, as indicated in Table 2. A larger road with speed limits of 90 km/h and a start criterion of 1 cm could see fuel savings of 1.9% during snow removal. If, however, the start criterion were changed to 2 cm, the traffic fuel consumption would decrease by 10.7% per maintenance area. Dropping the speed limit from 90 km/h to 70 km/h and at the same time changing the starting criterion to 2 cm could result in about 2,500 litres of fuel being saved, which is a reduction of about 17.2% in traffic energy use.

Table 2. Traffic fuel consumption changes from snow removal at different start criteria and speed limits.

Speed and start criteria	Fuel use in snow (litres)	Fuel use on dry, bare road (litres)	Decrease when removing snow (litres)	Decrease when removing snow (%)
70 km/h (2 cm)	14,200	12,000	2,200	15.5
90 km/h (1 cm)	13,200	12,950	250	1.9
90 km/h (2 cm)	14,500	12,950	1,550	10.7

### SAVINGS FROM DRIVER BEHAVIOUR CHANGES (PAPER IV)

The fuel use inventory analyses reported in Paper IV showed that the maintenance vehicles often drive at low velocities. As indicated earlier in Figure 6, the optimum speed was around 60 km/h for each type of maintenance activity.

The frequency with which the vehicles are driven at these low speeds is crucial in understanding the potential savings to be made from increasing the speed. As shown in Figure 8, the low speeds are in fact the most frequently used speeds.

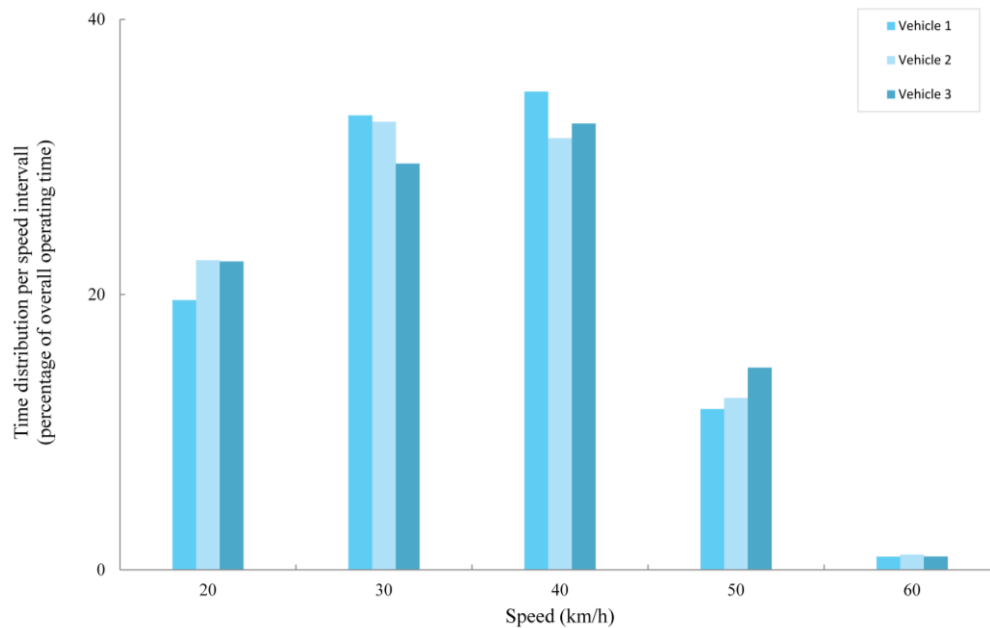


Figure 8. Frequency of each vehicle driven at each velocity range.

Next, it was important to understand whether set speed limits would hinder an increase in speed. This was done by connecting the average speed from the measurements to each road segment that had a given speed limit from the National Road Database. For road segments with a speed limit above 60 km/h, the difference between the actual speed and 60 km/h was calculated. Whenever the speed limit was lower than 60 km/h, the comparison was instead made with the set limit. This gave an average potential increase in speed limit per road segment of 35.2 km/h for vehicle 1 and 31.2 km/h for vehicle 2. An increase in speed would lower the average fuel consumption from 0.5 l/km at 30 km/h to 0.3 l/km for 60 km/h. The reduction in fuel consumption per road segment would be up to 40%.

However, driving at higher speeds might not be possible, since the maintenance vehicle also has to cover all exit ramps, bus stops and lay-bys. This situation could be overcome by, for example, installing fixed road surface salt spreaders in the pavement or using underground heating systems. Such methods are further discussed in Paper V.

### ESTIMATING SAVINGS POTENTIALS USING ROUTE OPTIMISATION (PAPER V)

The winter road maintenance contract area of Trollhättan, was used in the study addressed in Paper V. Four cases were tested using the same route optimisation programme used at that time in the contract area and with the same settings. The aim was to propose a method for evaluating potential efficiency measures within a maintenance contract area. As mentioned in Paper IV, there are indications that increased fuel consumption might come from reduced speed at exit ramps, bus stops and lay-bys. The FAST technology described in Paper V has been operational in Europe since the mid-1980s and in North America since the late 1990s. The technique basically amount to anti-icing agents automatically being spread on roads whenever the RWIS indicates slipperiness. By using the route optimisation programme, it was possible to compare the route lengths actually covered in the contract area to the route lengths that would have been covered if fixed salt spreaders or other related techniques giving similar results had been installed in strategic locations.

The same thoughts and techniques are behind investigating a bridge in the area. As described in Paper I, many of the RWIS stations have an additional surface temperature sensor installed, which might

bring about some frost warnings that are not representative of the whole area. However, it must be mentioned that the RWIS at first was set to give as early an indication of slipperiness as possible, to be sure to cover all cases of slipperiness. This approach will not be as convenient as the winter road maintenance continuously strive to become increasingly precise and efficient. Having exact information on the road conditions is therefore crucial. The particular bridge of interest lies about 26.6 km from the maintenance materials depot and has an additional sensor installed at the bridge deck about 15 metres from the standard installed station. Four years of RWIS data were analysed using the same method as in Paper I, to estimate the number of maintenance operations based on frost warnings. Every warning that was followed by at least two more warnings and with no following warnings for the next 6 hours was set as a maintenance action. This resulted in that 40% of the presumed maintenance activities in a winter would hence only be concerning the bridge and not the standard installed sensor on the road 15 metres away. These calculations are of course site specific and will depend largely on distances from the materials depot to the bridge, as well as certain conditions at the site location that can affect the local climate.

Changing road standard class within winter road operations would mean a lower or higher demand for treatments of the roads. The VTI winter model, which was partially used in Paper III, is intended to estimate changes in winter road standards in terms of traffic and environmental costs. Arvidsson (2014) evaluated seven scenarios of changes between different road classes and standards. However, they all meant that the standards were lowered and mainly concerned consideration of the types of treatment changes, such as from the snow removal and anti-icing approach to snow removal only. For this study, a change from sanding is considered, which often requires one or two refills of sand along the route, to anti-icing on the same route length, which would not require any refills. Normally, anti-iced roads have a higher standard and should be treated with anti-icing more frequently than lower standard roads. However, for this study the same standards i.e. the same time constraints were used as for sanding, hence the roads are treated less frequently and with no change in standards, but instead of sanding they would do anti-icing treatments.

Studies from North America have indicated that additional materials depots would increase the efficiency of the winter road maintenance practice (Perrier et al., 2007). Adding depots is also a common measure to take when optimising the use of delivery trucks and the like. This measure was therefore tested in the route optimisation programme used in the Paper V study. Perrier et al. also mentioned that anti-icing operations usually do not have the same need for refilling as other types of maintenance activities such as sanding have.

## RESULTS – PART III: FOCUSING ON THE FINDINGS OF PAPER V

It is common practice, in some districts, to route one vehicle to cover all exits in a maintenance area. This approach was tested in Paper V, using a route optimisation programme for the contract area of Trollhättan. First, the anti-icing operations of the contract area were routed as a total, meaning that the exit ramps were included. Then a special exit ramp-covering route was created for one vehicle, and a new route optimisation for the whole contract area minus the exits was calculated. The result was an exit ramp-covering route of 114 km, while the saving from covering the exits compared with not covering the exits was estimated as only 93 km per run. So the creation of an exit ramp-covering route would increase the number of kilometres driven. Regarding the study addressed in Paper IV, this approach might not necessarily mean that the fuel consumption is increased, as those vehicles that do not have to take the exits may perhaps be able to drive at higher speeds and with fewer interruptions, thus using less fuel. However, installing fixed salt spreaders or underground heating on the ramp exits

would mean a saving of 93 km per slipperiness treatment. During a winter in the Trollhättan area, there were about 53 anti-icing treatments. The study in Paper IV revealed that the maintenance vehicles in this area use about 0.37 l/km during anti-icing, which in one winter would mean a saving of 1,824 litres of fuel.

In the bridge study of Paper V, it was established that the bridge would freeze on 40% of 53 salting occasions. The minimum distance to drive from the materials depot to the bridge and back is 26.6 km. The savings to be made in a winter by installing the systems discussed in the maintenance area in question are therefore 564 km. If on the other hand the entire 114 km route, which at present includes the bridge, were to be driven, the saving would be 2,417 km. The equivalent fuel consumption would be up to 900 litres.

The change from sanding to anti-icing showed that the trips needed to treat a route were reduced from two or three trips to just one trip, as shown in Table 3. To anti-ice all classes would require nine vehicles, the same number as would result from adding the existing number of anti-icing vehicles (i.e. 5) to the existing sanding vehicles (i.e. 4). With these changes in practice, about 200 km per anti-icing event could be saved, which is equal to about two anti-icing units per sanding occasion. There are about 30 such events during a winter, which would give a saving of more than 6,100 km. With a fuel consumption of 0.44 l/km, about 2,700 litres of fuel could be saved with such a measure.

Table 3. The route lengths for anti-icing class 1-3 roads (AI) for sanding class 4 and 5 roads (S) and anti-icing all classes of road (AIA). The demand in column 3 shows the tonnes of material used – for anti-icing it is salt solution and for sanding it is sand.

Route name	Time (hh:mm)	Demand (tonnes)	Distance (km)	Number of trips
1-AI	03:01	7.0	113.7	1
2-AI	03:05	7.0	117.4	1
3-AI	03:02	7.0	116.0	1
4-AI	03:50	7.0	170.6	1
5-AI	03:33	7.0	141.6	1
1-S	07:41	25.5	194.6	2
2-S	07:12	21.4	206.1	2
3-S	09:05	29.3	229.9	3
4-S	08:47	24.7	280.9	2
1-AIA	04:44	4.4	171.8	1
2-AIA	04:30	4.4	170.3	1
3-AIA	03:37	4.4	146.7	1
4-AIA	04:30	4.4	163.2	1
5-AIA	04:42	3.3	174.0	1
6-AIA	04:58	3.3	167.8	1
7-AIA	04:53	4.3	189.8	1
8-AIA	05:06	3.3	176.8	1
9-AIA	04:55	3.3	172.9	1

It was shown in Paper V, that the suggestion about additional depots would not give any particular savings for the contract area of study regarding anti-icing. However, the driving distance for sanding treatments could be reduced by 180 km per event, totalling about 5,500 km in a winter of 30 sanding events. The duration and routes could also be reduced by about 8%.



### SUMMARISING THE POTENTIAL EFFICIENCIES WITHIN THE MAINTENANCE AREA

Installing an underground heating system or road surface–installed salt spreaders on the exit ramps would for maintenance area Trollhättan save one anti-icing unit (93 km) per slipperiness event. The same type of installation on the bridge would save up to another anti-icing unit (114 km), and changing from sanding to salting would save two units (200 km) per event. Two additional depots would also yield the potential of removing two units from the operations. Put together this would result in a saving of about 7,800 litres in a winter, which represents 17 times the total road lengths in the maintenance area.

Furthermore, excluding the exit ramps could result in potential savings to be made if such measures would in fact increase the drivers' speed, as is discussed in Paper IV.

## THESIS DISCUSSION

The quest for finding energy efficiencies, described in this thesis, added a new level to the research field of winter road maintenance. As a result, the methods and the materials to use were not initially defined. It was therefore interesting to try various methods already in use, not only in winter road maintenance research, but also methods used in other fields of research. As the project unfolded, it became more obvious that knowing where and how much energy was used within WRM would also make it possible to understand where efficiencies could be made.

The first part of the thesis concerned the slipperiness in the winter road maintenance system. By knowing where and when the slipperiness occurs, WRM personnel can decide when to take action. It was therefore crucial to understand the accuracy of the RWIS, which influences the decisions on maintenance treatments to a significant extent. The RWIS is used at three levels that equate to the levels at which this thesis identified transdisciplinarity: the decision makers, the scientists and the stakeholders. Since many of the warnings are dependent on the accuracy of the system, it was interesting to analyse what effects an error might have on energy. The analyses revealed that many more frost warnings come from certain stations and that some of those stations have an additional sensor installed; these two findings led to further analysis of such stations. It was clear that almost all of the 42 investigated RWIS stations with an additional sensor differed in the number of frost warnings when comparing between using data from the standard installed sensor and using data from the additional sensor. Savings could potentially be made if understanding what would cause such differences and to what extent frost warnings would vary between using a standard sensor compared to an additional. The concept had surfaced as a possible area of interest during the thesis work, so when the opportunity arose, to use the route optimisation programme that was currently employed in the WRM area of Trollhättan, the concept was further investigated (Paper V).

To be able to be more energy efficient, it is apparent that better and more detailed information would be a motivating factor. Mobile measurements are becoming increasingly common, since it has been known for some time that even though the RWIS can give a good indication of early slipperiness, it is still only a single data point at somewhat distant locations. As new and interesting projects integrate road users' information into the RWIS to better indicate slipperiness between RWIS stations, other projects concern increasing the accuracy of measurements on road maintenance vehicles, thereby increasing the possibility of using the exact amount of chemicals needed for optimal WRM measures. The mobile measurements performed in the Paper II study indicated that it is possible to measure road surface wetness with a mobile sensor. The study also clearly showed that most water lies on the exit ramps. These are crucial parts of the road system, since they are not used as frequently as the rest of the roads, meaning that less traffic is contributing with friction, heat and splash. The velocities are lower also, which might affect the potential of traffic to splash away the water. Additionally, spreading the same amount of anti-icing agent on the exit ramps as on the rest of the road might result in a higher freezing point on the ramps, since the higher volume of water will dilute the anti-icing agent, decreasing its ability to lower the freezing point. The fact that more water would stay on the ramps could further fortify an installation of either the underground heating or the road surface-installed salt spreaders, discussed in Paper V, as the ramps would be more prone to slipperiness.

Furthermore by measuring the road surface wetness it is also possible to know when there is no water on the roads. This is a good indication for non-slipperiness and if included in the weather information it could result in potential savings as the RWIS can warn about temperature falls and air humidity but not about road surface temperatures.

Road traffic models and fuel consumption and emissions models are regularly used within route optimising and energy efficiency studies. In this thesis, two model approaches were taken. The first was again considering the road users of the winter road maintenance system. The comprehensive VTI winter model was used in order to quantify the need for winter road maintenance and in that way optimise the energy use of traffic in terms of weather and climate influences. This approach made it possible to understand what effects the various changes to WRM would have on traffic energy use, in terms of criteria for when to start a snow removal activity. The results are somewhat controversial, since it was shown that anti-icing a road was not energy efficient. Road users will keep at the same high velocity when the roads are always clear of snow and ice. Lowering the standards of the roads as well as lowering the traffic velocity would save energy, but the risk of accidents would increase. The complete winter model calculates the total costs of changing the road standards, including accident and environmental aspects (in terms of salt usage), whereas the study in Paper III used only one of the sub-models in considering the energy aspects, without the influence of other parameters. When Arvidsson (2014) tested the complete winter model in such a way it did indeed yield an increased risk of accidents.

The other model approach was considering fuel consumption of maintenance vehicles. An ordinary traffic and emissions model that was originally applied by Tavares et al. (2009) to calculate the energy use of waste trucks using the equations of Ntziachristos and Samaras (2000) was used with inputs corresponding to those of the actual WRMs. The measured values of the WRM vehicles in Paper IV were then compared with the model values. The model could not be used for WRM immediately, as neither the use of road gradient, loading factor or speed, could be able to estimate the correct fuel consumption, when put into the model. From further investigation of the measured fuel consumptions, it was clear that snow density would impact the energy use. For this study, it was discussed whether the use or development of yet another model would be the best approach to take, since it seemed best, easiest and most accurate to simply use the in-vehicle data for analysing fuel use of the system.

Within energy efficiency of traffic or other motorised vehicles, as well as of delivery firms and the like, it is standard to use route optimisation programmes. These programmes are also important tools for WRM contractors when considering a tender for procurement, as well as planning for the various maintenance activities. Only by using such a programme is it possible to become more efficient. For the WRM area in question, such a programme was already implemented, and it seemed unnecessary to apply it in the usual way. Instead, it was used to test a number of scenarios that were suggested for bringing about efficiency measures. The use of route optimisation programmes for estimating fuel savings is something that could be further investigated in other maintenance areas for the same type of scenarios as discussed in Paper V.

## FINDING ENERGY EFFICIENCY IN WINTER ROAD MAINTENANCE – A GENERAL APPROACH

Generalising the methods and findings of this thesis to methods for finding energy efficiency within any maintenance area would benefit from three approaches being considered. First, a focus on in-vehicle measurements would assist in understanding the WRM practice. Where are speeds too low and why? Is it possible to install underground heating or similar techniques at crucial spots to overcome low speed and frequent stopping?

Second, it would be valuable to obtain an overview of the RWIS, to analyse the risk of inaccurate data or measures. As part of this overview, another idea is to consider including road user information or mobile measurements to optimise chemical use. With the fuel amount per anti-icing activity, as well as per sanding, de-icing and snow removal activities, it is possible to include this information in an energy index. Such an index basically compares the total number of driven kilometres of anti-icing in

relation to road class length and number of slipperiness events. If the index was calculated each year, it would be possible to compare between years and to quantify changes in practice from year to year within a maintenance area.

The third approach is to use a route optimisation programme to quantify different scenarios at hand. By investigating various warnings from the RWIS, it is possible to find anomalies that can be further investigated – for example, in terms of existing additional sensors.

When the suggested efficiency measures have been calculated for in the route optimisation programme, it is time for implementing the ideas. This stage is when the in-vehicle fuel measurements can be further used in analysing differences in fuel consumption between various types of practices or changes in route lengths.

## CONCLUSIONS

From analysis of the RWIS data it is clear that the effects of frost warnings being under- or overestimated could be substantial in terms of energy use, where small measuring errors of temperature could result in large percentages of unnecessary treatments.

Knowledge about the road climate and weather is crucial for optimised winter road maintenance. The RWIS system measures weather at widespread locations. By adding mobile measurements of water amount, the gap of knowledge in between stations will be filled which would add a new dimension to the information system as well as increasing potentials for salt use optimisation.

Snow density and amount will influence fuel consumption of traffic which is why snow removal practices actually can reduce such consumption. The effect depends, however, both on speed and density. It was concluded in Paper III, that the performance of anti-icing was not efficient when considering traffic energy use. This is due to the fact that drivers tend to choose a higher speed, if knowing that roads are salted.

Using regular fuel consumption models to estimate fuel consumption within winter road maintenance is at present not viable. Other parameters such as the weather and the way of working (mostly regarding speeds) influence this type of operation. Alterations concerning snow densities for instance, could possibly be made to existing models, but at present it is much more convenient to use the in-vehicle information provided by manufacturers via an easily accessible fleet management system. This way, it is possible to quantify energy use in a winter road maintenance area more accurately than a model can.

By knowing the energy use of WRM vehicles it is also possible to realise potential efficiency measures. Increasing the speed seems to offer the largest potential for fuel efficiency.

- Route optimisation programmes can be used not only to optimise the various anti-icing and snow removal routes in everyday practice but also to estimate the effects of the suggested efficiency measures. Installing underground heating systems or road surface installed salt spreaders at strategic locations could save fuel consumption.
- Changing operations on class 4 and 5 roads from sanding to salting would save driving lengths with about 200 km per slippery event in an area where about 400 km of roads are normally sanded. An additional materials depot would not necessarily generate increased efficiencies, as no change was shown in the number of routes or distances for the investigated area in terms of anti-icing measures. The sanding operations could, however, save in both distance and duration.

This thesis has shown that it is important to know the system you are investigating before attempting to find energy efficiency measures. The main issues to consider are the energy use of the winter road maintenance vehicles and the RWIS which is crucial part to everything concerning winter road maintenance. In the end, though it still is the weather that decides when and where slipperiness might occur.

## FUTURE OUTLOOK

As increased speeds of winter road maintenance vehicles seem to be a large potential for decreased fuel consumption it would be necessary to investigate why operations are performed at such low speeds. A plausible cause could be the interruptions of having to cover exit ramps, bus stops and lay-bys. If such parts of the system could in some way be excluded from the routes it might be possible to increase the speed to such an extent that it would decrease the total fuel consumption of the Winter road maintenance. It is however, also important to consider whether the quality of the performance of snow removal would become poorer at higher speeds.

The suggestions of this thesis are only tested in theory. The next step would be to test them in reality. It would for such an investigation be important to test in a few different maintenance areas.

In paper I, suggestions to improve the accuracy of a RWIS station are mentioned. Such improvements would also be interesting to test, specifically regarding the measurements of humidity. If a humidity sensor was installed at the bridge where the additional sensor was located in paper V, would the number of frost warnings still vary from the standard sensor?

By measuring road surface wetness along the roads you could get an implication of where there is no water on the roads. It is important to investigate this further to understand how such indications could be used for the planning of the next maintenance treatment. Would it be possible to conclude that if no further water deposition has been detected by the system, then no further treatments are needed? Such suggestions would have to be tested before introduced into the RWIS.

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*“Don't cry because it's over, smile because it happened”  
Dr. Seuss*

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## **Papers I-V**

*”Bättre en tia i handen än en tjuga i foten”  
Swedish saying*

