Energy Use within Road Maintenance Operations with Potentials for Increased Efficiency

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Abstract

This Licentiate thesis is done within the scope of the doctoral thesis project Energy Efficiency within Road Maintenance Operations. This initiation part forms the base of the energy use within these operations. The aim is to create an energy model for the mapping of the energy consumption within road operations. The model could be used to evaluate possible energy efficiency measures and also as a reporting tool for energy use within different road maintenance districts.

To be able to map the energy use a questionnaire was sent to the road maintenance districts run by the contractor SKANSKA. Since it is difficult to know about the energy consumption within the different parts of the operations, the hours were used as unit for the answers. This is information that every road manager have some knowledge about because of the different time report systems that are used within the organisation. The time that each type of vehicle was employed for a specific operation were given and the model recalculated the hours into fuel and eventually energy by the use of fuel consumption values from previous studies. This way the model can easily be modified to suite the user depending on the purpose, the fuel consumption of the vehicles and which vehicles that are used for the specific operation activities within the particular maintenance district.

The results of the questionnaire together with the model calculations showed that winter operations were the most energy consuming part of the road operations, where ploughing constituted to about 30 % of the total consumption. Salting and sanding were the second and third largest consuming operations. These three operation activities were also considered to have the largest potentials for savings according to discussions made at a workshop regarding the questionnaire.

The winter operations are to a large extent affected by the weather, hence efforts were made into finding potentials for efficiency by analysing the most frequently used support tool within the winter road operations, namely the Road Weather Information System (RWIS). A literature review along with an uncertainty analysis of the system was made within the scope of this thesis. It showed, by the use of energy calculations, that there are several potentials for savings to be made with an improved system.

Sammanfattning

Inom ramen för doktorandprojektet Energieffektivisering av ett driftområde gjordes denna Licentiatavhandling. Denna del är den första delen av projektet och utgör basen för energianvändningen inom driften av vägarna. Syftet är att skapa en energimodell för att kartlägga vägdriftens energiförbrukning. Modellen skall kunna användas för att utvärdera effekterna av tänkbara energieffektiviseringsmetoder samt som ett inrapporteringsverktyg för just energianvändningen inom olika driftområden.

För att kunna kartlägga energianvändningen skickades en enkät ut till Skanskas driftområden. Eftersom det är svårt att veta och hålla koll på energiförbrukningen inom driftens olika delar valdes timmar som enhet för svaren. Det är information som varje driftarbetare har koll på i och med de olika inrapporteringssystem som styr verksamheten. För varje fordonstyp skulle antalet timmar per aktivitet uppges. Modellen bygger sedan på bränsleförbrukningsinformation från tidigare studier och timmarna kan därmed räknas om till bränsle och energi. Det gör att modellen enkelt kan modifieras till att passa användaren beroende på syftet, vilken bränsleförbrukning fordonsflottan har eller vilka fordon som används till respektive aktivitet.

Resultaten från enkätstudien samt modellberäkningarna visade att vinterdriften var den i särklass mest energiförbrukande delen av driften, där plogningen ensam står för ca 30 % av den totala energiförbrukningen. Även saltning och sandning utgör stora delar av driften, och dessa aktiviteter ansågs också ha de största potentialerna för energieffektivisering enligt diskussioner gjorda vid en workshop kring enkätstudien.

Vinterdriften styrs till stor del av vädret och därför lades vikt vid att hitta potentialer för effektiviseringar genom att analysera det hjälpmedel som används flitigast inom vinterdriften nämligen VägVäderInformationsSystemet (VVIS). En litteraturgenomgång samt en osäkerhetsanalys av systemet gjordes inom ramen för denna avhandling. Den visade genom energiberäkningar att det finns flera potentialer till besparingar med ett förbättrat system.

Preface

This thesis includes two papers.

I. Nordin L., Gustavsson T., Bogren J., Sköld D-M., Odermatt N., 2011. Energy use within road maintenance operations in Sweden. Submitted to Energy Policy

II. Riehm M., Nordin L., 2011. Optimization of Winter Maintenance Energy Costs in Sweden: a critique of site specific frost warning techniques. Re-submitted after revisions to Meteorological Applications.

The above papers were written and discussed in collaboration with colleagues at the Department of Earth Sciences, University of Gothenburg; KTH, Royal Institute of Technology and Skanska. The questionnaire in paper I was constructed in close collaboration with Sköld and Odermatt, whom also contributed with retrieving the answers. The major writing was performed by Nordin. The energy calculations of paper II was along with some major ideas for the paper and writing performed by Nordin.

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1. Introduction

The maintenance operations of the roads are to some extent more important than the roads themselves. Without the road maintenance and operations the roads will be deteriorated and unsafe to use. Every year about 4000 million SEK are used for operating the 98400 km long Swedish national roads (STA, 2010). Just imagine how much energy is used to uphold the high standards of these roads. Every year the Swedish Transport Administration (STA) makes plans for new road stretches that will be safer to use and save time and energy for the road users. As the climate debates and oil crises in recent years have brought on discussions of reduced emissions and energy use, the STA have employed prominent goals of reducing the energy use by 20 % and greenhouse gas emissions by 20 % by the year 2020 (STA, 2007). These goals are in agreement with the goals set by the Swedish government and the EU in their respective action plans. A means of reaching these goals is to take energy efficiency measures. Oikonomou et al. 2009 described energy efficiency as a ratio of primary energy use, or energy input, to the quantity of maximum energy output. This was described by Herring (2006) as getting as much work out of the energy input as possible. Oikonomou *et al.* (2009) further suggested that savings would be the reduction of energy use by the means of efficiency measures. To be able to investigate such savings the original use or the baseline use of energy before any efficiency measures are taken, needs to be established.

The STA also have the responsibility to report the energy use within their different sectors. There are ongoing discussions and reporting policies at work within the organization to regulate the demands for energy declarations within different projects as well as within the maintenance operations. The difficulties have been to distinguish for what purpose the energy was used since many of the vehicles employed often are operated for multiple tasks simultaneously.

1.2. Maintenance operations

The national roads in Sweden are managed via procurements running over a time period of six years. It is important for the contractor to win new procurements as well as keeping the ones they already have. Working more energy efficient will enhance the competitiveness of the contractor since they might have a better offer to give than their competitors. There are still some rules of regulations that need to be followed. These rules are given by the function and standards description conducted for each specific maintenance district and regulates what needs to be done and when. The rules may vary depending on the different road classes in the area. Roads with high traffic flow have higher priority hence a higher road class standard than roads with low traffic flow. Road class 1, often a motorway, with about 16 000 vehicle passes every day, has the highest standard while class 5, with less than 500 vehicle passes a day, has the lowest.

The inspection routines needed to examine the status of the roads follow such a priority, where road class 1 needs to be inspected three times during the course of a week. Road class 2 is to be inspected two times and class 3, one time. Classes 4 and 5 need only be inspected once every two weeks. During these inspection routines different obstacles, holes or cracks are registered and sometimes repaired.

Other maintenance operations are for example ditching and ditch clearing, dust binding, gravel covering, bridge cleaning, harvesting and brushwood clearing, sweeping, gardening (e.g. mowing grass in parking areas) and cleaning road signs and road construction. Such operations are more time dependent and often performed once a year. Lay-by cleaning is dependent on road travel and is performed more frequently during the summer when more people are using the roads. The free room is the space 5.0 m right above the road and 1.0 m at either side of the road. This area should be free from obstacles such as tree branches at all times.

The most expensive task of road maintenance operations are the winter operations, such as snowploughing, salt- and sand gritting. These operations are, as implied, driven by the winter weather and constitute to about half of the operational costs every year (STA 2010). The road classes 1-3 are chemically treated with de-icing agents such as salt. During the salting operations the roads along with ramps, refuges, viaducts, bus-stops and lay-bys are sprayed with brine from a heavy salting vehicle. This has shown to be more efficient than using solid salt and the salt use on the Swedish roads was decreased by 10 % when changing from solid to solution (Ljungberg, 2001). The salting operations are performed preventively i.e. before it freezes. This is because less energy, hence less salt, is needed to obstruct ice to form than to melt already existing ice (Ljungberg, 2001, O'Keefe and Shi, 2006). Yet about 200 000 tons of salt is spread on the Swedish roads annually.

All of these operations demand transportation and thereby a lot of energy, since heavy vehicles are most often used for such operations. Heavy vehicles may also seem like a safety barrier for the road worker but it is not always enough. Working on the road is precarious and it is hence important to uphold security regulations. The vehicles used within road operations are therefore either equipped with truck mounted attenuators (TMA) or followed by a vehicle with such equipment. These attenuators are safety precautions not only for the road workers but also for the road users.

1.3. Maintenance operation support tools

The ***Rules of regulation*** include criterions such as how deep the snow layer may be before snow removal is initiated. These rules are not easy to change. However, the effects of an eventual change may theoretically be estimated. Öberg et al. (1985) made such an investigation where the treatments were changed from salt gritting to unsalted roads with occasional sanding. The focus lay in reducing the salt not considering the energy use. Indications were made by Wallman et al. (2006) that further investigations were needed since other road operations may be increased if salting was reduced. Öberg and Möller (2009) discussed the potential of changing the standard of the road and what this might do to the road conditions. When considering this a road standard which was not salted was changed into a road standard that was salted. The distribution of the road conditions over a year was calculated as well as the estimated cost for maintenance. The raise in standard level will however create more costs in terms of maintenance according to Öberg and Möller. This is probably because a lift in standards brings about increased maintenance activities in terms of regularity and higher demands. If on the other hand the standards were the same only the sand was changed to salt spread, the level of maintenance operations should remain the same. This is interesting and will be further discussed in the section about potentials for energy efficiency.

To know when to initiate the preventive winter operations advised by Ljungberg (2001) the maintenance personnel monitors the road weather data from the over 700 road side stations of the national **Road Weather Information System (RWIS)**. These stations typically measure the air and road surface temperature, the air humidity, the precipitation and the winds, usually in worst-case sites, to be able to detect risks for severe road conditions as soon as possible. The areas that freeze most quickly, such as shaded areas, on bridges or roads close to water, are typical examples of the worst-case regions where road weather stations will be positioned. The system gives in-time data about the actual road surface condition at the specific station. Each station is connected to a web-based system that quickly helps the maintenance managers to get an overview of the weather in the area. There are preset limits and calculations for frost and slipperiness risks that can be viewed as warnings in the map view.

The RWIS is hence a very important support tool for maintenance personnel and the accuracy of the system is crucial to be able to make the right decision. There have been extended studies and developments within the RWIS since it was first implemented in the late 1970's. This has also resulted in discrepancies in positioning, instrumentation and installation between stations. Gustavsson and Bogren (2002) revealed that some road surface temperature sensors lay deeper down in the road construction than others, while some had different type and colour of coating. These differences may have impact on the thermal reactions of the sensors used. Other studies have indicated that the dewpoint, which is calculated from the air temperature and humidity, of the air between 10 cm and 250 cm above the road may differ with as much as 2 °C (Almkvist et al, 2005, Baad and Brodersen, 2010; Karlsson, 1999). These insecurities may contribute in making the system inefficient. Paper II discusses the impact of such insecurities and errors on energy use.

Winter plan (Enera, 2011) is a route optimization tool especially developed for winter road operations, not only used in the everyday planning but also in procurements. It uses Geographical Information System (GIS) data of road networks, which provides a system with information about road width and speed limits on top of information about the maintenance vehicles used. It is developed by Enera International AB. Road maintenance operation managers are using this tool when planning salting and snow ploughing routes. This way they may optimize the number of vehicles used for a certain slipperiness event.

1.4. Aim and Scope

The overall objective of this thesis has been to create a model which uses accessible data to calculate and map the energy use within road maintenance operations. This has been requested from both authorities and contractors, since there is a need for reporting energy use within road management. The model is also intended to be used when evaluating possible changes within the maintenance operations.

The general model structure, the baseline use of energy for road operations (i.e. the use of energy of the different operational activities before efficiency measures are taken) and the activities with the largest potential for savings were obtained in **Paper I**.

As indicated previously there are a few insecurities that might reduce the effectiveness of the RWIS. Within the scope of this thesis the effect of such insecurities are investigated along with a discussion about the potentials for efficiencies within the RWIS. This is done in **Paper II**.

It is important to delimit the area of investigation; hence, the boundaries of a typical maintenance area are set as a demarcation. Only the transportation within these borders is considered. Transportation of material to and from the district will be neglected as will electricity and all energy use related to heating of buildings and production of materials.

2. Methods and Data

The methods used in this thesis are described in the following sections, starting with the overall model structure and energy calculations. This is followed by the baseline use of energy within maintenance operations where data is acquired through a questionnaire sent to maintenance district managers. Finally, a literature review and investigations of the RWIS data is made with focus on potentials for increased efficiency.

2.2. Model structure (Paper I)

As discussed in the previous sections the objective of the thesis is to analyze energy efficiency within road maintenance operations, by developing an energy model which uses accessible information such as the number of hours a specific vehicle is employed for a specific maintenance operation. The model is to be applied as a calculation aid when either declaring a baseline for the energy use within the operations, or evaluating the possible effects a shift in practice or change of vehicle might have on the energy use.

The fuel consumption of a vehicle is dependent on engine capacity, fuel quality, driver skills and workload. It was hence not viable to set an optimal fuel consumption value in the model, instead a range between minimum and maximum values were used. Hammarström and Yahya (2000) estimated fuel consumption values for heavy lorries while Flodström *et al.* (2004) made an inventory of fuel consumptions and emission factors from other vehicles and working machinery used within maintenance operations of the roads. These values were used in the model to calculate the total energy use within the road operations. The fuel consumptions of Hammarström and Yahya, given in litre per kilometre, needed to be recalculated on the form of litres/hour. It was therefore assumed that the lorries used in the operations worked at a speed of 40 km/h on the average.

2.3. Energy use calculations

The fuel consumptions and ultimately the energy use of the different operations may also be calculated using different methods and approximations. In paper I the estimated fuel consumption values reported in literature was recalculated into energy using the approximation that 1litre diesel equals to 1 kWh of energy. The calculated energy use was compared to the energy calculations by Stripple 2001.

In paper II the energy use of salt spreading lorries was calculated by using the methods and data of NTM (NTM, 2010) along with assumptions made by Stripple (2001). Stripple made a Life Cycle Assessment (LCA) analysis of the road operations in Sweden, where he calculated the energy use of a 13 metre wide and 1 km long road object. Since the spreading width of the discs used in the spreading operations is up to 8 m wide the salt spreading lorry would need to pass each road segment twice to be sure to have operated the whole road area. The NTM values for a medium size lorry using EURO III fuel, with a load factor of 50%, were used to calculate the fuel consumption. These calculations resulted in a fuel consumption of 2.23 litres per 10 km and an energy use per maintenance operation of 330000 MJ for a maintenance district of 21000 km road. The energy content of 1 litre of diesel was set to be equal to 1 kWh.

Stripple assumed that salt would be spread about 40 times in a winter, which would amount to 17.1 MJ/km. When applying this to the maintenance district the energy use for one salt spreading in the area is 360000 MJ. It was concluded in paper II that either way of calculating would be sufficient.

Furthermore, the Swedish National Road and Transport research institute made a comprehensive winter road maintenance operation model including a sub-model of fuel consumption (Wallman *et al.,* 2006). This model would calculate the fuel consumption in units of litres per 10 km, for personal car, lorry without trailer and lorry with trailer according to the following equations:

$q1= 0.0033 \cdot v+0.44$ for car
$q2=0.0153 \cdot v+0.38$ for lorry without trailer
$q3=0.04 \cdot v+1.3$ for lorry with trailer

Recalculating this into l/hour would give the values of 0.057l/km 2.3 l/hour for personal car, 0.099 l/km and 3.9 l/hour for lorry without trailer and 0.29l/km and 11.6 l/hour for lorry with trailer. These values are calculated for bare and dry road conditions, the values may hence vary depending on the weather. The values for lorry with trailer agree with the values given by Hammarström and Yahya (2000), but the values for lorries without trailer are diverse. Hammarström and Yahya use however a weighted mean value for the fuel consumption for lorries without trailer, the range from the minimum to the maximum values were of the size of one decimal from 0.107 to 1.75 l/km. Those values were gained through 1513 answers from a survey made by statistics Sweden about fuel consumption for heavy vehicles over 3.5 tonnes. The survey was done in 1997 the fuel consumptions may have changed during this time, since the vehicle fleet may have been upgraded and become more fuel efficient.

2.4. Energy Baseline (Paper I)

When considering energy efficiency measures, the state of the art or the baseline use of energy i.e. the use of energy before any efficiency measures are taken, need to be established. This was done in paper I, by gathering information about the number of hours each maintenance vehicle was used for a specific operation. The data was used as input to the model for calculating the energy use, as well as obtaining an understanding of how the energy use was distributed between the different maintenance operations and were the greatest potentials for savings were.

2.4.1. Questionnaire

Even though information about amount of fuel used within operations may exist, it would not be specified for what. Contractors use subcontractors for many different areas of operation, hence the fuel may be used not only for duct changing but also for repairing of potholes. To get the energy baseline for the road maintenance operations a questionnaire was sent to SKANSKA maintenance districts (Paper I). Since the objective was to figure out an easy way to report energy the questionnaire was based on the vehicles used in maintenance as well as the number of hours each vehicle was used for a specific maintenance task.

2.4.2. Workshop

The results from the questionnaire were discussed at a workshop with experts within the field of road maintenance. There were experienced maintenance personnel as well as accomplished managers from three different contractors; researchers from two departments of the Gothenburg University and representatives from the Swedish Transport Administration. The participants were divided into three groups with 5-6 people in each. They were also to discuss the potentials for energy efficiency and to single out 5 operations with the largest potentials. The aim was to find 2-3 types of operations that all three discussion groups had found to have the greatest potentials for saving.

2.5. Efficiency potentials within the RWIS (Paper II)

The RWIS is commonly used as a support tool within winter maintenance. It is needed to evaluate the road conditions. In Sweden it is not supposed to be used as a decision maker, but rather as a help in deciding when to initiate operations. As described earlier there are some uncertainties within the instrumentation and positioning of the RWIS that might induce errors that consequently may lead to unnecessary use of energy. In paper II, the frost warnings of the system were investigated since those warnings were the most common.

The first part of the study was made as a thoroughly literature investigation about insecurities and possible errors in the instrumentation and measuring techniques of the RWIS and its sensors. The temperature sensors used in the Swedish RWIS measure with an accuracy of ± 0.3°C, while the accuracy of the humidity sensors is less than ± 3% RH. The different insecurities connected to the positioning of the RWIS stations as well as their installed sensors were divided into uncertainties due to positioning of the sensors, uncertainties in RWIS station positions and uncertainties within sensors.

To investigate the impact such deficiencies might have, data from 166 road side stations in south-western Sweden for the three winters of 07/08, 08/09 and 09/10 was used. 42 out the 166 stations had an additional temperature sensor. Stations with an additional sensor are often considered more prone to slippery conditions thus the use of an extra sensor, usually on a bridge or in another lane. There had been some indications prior to the study with regard to unusually large number of frost warnings from such a roadside station, hence some further investigations was made in paper I.

The frost warnings are a useful indicator for when there might be risk for slipperiness. Maintenance operation managers in charge of deciding when to initiate operations often use the information from the system. False warnings might hence lead to unnecessary salting operations with excessive use of energy and salt. The system might on the other hand miss to warn if insecurities in sensors or the temperature limits of the warnings were set too low. This would lead to hazardous road conditions. Another concern is for how long the salt will remain effective on the road surface. Gustafsson and Blomqvist (2004) found a relationship between residual salt and the traffic as well as with precipitation. They concluded that salt might linger for several days. Their study was however conducted during dry to moist road weather conditions, while the winter weather in south-western Sweden usually is wet resulting in salt spray off road. There is hence no obvious time range for when the amount of residual salt will have reached a dangerously low level. For the study in paper II the common time range of six hours was used. Missing data for longer than 2 hours were excluded from the study, which yielded 143 stations in 2007-2008, 152 stations in 2008-2009 and 166 stations 2009-2010. A maintenance activity was defined as a frost warning followed by at least 2 other warnings and was not preceded by another warning for the at least 6 previous hours.

3. Results

The following sections will highlight some of the results of paper I and II. First the general model structure which in paper I will be fed with data from the maintenance districts and finally the potentials for efficiency within the RWIS. Some of those potentials are put in the general model for evaluation.

3.2. Model structure

The general model structure is shown in figure 1. Since the fuel consumptions for the vehicles used in the operations can be given in litres/hour it was clear that the number of hours could be used as input to the model. This is important since even though records of energy use within the operations are difficult to attain the hours are already reported hence accessible for the model calculations. The use of hours also opens for the possibility to modify the model to suite a specific maintenance district in terms of type of operations performed, the vehicles used and their respective fuel consumption. Each maintenance district can put their own operations to the model as well as the vehicles used and their respective fuel consumptions. The time in hours will then be calculated against the fuel consumption (in litre/h) to get the total fuel consumption per operations as well as for the whole maintenance district.

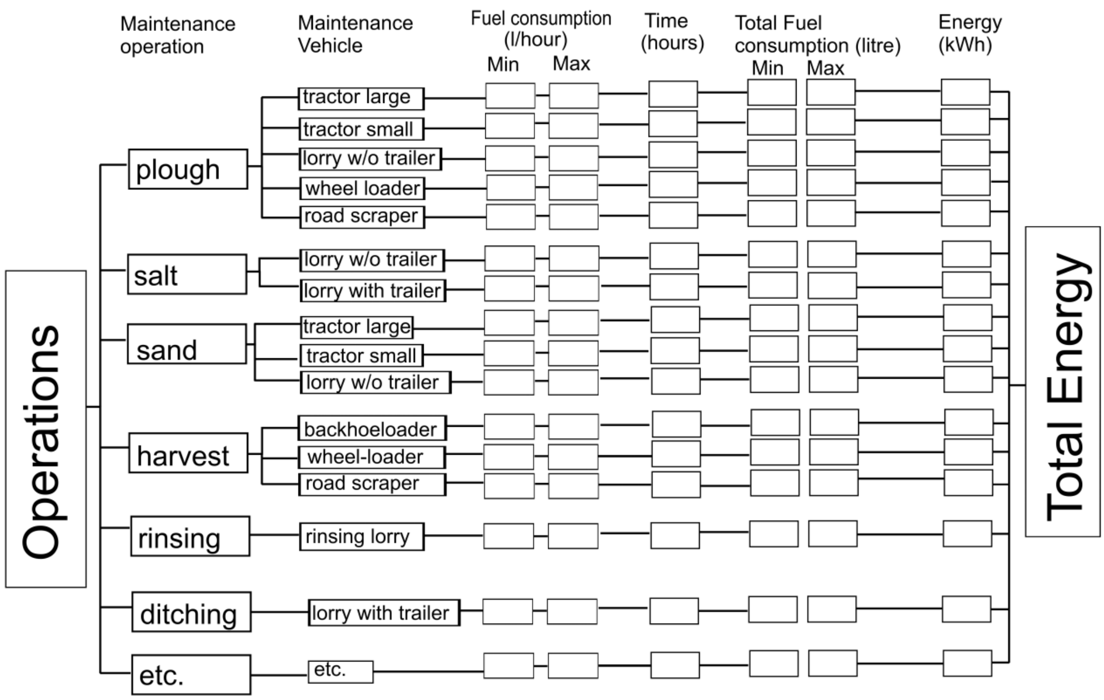

Figure 1, the general model structure, where the maintenance operations may be altered depending on the needs of the maintenance district at evaluation.

To be able to analyse the energy use within the maintenance operations in Sweden, the model was fed with information from the questionnaire answers of the energy baseline study.

3.3. Energy baseline

Seven out of ten maintenance districts answered the questionnaire about number of hours their operation vehicles were used for the different activities. Winter operations, including not only salting, snow ploughing and sand gritting but also snowblower, ice scraping, salt and sand loading, used over 50% of the total calculated fuel consumptions. It was however the snow ploughing operations that are the single most energy demanding operation all over, with the use of up to 30 % of all energy use. These figures are dependent on whether or not the maximum or minimum fuel consumptions are used. The ploughing would however still consume 20% of all the energy use even if the calculations was done in such a way that ploughing operations would use the minimum value for fuel consumption while the other operations would use the maximum. Table II, shows the distribution of hours per maintenance operation as well as between the different districts. The minimum and maximum values represent the maintenance districts that put less or most time into the particular operation. The average is for all the seven districts. The range of minimum and maximum fuel consumptions are on the other hand based on the values in Hammarström and Yahya (2000).

Table I, the distribution of number of hours for each maintenance operations as a maximum, minimum and average between the seven maintenance districts.

				Fuel consumption (litres)	
Maintenance Operations	*Min (hours)*	*Max (hours)*	*Average (hours)*	*Min*	*Max*
Ploughing	1680	9735	6120	73690	138120
Salting	900	4000	2390	31158	51189
Sanding	540	2045	1295	16187	33595
Harvesting	0	2460	1046	16624	30411
Material transportation	0	2000	1357	17735	29136
Ditching and ditch clearing	15	1460	904	15790	28061
Inspection routines	500	4800	2343	7803	20808
TMA	200	1800	859	9616	15798
bridges, cleaning	0	400	120	7540	12388
Snow stick	0	2000	516	6739	11071
Snowremoval/Snowblower	0	900	371	4333	8667
sweeping	0	290	139	3999	8048
cleaning road construction	0	820	134	3992	7844
Gardening	0	600	234	4499	7499
Cracks and hole repair	0	520	196	3069	5042
Sand/salt loading	0	500	210	2445	4890
Gravel covering, scraping	0	600	150	4463	4463
Ice scraping	0	528	225	4460	4460
Dust binding, irrigation	0	550	131	2576	4232
Refuse and container transport	0	576	153	2392	3930
Free room	30	1744	525	1795	3573
Edge cutting /snow ditching	0	400	90	3570	3570
Sealing	0	200	54	1419	2331
Various service	0	400	100	1080	2160
Sand uptake	0	350	107	1050	1050
Sum fuel consumption				***248 024***	***442336***

3.4. Potentials

Potentials for efficiency were discussed at the workshop, where the different discussion groups ranked the activities with highest potential for saving. All three groups considered snowploughing to be the most potential sanding, salting and harvesting was also ranked in the top five for all three groups. This indicated that the winter operations were not only the most energy demanding but were also estimated to have the greatest potential for savings. It was hence interesting to further investigate those specific operations.

3.4.1. Efficiency potentials within the RWIS

Paper 2 discusses some of the insecurities of the RWIS, which might represent potentials for energy savings.

As described in the methods section the frost warnings were studied since those were the most common. The number of frost warnings in the studied area ranged from 10 warnings for one station up to 2931 for another station in the same region, while the average value was 608 warnings. Out of the about 179 000 frost warnings analysed in the years of 2007-2010, 41 % were triggered with a dew point oversaturation (i.e. the difference between the dew point temperature and the air temperature) of 1 °C or less. If the limit for frost warning was to be changed from 0.5°C to 0.6°C there would be a reduction of 10.3% in number of frost warnings. If the values of the current system were to be inaccurate by 0.1°C it would hence mean about 10% unnecessary warnings. Returning to the previous studies about temperature differences of 2 °C depending on height above the road surface such a small error as 0.1°C is not uncalled for. Such an error would yield about 10 unnecessary maintenance operations in a winter.

When applying this into the baseline model for one of the maintenance district in paper 1 with 400 km of salted roads it can be assumed that one salting route is 70 km and it takes 3 hours to run, the maintenance district had about 200 km of salted roads. One operation in this area would give about 9 hours of labour. Ten unnecessary warnings would then yield 90 hours, which equals to 3 % of the 2800 hours that particular district put into salting operations. This furthermore yields to 0.6 % of the total number of hours the particular maintenance district use in a year. 90 hours times the 11.2 – 18.4 l/hour fuel consumption span would yield an energy use of 10080-16560 kWh.

The warnings of the roadside stations with an additional temperature sensor were compared to the number of warnings at that particular station if only using temperature data of the standard sensor. As seen in figure 1 there were both positive and negative differences between the two sensors and at some stations the differences were as large as 3651 extra warnings. The data of the two temperature sensors were compared resulting in discrepancies ranging from 15 °C above and 5 °C below for the additional sensor compared to the standard sensor. The roadside stations that are equipped with both of these sensors are programmed to use whatever temperature is the lowest while the humidity is used in either case, resulting in higher frequency of road frost warnings.

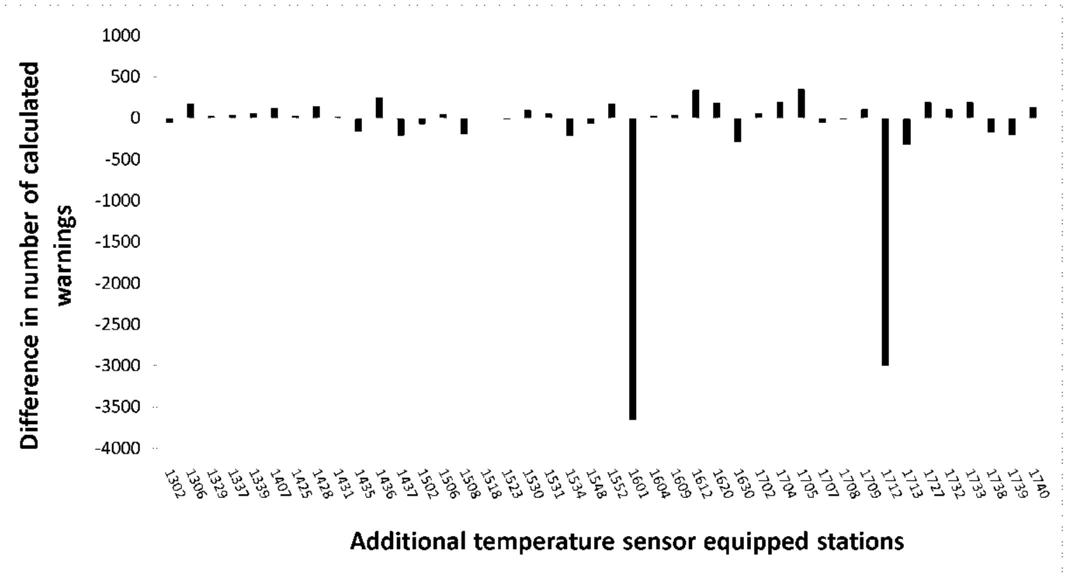

Figure 2, The differences in calculated frost warnings using the additional sensor data or the standard thermometer data

If the maintenance managers would have based their decisions on the warnings produced at the stations with over 3000 additional warnings it would yield to about 157 extra salting routes. When applying this to the model for the same maintenance district as used in previous calculations it would yield 1410 hours which would equal to 50% of the salting hours and 9.6% of the total use in the district. This is however only hypothetical since the road maintenance personnel often work for several years within the same district and have a special feeling for the conditions in the area. If something was out of the ordinary they would consider this before taking action. It is however an interesting result which clearly indicates that there are something odd at these stations, either it depends on the additional sensor or the standard installed sensor. Further studies about these large differences are needed to know whether this is true values or potentially false warnings.

4. Discussion

This thesis has shown that there are potentials for increased energy efficiency within road maintenance operations. Here follows a discussion about different measures that potentially might bring about increased energy efficiency.

As mentioned in the section about maintenance support tools, there could be potentials for savings if the sand was changed to salt for road classes 4 and 5, which are not salted today. Instead they are sanded but not as frequently as the roads with standard classes of 1-3. When considering the road maintenance operations log-books it could be concluded that even though the sanding occasions were much scarce, the amount of sand was about 10 times more than that of salting. A quick calculation will bring about the interesting thought of what would happen if the roads of class four were not maintained more frequently but instead of those few occasions of sanding they would be salted instead. One example is for a day in February where the roads of class four were sanded. About 50 tonnes of salt was used on the about 100 km of road that was sanded. During the same day a class 1-3 road was salted with a salt solution of 5 tonnes on a road stretch of about 90 km. Take also into account that the vehicles used have a maximum load of 12-14 tonnes. The salt spreading route could be done with one vehicle. The sanding would have to be done by at least three rounds or using three different vehicles. There are hence potentials for saving energy if making such a change to the operations. There are also other potential energy savings to come with such a change, since less ditching and sweeping is needed if no sand is gritted and eventually gathered in the nearby ditches.

The previous discussion opens for some forbidden remarks; would it be better for the environment if we salted more roads? Ever since the mid 1980's there have been projects and investigations of how to reduce the use of salt. As described earlier the amount of salt used has been reduced since we changed from solid salt to solution, but it is still a very hot topic. Depending on what the focus is; energy or salt, the way of practice hence the regulations should be reconsidered.

The RWIS used in Sweden gives single-point data, which causes insecurities when trying to understand what happens in between stations, hence, a lot of developments are being done in creating models that interpolates information from many different road weather stations as well as from other sources such as land-use, road construction, sky-view factor, topography and meteorological data. Such systems are often called Maintenance Decision Support Systems (MDSS), and are frequently used in the USA (Pisano *et al*., 2006). These models often give route specific forecast about the road conditions and recommendations for maintenance operations. Other developers use GIS-based road surface temperature models to predict the surface temperatures (Chapman and Thornes, 2006).

Another potential saving is to use permanent salt sprayers in the road which automatically sprays specifically slippery prone areas. Such salt sprayers are used on bridges in the USA with good results (Khattak, Pesti, 2003). Using such techniques, operational salting would be unnecessary during certain weather conditions.

5. Conclusions

The following main conclusions can be drawn from this thesis.

It is possible to use accessible time information about road maintenance vehicles in the model developed in this thesis to calculate the energy use within a road maintenance district.

The model can be modified to suite the specific needs of the user and the fuel consumptions may be altered along with a more fuel efficiency vehicle fleet. This is also why the model makes it possible to evaluate potential savings as a result of the implementation of new techniques or methods.

A general baseline for the energy use within maintenance operations is attained through information given by maintenance managers. The winter maintenance and snow ploughing especially uses most energy. About 50% of the maintenance is used in winter related operations. It is concluded from discussions at a workshop that the winter operations of ploughing, salting and sanding also have the highest potentials for savings.

The different operation support tools such as the RWIS may help in making the operations efficient. They may however overturn if the system is not trusted or inaccurate. Paper II concludes that there are uncertainties in the RWIS system, depending on sensor positions and accuracy. A small error such as 0.1 °C in the measurements might cause large errors in the calculations and give about 10% false warnings during a winter. Using the energy model for this on a maintenance district with about 400 km of salted roads would give a potential saving of 10 000 – 16600 kWh. This is about as much as the annual energy consumption of a one family household.

There are potentials for efficiencies if the regulations concerning winter operations were to be changed. The discussed change would however bring about other environmental issues since it suggests further salt use. This opens for future discussions of the way of thinking within the managements of the roads. What is more important, saving energy or saving salt? Which alternative will be the best overall method to use?

6. Future

The project energy efficiency within road maintenance operations will continue by investigating different ways for efficiency. The next step is to investigate the potentials by using a route optimizing system. The use of the support tool Winterplan described in the introduction will probably be considered for such measures.

7. Acknowledgements

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Lina Nordin

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Paper I

Energy Use within Road Maintenance Operations in Sweden

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Abstract: How much energy is used within road maintenance operations in Sweden? This question is addressed in the present study. The road authorities as well as the contractors are requesting a model to be able to monitor the energy use within the sector. This is met by considering energy consumptions by the time use of the different vehicles employed within road maintenance operations and to recalculate this into energy use. A questionnaire was sent to different maintenance areas in Sweden. The study gave a very clear answer; most energy is spent on winter maintenance activities. Winter operations amount to 25 % of the number of activities but consume more than 50 % of the total energy used. Furthermore the potentials for savings are discussed at a workshop with practitioners involved in maintenance operations on different levels. The outcome shows that the largest potentials for energy savings are within winter operations as well. Finally a model is constructed to be able to monitor the energy use within the road operations as well as evaluating energy efficiency measures. The model input is based on the fuel consumption as well as the number of hours a vehicle is used for a specific activity.

1. Introduction

High quality road maintenance is demanded from road users, private as well as industrial. When roads are not properly maintained it may have negative impacts on trade and industry, such as delayed personnel or merchandise, disrupted production as well as reduced profitability (SRA, 2000). Well maintained roads are also important when discussing energy efficient transportation. Several studies conclude that the fuel consumption could increase when driving at constant speed on roads with different surface characteristics. The size of the increase seems to depend both on type of vehicle as well as surface texture. A field experiment in South Africa predicted that the fuel consumption could increase with up to 7 % for passenger car and 20% for lorries and busses if driven at constant speed depending on the different road surface characteristics (du Plessis et al, 1990). Sandberg (1990) conducted tests with different roughness and came up with similar results. He also found a very high correlation between fuel consumption and road surface texture. It is hence important to keep the roads as even and clean as possible, which is one of the main focuses for road maintenance operations. However, the friction of the roads is even more important since low friction is a severe safety hazard. Maintenance operations needed to uphold those conditions are for example ploughing, salt gritting, crack-sealing, and sweeping. Each of those maintenance operations demands the work of a light to heavy duty vehicle hence presumably also a lot of energy.

Previous studies about efficiency within road maintenance operations have mainly been about new methods or decision support systems to make the operations more efficient. These methods could in the elongation lead to less use of energy even though it would not have been the main focus. A study about energy savings within road maintenance in Japan, discussed ways of saving energy by changing the use of electricity, since electrical power was used to melt the snow (Soma *et al*, 2008). There are also different measures that have been taken in Swedish municipalities concerning energy savings within road maintenance operations as well as testing of new techniques such as snow ploughs. Möller and Gabrielsson (2010) conducted tests of three new snow ploughs to investigate their effectiveness in clearing snow as well as their impact on fuel consumption. Many studies concerning energy use and efficiency are those using life cycle assessment (LCA) methodologies. The LCA methodology, measures the impact a product has on the environment during its life time. There are many studies about energy use and LCA within road construction. These studies mainly focus on the impacts from production and transportation of materials used in constructing the roads (Huang et al. 2009). Stripple (2001) made a comprehensive LCA of road construction, road maintenance and road operations in Sweden, using a lifetime of 40 years. The present study will however analyze the energy use within maintenance operations as a first step towards energy efficiency within road maintenance, by using information provided by the contractors themselves. The LCA made by Stripple will somewhat pose as a validity measure for those results.

Energy efficiency within road maintenance operations has three main driving forces; environment, safety and economy. Political goals are often driven by all of these, while contractors are mainly driven by economy but also to some extent by the environment. Safety is however the main interest for each contractor, the foremost reason of their needfulness. When considering different efficiency measures safety will hence always lead the way. It cannot be tampered with. Energy efficiency within road maintenance is hence a complicated balance walk between these three driving forces.

At the different levels of road authority the steering goals are thus diverse in nature, influenced by the aims and objectives of both national and international policies. At the top, the European Union, the Swedish government and the Swedish Transport Administration each have their own policies and regulations to be followed. At the bottom lies each separate contractor with the aim of reaching both its own goals but also those of the government.

The Swedish Transport Administration (STA) is regulated by the Swedish government, therefore the goals of working for a 10% reduction in greenhouse gas emissions within transportation (STA, 2007) are set in accordance with the governmental goals also stated in the national action plan for energy efficiency (SOU, 2008). The STA has the overall responsibility for the national roads in Sweden but the maintenance is distributed onto contractors via procurement. There are, however, ways for the STA to involve environmental requirements in the road maintenance by introducing green procurements. The implementation of these requirements has hitherto been difficult to employ caused by e.g. ineffective ways of follow-up. Such deficiencies could be surmounted, if these follow-up routines could be more effective (Faith-Ell *et al.* 2004).

Since each maintenance district is attained through procurement it is important for contractors to be able to cut their expenses wherever possible. There are however a set of rules of regulations, security levels of roads and road conditions that need to be upheld, the rest is up to the contractors in each region. This means that in order for the roads to sustain a certain standard they need to be clear from snow, ice, oil or other obstacles. The roads security level is also affected by the areas close to the roads such as ditches, and nearby forests. Mowing grass and thinning out brushwood is consequently also a part of the regular maintenance operations of the roads. To do all this while upholding the environmental requirements of the STA is not uncomplicated. However; working more energy efficiently is not only about caring for the environment it is hence also a question of saving money or in the elongation winning more procurements as a contractor.

As described previously there is an attempt to work towards increased energy efficiency at many levels within the maintenance operations of the roads. Even though the energy use in a LCA perspective has been established in previous studies, a general report system for energy use within road maintenance is deficient but required from the authorities. The problem has been about the difficulty of distinguishing between different uses of fuel when a vehicle is employed for multiple tasks during the same time period. The aim of this study is therefore to provide a solution for defining energy use within the maintenance operations in Sweden, as well as, to recognise main groups within the operations with potentials for improving energy efficiency. To be able to discuss whether or not a shift in practice is more or less energy efficient; the present use, or the baseline of the use, of energy and resources needs to be established.

The difficulty of setting a demarcation is resolved by using the borders of the maintenance district as boundary. Only the operations performed directly within these boundaries are considered. The production of materials used or transportation to and from the maintenance district is hence neglected in this study. Since most of the maintenance operations are performed while transportation i.e. vehicles are involved, buildings and electricity are also neglected.

2. Energy efficiency

In order to develop a model for energy efficiency it is crucial to understand the term of energy efficiency. What does it mean? Although it is a popular term to use in almost all links of today’s society as well as in the tremendous quantities of research going on within the topic, the term is not always used in the same context.

In general the term energy efficiency is defined as reduction of energy consumption while retaining the same outcome (Oikonomou *et al*, 2009, Patterson, 1996). This could in other words be described as getting as much work out of the energy input as possible (Herring, 2006). Further on this could be described in terms of a ratio between energy input and the maximum outcome of the process (Oikonomou et al, 2009, Patterson, 1996), or to put it in a more recognizable way as km/litre (Herring, 1999).

For freight or transportation the terms of energy input / tonne kilometre or vehicle kilometre (Patterson, 1996) are used, or for maintenance operations: fuel or energy input / total transport distance or effective hours in production (Hjalmarsson and Odeck, 1996). This because tonne kilometre is difficult to address within road maintenance since they do not weigh the amount of snow moved from the roads.

Within the field of road maintenance operations, most of the operations are performed by transporting materials or personnel, spreading salt or sand, removing snow or mowing lawns. It is hence easier to look upon as sort of a freights company, transporting freight from point A to point B. This approach would fall under Patterson's physical-thermodynamic indicators group (Patterson, 1996), where the energy efficiency could be calculated through:

$$\frac{Output\ (tonne\ kilometers)}{Energy\ input\ (\Delta H)}$$

The question though is to define the energy input, since the maintenance operations in Sweden most often is operated by subcontractors who also perform other duties than those of the maintenance operations. Consequently, the amount of energy input is very difficult to quantify even in terms of litres of fuel. This problem is met in the presented paper by using amount of hours in production as a measure for energy input and to recalculate the hours into litres of fuel.

2.1.Reasons for energy efficiency measures

As described earlier the aim of this project is to isolate groups within the maintenance of the roads in Sweden that have great potential for energy efficiency. The interest in this subject is large both within government and contractors.

There are however, many debates about whether energy efficiency is constructive or not. What is the purpose of such measures? Is it truly good for the environment? Herring (1999, 2006) discusses about energy prices as well as environmental effects to be less than what is in general expected from energy efficiency projects. Herring concludes that economists seem convinced that such efficiency matters would lead to increased use of energy since the use of energy through new more efficient techniques would be more affordable, hence result in an accelerated use of such techniques. This could indeed be the case for new techniques or more fuel efficient vehicles within road operations unless there was an overall interest in using less energy and consequently reaching emission goals as well as saving costs. Herring (2006) further suggests that if the goal is to save the environment the best thing to do is to use non fossil fuels instead of fossil fuels.

The oil crisis in the 1970's where many of the world's resources of oil reached a peak in discovery, is however another aspect to the question of taking energy efficiency measures or not. The modern way of life is vulnerable to changes in oil supply. The years after the 1970's crisis taught us that we need to learn how to use energy more efficiently. The resources are limited. But even though many of the world's resources of oil have already reached their peak in production their assets are still a third or up to half of the original endowments (Bentley, 2010). According to Bentley the global oil production will reach maxima somewhere between now and the year 2020. Whether or not he is right, we will need to find other ways to use energy. The recent economic crisis also opened the eyes for reducing costs where ever possible. The energy usage is an obvious area to start with, where numerous measures can be taken.

3. The practice of maintenance operations

The contracts set up by the Swedish Transport Administration (STA) and the contractor of each maintenance district regulates what needs to be done and when. The winter operations have a specific rules of regulations manual (STA, 2002) , the ATB Vinter 2003, General technical instructions, winter 2003. Within this manual there are definitions about the roads, the de-icing chemicals to be used as well as their concentrations. There is also information about snow sticks, visibility, bus-stops etc. The actual performance of the different maintenance tasks are often performed by subcontractors, which apart from the different maintenance tasks also perform other distribution tasks with their vehicles. They are normally paid per hour which means that there are no records over their fuel consumption in regards to maintenance operations.

3.1. Road Operations description

To understand the energy use within road maintenance a short description of the operations that demands most attention is given in the following sections. The information about these operations is given by the function and standards description for a typical maintenance district.

The Swedish national roads are classified according to the annual daily traffic flow i.e. number of vehicles passing every day, see table I. The higher the traffic flow the higher the standards of the roads; meaning that road class 1 has the highest priority and is also the largest, usually a motorway.

Table I,

Road Class	***Annual Daily traffic flow (No. vehicles passing/day)***
1	> 16000
2	800 – 15999
3	2000 – 7999
4	500 – 1999
5	< 500

The classes 1-3 are operated in the same manner with a slight difference to the third class where for example snow may linger for a little longer before it needs to be removed. Classes 4 and 5 are usually not chemically treated in winter unless very severe weather.

3.1.1. Inspection routines

In order for the roads to maintain the same standards every day there are some inspection routines that needs to be done during the course of the week. At a minimum class 1 need to be inspected 3 times evenly spread over the week, class 2, two times and class 3 one time each week. Classes four and five need only be inspected once every two weeks. During an inspection route the whole of the road length need to be inspected for obstacles or damage to the road construction.

3.1.2. Slipperiness

To know when to initiate maintenance operations due to slippery road conditions, the personnel use information from the Road Weather Information System (RWIS). It consists of weather stations positioned along the roads, measuring air and road surface temperatures, air humidity, precipitation and winds. The use of this system has in many ways made the operations concerning slipperiness, more efficient, since it gives information about the weather conditions on the actual road. During the winter months the maintenance personnel closely follow the information given from these stations to be sure to hit the roads with de-icing chemicals such as salt, before slipperiness occur. During salting operations every inch of the road is passed over by maintenance vehicles, this also means bus-stops, ramps, refuges, viaducts and lay-bys. The start criterion during snowfall differs between different road classes. In short, whenever snow falls on road classes 1 and 2, the roads need to be clear from snow within a certain time span from the end of the snowfall, this time span will be longer for less prioritized roads. However there are also start criterions dependent on the snow depth. For classes 4 and 5, these starting criterions are lower and there can still be snow left on the roads after clearing.

3.1.3. Repairs

Holes or cracks on the road should be repaired as well as obstacles removed from the road. Smaller road repairs need to be performed within the contract. During such repairs security regulations need to be upheld. Such security measures may be the use of Truck mounted attenuators, TMA. These attenuators will often be mounted on another vehicle than the one performing the operation. These are safety precautions not only for the road workers but also for the road users.

3.1.4. The Free Room

The air space across to one meter on either side of the road with a height of five metres above the road will create an invisible room that should be free from obstacles, such as tree branches, at all times.

3.1.5. Harvesting and brushwood clearing

The verges and ditches should be harvested every year at a width of 3 m, and every other year at a width of 7 m. After harvesting the vegetation should be no more than 15 cm high.

3.1.6. Lay-by cleaning

Every parking and lay-by area should be cleaned and maintained throughout the year. During summer there are however more travellers on the roads hence the regular cleaning is needed more often. This means that cleaning is needed twice a day during the summer while it is only demanded one a day in winter. Garbage is cleared twice a day in summer and once a week for the rest of the year.

3.1.7. Other operations

Other operations within the contract which may take up considerate amount of time, follows in table II.

Table II, Different types of maintenance operations and the criterions for how often the operation should occur, as set by the regulations

Maintenance operation	Criterion
Ditching and ditch clearing	Every year
Dust binding	Is performed every year when needed.
Gravel covering	Every year where ever needed
Bridges, cleaning etc	Once every year
Gardening	Parking areas as well as lay-bys, need mowing and caring
Cleaning of road construction	Once every year
Sweeping	After winter season

Each of these operations demands some sort of transportation and the use of light to heavy duty vehicles thus a lot of energy is used.

3.2.Energy use within maintenance operations

There are extended studies about the energy use and emissions from the ordinary traffic on the roads. However studies about the fuel consumption or energy use within road maintenance operations are scarce. Stripple (2001) made an extensive Life Cycle Analysis of the road maintenance in Sweden. The results made by Stripple were used by Karlsson and Carlson (2010) in calculating the energy use and CO_2 emissions from construction and maintenance of the roads over a 60 years period. The results from Stripple are also considered in this study but more as a validity measure.

As mentioned earlier there is a growing need for energy efficiency measures and the starting point is always to know the baseline of the use (i.e. the use before any efficiency measures are made), to have something to measure against. The striving of the authorities is to make energy out of easily reported information. Since each contractor already needs to deliver information about how many hours it takes to perform a certain maintenance operation, an easy way would be to use this information in creating a model for energy use.

4. Methods and data

The methods of this study were divided into two main parts, a questionnaire and a workshop. The objective was, based in the results of these two activities to develop a general model for energy use within road maintenance operations. The model structure would hence also be part of the methods description as well as a section about validation of the results from the questionnaire.

4.1.Energy inventory

To get a distribution of how the energy is used between different maintenance operations a questionnaire was created and sent to ten maintenance districts run by the contractor Skanska, Sweden. Skanska managed ten out of 124 maintenance districts in Sweden during the year for the inventory. The questionnaire was sent to their districts since they continuously work with climate and efficiency measures within their different fields of operation as well as being ISO 14001 certified. Road maintenance is however a relatively new area for them hence their interest in being involved in such research. Seven districts out of ten answered the questions about number of vehicles as well as the hours each type of vehicle is used for different maintenance operations. These districts were distributed from Lat 56°N to 64 °N and Lon 12°E to 21° E, and marked by circles in figure 1.

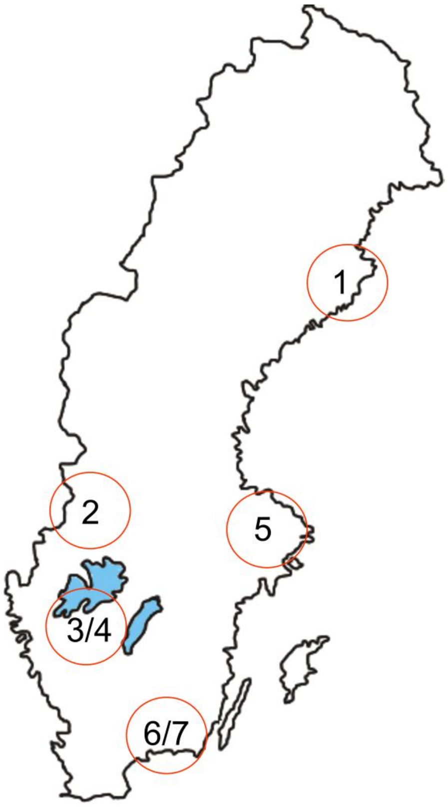

Figure 1, The regions where the maintenance districts in the study are situated. The numbers represent the numerical name of each maintenance district

Some general information about the roads in each district is listed in table III. The road lengths are around 1000 km with one high of 1666 km and one low of 560 km the road lengths of classes 1 and 2 are however very varied in between the districts, which may affect the number of hours put into different maintenance operations.

Table III, General information about the different maintenance districts used in the study

	Districts						
	1	**2**	**3**	**4**	**5**	**6**	**7**
km road	1040	1000	560	891	970	1310	1666
km gravel	345	300	106	41	100	100	40
km asphalt	695	700	454	850	870	1210	1626
km class 1 and 2	0	0	406	174	87	50	214

The answers from the questionnaire were organized into groups of maintenance tasks for each maintenance district. The distribution of the maintenance areas, as well as the maintenance standard of the roads in each district, contributed to the contrast in hours spent on different tasks, in the different maintenance areas.

4.2. Validation

Validation of the results from the questionnaire was done in two ways; a workshop and a comparison with previous investigations. The results were recalculated into fuel consumption and compared to the work made by Stripple (2001). The energy values Stripple used for salting, snow ploughing and sanding of a road object of 1 km was summarized to 11.22 MJ, where it was assumed that those operations together occurred 52 times each winter. When considering a road maintenance area of 800 km of road, during the course of a winter season, the total amount of energy used would then be 466 752 MJ. The questionnaire generated information about how many hours each type of maintenance vehicle was used for a certain operation. The minimum and maximum fuel consumptions for the different maintenance vehicles were estimated from two separate reports (VTI, 2000 and SMED, 2004). With the approximation that 1 litre of diesel is equal to 1 kWh; an energy use span for each vehicle type was calculated based on the minimum and maximum fuel consumptions. These calculations were compared to the recalculated energy values of Stripple.

4.2.1. Workshop

The other validation was done in a workshop, where experts within road maintenance discussed the results from the questionnaire. The experts represented the Swedish Transport Administration (STA), three different contractors with long experience within road maintenance at organisational level as well as maintenance operation, Skanska, PEAB and Svevia, and two departments of the University of Gothenburg. The STA representatives had long experience within winter road maintenance on the authority and research and development level. The researchers from the university had extensive experience from winter road maintenance and climatology as well as from transportation logistics.

The participants at the workshop were also asked to discuss about the potentials for energy savings. They were divided into three groups of 5-6 people in each and introduced to the 35 different maintenance operation tasks. Each discussion group was to distinguish the five operation tasks they thought had the highest potential for energy efficiency and label those according to importance. The results from each group were matched with an overall objective to find 2-3 maintenance tasks that all three groups had distinguished to have highest potentials for efficiency.

4.3. Model

The objective of finding a solution to the problems of defining energy use within road maintenance operations was resolved by creating a model which would calculate the energy usage span, utilizing fuel consumptions. By adding the number of hours that the different vehicles were used for different maintenance operations, the model would calculate the energy use within the specific maintenance district in question. This way, a baseline for the energy use could be established.

5. Results

The results of the study are separated into the energy inventory analysis, the validation measure, the workshop, including the potentials for efficiency, and the general model structure.

5.1. Energy inventory

There are some difficulties when working with fuel consumptions depending on the difference in working load and driving. Hence a consumption span of minimum and maximum values was set for each vehicle specified in the questionnaire, by using fuel consumption values from Flodström *et al.* (2004) as well as Hammarström and Yahya (2000). The different vehicles and their presumed fuel consumption are displayed in table IV.

Table IV, Vehicles used within maintenance operations and assumed fuel consumptions .

Maintenance Operation Vehicles	***Fuel cons. (l/10km)***	***Fuel cons. (l/hour)***
Inspection vehicle (yr 98-2009)	0.6-1.6	2.4-6.4 #
Tractor large		7-16 **
Tractor small		3-15 **
Backhoeloader		9-18 **
Heavy lorry without trailer	2.8-4.6 *	11.2-18.4 #
Lorry with trailer	2.8-4.6 *	11.2-18.4 #
Wheel-loader		10-20 **
HP27	2.8-4.6 *	11.2-18.4 #
Crack sealer	2.8-4.6 *	11.2-18.4 #
Sewer cleaning / rinsing lorry	2.8-4.6 *	11.2-18.4 #
Road scraper		17 **
Lawnmower		1 **
Power saw		1 **
Clearing saw		1 **
Refuse lorry	2.8-4.6 *	11.2-18.4 #
Sweeper, self-acting		7 **

* estimates of fuel consumption data for lorries, compiled from VTI rapport 445, 2000

** estimated from Report SMED, No 2, 2004

with the assumption that ploughing is performed when driving at speeds of 40 km/h on average

Based on the above specified values concerning fuel consumption for the different vehicles, a transformation to fuel consumption for the different activities was possible to make. Table 5 shows the mean, the minimum and the maximum distribution in hours for each maintenance operation, as well as their respective fuel consumptions. These values were attained by multiplying the average number of hours per maintenance operation with the fuel consumptions of table 4. The minimum hours represent the maintenance district that put less time into that certain operation, meaning that whenever the minimum value is zero there was at least one maintenance district that did not carry out that certain operation. A striking feature was that 25% of the identified activities were connected to winter operations and that these operations consumed more than 50% of the total energy usage. The single most energy consuming activity was snow ploughing which consumed 30% of the overall energy usage. Furthermore the results showed that winter operations were the most energy demanding operations both on average as well as between the different maintenance districts. There were some differences between the southern areas and the northern area as well as between areas with different road lengths and distribution of road classes. Other energy prone areas, apart from the winter operations, were material transport, harvesting, inspection routines, TMA and ditching according to the overall average, as well as for each of the different maintenance areas. Vehicles used for inspection routines differed a lot hence also the fuel consumptions of those vehicles, as can be seen in the fuel consumption span of table V. If, as implied, it would depend on the size of the vehicle used, savings or efficiencies could easily be made by the simple means of changing type of vehicle.

Table V, the distribution of number of hours for each maintenance operations as a maximum, minimum and average between the seven maintenance districts.

				Fuel consumption (litres)	
Maintenance Operations	***Min (hours)***	***Max (hours)***	***Average (hours)***	***Min***	***Max***
Ploughing	1680	9735	6120	73690	138120
Salting	900	4000	2390	31158	51189
Sanding	540	2045	1295	16187	33595
Harvesting	0	2460	1046	16624	30411
Material transportation	0	2000	1357	17735	29136
Ditching and ditch clearing	15	1460	904	15790	28061
Inspection routines	500	4800	2343	7803	20808
TMA	200	1800	859	9616	15798
bridges, cleaning	0	400	120	7540	12388
Snow stick	0	2000	516	6739	11071
Snowremoval/Snowblower	0	900	371	4333	8667
sweeping	0	290	139	3999	8048
cleaning road construction	0	820	134	3992	7844
Gardening	0	600	234	4499	7499
Cracks and hole repair	0	520	196	3069	5042
Sand/salt loading	0	500	210	2445	4890
Gravel covering, scraping	0	600	150	4463	4463
Ice scraping	0	528	225	4460	4460
Dust binding, irrigation	0	550	131	2576	4232
Refuse and container transport	0	576	153	2392	3930
Free room	30	1744	525	1795	3573
Edge cutting /snow ditching	0	400	90	3570	3570
Sealing	0	200	54	1419	2331
Various service	0	400	100	1080	2160
Sand uptake	0	350	107	1050	1050
Sum fuel consumption				***248 024***	***442336***

Another outcome of the questionnaire was that the distribution of salt use was dependent on where in the country the particular district was located. The northern district as well as the inland district did not have roads of class 1 and 2 which are in general primarily treated with salt. This gives that the hours spent on salting in different maintenance districts were dependent on type of road class as well as on location. Analysis of data from the Road Weather Information system (RWIS) positioned along the roads, showed that the amount of snow was increasing towards the north, but the number of hours spent on snow ploughing per amount of snow was increasing towards the south. The amount of snow per each snow ploughing hour is plotted in figure 5. The ploughing hours were corrected for the road length of each maintenance district. There are two possible explanations to the results. Either the routines were the same regardless of amount of snow per snowfall event; meaning that a snowfall of 4 cm would be treated by one snow removal passing, as would a snowfall of 7 cm but the amount of snow removed would be more. If this happened regularly it would mean large differences in total amount of snow at the end of the winter, yet the same number of hours spent on snow removal practices. In that case, it would hence be more energy efficient to remove snow in the northern parts of the country. It could of course also be because road classes 1 and 2 demand more maintenance since they have stricter regulations hence more attention in terms of snow removal practices are needed on such roads. Since the areas to the north did not have any roads of class 1 and 2 this theory seems to be most possible. These are only preliminary results from the questionnaire and hence only an indication of the pattern. Further studies are needed to ensure such results.

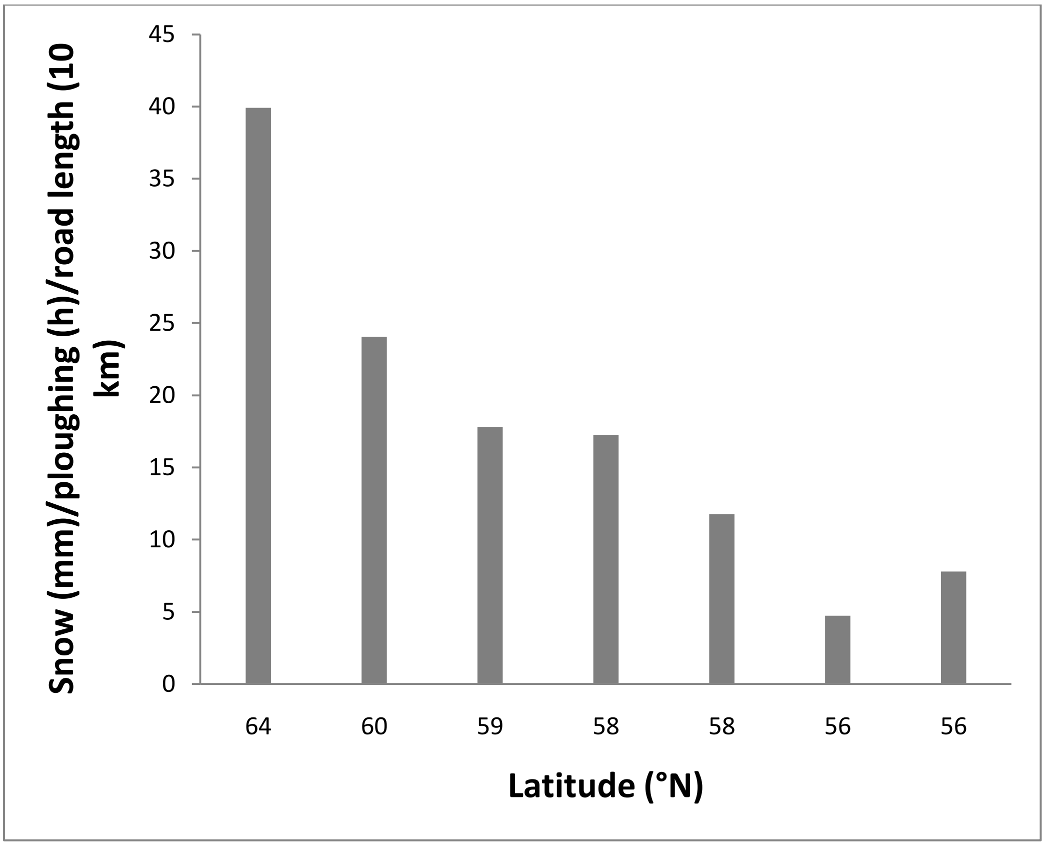

Figure 2, Amount of snow in mm which is removed every ploughing hour with a latitudinal distribution.

5.2.Validation

The energy use calculated by Stripple (2001) was used to validate the results and fuel consumption calculations made in table 5. Using the minimum and maximum fuel consumption values in table 5, and the estimate that 1 litre of diesel is approximately 1 kWh, a span between 312 480 MJ and 513 360 MJ would be expected for winter maintenance operations using distribution lorries as was used in the calculations made by Stripple. This matched into the value that could be withdrawn from the work by Stripple, which was 466 752 MJ. The values are dependent on vehicle age and performance as well as on the driver and the task at force. This is why the fuel consumption values will have such a large range.

5.3.Workshop

Apart from validating the results of the questionnaire the workshop discussion groups conferred about which maintenance tasks that had the largest potentials in energy efficiency. The results of the discussions in the three groups are shown in table VI. Out of 35 tasks 5 was sorted out as having the greatest potentials for efficiency.

Table VI, Results from group discussions

Group 1	**Group 2**	**Group 3**
Ploughing	Ploughing	Ploughing
Salting	Salting	TMA
Sanding	TMA	Salting
TMA	Brushwood/Harvesting	Sanding
Brushwood/Harvesting	Drainage/services	Harvesting

The operation tasks that were considered most potential for efficiency were similar for each of the discussion groups. As can be seen in table 6, ploughing was considered the most potential operation, followed by salting, TMA and sanding. Since TMA is not actually a specific maintenance operation but rather a safety precaution it will not be considered further. As the objective of the workshop was to find 2-3 maintenance tasks that all three groups had distinguished as having the greatest potentials for efficiency, table 6 indicates that this objective was met.

Even though it was clear that winter maintenance operations use most energy, it was not obvious that those operations had the greatest potentials in saving energy. However, when calculating a presumptive energy saving of 5 % for each respective operation, it was clear that the sum of those presumed savings for winter maintenance operations (i.e. sanding, salting and ploughing) would be as large as the sum of the savings for all the rest of the maintenance operations put together (figure 4).

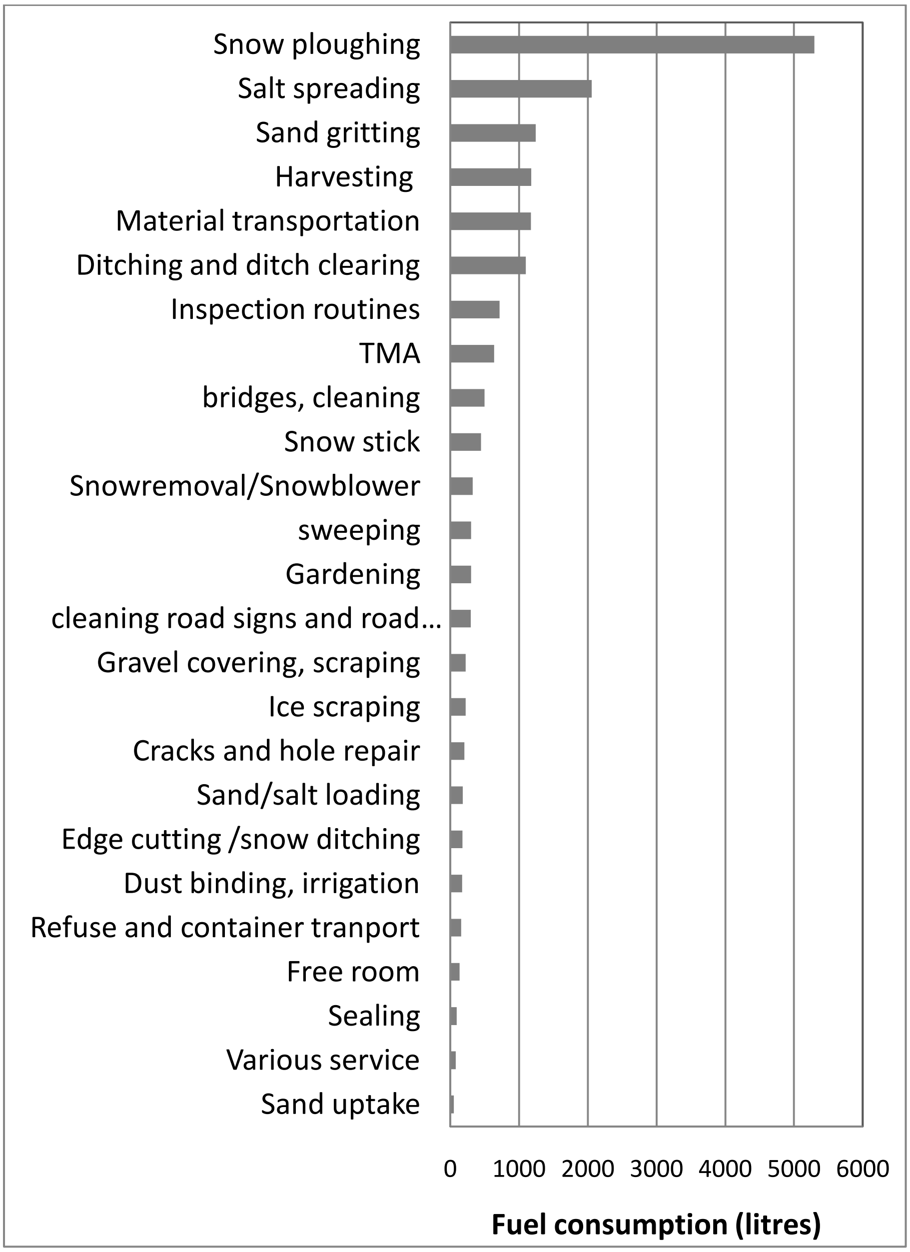

Figure 3, Presumed 5 % savings of fuel consumption for each maintenance operation

5.4.Model structure

The overall road operations were divided into the general model structure in figure 6. The model was able to calculate the baseline use of energy within a maintenance district by the simple means of time. For this model the fuel consumptions of table 4 were used. Since those values were withdrawn from previous reports they were just assumptions, hence a minimum and maximum fuel consumption span was set. Those values may however shift depending on how the vehicle is driven and for what it will be used. The model may hence be modified in many different ways to suite the user. It will for example be possible to use the model to visualize the differences in energy cost if changing type of vehicle for a specific maintenance operation.

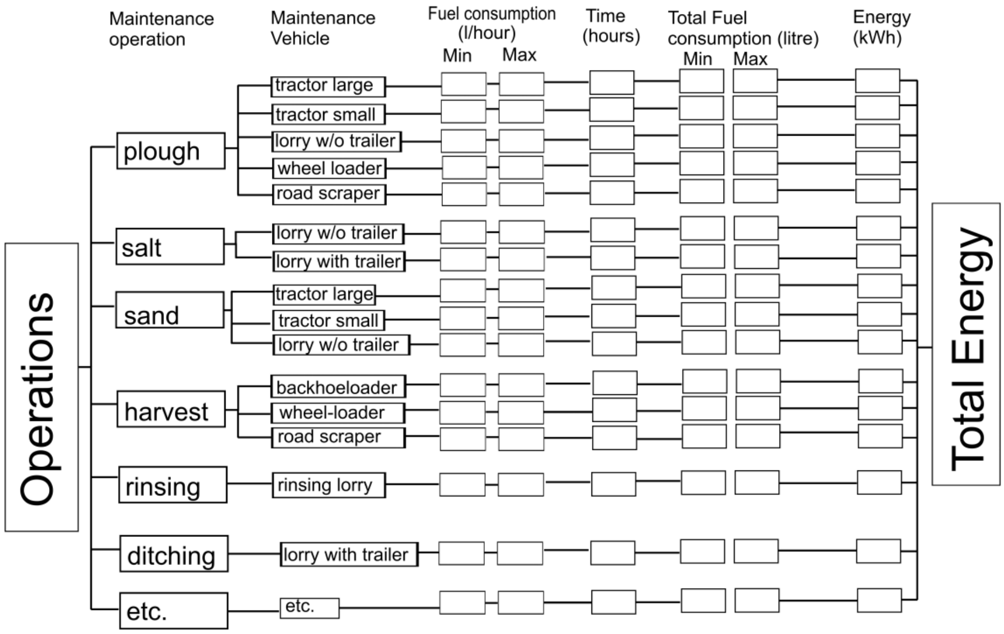

Figure 4, Model structure, the maintenance operations, vehicles and fuel consumptions listed in the boxes are only examples and will change dependent on types of vehicles and operations used in each specific maintenance district

This model will pose as a measure for energy use within road operations. Future developments may include other types of road maintenance as well as emission values. The outcome of the model may change if better estimates of fuel consumption will be set. The total energy use based on the average values of the seven districts of the questionnaire as well as the average fuel consumption values, were 345180 kWh which equals to 1 242 650 MJ.

6. Discussion

When considering the potentials for savings in road maintenance operations the results of the questionnaire in presented study showed that the winter operations were the operations with largest consumption as well as potentials for savings. It is therefore interesting to discuss previous efficiency measures within this field of work. There have been many reports about how the road maintenance affects the road side environment and the ground water etc. Such studies as well as the impact road salting made on road construction, gave rise to the eagerness of decreasing the usage of salt on roads. This was e.g. done by using brine instead of solid salt. According to Ljungberg (2001) the salt use was decreased by 10% when changing from solid to solution within the Swedish road maintenance. Ljungberg further promoted the preventive slipperiness operation since it uses less road salt because less energy is needed to obstruct ice to form than to melt already existing ice. This was also the findings of other studies e.g.O’Keefe and Shi (2006). Better forecasting as well as GPS located spreading and route optimizing are further developments within the road management operations that will optimize the operations and reduce the use of salt. The closed-loop snowplough applicator described by Erdogan *et al*. (2010) combines the information from a direct friction measure with the application of salt. This way the salt will only be spread where it is required. The amount of salt used for winter maintenance is closely linked to the prevailing weather conditions. This fact has become evident during the last couple of winters in northern Europe where the salt has been short in supply. In Sweden the salt usage is about 200 000 tons a year. There are hence still needs for de-icing treatments on the roads as well as other maintenance operations that demands transportation and consequently energy. Future outcome of this study might be to examine the practice of winter operations to find further potentials for savings as well as testing the model.

7. Conclusions

There are policies and goals set to save energy at many levels of transportation hence also within maintenance operations of roads. Energy efficiency within these operations is complex since it may interfere with the safety of the roads as well as the road users. The problems have yet been to acquire information about the energy use within road maintenance operations since the vehicles are often used for multiple tasks, not limited to the specific maintenance operation or district. The time each maintenance vehicle is used for a specific maintenance task, was easier to obtain, hence the model for the energy baseline, was based on hours. The results from the questionnaire showed that most energy was used within winter operations, where also the highest potentials for efficiency were assumed to be. A presumed 5 % reduction of energy use within winter maintenance operations will correspond to a 5% reduction of all the other maintenance operations put together.

The hours were recalculated into energy, using estimated fuel consumption values. The energy use could be validated with the LCA calculations made by Stripple (2001) and may hence pose as a baseline for future energy efficiency measures within maintenance operations in Sweden.

The general model makes it possible to discuss a shift in practice or rather a shift in vehicles, in terms of energy. The model could hence be used to evaluate whether or not to invest in new, less fuel consuming vehicles for the inspection routines, or to change vehicle from large tractor to a distribution lorry when snow ploughing. The model may easily be modified to fit the needs of the user and future developments may include other maintenance tasks as well as greenhouse gas emission values.

8. Acknowledgement

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Paper II

Optimization of Winter Maintenance Energy Costs in Sweden: a critique of site specific frost warning techniques

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ABSTRACT: Frost formation on roads may cause slippery conditions and thereby increase the risk of accidents to occur. Roads are often treated with preventive operations using de-icing agents (e.g. road salt), which are ideally planned and performed previous to frost formation. The decisions on when and where to treat different road stretches with salt are based on meteorological measurements and forecasts. In this paper it is investigated how uncertainties in meteorological measurements for frost prediction at road weather stations affect the efficiency of winter road maintenance. Different types of uncertainties and errors are discussed together with potential solutions. The effects on winter road maintenance efficiency are discussed in terms of energy and cost. It was found that improvements in frost warning accuracy and reliability can lead to considerable savings and more efficient winter road maintenance.

1. Introduction

There is an increasing interest in improving energy efficiency within many sectors of today's society including winter maintenance of roads. There are several important aspects within winter maintenance of roads, the weather for one. Since most winter operations of the roads are planned according to whether or not slipperiness will occur on the road, it is of great importance to have consistent and reliable Road Weather Information System (RWIS). The system automatically calculates and warns about the risks for different types of slipperiness. Since maintenance actions are planned based on the RWIS, the system will inevitably have consequences for the efficiency in winter road maintenance as inaccurate information may lead to unnecessary actions.

Apart from measuring and planning winter operations in response to the weather by implementing a RWIS, other measures can be used to improve energy efficiency in winter road maintenance. The easiest and most common way is to use Eco-driving practises which have been claimed to potentially save 10-15% fuel (Zarkadoula *et al.* 2007). Many of the contractors in charge of road maintenance in Sweden demand Eco-driving skills of their drivers and subcontractors. It is also of interest for each contractor to invest in the latest developments within vehicles, fuels and methods for spreading salt. However, there is a gap in knowledge on how the weather, and meteorological measurements, will affect energy efficiency in winter road maintenance.

Frost is the most common road slipperiness in southern Sweden except for snowfall on cold surfaces (Eriksson, 2001; Norrman *et al.*, 2001). Frost can form if the air or surface temperature is below 0°C and cools to a point which is lower than the frost point temperature of the air. The frost point temperature is the temperature at which the air is saturated i.e. it cannot hold its water vapour any longer, hence the water vapour deposits as ice molecules. Frost is often formed on clear, calm and cold nights when radiative heat loss causes the surface temperature to sink below the temperature of the ambient air. The frost point temperature is related to the dew point which is the temperature at which water vapour in the air will condense as liquid water. In road weather practise the term frost point is not common; instead the dew point is used for both the cases of dew and frost. For the sake of simplicity the term dew point will be used for the remainder of this article even though, in many cases, the frost point would be the more appropriate term. The warnings of frost from a RWIS system are based on measurements of road surface temperature and air humidity at road weather stations. Due to frost being one of the most common causes for slippery roads it is also one of the main factors to consider when investigating winter road maintenance cost and energy efficiency.

Preceding reasoning raises the research question of: what are the impacts in terms of energy if the system and its measurements in aspect of frost formation are inaccurate? It is believed that correct measurements can contribute in taking correct actions, which in turn will influence winter road maintenance efficiency. On the other hand, incorrect measurements can lead to incorrect decisions and less efficient winter road maintenance. The objective of this study is to visualize this by pointing out different types of errors or inaccuracies connected to frost warnings and to quantify such plausible errors in terms of energy and cost. The aim is to highlight the importance of measuring with high accuracy and frequency. This is one of many important factors for achieving a reduction of winter maintenance energy consumption as well as upholding reliable road conditions.

2. Road frost in south-western Sweden

For the purpose of studying the frequency and distribution of road frost warnings, a study area in south-western Sweden was chosen. The climate in this region is influenced by the North Atlantic Sea and the prevailing westerlies, with frequent low pressure cyclones, which brings mild and wet winters to the area. The climate varies from warm temperate at the coast to cold temperate in the inlands. The two large lakes Vänern and Vättern also influence the climate in the region. For the 1961-1990 baseline the winter mean temperatures varies between -1 and -4 °C and the mean annual precipitation between 500-1000 mm (SMHI, 2010). Climate data from 166 RWIS weather stations for the winters of 2007-08, 2008-09 and 2009-10 was collected and analysed. A map of the stations which were included in the study can be seen in Figure 1. There were some small changes in the number of stations used between the years, due to new as well as retired stations.

The Swedish road weather information system warns about frost, as well as if a wet surface becomes cold or if there is wet precipitation on a cold surface, based on the road surface temperature, humidity, and precipitation sensors. The risks of frost formation can be estimated at the roadside weather stations by measuring the road surface temperature, the air temperature and the relative humidity, typically a few metres above the road surface. The system has a predefined condition for sending frost warnings which is met when the road surface temperature is less than +1 °C and at least 0.5 °C less than the dew point temperature. The dew point temperature is calculated using air temperature and relative humidity (RH).

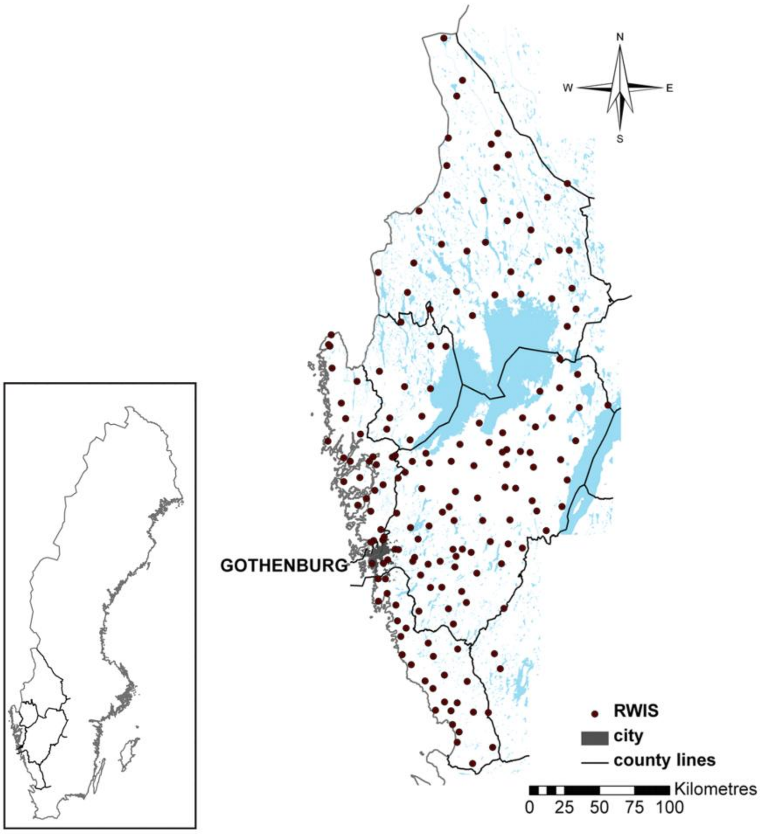

Figure 1, Map view over the weather stations used in the present study. The maps are created based on data from ©Lantmäteriet Gävle 2010, medgivande I 2010/0034

This method, to compare the road surface temperature with the dew point temperature a few metres above the road, is indirect i.e. it does not measure actually say if frost has formed. Several studies have consequently indicated that the system might be inaccurate (Bogren *et al*., 2001; Karlsson, 2001). The frost warnings are used by maintenance personnel in their daily planning of maintenance operations. These warnings are also used when resolving financial compensations for contractors. To distinguish the frequency distribution of the different types of warnings a pie chart can be used (Figure 2). Snow has been excluded in this chart since it causes other types of maintenance activities than those caused by freezing surfaces. In the three studied winters the most common warnings were the frost warnings with about 52 % of the total. 31 % of the warnings were caused due to more than one type of slippery condition e.g. risk of frost in combination with a cold and wet road. This was also a large part of the total amount of warnings but since many different types of slipperiness could be involved it would be more difficult to investigate. Since frost formation is the most common warning; reducing or increasing the accuracy of these warnings have the biggest potential for savings in winter road maintenance. It was hence decided that the present study should focus on frost, rather than other types of weather warnings.

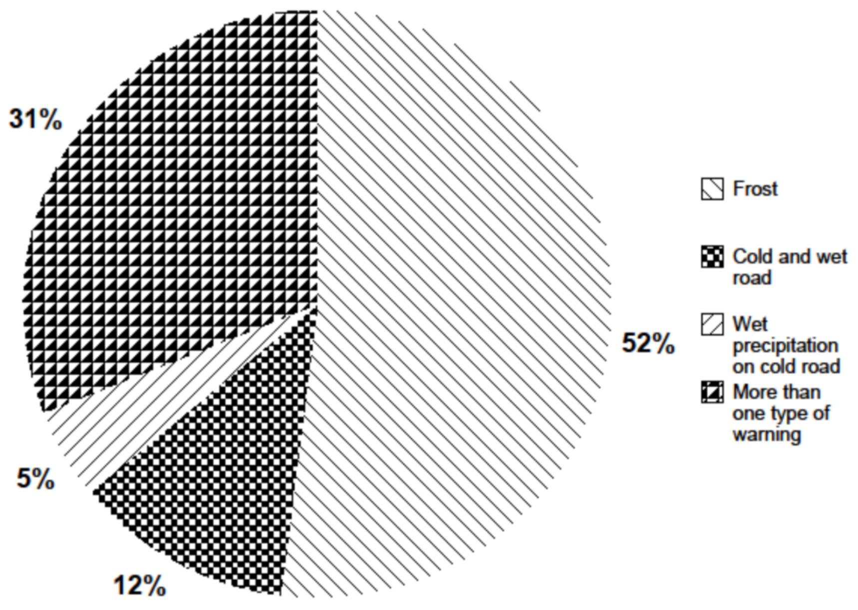

Figure 2, Distribution of different types of warnings in the Swedish RWIS. Frost 52%, cold and wet surface 12%, wet precipitation on cold surface 5% and a combination of the warnings 31%

Substantial amounts of frost may lead to reduced friction as described by Eriksson (2001) who found a correlation between increased difference of frost point temperature and road surface temperatures with decreased friction. Several studies have also described the correlation between reduced friction and traffic accidents (Andersson, 2010; Norrman *et al*., 2001). The amount and the impact of the frost are also dependent on traffic which may reform the frost to more densely packed ice, melt it through engine heat or simply wear it off. The balance between these parameters is difficult to estimate but it could mean that some roads with a certain traffic flow would not need slipperiness treatments during frost occasions.

Local geography and climate are decisive for which parts of a landscape that will be subjected to frost. Studies have shown that frost is more frequent in narrow valleys than in flat locations (Lindkvist *et al*., 2000). Furthermore, research has indicated that dew and frost is more common in rural areas than in urban due to the urban heat island effect and reduced vapour supply (Richards, 2004). Typically frost can be observed on cars or in grass due to these objects being colder than the air. This means that frost can form on the surface of the roads and other objects even though the air temperature a few metres above the road is over 0 °C, as long as the road surface is below freezing. An accurate measurement of the road surface temperature is therefore needed when deciding if the temperature is close to the frost point and there is a risk of frost.

The amount of frost is dependent on the magnitude and duration of oversaturation of the air directly above the road surface i.e. the difference between the surface temperature and the dew point temperature (Karlsson, 2001). The wind and turbulence will also have an impact on dew or frost formation. If there is no or very little wind the air layer right above the surface will become drier and it will not mix with the more humid air layers above (Jordan and Smith, 1994). Due to the air becoming drier right above the surface, the dewfall or frost deposition will cease (Oke, 1987). More humid air will reach the surface and more dew or frost can form if the air is mixed due to wind. On the other hand, if there is very strong turbulence the surface temperature will adapt to the ambient air temperature and rise above the dew point temperature.

In the following section measurement techniques used for road frost warnings will be described, as well as different types of uncertainties which can affect the reliability of the frost warnings and thereby the energy efficiency of winter road maintenance.

3. Measurement techniques

RWIS are used in many countries to measure and forecast road weather. Different variations of RWIS have been developed and are in some countries combined with maintenance decision support systems (MDSS) to aid the maintenance personnel in deciding when and where a certain action is required (Mahoney and Myers, 2003). Road weather stations are the core in all RWIS. The stations typically combine pavement sensors with sensors mounted nearby the road to measure air and road surface temperature, air humidity, precipitation and wind. New types of sensors and technologies emerge every year with the purpose of giving a more complete description of the road weather conditions.

Swedish RWIS have temperature sensors that measure with an accuracy of ± 0.3 °C and humidity sensors that measure with an accuracy of less than ±3% RH. The accuracy and calibration certificates of the sensors used in RWIS are usually intended for sheltered and cleaned sensors. However, the road environment is very harsh towards any technical equipment and sensors will very quickly be influenced by the surroundings. Road-side sensors might be smeared with dirt and paved sensors might be depressed into the road surface or placed in a wheel track which is considerably lower than the surrounding surface. The accuracy and reliability of RWIS sensors have been tested by road administrations and institutes but few tests are published in scientific journals. Jonsson (2009) concluded that there are discrepancies in accuracy between different types of road surface condition sensors. On occasions when sensors are not accurate it is possible that the efficiency of the winter maintenance is deficient even though it looks statistically assuring when performed actions are compared with data from the weather stations. The lack of good measurement techniques and/or lack of use of existing techniques are likely to lead to an over-use of road salt since maintenance personnel do not know whether or not there are still chemicals on the roads, hence they perform actions to ensure safety. It is likely that this will result in increased costs and a negative environmental impact.

The uncertainties related to frost warnings are closely linked to the uncertainties in the sensors used for measuring the air humidity and the road surface temperature. Some uncertainties are related to the positioning of the sensors at the road weather stations which will be discussed in section 3.1. Other uncertainty originates from the positioning of the road weather stations themselves, this will be further discussed in section 3.2. There are also uncertainties which originate from the sensor itself, discussed in section 3.3.

3.1. Uncertainties due to positioning of the sensors

Ideally, when measuring the state or magnitude of an object or volume the sensors should be as close to the object or volume as possible. In the road environment, air humidity and temperature used in the dew point calculations are often measured at a distance from the road surface. While the road surface temperature is often measured 1-2 cm below the surface, the relative humidity measurements are instead situated 2 m above the road surface. A study made by Gustavsson and Bogren (2002) of roadside stations in the county of Halland in Sweden revealed that some paved road temperature sensors were visible in the road surface while others lay deeper down in the road construction. The road surface temperature sensors also differed in coating which may influence the thermal reactions of the sensor.

Within the Swedish RWIS, humidity and temperature data from sensors on the roadside mast are used in the dew point calculations. If the sensors are placed in different radiation shields at different heights the calculated dew point will not be representative for neither of those positions. In addition, using two separate sensors for measuring one variable (e.g. measuring relative humidity and air temperature with two different sensors for calculating dew point) involves the risk of not knowing which sensor to calibrate or which one that might have caused an error. The air temperature and relative humidity will differ depending on the height above the road. These differences in temperature and humidity have been measured in previous research (Almkvist *et al.*, 2005; Baad and Brodersen, 2010; Chen *et al.*, 1999; Karlsson, 1999) which indicated that the dew point could differ as much as 2°C between 10 cm and 250 cm of height above the road surface. Bogren et al. (2001) noticed that these differences were larger during changing weather as well as in clear and calm weather than during cloudy and windy situations. This could be caused by an inversion, formed during clear and calm nights where the temperature above the road would increase with height. The 10 cm dew point temperature measurement performed by Baad and Brodersen (2010) was in general lower compared to the 2 m level which indicated that frost would form at a later time or not at all.

The road surface temperature sensors used at Swedish RWIS-stations are PT100 temperature probes which are not measuring the skin temperature. Instead they are installed 1-2 cm below the actual surface to protect the sensors. This installation procedure is leading to an inherent positioning uncertainty since ideally the temperature measurement should be at the actual surface. The practises in installing a RWIS is not always the same, hence some road installed temperature sensors lie further down in the pavement as previously discussed, they may also vary in distance from the hard shoulder. This is important when considering the positioning of road-mounted sensors since there are also temperature differences between the lanes. In a study Gustavsson and Bogren (1991) used infrared thermography to study the temperature differences between lanes in the roadway. They found that there were differences between the fast speed lane and the slow speed lane both during clear and calm nights as well as on more turbulent nights.

3.2. Uncertainties in RWIS station positions

The distance between the road and the roadside stations will differ depending on practical aspects such as safety for the personnel who maintain the station. Several variables measured at the station, such as air temperature, will be less representative for the road surface the further away they are measured. RWIS stations are often placed in positions where the risk of ice and frost are believed to be more significant, e.g. on bridges, in shaded areas or close to water. The placing of a station is often determined by using thermal mapping of a road network (Gustavsson, 1999). Sometimes the RWIS stations are sparse and a large area or road stretch relies on information from one single road weather station. An error on such a station could result in false frost warnings and incorrect decisions for maintenance operations. It is a well-known problem to use single-point data; hence, a lot of developments are being done in creating models that interpolates information from many different road weather stations as well as from other sources such as land-use, road construction, sky-view factor, topography and meteorological data. Various research have been done in this field and models are continuously developed and improved. Chapman and Thornes (2006) created a GIS-based road surface temperature model which could predict the road surface temperatures in the area of West Midlands in UK. Pisano *et al*. (2006) discussed the Federal Highway Administration MDSS used in winter maintenance in several states in the USA. The MDSS uses information from different weather forecasts as well as meteorological observations and data from road weather stations. The model output includes route-specific forecasts, road conditions as well as recommendations for maintenance operations. Perrier *et al.* (2007) made a comprehensive review of the different models and algorithms used in the routing of winter maintenance vehicles and Handa *et al.* (2005, 2007) presented how route optimization using evolutionary algorithms and computations could increase the efficiency of salting operations by producing optimized routes for a fleet of salting gritting lorries. It can be assumed that future RWIS will become increasingly more focused on road stretches rather than point measurements and that recommendations for salting and snow ploughing will be based on methods using route optimization. Such development could decrease the negative consequences from uncertainties in RWIS station positioning, since the data from a single station today might lead to a flawed maintenance recommendation for a whole region.

3.3 Uncertainties within sensors

The different sensors used in RWIS all have inherent uncertainties. For example, the accuracy of the PT100 temperature sensors used in the Swedish RWIS, are ± 0.3 °C according to the suppliers datasheet. The relative humidity is often measured with a hair hygrometer with an accuracy of ± 3 %. Calibration is always an issue; the PT100 sensors have good long-term stability which reduces the need for calibration. Furthermore, the PT100 are embedded in the road which means that it would not be practical to send them for calibration. Air humidity sensors are not as long-term stable as the temperature sensors, since the former must be in direct contact with the environment they are measuring as compared to the latter. The sensor often includes some kind of filter to avoid dirt on the internal structure. The possible accuracy listed in datasheets for humidity sensors refer to well calibrated instruments that are well operated and maintained. This is difficult to achieve, especially in a dirty road environment where the stations are widely distributed. In practise this means that many labour hours have to be spent on cleaning and maintaining the humidity sensors. Since humidity sensors are often subject to drift they should be re-calibrated frequently. If the frequent need of cleaning, maintenance and calibration is disregarded, the measurement accuracy might become worse than stated in the datasheet.

Even if a sensor would measure with very high accuracy in every moment, it is technically impossible to store data for each of those moments due to limited bandwidth and the large amount of data that would have to be stored on servers. Often mean values over a time period of 10 or 30 min are stored in a RWIS. Since the temperature and humidity is constantly evolving it means that the recorded value might differ from the actual value on the road. This is a type of uncertainty which can be dealt with using improved data bandwidth and storage.

3.4 Different consequences due to uncertainties and errors

Depending on the errors of dew point and road surface temperature being positive or negative the effect would be both missed warnings as well as false warnings (Table I). In the table a DP error of < 0 °C means that the sensor sends an output which is less than the true value. This means the sensor would indicate that the air would be drier than it actually is, hence the risk of frost would be underestimated and a frost situation could be missed (situation D and E)

Table I, Consequences due to different type of errors in sensors

DP error \ RST error	< 0°	0°	> 0°
< 0°	A	D	E
0°	B	A	D
> 0°	C	B	A

A – No errors or errors are evened out
B – Errors causes false warnings
C – Errors causes false warnings more often
D – Errors makes system miss warnings
E – Errors makes system miss warnings more often

Errors B and C are false warnings which can potentially lead to a road stretch being unnecessarily treated with de-icing agents if maintenance personnel act on the warning. Since the dew point often will be overestimated, (i.e. indicate more moist air than what is true for the air right above the road surface) as described in section 2, the B and C errors will be more common than D and E. Consequently the RWIS system will more often send out a false warning than it will fail to detect a frost situation. Present study will focus on the consequences in excess energy use due to false warnings. It is however also of great importance to consider situations D and E where warnings might be missed. Such missed warnings may lead to very hazardous traffic conditions since slippery roads might not be treated.

4. Results

4.1 Consequences on frost warnings due to uncertainties and errors

The three investigated winters differed somewhat in character. The first two were warmer than normal (i.e. the baseline of 1961-1990), while the third winter was colder than normal. The precipitation was close to normal in all three winters. The frost warnings were not evenly distributed in the landscape, but the general distribution can be seen in Figure 3. The frost prone areas increased towards the north and further away from the coastline. The distribution also shows local variations which could be due to local topoclimatological parameters as well as the microclimate around a certain station. Typically this could be a station near or on a bridge where the close proximity to water increases air humidity and the road surface on the bridge would be colder than the road in general. Both variables will then point at an increased risk of frost. Furthermore, there were a few stations which during one or several years sent a considerably higher amount of frost warnings compared to surrounding stations. Without investigating the exact positions and condition of the sensor at these sites, it would be difficult to conclude if these abnormalities are due to errors or not.

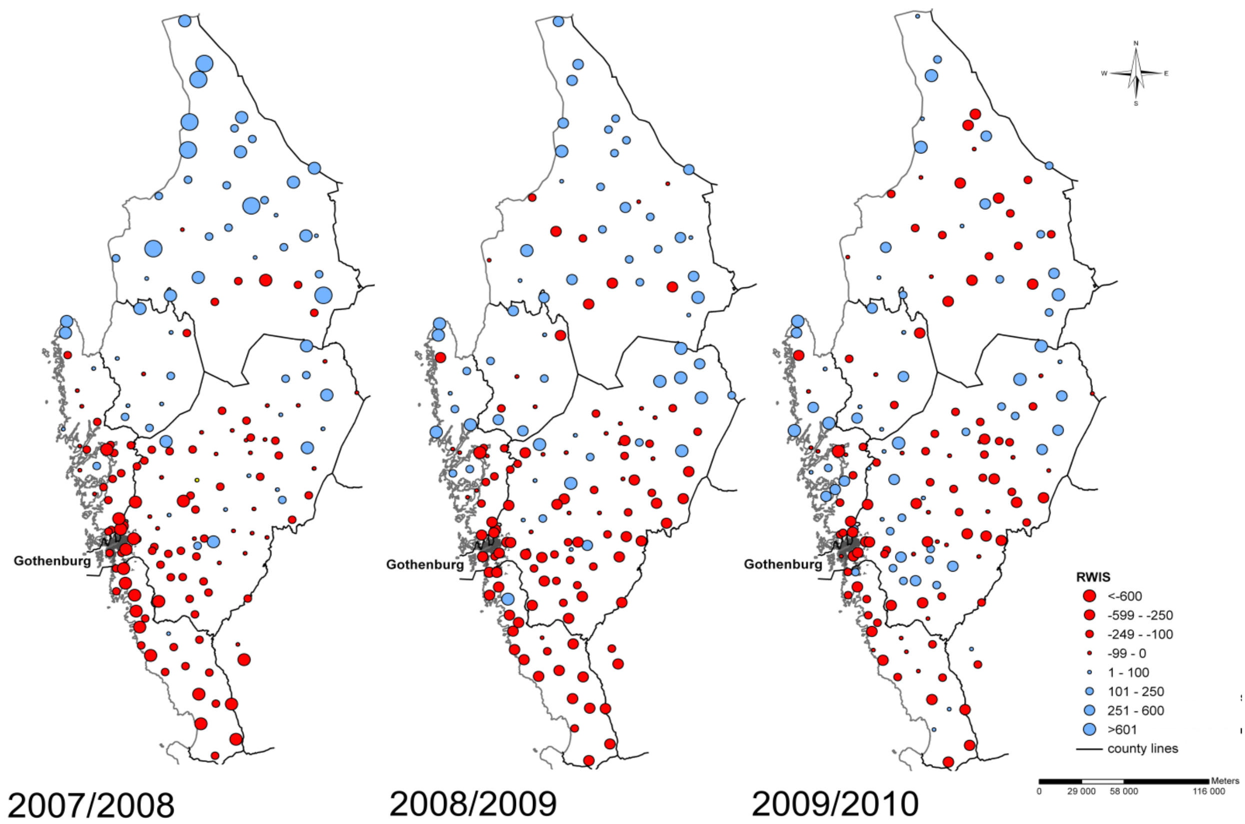

Figure 3, Spatial distribution of number of frost warnings during three winter seasons in south-western Sweden

42 out of the 166 stations used in the overall study had, however, an additional temperature sensor. The reason for a station to have an additional temperature sensor could be that measurements are performed in two different lanes or on different sections of a bridge. An additional sensor is often installed at stations which are considered more prone to slippery conditions. When comparing the additional measured temperatures with the standard measured temperature at the same stations, discrepancies were found. The histogram in Figure 4 shows the number of occasion at a particular station where the additional sensor temperatures differed from the standard installed sensor. The discrepancies ranged from 15 °C above and 5 °C below the temperatures of the standard installed sensor.

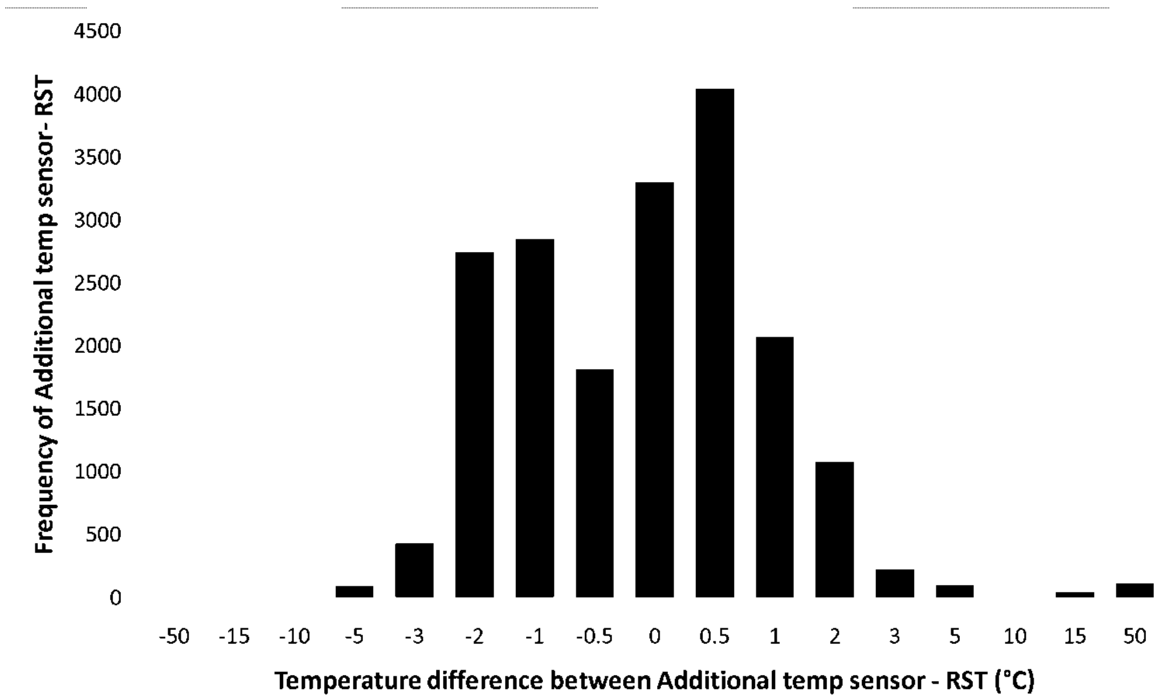

Figure 4, Distribution of the amount of half-hour temperature readings differences between additional temperature sensor data and permanent road installed temperature sensor

Additional analysis of the frost warning calculations from these stations were made based on both temperature readings separately. When comparing the amount of warnings based on either sensor it can be noticed that the amount of frost warnings from a station will depend on how many temperature sensors that are installed at the station and which one of them that will be regarded as more true. The differences are both positive and negative (Figure 5), which means that the difference between the standard sensor and the additional sensor are not consistent. The roadside stations that are equipped with both of these sensors are programmed to use whatever temperature is the lowest while the same humidity is used in either case. These stations would hence send more warnings than they would have done with just the standard installed sensor.

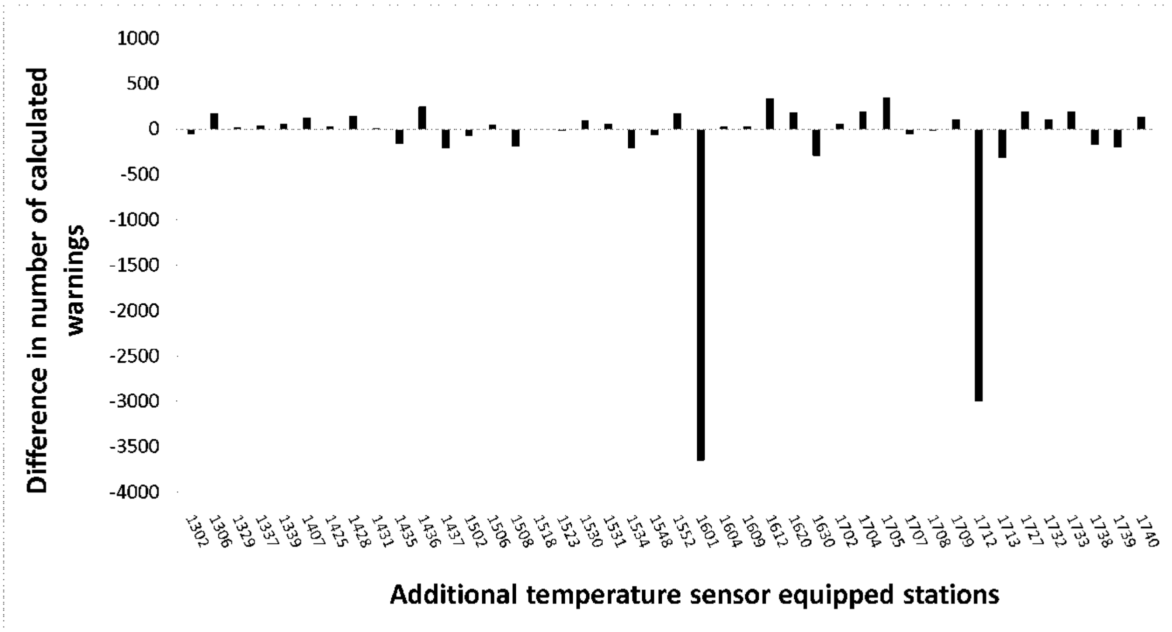

Figure 5, The differences in calculated frost warnings using the additional sensor data or the standard thermometer data

As mentioned all stations will be more or less prone to send frost warnings dependent on a number of factors. It is therefore important to note that some stations will send a lot more frost warnings than others. If a maintenance district includes such a station and the station which presents the worst case is used this might lead to overcompensating the risk of frost in that district. As shown in Figure 6, where each bar represents the amount of frost warnings from one station during the winter of 2009-2010, it can be concluded that some stations send significantly more warnings than others. While the mean amount of frost warnings per station was 608 during this winter, one station sent only 10 warnings and another as many as 2931. Those stations that sent numerous amounts of warnings have to be treated with extra care since it might mean that the location they represent are very prone to frost formation. It could also be possible that the measurements from these stations are not representative due to sensor errors. In either case a whole district should not be treated with de-icing agents based on warnings from these stations alone.

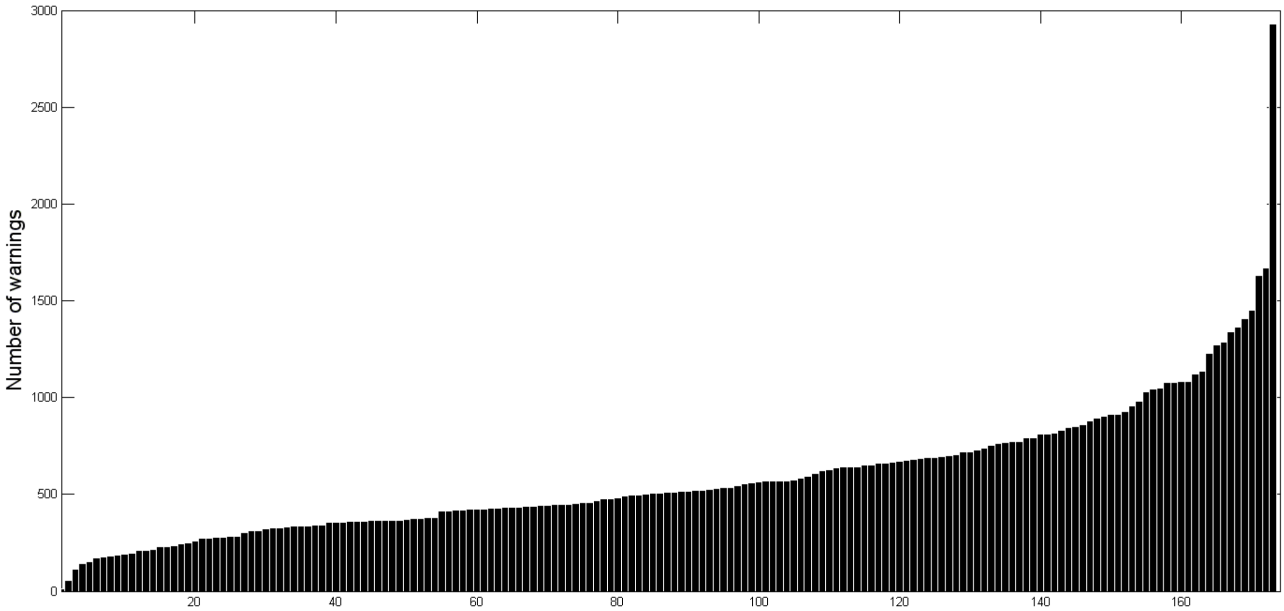

Figure 6, Distribution of number of frost warnings per station during the winter on 2009-2010

If the difference in number of warnings per station were only due to errors in the sensors which are stated in datasheets, the distribution would be normal distributed. In Figure 7 a quantile-quantile plot is shown where the dataset representing number of warnings per station is compared to the normal distribution. If the dataset were normally distributed the data points would follow a linear pattern which they do not in this case. Instead, stations with a few amount of warnings and stations with a lot of warnings are overrepresented.

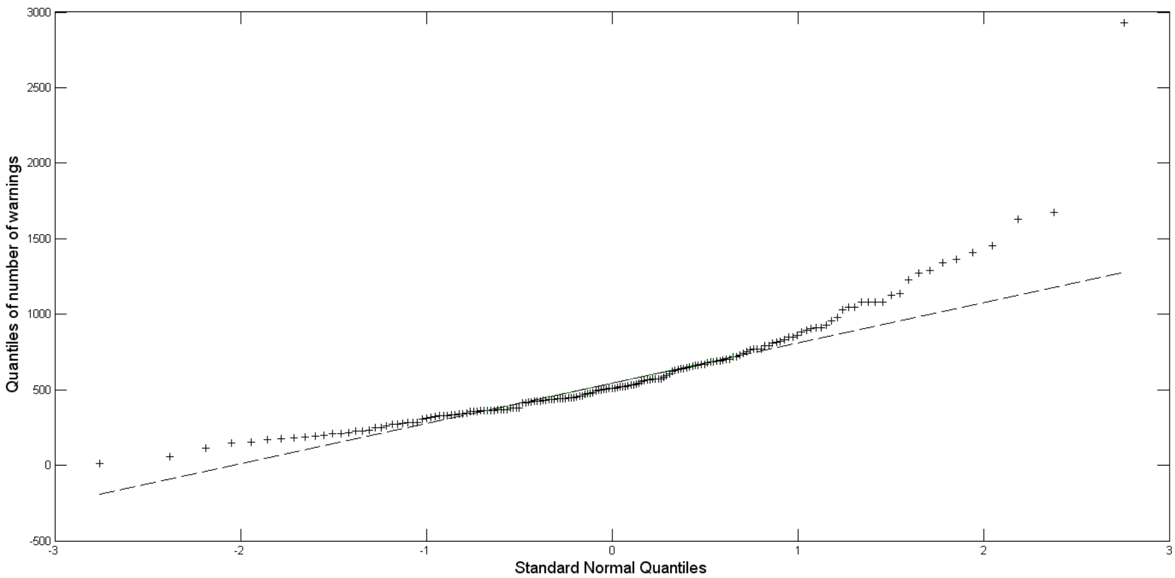

Figure 7, Quantile-Quantile plot between the number of warnings per station and a standard normal distribution

The reason for some stations to send a lot of warnings could be because they are positioned at sites where frost is more common, such as on bridges. It is harder to determine why stations with very few warnings are overrepresented, e.g. one station send only 10 warnings compared to the mean value of 608. Positioning and microclimate could still be explanations but it is possible that sensor errors due to faulty installation, positioning, lack of calibration could explain why some stations show very few or very many warnings. When dew or frost is deposited energy is released due to latent heat of condensation. This will prevent the temperature to rapidly fall when the air is close to saturation. In some cases during the investigated winters frost warnings were given even though the road surface temperature was not under 0 °C, this was due to the temperature limits of the frost warnings in the RWIS described in the previous section. The difference between the road surface temperature and the dew point (DP-RST) has to be 0.5 °C or higher for the frost warnings of the dataset used. The larger the difference, the more dew or frost could potentially be deposited. The distribution of DP-RST during all frost warnings in south-western Sweden during 2007-2010 is presented in Figure 8. It can be noted that DP-RST of more than 4 degrees are very rare. 41 % of all frost warnings are triggered with a DP-RST between 0.5 and 1 °C. Figure 8 can be used for estimating the consequences of different types of errors.

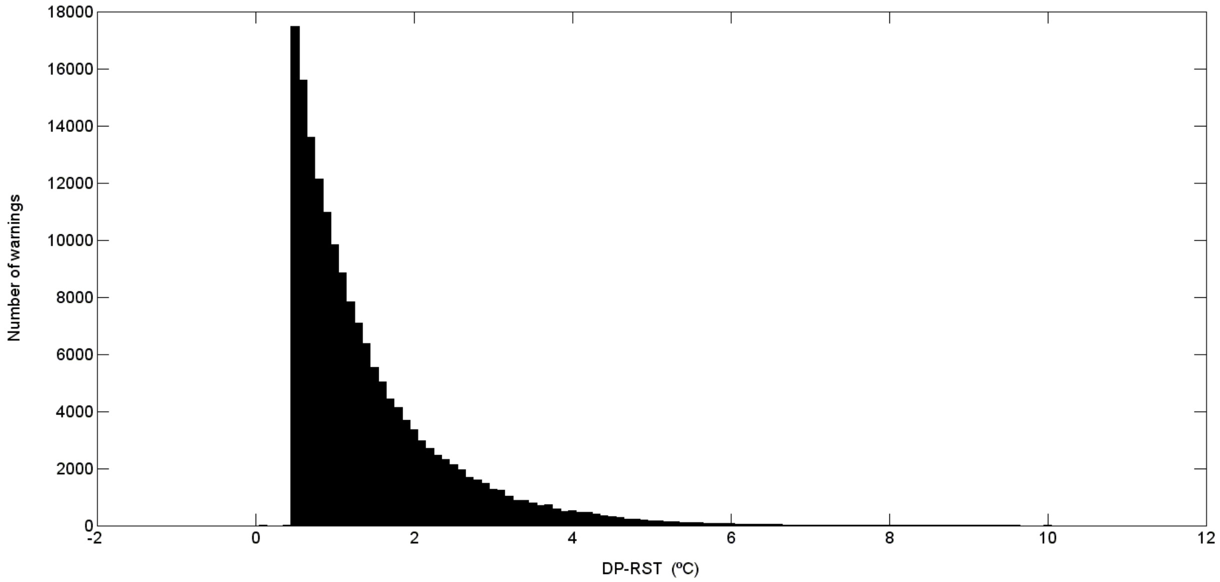

Figure8, DP-RST during 178.547 frost warnings in western Sweden during 2007-2010

Considering the references in section 2 where it was concluded that the dew point temperature at 2.5 m level could be up to 2 °C higher than at 10 cm, many of the warnings in the dataset would have been excluded if a 10 cm dew point measurement were to be used. Apart from the measuring problems the impact of choosing another limit for DP-RST to trigger a frost warning would be significant. A condition for frost warnings to be triggered at a DP-RST of 0 °C would lead to an immense quantity of frost warnings. If on the other hand the limit would be changed from 0.5 to 0.6 °C the amount of warnings would be reduced with 10.3 %. If the DP-RST was exaggerated with 1.5 °C due to measuring errors, about 78 % of all warnings would have been unnecessary. Analogously, small errors, e.g. errors due to the road sensor inaccuracies of ± 0.3 °C can lead to a large amount of false warnings while systematic errors like the measurement height above the surface might cause more than 50 % of the warnings to be false.

If it would be assumed that there is a consistent over exaggeration of DP-RST of 1.5 °C the picture of the frost warning distribution of Figure 3 would change dramatically. In figure 9 the criteria for frost warning have been changed to a DP-RST of at least 2 degrees compared to the standard limit of 0.5 degrees. It can be seen how the amount of frost warnings changes dramatically over the whole region and thereby also the need for winter road maintenance actions. Some stations still trigger many frost warnings, why this is the case has to be further investigated.

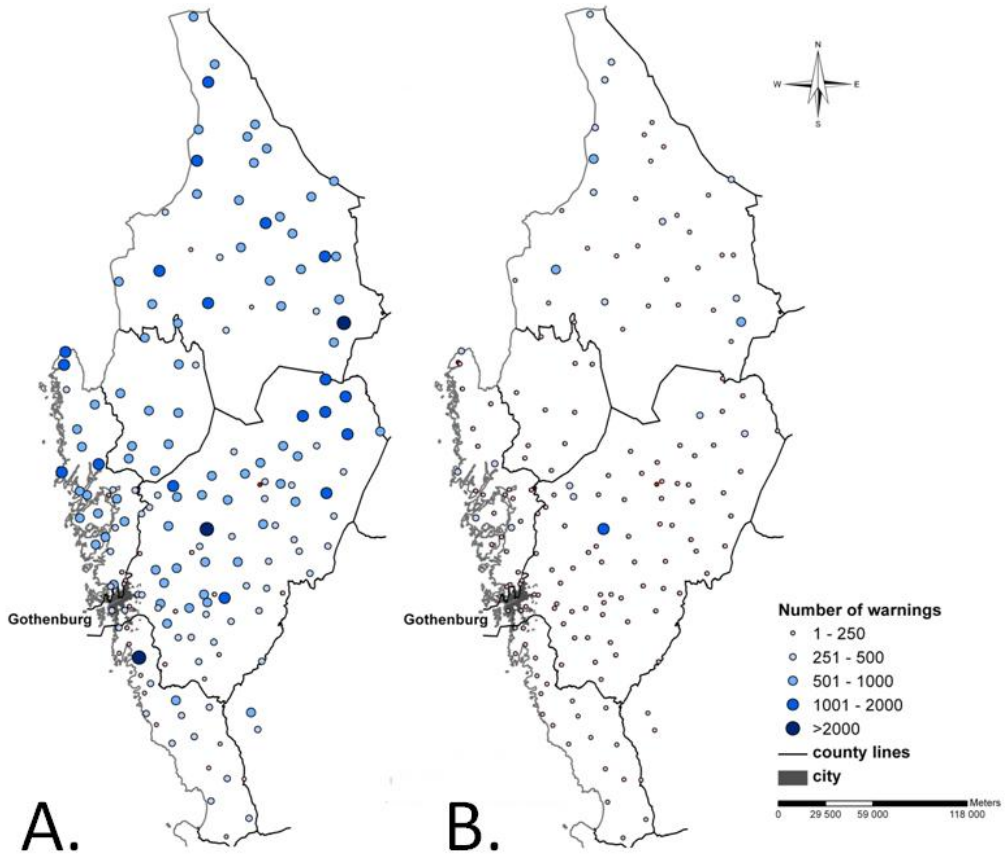

Figure 9, Distribution of frost warnings in 2008-09 with currently used criteria (a) compared to an adopted frost warning criteria of DP-RST of 2.0 °C (b)

4.2. Potential energy and costs effects of false frost warnings

Frost warnings from the RWIS system are used by maintenance personnel in deciding where and when road salt is needed. False warnings might lead to unnecessary use of salt as well as energy and financial resources. If the maintenance operations where to entirely rely upon the weather with no influence of other parameters, such as traffic peaks etc., the operations would need to be performed according to the frost warnings. It is unsure how long time previously spread salt will last on the road but some studies have been made to investigate this. Gustafsson and Blomqvist (2004) found a relationship between residual salt and the traffic as well as with precipitation. Their study was conducted during dry to moist road weather conditions. During such conditions the residual salt may last for several days. However, in south-western Sweden the winter weather is usually wet and residual salt may then easier be sprayed off the road. The time range of residual salt is depending on factors such as traffic load and precipitation. One common time range is six hours. This time range was hence used in the analyses of present study.

Missing data for longer than 2 hours were excluded from the study, which yielded 143 stations in 2007-2008, 152 stations in 2008-2009 and 166 stations 2009-2010. Every frost warning that was followed by at least 2 warnings and that was not preceded by another warning for at least 6 previous hours was summarized as maintenance actions. An average over the three winters as well as the 166 stations of the study area gave the number of frost warnings per maintenance operations to be 20. The total number of frost warnings per station in the region averaged over the three studied years was 497. The total road length of the region in the study was 20816 km, with an average road width of 13 m.

There are different ways of calculating energy use. Present study focuses on two different measures to validate the results. Stripple (2001) made a thorough investigation of the energy use within all different parts of road maintenance. When estimating the energy use of winter operations he calculated salt and sand gritting as well as snow removal. However, the practise of salt gritting is no longer that common in Sweden since less salt is used when spreading salt in a solution (i.e. brine) and with better results. The brine spreading practise is more commensurate with the snow removal practise since the brine routes are optimized according to the volume of the solution canister mounted on the vehicle. This means that the routes can be run without having to return to depot for refilling as needing when sand or salt gritting. For the calculations in this study the energy value for snow removal of one kilometre of a 13 metre wide road set by Stripple was hence used. The value set by Stripple was 17.1 MJ km^{-1}. When applying this to the 20816 km road length the energy use for one salt spreading in the area is 360000 MJ.

The other way of calculating the energy use is by calculating the energy use based on NTMs methods and data (NTM, 2010). Here some assumptions were made; the spreading vehicles weigh about 12-14 tonnes hence the fuel consumption using EURO III fuel with a 50 % load factor was calculated using the NTM values for a medium lorry. It was calculated that each vehicle use 2.23 l per 10 km. The road length used was set as twice the actual road length since the road width was 13 m and the spreaders used in the particular area has a spreading width of up to 8 m. These calculations resulted in an energy use per maintenance operation of 330000 MJ.

Since the two different methods corresponded well with each other, the average of 345000 MJ was used in further calculations. With the fuel consumption of 2,23 l per 10 km, one region wide maintenance operation would need 9284 l. The calculated fuel costs for one maintenance operation in the selected district based on the Swedish fuel price per litre, of approximately 1 EUR, were 9284 EUR. Table II shows the energy and fuel cost savings that the measuring errors discussed in present study could result in.

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

Error in DP-RST	% of unnecessary warnings	No. of unnecessary warnings in a operation area	No. of unnecessary actions in an operation area	Energy rel. to actions (kWh)	Cost (€) rel. to actions (diesel price of 1 € / litre assumed)
-0.1	10.3	52	3	287499	27852
-0.5	41.4	207	10	958331	92839
-1	65	325	16	1533329	148543
-1.5	78	390	20	1916661	185679
-2	86.5	433	22	2108327	204247

Taking into account the differences in remote sensor temperatures and the road installed surface temperatures described earlier; an error of 0.5 °C would not be uncalled for. Such an error would yield about 10 unnecessary maintenance operations in a winter, with an energy use of about 3450000 MJ which equals to about 958000 kWh. The unnecessary maintenance operations within the district would hence use as much as 92840 l of fuel. The difference between calculated frost warnings using additional in opposition to the standard road installed temperature data at one particular station was as much as 3651 warnings. If maintenance operations would have based their decisions on this it would have meant over 157 extra treatments and as much as over 1458000 l of fuel. Hopefully this was not the case, but the fact that some stations deliver so many frost warnings tends to make the system look less credible. Such an impression of the system would undermine its usefulness.

5. Discussion & Conclusions

Several improvements in measurement methodology at road weather stations should be considered to improve the accuracy and certainty of the road weather station measurements. For example, the relative humidity and air temperature sensor could be replaced by a single dew point sensor measuring dew point temperature directly without having to calculate it from the relative humidity. This would limit the uncertainties of the dew point measurement to only one sensor. It would also be clear which position the measured dew point would represent which is not the case if separate relative humidity and temperature sensors are used.

Both the timing and the intensity of the frost formation should be better estimated if the humidity is measured closer to the road surface. However, it would be practically difficult measuring the humidity at the actual road surface. The problems related to measuring humidity close to the surface were discussed by Baad (2010) and included splash from the traffic and snow cover. Since it is difficult to measure at the road surface, or even close to it, the best practises would be to measure temperature and humidity in profiles at different levels above the road surface, e.g. at 10 cm, 100 cm and 200 cm. This has been discussed in several previous studies (Knollhoff *et al*., 2003; Sass, 1992). Such a temperature profile could give indications of whether or not there is a downward flux towards the road surface and hence a risk for frost formation. Knollhoff *et al*. (2003) used the condition that the road surface temperature should be less than the 2 metre dew point temperature as well as less than the 2 metre air temperature to ensure that there was a downward flux towards the road surface in their frost accumulation model.

The problem with road-mounted temperature probes not representing the skin surface temperature could be avoided by using non-intrusive infrared sensors placed at the road weather station mast. However, the use of infrared thermometers introduces other types of positioning uncertainties such as traffic obstructing the field of view which has to be accounted for.

The uncertainties are related to measurements of the frost point temperature and road surface temperature on roads. These uncertainties will affect the amount of frost warnings sent out through the RWIS and thus the salt operations. In south-western Sweden during 2007-2010 there were 178547 frost warnings analysed. In those frost warnings 41% were triggered with a dew point oversaturation of 1 °C or less, which is low compared to uncertainties related to dew point measurements. The error due to the sensor being installed at an unrepresentative height could alone amount up to 2 degrees. If the limit for frost point oversaturation was to be changed from 0.5 to 0.6 °C this would result in a 10.3 % reduction in the number of frost warnings. Likewise, if the difference between the frost point and road surface temperature were exaggerated with 0.1 degree it would mean that 10.3 % of the warnings sent during those circumstances were false. With the perspective that the height of the humidity sensor over the road might affect measurements with up to 2 degrees it is likely that unnecessary maintenance operations are performed due to false frost warnings. These operations can be directly related to energy and cost under some assumptions. A measurement error resulting in an exaggerated difference between frost point and road surface temperature of 0.1 °C in the region could result in costs of close to 28000 EUR, while an error of 0.5 °C could result in a cost of 93000 EUR each winter.

More accurate dew point measurements closer to the actual surface combined with more intelligent frost warnings could reduce the amount of unnecessary frost warnings. Investments in upgrading RWIS both sensorwise and through modelling and route optimising can result in more energy efficient winter road maintenance. It could also lead to positive environmental effects since reduced salting of the roads would be beneficial to watersheds and vegetation which are often harmed due to high salt concentrations. The traffic safety could be improved due to maintenance being available for treating the stretches where the salt is most needed. The calculations in present study can be adapted for other areas where frost warnings are triggered under other circumstances and where other assumptions for the energy and cost model are justified. The results can be used to evaluate new investments in RWIS and also to highlight the importance of measuring with high quality, frequency and accuracy to achieve a reduction of winter maintenance energy consumption as well as upholding reliable road conditions.

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