

PIARC 2002

XIth International Winter Road Congress

28-31 January 2002 - Sapporo (Japan)

Reprints from Proceedings of Oral Presentations:

COST Action 344: Improvements to Snow and Ice Control on European Roads and Bridges

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Winter Maintenance Standards in Cycleways

- Appropriate Road Condition for Increased Cycling during Winter

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COST ACTION 344: IMPROVEMENTS TO SNOW AND ICE CONTROL ON EUROPEAN ROADS AND BRIDGES

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1. Abstract

Effective snow and ice control is a vital service provided by European highway authorities in order to ensure, as far as possible, that road users can travel safely and with minimum disruption in cold and severe climatic conditions. The need for innovative snow and ice control techniques and processes has continued to grow as national and European road networks have developed substantially over recent decades. The demand for improvement, including the sophistication of the techniques and technology used, continues to be driven by the increasing need for safe and efficient national and international road freight and passenger transport and by the environmental and other policies affecting highways.

European Commission project, COST Action 344: Improvements to snow and ice control on European roads and bridges, started in April 1999, is a three-year project with participation from eighteen European countries.

The project aims are:

- 1) Review of existing international practices
- 2) Definition of snow and ice control requirements in different European climatic regions.
- 3) Specification of 'Best Practice' in different European climatic regions.
- 4) Development of guidelines for the integration of specified snow and ice control methods into network level road management and maintenance systems.
- 5) Recommendations for improvements to driver information and traffic management systems.
- 6) Recommendations for future research.

This COST Action will promote the exploitation of technological advances in the application and distribution of snow and ice control measures, with a view to providing significant environmental and safety benefits and lower operational costs. Millions of ECUs could be saved through lower operational costs and a reduction in adverse effects on the highway infrastructure and the environment. For the road users, more effective management of winter operations could lead to a reduction in traffic delays and accidents. For practitioners, implementation of 'Best Practice' should enhance standards and lead to Best Value being achieved. The implementation of Best Value could provide the means to measure the performance of the winter maintenance service within various road administrations.

Interim results of the COST Action are being disseminated to European and national policymakers, regional planners, engineers, road and vehicle operators, industry and academia. This approach ensures maximum dissemination of knowledge. The Internet, a CD-ROM, Email, handbooks and events such as workshops, conferences and seminars are being used to target a wider audience.

2. Introduction

Effective snow and ice control is vital to ensure, as far as possible that road users can travel safely and with minimum disruption in cold and severe weather conditions. However, it is important that the winter maintenance service is provided at an affordable price and that 'Best Value' is achieved with minimum environmental impact and traffic disruption, and with high standards of safety. Information on 'Best Practice' is therefore essential to ensure widespread implementation of appropriate standards of service.

The need for innovative snow and ice control techniques and processes has grown over recent decades in line with the development of national and European road networks. The demand for improvement,

including the sophistication of the techniques and technology used, continues to be driven by the increasing need for safe and efficient road freight and passenger transport, and by the environmental and other policies affecting highways.

The COST Action 344: Improvements to snow and ice control on European roads and bridges, started in April 1999 and is part funded by the European COST (Co-operation in the field of Scientific and Technical Research) programme (EU, 1999). The Action (www.cordis.lu/cost-transport/home.html) is a three-year project with participation from eighteen European countries. TRL is the Chair of the COST Action and represents the UK Highways Agency, which is responsible for the operation and maintenance of the Trunk Roads and motorways in England. VTI is the Vice Chair and represents the Swedish National Roads Administration, which is responsible for the operation and maintenance of the Swedish national road network. These organisations are members of the COST 344 Management Committee.

3. Objectives of the research

The main aim of the COST project is to improve the performance of snow and ice control methods and operations by defining the requirements for 'Best Practice' in different climate domains, across the EU and other COST member states. This will provide national highway authorities with information on the best materials, techniques and procedures to meet the changing demands of the European road infrastructure and, at the same time, harmonise safety and environmental standards. It will thus provide guidance to decision makers.

A significant contribution will be provided to meet the stated goals of the Transport European Road Network (TERN) as below:

- Sustainable mobility of persons and goods within the EU under the best possible social and safety conditions (Article 2.2a).
- Integration of environmental concerns into the design and development of the network (Article 5d).
- Promotion of network interconnection and inter-operability between the EU and the third world countries (Article 6).

Assessments of operational practices, employed at national level, are also expected to result in the development of objective criteria and benchmarks for various aspects of snow and ice control and their impact.

4. Work programme

The aims of the research project are:

- a) To review existing international practices, involving the following elements:
 - terminology review and creation of a European glossary;
 - literature review covering the years 1990 to 2000 to establish the state-of-the-art practice and research in snow and ice control methodologies;
 - review of current research and development work, in both the public and private sectors;
 - review of current practices by evaluating selected case studies in targeted EU regions; and
 - creation of an inventory of snow and ice control methods, equipment and materials.
- b) to define snow and ice control requirements in different European regions;
- c) to determine 'Best Practice' in different European regions;
- d) to develop guidelines for the integration of specified snow and ice control methods into network level road management and maintenance systems;
- e) to make recommendations for improvements to driver information systems and traffic management systems; and

- f) to make recommendations for future winter maintenance research, which has potential benefits for practitioners and road users.

Particular areas where further investigation has been proposed are:

- the most effective and least environmentally harmful de-icing/anti-icing materials, and the most effective treatments in the various climates encountered across COST member states;
- implications resulting from the introduction of innovative road surfacings to establish benchmarks for safe and effective winter maintenance;
- innovative Road Weather Information Systems (RWISs), which would benefit from a review of accuracy, reliability and the introduction of developing capabilities such as residual salt sensors; and
- road icing information and prognosis systems.

Investigations are also underway on the following:

- Operational procedures:
 - driver information systems using existing methods and innovative developments employing advanced telematics; and
 - the impact of methods designed to maximise traffic flows and reduce accident severity in winter conditions.

Information on many of these research elements has been drawn from the experience and knowledge of participating member states through detailed assessments and a review of current and ongoing research. The common interests and general objectives are shared by the member states and the planned work is drawing upon most of the relevant work currently in progress and planned within all COST countries together with the results of work undertaken previously.

5. Task Groups

Six Task Groups, TG1 to TG6 with nominated leaders, will run through the three-year life of the Action. The seventh group, TG7 will start in year 3 of the project. These Groups involve the most appropriate blend of technical expertise for the tasks from a broad geographical distribution across Europe to ensure an extensive input and high quality outputs. The Groups are:

- TG1 – Information gathering, literature review and glossary
- TG2 – Definition of requirements
- TG3 – ‘Best Practice’
- TG4 – Future research
- TG5 – Road management system
- TG6 – Driver information systems
- TG7 – Final report

Each Group has submitted at least one technical deliverable and, these will form a major part of the final report of the Action.

5.1 Task Group 1 - information gathering, literature and glossary

A glossary of winter maintenance terms in six languages – Dutch, English, French, German, Swedish and Spanish has been produced. It is expected that PIARC will adopt the COST glossary, in 2002 at the end of the Action, to complement its own glossary. A European review of literature from 1990 to 2000, which includes over 600 research papers and reports, has been divided into topics (weather and climate, equipment, effects, management, de-icing products, equipment for road users, risk management, strategy, design and construction of the road, costs of winter maintenance, road user information and overview).

The work has also identified about 150 current research projects throughout Europe on winter maintenance practice and management issues.

The review of literature and current projects has identified the gaps in our knowledge and thus where future research efforts should be directed.

5.2 Task Group 2 – definition of requirements

The objectives of TG2 were to consider safety, environmental and information criteria, the management and operations of snow and ice control and, to identify improvements that would enable delivery of a more cost-effective and efficient service. To achieve this it is important to set down the components of a winter maintenance management system which, on balance, will produce a quality service. The work of TG2 complements the work carried out in TG3 - 'Best Practice'.

TG2 members have identified the following generic business areas as being of fundamental importance to road administrations:

- a) **Service levels** – Relate to the winter maintenance operation itself and includes the effectiveness of the treatment in preventing ice and snow adversely affecting the highway. It does not however include safety and traffic movement considerations, which it is argued, are secondary effects and can be influenced by factors other than the quality of the winter maintenance operations.
- b) **Environment** – Includes the effect of winter maintenance operations on the natural environment, including flora, fauna and marine life.
- c) **Safety** – Includes the safety of the winter maintenance operatives and the road users. Care must be exercised to ensure that the reasons for safety performance are understood since factors other than the quality of winter maintenance may be relevant.
- d) **Traffic movement** – Includes traffic flow during winter conditions, which may again be affected by factors other than effectiveness of the winter maintenance operation.
- e) **Cost optimisation** – Includes analysis of all the factors that contribute to the delivery of a cost-effective winter maintenance service.
- f) **Information to the administration** – Includes the provision and management of information about the performance of the operation so that proper accountability can be achieved.
- g) **Information to the road users** – Includes the appropriate level of information to road users in various forms both before and during the journey made.

These generic issues are set out graphically in Figure 1. They have been disaggregated to a) identify more detailed issues requiring analysis and b) deliver the appropriate quality of winter maintenance service. Items (a), (b), (e), (f) and (g) above are those issues over which the administration has a significant level of control whereas items (c) and (d) are random occurrences influenced by other factors including driver behaviour.

The type of climate is also a prime factor - this depends on the altitude and geographical location, and is manifest through the frequency, duration and intensity of the winter weather conditions (COST 309, 1992). Conventional classifications can be made ranging from mild to very cold climates. A winter index is a given function of the number of days with icy conditions with the minimum and mean temperature. This determines the frequency and duration of ice on the roads. A Road Weather Information System (RWIS) determines the adverse winter conditions in order to make the necessary decisions with sufficient time in hand. Winter weather conditions include snowfalls, ice, freezing rain, fog, snowdrifts, avalanches etc. Their frequency, duration and intensity depend on the meteorology of each area. The onset of winter weather triggers the resources needed to re-establish the serviceability of the road.

Important characteristics of the road are the road type (high capacity or conventional), carriageway

width, layout, gradient, pavement type, frequency and length of bridges and tunnels etc.

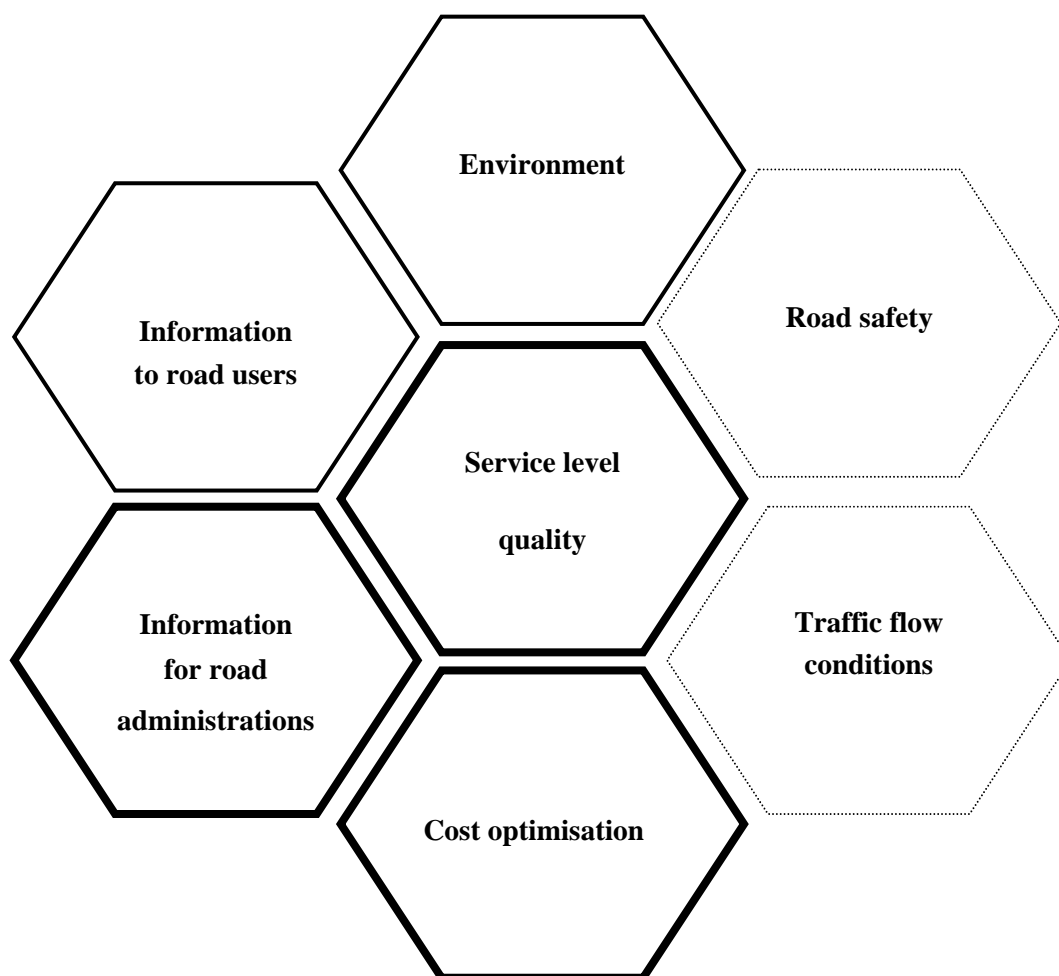


Figure 1. Schematic diagram of the links in the winter maintenance processes

Key:

- Issues over which the administration has substantial control.
- Issues over which the administration has significant control.
- Issues over which the administration has limited control.

5.3 Task Group 3 – ‘Best Practice’

The objectives of TG3 are to identify ‘Best Practice’ in the field of winter maintenance, including the impact of operations on the environment and benefits to service providers and road users. The identification of ‘Best Practice’ will encompass all the needs of the European Community specific to particular countries and/or climates involved in winter maintenance activities. A questionnaire, in the form of a detailed subject list, was prepared and distributed to EU member states to determine current winter maintenance practices. The responses have been compiled and compared for common climate domains (Scandinavian, Maritime, Central European, Continental, Mediterranean and Alpine). The

climate domains differ especially in temperature (daily and yearly), humidity, probability of snow, wind and expectations of the user. A wide range of practice, environmental issues and benefits have therefore been compared and evaluated.

When preparing a winter maintenance procedural statement, it is necessary to consider climate and weather information, methods, resources (eg manpower, equipment and materials) that will need to be employed. This will include information about chemical de-icers, gritting materials, mechanical snow and ice removal equipment, and special treatments applicable to certain types of road surfacing materials, bridges, cycletracks and pedestrian footways. It will also include developments in RWISs, specifically the measurement of residual chemical on the road surface. The efficiency of the chosen procedures can be measured using internal performance audit methods. An external audit could measure the number and severity of accidents, travel time delay, user satisfaction and environmental impact.

It is also important to have in mind the owner of the road, contract manager, operational staff and road users before decisions about winter maintenance procedures are taken. Fundamental issues, which influence winter maintenance, are climatic conditions, standards and legal obligations. Consideration of the points covered above will enable improvements in 'Best Practice' to be made throughout Europe.

5.4 Task Group 4 – future research

At present, various institutions are carrying out work into improvements in winter maintenance management, procedures, techniques, treatments, weather and climate, safety and other effects. Whilst valuable, these are largely uncoordinated initiatives and the COST Action has brought these together to identify 'Best Practice'.

The objective of TG4 was to identify the most important topics for future research activities in the domain of COST 344.

The work of the task group was carried out in three phases:

- identification of topics for future research;
- prioritisation of future research topics; and
- selection and task description of the most important topics for future research.

The topics for future research were collected via an e-mail survey sent to the COST 344 Management Committee and other international experts. About 90 respondents sent proposals for research topics. TG4 members analysed the list of about 200 different topics received and produced, by merging, a list of 93 research topics for prioritisation.

This topic list was used as a basis for an Internet survey, where experts from different countries and representing different organisations (authority, industry, research or academia) were asked to prioritise the research topics. In all, 57 experts completed the survey.

A number of topics were regarded as very important or important and TG members produced tentative research task descriptions for these topics. The six most important future research topics are:

1. Forecasting, measuring and modelling the road surface condition.
2. Winter maintenance and management policies and strategies (service performance, harmonised quality levels etc).
3. Costs and benefits of operational practice in rural and urban areas.
4. Effects of road weather conditions and winter maintenance on traffic flow and safety, capacity and road user behaviour.
5. More cost-effective, efficient and environmentally friendly de-icing products.
6. Weather-related traffic management and information systems optimal for traffic safety and efficiency.

5.5 Task Group 5 – road management system

A Winter Maintenance Management System (WMMS) is an important integral part of an integrated

Road Management System (RMS) and financial, quality, legal and social aspects need to be considered.

There are two levels of a WMMS that should be considered - the strategic level where the socio-economic consequences of a chosen winter maintenance strategy are calculated, and the day-to-day level used for the management of the winter maintenance activities.

On a strategic level, it is not the objective to define the level of service but to define which parameters have to be considered when defining the level of service. In practice, it is an optimisation process between costs and benefits, as far as is practicable, because of the limited funds available. The efficiency and effectiveness of the service provision and the chosen optimisation process, which must be continually reviewed, determines delivery. New research ideas need to be fed into this optimisation process to continually improve it and the subsequent service.

A WMMS on the day-to-day level may consist of several parts/systems such as:

- administrative information;
- route planning;
- Road Weather Information System (RWIS);
- call-out system;
- reporting and documentation of actions;
- information to road users; and
- follow-up of actions.

Some European countries have a WMMS that includes many of the above parts but many countries have one or more of the parts as separate systems, eg Road Weather Information System (RWIS). A RWIS includes outstations, which measure parameters close to the road, eg road surface temperature, and common meteorological information, eg wind speed, humidity etc.

TG5 members are considering the components and inputs and outputs required for a WMMS and its compatibility with other modules or systems in a RMS. Comments on the benefits of introducing a WMMS into a RMS will be included in the final report from the Action.

5.6 Task Group 6 –driver information systems

TG6 members are considering the effectiveness and benefits of driver information and traffic management systems for road users in adverse weather conditions. Information for drivers is essential if they are to travel safely on the road network in winter but the nature of the information given needs to be timely and accurate. Ways of disseminating the information could include telematics (in-driver vehicle systems), the Internet, radio, telephone, journals, teletext and variable message signs alongside the road.

It is recognised that road users comprise different driver groups, which have different needs for pre-trip and on-trip information. The driver groups have been identified as:

- Professional drivers (eg public transport, haulage, security services)
- Frequent drivers (eg commuters)
- Occasional drivers (eg school errands, tourists)
- Related businesses (eg travel agencies, private information services).

It is important to identify what sort of information each driver group requires. For example, Finland has carried out a study of the frequent and occasional drivers, and this is being examined in detail for the purposes of the Action. This work may be considered as a good example of 'Best Practice' and much can be learned from it.

A questionnaire has been compiled by TG 6 members and circulated to all the European members of the Action to seek answers to a series of questions regarding driver information and related information systems. The questions include:

- What actions are used now?

- What are the effects of these actions?
- What are the costs and benefits of driver information systems?
- What do road users need?
- What could be done better?
- What could be provided but is not?

The usefulness of information needs to be considered to avoid information ‘overload’ and the timing of this information is also important. Three stages of the information process are essential – at the onset of winter weather, during winter events, and in the case of a crisis. This will ensure that the drivers have timely information and can plan their journeys in advance or during their travel on the road network. When faced with exceptional circumstances such as heavy snowstorms and traffic difficulties, collaboration with the police and other bodies is essential.

Private radio systems utilise the information services of the roads administration in Iceland and Finland. For example, TRAVEL-GUIDE is a current project undertaken in Finland and is concerned with traffic management and information services. The approach is to specify a commonly agreed data exchange interface, via which private service providers have access to public organisation information and vice versa. The Viking Travel and Traffic Information Service (www.ten-t.com/viking) and its guidelines propose quality requirements for road weather and road surface condition information. Systems such as these described above are being investigated further in the COST Action.

5.7 Task Group 7 – final report

The final report will include summaries of the Task Group reports, benefits of the project to different user groups, a discussion, and conclusions together with overall recommendations.

6. Dissemination of information from the Action

A dissemination plan has been produced to promote the results of the Action to European and national policymakers, regional planners, engineers, road and vehicle operators, industry and academia. This approach will ensure maximum dissemination of knowledge. Results of the Action are to be disseminated to a wider audience by means of events such as workshops, conferences and seminars in the participating EU countries and member states and by e-mails and the Internet. At the end of the Action, the final report, a CD-ROM and a series of handbooks will be made available to interested winter maintenance personnel in the participating EU Countries and member states.

7. Summary

The COST Action will:

- Identify ‘Best Practice’ and emerging developments within and between EU and other COST member states.
- Investigate necessary improvements to RWISs to introduce any latest available features such as residual salt sensors.
- Ensure that treatments are carried out to reduce any harmful effects in the environment.
- Assess the impact of methods designed to maximise traffic flows and reduce accident severity in winter conditions.
- Generate recommendations for the integration of specified snow and ice control methods into network level road management and maintenance systems.
- Develop recommendations for further improvement in the dissemination of up to date and reliable information to practitioners and road users.
- Generate recommendations for improving the level and quality of user input information in snow and ice control decision making.
- Identify future research.

8. Benefits

The Action has promoted exploitation of technological advances in application and distribution of snow

and ice control measures leading to significant environmental benefits. With the application of the knowledge gained, millions of ECUs could be saved through lower operational costs and a reduction in adverse effects on highway infrastructure and the environment.

For the road users and communities, more effective management of winter operations will lead to a reduction in traffic delays and accidents.

9. Acknowledgements

The authors wish to thank the members of COST Action 344 Management Committee for their contributions to the project.

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WINTER MAINTENANCE STANDARDS ON CYCLEWAYS

- Appropriate Road Condition for Increased Cycling During Winter

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1. Abstract

From an environmental perspective, a reduction in motor traffic would be desirable. In urban regions, this could be achieved by increasing cycling as a means of personal travel. Improved winter maintenance of cycleways could lead to more winter cyclists. In this paper, the results of a Swedish PhD project, with the purpose of studying the effects of winter road maintenance on cycling, will be summarised. Included in the paper are the results from a literature review focusing on winter maintenance of cycleways, an introductory questionnaire survey to improve the knowledge about travel behaviour during winter, and a field study to see whether it was possible to attain an improved service level. Focus is set on the field study where “new” equipment for snow clearance and de-icing of cycleways was tested.

Results are presented indicating that there seems to be a prevailing discontent among the public concerning winter maintenance of cycleways, and that better winter maintenance could lead to increased cycling. Although slippery surfaces are of great importance for the safety of cyclists, cycleways not cleared from snow seem to be more important for the mode choice.

The results presented from the field study will show that a test method using a broom for snow clearance and brine for de-icing, provided a higher maintenance service level than methods normally used on cycleways.

2. Introduction

Car-based transport has a wide range of impacts upon society and the broader environment. Air pollution, congestion, noise, road accidents, and extensive land use for parking facilities and road constructions, are some of the effects generating large costs for the society. A reduction in motor traffic especially in urban regions would therefore be desirable. This could be achieved by increasing cycling as a means of personal travel, leading to a more economical use of resources such as materials and energy. Regular cycling also contributes to keeping people fit and healthy. From an environmental perspective it is especially important to reduce the number of short car trips since they are responsible for a relatively large amount of the emissions caused by traffic. This is particularly true in winter due to all the cold starts.

Half of all the car trips made in Sweden are shorter than 5 km (Riks-RVU, 1998), and since most people consider there is no difficulty in cycling distances less than 5 km (Herrstedt et al., 1995; Nilsson, 1995), there is a potential for an increased cycling. However, in Sweden, the cycling frequency during the winter is only about a third of that during the summer (Öberg et al., 1996). This decrease during winter is probably largely due to the less favourable weather conditions; low temperatures, strong winds, and precipitation all have a negative influence on cycling (Emmerson, Ryley and Davies, 1998). But, road conditions are also of importance. A cycleway with poor snow clearance means limited accessibility, and a slippery cycleway increases the risk of fall accidents, which deters many from cycling during winter.

In seeking to promote cycling in winter, it is important to know the significance of maintenance service levels of cycleways for travel behaviour. Even though bad road conditions affect cycling negatively, it is not certain that improved winter maintenance standards could lead to more winter cyclists. If it could, it would be desirable to identify the potential for winter cycling. There is also a

need to identify current winter maintenance service levels of cycleways, and the possibilities for making improvements at a reasonable cost.

Considering this, a PhD project with the objective of studying the effects of winter road maintenance on cycling was initiated in 1997 by the Centre for Research and Education in Operation and Maintenance of Infrastructure (CDU). The project is presently being conducted at the Swedish National Road and Transport Research Institute (VTI), and supported financially by the Swedish National Road Administration. The project will result in a doctoral dissertation, which is planned for December 2001.

The objective of this paper is to summarise the results of the PhD project, including a literature review, an introductory questionnaire survey, and field studies. The main focus is set on the field study where “new” equipment for snow clearance and de-icing of cycleways was tested. The field study included a pilot study, and a two-year large-scale study, and was evaluated through road condition observations, measurements of friction, traffic censuses, and a questionnaire survey. In particular the results from that questionnaire survey, which aimed to get the users’ opinion of the method tested, will be presented in this paper.

3. Literature Review

Throughout the PhD project relevant literature has been reviewed. The literature review focused on winter maintenance of cycleways, such as methods for snow clearance and skid control, requirements of road operation service levels during winter, and methods of monitoring road condition and evaluating the level of service. Other factors associated with winter cycling were also of interest, in particular those related to the mode choice, but even more general topics, such as accidents involving cyclists, were included. Reports representing results not relevant to Swedish conditions were excluded, implying that most of the literature studied was Swedish. Unfortunately, there was not much to be found concerning winter maintenance of cycleways. Most studies in relation to cyclists and cycleways involve accident studies or travel surveys from a summer conditions perspective.

Nevertheless, in the literature it was found that the methods and equipment used for cycleway maintenance are usually the same as for roads and streets (NVF, 1984). Therefore, in many cases, the equipment is too large and heavy for this purpose, and can cause damage to cycleways; it is also difficult for it to pass through tunnels and narrow passages. Its usability is also reduced to a certain degree by low speed. In recent years, however, a new generation of vehicles, for example the Multicar and the Mercedes Benz UX 100 (Figure 1) have become available on the market. These vehicles are light, manoeuvrable, and fast (although engendering high safety), and can be easily equipped for a variety of applications (NVF, 1999). The possibility of changing the application of the vehicle by alternating the equipment makes for good economy, since it enables the same vehicle to be used for both winter and summer maintenance operations. Consequently, these smaller vehicles are becoming more and more popular for municipal use, although they are not yet common in all Swedish municipalities. The new vehicles are rather expensive to purchase, and functioning old equipment is not exchanged simply because it is old fashioned. The most common vehicles used for snow clearance on cycleways today are several kinds of tractors such as the Volvo BM 650 or bucket chargers such as the Lundberg 341 (Lindmark and Lundborg, 1987; NVF, 1984).

There seems to be no specific methods of monitoring road conditions on cycleways. The methods available were developed for roads and street (Gabestad, 1988; Möller and Öberg, 1990), and although some of them can be used for cycleways, they are not well adapted for it. During winter the road condition changes continuously with the weather, as well as being influenced by traffic. Therefore, a visual inspection is almost the only suitable method of monitoring road conditions during winter, although the assessment is subjective and entails considerable manual efforts. Measurement of friction is one of few objective methods of evaluating the level of service on roads during winter. However, the friction measurement devices available, like the methods for maintenance, are usually too large and heavy to be suitable for the use on cycleways.

In the literature review it was also found that there seems to be a prevailing discontent among the public concerning winter maintenance of cycleways. In a survey performed among citizens in 12 Swedish municipalities (SALA, 1998), only 29% of the respondents thought that snow clearance and

skid control of facilities for cyclists and pedestrians were “very good” or “rather good”, while 68% were satisfied with winter maintenance of motor traffic roads in central areas. This indicates that there is a need to improve winter maintenance on cycleways. However, it is unclear if the dissatisfaction is due to insufficient service level requirements, or if the requirements in reality are poorly met.

According to Möller, Wallman and Gregersen (1991) the accident risk for cyclists increases 5 to 10 times during icy and snowy road conditions compared to bare surfaces. Single accidents in particular are more prevalent during winter. Besides ice and snow, grit from winter maintenance also constitutes a safety hazard for cyclists. According to Binderup Larsen et al. (1991), 10% of all single accidents are caused by loose grit on the road surface. Although slippery surfaces are of great importance for the safety of cyclists, cycleways not cleared from snow seem to be more important in the choice to cycle or not during winter (Giæver, Øvstedal and Lindland, 1998).

4. Questionnaire Survey

To improve the knowledge about travel behaviour during winter, a questionnaire survey was conducted in the PhD project, in 1998 (Bergström 1999, and 2000). The survey focused on journeys to work, and questionnaires were answered by a total of 499 employees at three large companies in two Swedish cities, Luleå and Linköping. The survey aimed to clarify the importance of winter maintenance service level of cycleways for the choice of mode, and to get the respondents opinion concerning the current service level of cycleways.

In the survey it was found that the total number of bicycle trips to work decreased by 47% from the summer period, April to October, to the winter period, November to March. During summer 36%, and during winter 19%, of all the trips to work were bicycle trips. At the same time the number of car trips increased by 27% from 53% during the summer period to 68% during the winter period. In total, 38% of the respondents stated that they would cycle more during winter if the maintenance service level of cycleways was improved. A majority of the respondents, 57%, thought that winter maintenance on cycleways needed to be improved, 9% thought that it was satisfactory, and 30% were uncertain or had no opinion. The survey also concluded, in accordance with the literature review, that snow clearance is more important than skid control for the choice of mode.

Another conclusion from the questionnaire survey worth mentioning is that distance seems to be more important for the mode choice during winter than in summer. In summer, one can hope to transfer some of the car trips up to 5 km to bicycle, while it seems that the critical distance is shortened to about 3 km during winter.

5. Test of Unconventional Methods for Winter Maintenance on Cycleways

Both the literature review (SALA, 1998) and the questionnaire survey (Bergström, 1999; Bergström, 2000) indicated that the public is unsatisfied with the service levels provided on cycleways during winter, and that improved winter maintenance on cycleways could lead to increased cycling. However, it is uncertain whether it is possible to improve the service level of cycleways at a reasonable cost, what maintenance methods are to be used, and how much they are able to affect the choice of mode during winter. Further studies are therefore needed, and in the PhD project it was decided to conduct field studies to test unconventional methods of snow clearance and skid control of cycleways. The methods tested were compared to traditional maintenance methods with respect to service levels achieved, such as the degree of snow clearance and the surface friction. Interviews and questionnaire surveys were also done, to see if the road users noticed any difference in the level of service achieved with the equipment tested. To see if an improved standard would lead to an increase in cycling, bicycle censuses related to different road conditions were also conducted.

5.1 Method

To find a winter maintenance method that could improve the service level of cycleways, and to get experience, with a view to a large-scale study, of the problems resulting from certain maintenance methods, a pilot study was carried out in Linköping (Sweden) in 1999. Traditionally, in Linköping cycleways are cleared through ploughing and skid control is attained by abrasives in 4 to 8 mm size. In the pilot study, two different and unconventional methods of snow clearance and skid control were

tested on two selected cycleways. One of the methods used a traditional steel plough for snow clearance and graded gravel for skid control. The graded gravel consisted of natural granular stone particles washed and processed to obtain a size of between 2 and 5 mm. This test method was similar to the method normally used on cycleways in Linköping, but was still meant to produce a higher service level by having a tougher starting condition and by using the graded gravel with the purpose of reducing cyclists' problems with punctured tyres. The other test method used a front-mounted broom for snow clearance combined with a brine spreader for de-icing. Using the snow broom was meant to reduce any remaining layer of ice and snow so that the salt dosage needed to achieve a bare surface could be minimised. The idea of this "brine method" originated from Odense in Denmark (Mikkelsen and Prahl, 1998), where a similar method had been used for winter maintenance on cycleways for several years. However, it was uncertain if this method was applicable to the Swedish winter climate.

The results achieved in the pilot study were limited and uncertain, since the test was performed for only a little more than a month. However, it was concluded that the method of using a broom for snow clearance and brine for de-icing produced a higher level of service compared to a traditional method, and was therefore considered of sufficient interest for further research in a large-scale study. The method using the graded gravel did not notably improve the service level, and although graded gravel might reduce cyclists' problems with punctured tyres, it may also increase the problem with poor friction on bare surfaces. Therefore it was decided not to go on with that method.

The large-scale study was carried out during two winters, between October 1999 and March 2001. In this study a housing area, *Ekholmen*, within cycling distance of a large workplace, *Saab AB*, in Linköping, Sweden, was used as a test area. In addition to all the cycleways within Ekholmen, three major routes from Ekholmen to Saab AB were included in the test area, resulting in a total of about 23 km of cycleway. In the test area the cycleways were given a higher level of service than usual in Linköping by using the front-mounted broom for snow clearance and brine, or on some difficult occasions pre-wetted salt, for de-icing. The equipment used was almost the same as that used in the pilot study, but instead of a Multicar used in the pilot study a new vehicle, a Mercedes Benz UX 100, was purchased for the large-scale study (Figure 1). Another modification before the large-scale study, was the use of a spinner, instead of a spraying boom, for brine spreading. As in the pilot study, snow clearance and skid control were performed more frequently than on other cycleways, starting snow clearance at a snow depth of 1 cm loose snow and de-icing on every occasion ice, snow, or hoarfrost occurred. In Linköping snow clearance is normally started at a depth of 3 cm.

In the large-scale study, as well as during the pilot study, observations of the road surface conditions were conducted after each occurrence of snowfall or hoarfrost. For these observations, a method for roadways (Möller and Öberg, 1990) modified to better describe the prevailing conditions on cycleways (Bergström, 2000) was used. Observations were done on both cycleways included in the test and maintained with the "brine method", and on cycleways used as controls and maintained traditionally. As a complement to the observations, measurements of friction were conducted on a few occasions. These measurements were performed with a Portable Friction Tester (PFT), developed at the Swedish National Road and Transport Research Institute (VTI) to measure friction on road markings in wet conditions (Lundkvist and Lindén, 1994). Since the PFT is reasonably small and handy, it was considered practicable in this case when measuring friction on cycleway surfaces where it can be difficult to use other measuring devices (Bergström, 2001).

To get the users' opinions of the test method, interviews were carried out on a few occasions, especially in the pilot study. The large-scale study was also evaluated through a questionnaire survey, performed in 2000. A total of 570 questionnaires were answered by employees at Saab AB living in the test area of Ekholmen, and by reference groups. The large-scale study was also evaluated by counting cyclists, particularly during the second winter of 2000/2001.



Figure 1. The Mercedes Benz UX 100 Used in the Large-scale Study, Equipped with a Front-mounted Broom for Snow Clearance and a Spinner for Spreading Brine, or Pre-wetted Salt.

5.2 Results

In the pilot study, and in the first winter of the large-scale study, the weather conditions were not ideal for the purpose of testing new winter maintenance methods since it was fairly mild, with high average temperatures and less snow than normal. During the second winter of the large-scale study, there were periods of high snow intensity, but overall one could say that this winter was also milder than normal. Unfortunately, this means that the results cannot apply to the typical winter conditions in this region.

The large-scale study has not yet been fully evaluated. Bicycle censuses related to different road conditions are not yet analysed, and a financial evaluation of the test method still remains to be made. Nevertheless, both in the pilot study and in the large-scale study, the observations of road surface conditions showed that there was almost always a dry, moist, or wet bare surface on cycleways in the test area, no matter what the conditions were on other cycleways in the municipality. This implies that the test method using a broom for snow clearance and brine for de-icing provides a higher maintenance service level than the methods traditionally used in Linköping. At the end of each study period, the effect of the midday thaw in combination with the “brine method” showed it to be very efficient for clearing the cycleways. If brine had been spread in the morning during a day of sunshine, the road condition on the cycleways in the afternoon was almost always dry bare surface.

During the pilot study, and the first winter of the large-scale study, on occasions with a snow depth over 2–3 cm of loose snow, and if the snow was very wet, the broom had problems clearing the snow. The effect of the broom was therefore improved by adding an extra hydraulic engine before the second winter of the large-scale study. This improved the snow clearing results considerably and at almost any snow depth, the snow could swiftly be swept away. Still, the operator had to maintain a slower speed than during traditional ploughing. Also, in a few stretches in the test area, where the pavement was in very bad condition, it was difficult to get good snow-clearing results, although the broom was likely more effective on such stretches than traditional ploughing.

The friction measurements, performed both in the pilot study and in the large-scale study, showed that the friction level on the cycleways maintained with the “brine method” was considerably higher than on cycleways maintained traditionally. At the time of the measurements, the surface on the cycleways included in the test was bare and wet and there was snow on the cycleways used as control. It is not surprising that a snowy surface is more slippery than a bare surface. Nevertheless, this showed that the test method using a broom for snow clearance and brine for de-icing resulted in a surface less slippery than would be the case with the maintenance methods normally used.

In the questionnaire survey conducted within the large-scale study (mainly to evaluate the winter of 1999/2000), 43% of the respondents stated that they would cycle more during the winter if the maintenance service level of cycleways was improved. A total of 62% thought that winter maintenance on cycleways needed to be improved, 12% thought that it was satisfactory, and 25% were uncertain or without an opinion. Naturally, most of those who were uncertain or without an opinion were those who did not cycle to work. This also applied to those who were satisfied with the winter maintenance. However, there were a number of winter cyclists who thought that winter maintenance on cycleways did not need to be improved. In the questionnaire the respondents were given the opportunity to specify how winter maintenance on cycleways should be improved. Most of the answers (162) suggested improved skid control, for example: “gritting should be done more often”, “prevent slush from creating frozen tracks”, and “use salt on cycleways”. Many (141) also suggested better snow clearance, such as “clear the cycleways more often”, and “clear the cycleways earlier in the morning”.

According to their mode choice for journeys to work in summer and winter, the respondents were divided into different categories of “cyclist”: “winter cyclist”, “summer-only cyclist”, “infrequent cyclist”, and “never cyclist”. A *winter cyclist* is defined as a person who uses a bicycle for travelling to work in at least two cases out of five during the period from November to March. A *summer-only cyclist* is defined as a person who uses a bicycle for travelling to work in at least two cases out of five during the period from April to October, but less during the period from November to March. An *infrequent cyclist* is a person who cycles only occasionally, fewer than two cases out of five, when travelling to work, no matter the season; and a *never cyclist* is a person who never uses a bicycle for a journey to work. In the survey, 51% were winter cyclists, 24% summer-only cyclists, 9% infrequent cyclists, and 16% never cyclists. It should be noted that the large number of winter cyclists in this survey is probably a lot higher than for an average Swedish workplace.

Of the 570 respondents, 214 lived within the test area of Ekholmen, and of those 128 were classified as winter cyclists. Winter cyclists within the test area were found to be more satisfied with the maintenance service level of cycleways during the winter of 1999/2000, compared to winter cyclists in the control areas (Table 1). This indicates that, in accordance with the measurements of friction, and the road condition observations, the test method did produce a higher maintenance service level than traditional methods.

Table 1: Respondents Satisfied with the Maintenance Service Level of Cycleways Concerning Different Road Conditions in the Test Area Compared to the Control Areas.

Road Condition:	Satisfied respondents in the:	
	Test Area	Control Areas
Slush	49%	28%
Loose Snow	62%	44%
Black Ice	50%	25%
Packed Snow/ Thick Ice	50%	24%
Total Average:	53%	30%

In addition, a majority of the winter cyclists in the test area thought that the maintenance service level during the large-scale study in 1999/2000 was higher compared to earlier winters (Figure 1). Also in the control areas, many winter cyclists thought that the service level of cycleways had improved during the test winter of 1999/2000. However, the number was not as striking as for the test area, in Ekholmen. It should be mentioned that winter cyclists in the control group in Hjulsbro, the first control group in Figure 2, were to some extent affected by the test, since the last part of their cycle route to Saab AB was located within the test area.

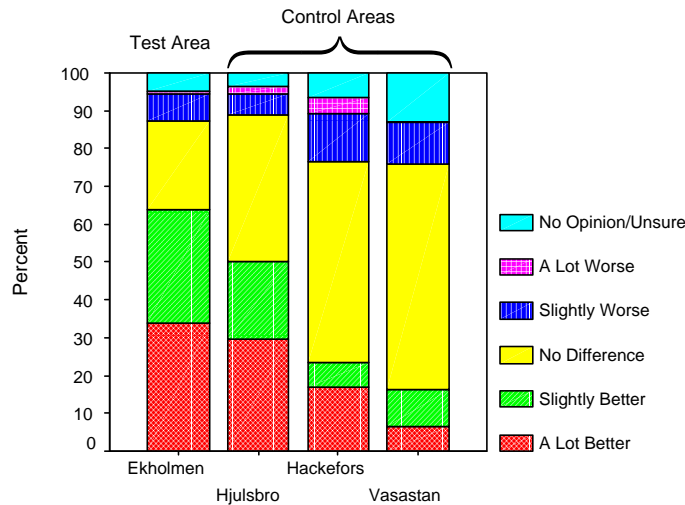


Figure 2. The Respondents' Evaluation of the Maintenance Service Level of Cycleways During the Test Winter of 1999/2000 Compared to Earlier Winters.

Even though most of the winter cyclists living in the test area, Ekholmen, were satisfied with the maintenance of cycleways provided during the winter of 1999/2000, and thought that it had been better compared to earlier winters, 44% were against the use of salt on cycleways. However, the attitude towards the use of salt on cycleways to combat icy conditions was more positive within the test area compared to the control areas. Of winter cyclists living in the test area of Ekholmen, 43% were positive to the use of salt compared to 23% of winter cyclists in the control areas. In total, all respondents included, 26% were positive to the use of salt on cycleway, 53% were against its use and 20% were unsure. A majority (52%) of those who were positive lived in Ekholmen, and thus had experienced the use of salt on cycleways, which was not the case for those who lived in the control areas.

The results from the questionnaire survey, concerning the use of salt on cycleways, can be compared to interviews conducted in the pilot study. Of the 122 people interviewed, on five different occasions, a majority (53%) thought that it was acceptable to use brine on cycleways, while 30% were against its use and the remainder were unsure.

6. Conclusions and Discussion

There seems to be a prevailing discontent among the public concerning winter maintenance of cycleways. This indicates that there is a need to improve winter maintenance on cycleways. However, it is unclear if the dissatisfaction is due to insufficient service level requirements, or if the requirements in reality are poorly met. If we want people to use their bicycles whenever possible, they have to be provided with safe and accessible cycleways. Wet snow freezing and creating icy tracks is the road condition cyclists fear most, and slippery surfaces of all kinds, including grit on bare surfaces, create a safety hazard for cyclists. Although slippery surfaces are of great importance for the safety of cyclists, cycleways not cleared from snow seem to be more important in the choice to cycle or not during winter. Further studies need to be carried out to clearly define a good road standard from a cyclist's point of view. When striving for good winter maintenance standards, the structural standards of the pavement should not be forgotten. Potholes or other irregularities that create an uneven surface can negatively affect the results of snow clearance.

Surveys presented in this paper indicate that improved winter maintenance on cycleways could lead to increased cycling. Since distance seems to be more important for the mode choice during winter than in summer, the critical distance of which one can hope to transfer some of the car trips to bicycle is shortened from 5 km in summer to about 3 km during winter.

Winter maintenance methods used on cycleways today are often adapted to the prevailing conditions on motor traffic roads. Consequently, they are not necessarily the best methods for bicycle traffic. However, there are equipment and methods available that are better adapted to cycleways. Since the surface conditions are very important for the safety and accessibility of cyclists, it is important that these methods are more widely used. It is also important to improve the methods available to better suit their purpose and also to become more cost effective. A combination of different methods adjusted to present weather and road conditions is likely to be the best solution.

Measurements of friction, road condition observations, and a questionnaire survey, presented in this paper, showed that a method using a front-mounted broom for snow clearance and brine for de-icing produced a higher maintenance service level than methods normally used on cycleways. In particular during spring, in combination with the midday thaw, this method proved to be efficient for clearing cycleways. Thus, the method using a front-mounted broom for snow clearance and brine for de-icing, is probably a good method for regions with low snow accumulations but with major ice formation problems. Linköping and many other municipalities in southern Sweden have winter conditions of this kind. Also in regions with a colder climate such as northern Sweden, this method is probably advantageous during spring and fall when the temperatures are higher and the amount of snow is less; during winter, however, other methods are likely to be better suited. A drawback with the method using a front-mounted broom for snow clearance was that the operator had to maintain a slower speed than during traditional ploughing. This increases the time to operate and hence increases the cost.

A majority of the winter cyclists living in the test area were satisfied with the maintenance service level achieved with the method using a front-mounted broom for snow clearance and brine for de-icing, and thought that it was improved compared to earlier winters. Nevertheless, many were still against the use of salt on cycleways. The fact that the attitude towards the use of salt on cycleways was more positive within the test area compared to that in the control areas indicates that the advantages of using salt become more evident for the road users when experienced directly. However, if the common opinion of the public is that salt should not be used on cycleways, it can be difficult to introduce such a method. The use of salt should always be as moderate as possible due to its environmental side effects. Its advantages and drawbacks need though to be compared with alternative methods such as the use of abrasives. On some occasions the use of salt can be more cost effective, even when the environmental effects have been taken into consideration. Further studies comparing the impact of abrasives and salt on the environment with security and economy are necessary to be able to make the right decisions concerning winter maintenance of cycleways and footways.

7. Acknowledgements

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DE-ICING SALT AND ROADSIDE ENVIRONMENT – STRATEGIES FOR IMPACT ANALYSES

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1. Abstract

Society needs to maintain road safety and accessibility of the road network at acceptable levels during the winter season. The use of sodium chloride as de-icing medium can lead to several impacts on human health and nature, as for instance damage to ground water resources and vegetation. The question of whether the political goals of accessibility, transport quality and safety can be fulfilled at the same time as the goal of a good environment is fulfilled, must be seen as a delicate matter of conflicting interests.

In order to be able to evaluate countermeasures taken against the undesired impacts, the system needs to be monitored with indicators at several levels within the system. An integrated environmental assessment framework that is suitable for such evaluations is the DPSIR-approach. It is for instance used by the Swedish Environmental Protection Agency for the follow-up of the national environmental quality objectives in Sweden. According to this framework there is a chain of causal links, from the societal need for transportation as driving force (D) of the system, over the pressure (P) of roadside exposure to salt, to an altered state (S) of the roadside environment leading to different kinds of impact (I), which may require some kind of societal response (R).

In most cases it is important to find useful indicators as early in the system as possible, especially when the environmental effect is delayed in time, as for instance regarding contamination of ground water resources. In that case an early warning could be reached.

By assigning adequate indicators to the different levels of the DPSIR model, the road keeper will not only strengthen his scientific understanding of the ecological effects, but also increase his possibilities to take appropriate measures to improve the sustainability of the system and finally increase the knowledge of the environmental utility of the strategic actions taken.

2. Introduction

In June 1998, the Swedish Parliament adopted a new transport policy on the basis of the Government Bill "Transport policy for sustainable development" (1997). The overall goal of the transport policy is defined to be a transport system that is environmentally, economically, culturally, and socially sustainable. The overall goal was divided into five sub-goals: an accessible transport system, a high transport quality, a safe traffic, a good environment, and a positive regional development. In addition to that, the Swedish Roads Act (1971, section 23) states that roads shall be held in a satisfactory state by maintenance and other measures. Therefore, in order to maintain road safety and accessibility of the road network at acceptable levels also during the winter season, the roads are kept free from ice and snow by ploughing and by the use of chemical de-icing. The winter road maintenance regulations of Sweden (Drift 96..., 1996) prescribe sodium chloride as the only allowed chemical de-icing agent to be used. Unfortunately the salt solution does not stay on the road surface where it has its desired effects, but will by different mechanisms be dispersed into the roadside where it may lead to undesired environmental impacts (Blomqvist, 1999; Thunqvist, 2000). The question of whether the goals of accessibility, transport quality and safety can be fulfilled at the same time as the goal of a good environment is fulfilled, must therefore be seen as a delicate matter of conflicting interests.

The Swedish National Road Administration (SNRA) is responsible for the winter road maintenance of about 98 000 km of state roads in Sweden (Ölander, 2000). Twenty-five per cent of the SNRA appropriation for road maintenance and operations is spent on winter road maintenance works, such as snow ploughing and de-icing (Ölander, 2000). The de-icing salt use on the national

road network has approximately doubled since the 1970's and has for the last six seasons varied in the size between 200 000 and 300 000 metric tonnes (figure 1).

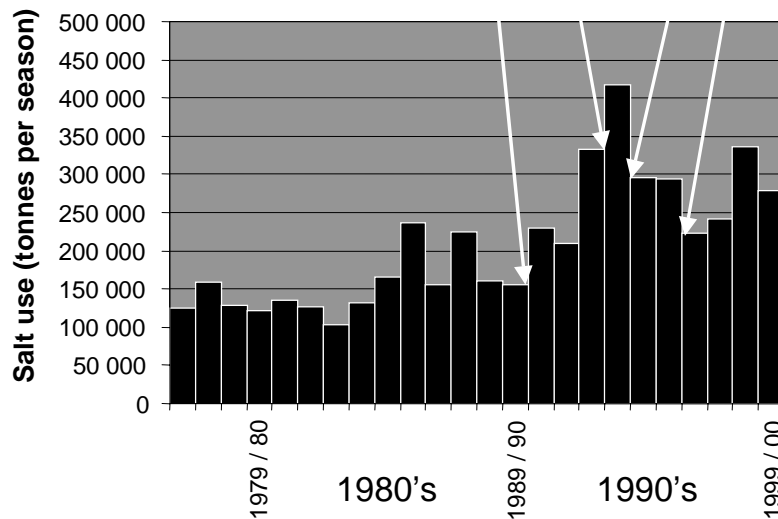


Figure 1 The Seasonal Salt Use On The Swedish National Road Network (Metric Tonnes Per Season). The Arrows Depict The Changes In The Winter Road Maintenance Regulations During The Last Decade. Before That The Winter Maintenance Was Regulated In Five-year Plans.

The SNRA has a constant ambition of improving the requirements of the winter road maintenance regulations. Therefore the regulations have changed several times during the last decade (figure 1). In 1996 a limit value of 200 000 tonnes salt per year was set up as a goal to be reached by the year 2000 (Kretsloppsanpassad väghållning... 1996). This goal was indeed reached as the salt-use in the calendar year of 2000 was 196 700 tonnes (Pettersson, personal communication). For the future, the strategy for decreasing the salt use is the development of a salt index that allows the actual salt use to be compared to the salt needed according to the weather conditions prevailing during the entire winter (Ölander, personal communication). In that way the actions of the contractors can be compared to the requirements of the regulations.

A key issue when taking management decisions in the road sector is to ensure that the limited funds are spent to greatest effect within the various constraints that pertain (Robinson et al., 1998). Knowledge of the different interrelationships within the system is therefore of great importance. Since 1999 the Swedish Environmental Code (1998, chapter 2, section 2) states that those who pursue an activity or take a measure, or intend to do so, must possess the knowledge that is necessary in view of the nature and scope of the activity or measure to protect human health and the environment against damage or detriment. After decades of investigations, however, we still have to deal with the problem of environmental effects of the use of de-icing salt in the winter road management. The regulations of the winter road management have changed four times during the 1990's (figure 1) but, since we don't have useful indicators of the environmental pressure, states and impacts, we still don't know the environmental utility of these changes. The objective of this paper is to describe the system of de-icing practices and their environmental effects with special reference to the salt exposure of the roadside environment and damage to Norway spruce seedlings. The objective is also to describe a monitoring system and discuss the importance of indicators for the follow-up, which ultimately will increase the knowledge of the environmental utility of the strategic actions taken by the road administrator.

3. Describing the system

Full understanding of the total system is probably not possible, but by simplifying the system of the real world into a model to start with, a conceptual understanding of the total system could be reached.

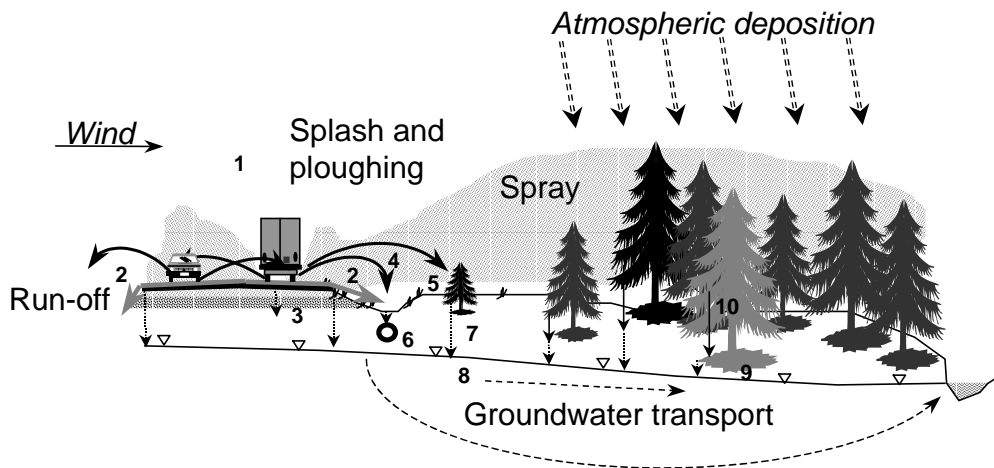


Figure 2 A Conceptual Model Of The Transport Mechanisms And Pathways From The Road.

The system of de-icing salt can be described in several ways. This can be illustrated e.g. as in the picture above (figure 2) showing the transport mechanisms and pathways from the road, or as a box model divided into several compartments as shown below (figure 3). The de-icing salt is either transported through the compartments or accumulated within them.

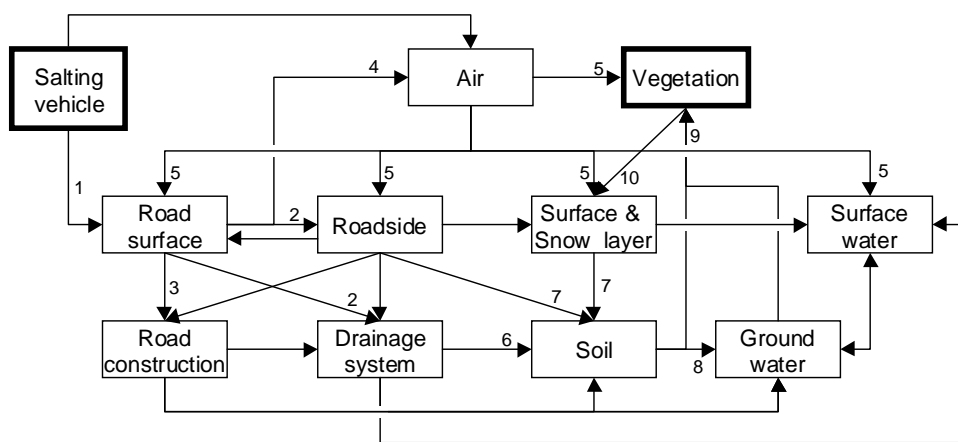


Figure 3 A Box Model Of The Physical System Of De-icing Salt Migration From The Vehicle That Carries On The De-icing Actions To The Compartments On, In Or Around The Road Which Are Involved In The Migration Or Accumulation Of De-icing Salt. The Boxes Depict The Compartments Where The De-icing Salt Either Is Passing Through Or – To Some Extent – Is Retained Or Accumulated. The Arrows Depict The Mechanisms That Govern The Migration Of The De-icing Salt, Such As: Deposition, Run-off, Infiltration, Percolation, and Root Uptake.

The de-icing vehicle applies the salt on to the road surface¹. This is the action where the entire system originates. The salt will then leave the road surface by itself (by gravity) or by the action from traffic in the following ways. By run-off,² the salt will reach the roadside or the drainage systems. Some parts may infiltrate³ the road surface and reach the interior of the road construction. By being forced into the air⁴ by the vehicles or by ploughing, the salt leaves the road as splash, spray or dry crystals to be deposited⁵ onto the road surface or roadside (roadside cover, ditch, etc.) of the technosphere or on the vegetation, soil surface, snow layer or surface waters in the surrounding

ecosphere. By leaving the drainage system⁶ or percolating⁷ from the roadside or soil surface through the soil the salt solution may reach the groundwater⁸. Where the soil solution and groundwater are in contact with the root zone of vegetation, uptake⁹ through the roots may occur. Some part of the salt deposited onto the foliage, stem and branches of the vegetation will enter the interior of the plant, but a large portion will be transported as throughfall¹⁰ and stemflow¹⁰ to the soil surface beneath the vegetation.

The pathways by which the de-icing salt may reach the different plant parts have been discussed extensively in the literature. There is no doubt that damage may occur either when the salt is deposited onto the foliage and when it reaches the root system. This has been shown both in field studies and in laboratory studies under controlled conditions (Dobson, 1991; Brod, 1993; Pedersen and Fostad, 1996). When the salt is deposited on to the foliage it may either stay on the exterior parts (needles, leaves, stem etc.) or be transported to the interior of the plants either through the leaf cuticle or through the bark on the branches or stem. Also the stomata have been suggested to be a pathway to the interior parts (Burkhardt and Eiden, 1994). Different kinds of particles deposited on the exterior parts of needles have been suggested to lead to additional damage (Flückiger et al. 1977).

The symptoms of salt damage in coniferous trees are often described as needle browning and needle loss (Pedersen and Fostad, 1996). Some trees are able to compensate for damage by producing new shoots, but when the damage is too great, this is not possible (Pyykkö, 1977; Blomqvist, 1999).

The consequences of this damage are many. One is the impact on biota in itself; another is the effect on the landscape. The impact of de-icing salt on conifers is a result of a complex interplay of many causal relationships (e.g. loss of needles: lower photosynthetic capacity; increased amount of salt in soil water: osmotic stress: inhibition of water uptake; stress avoidance of the plant: energy expenditure). Most of these effects will in the end result in diminished growth of the tree stand and can also predispose the tree to damage from fungi or insects. Such effects have been described by e.g. Pedersen and Fostad (1996). It is often difficult to separate between different stress factors since one factor may have predisposed the tree to damage, another factor can have triggered the damage, and a third factor may have contributed to the actual killing of the tree (Aronsson et al., 1995).

The extent of damage is governed by some kind of dose-response function. For some species, the function has been suggested to be S-shaped (Figure 4) (Dragsted, 1990). Many investigations of the amount of chloride in e.g. needle tissue compared to the extent of visible damage symptoms have been performed and comprehensive compilations have been published by e.g. Dobson (1991) and Brod (1993). The theoretical extent of damage can be calculated by combining the distance–exposure and exposure–damage functions (Figure 4). One should, however, keep in mind that the roadside environment is also exposed to many other stress factors (Viskari, 1999).

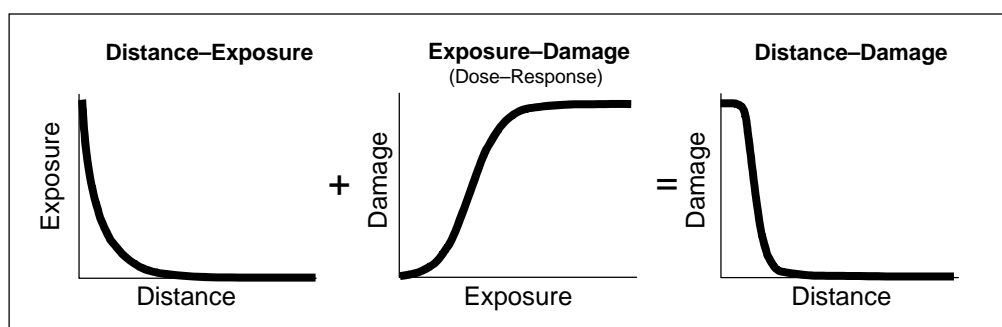


Figure 4 Theoretical Functions Of Exposure To Salt And Susceptibility To Salt Damage Give The Pattern Of Damage In The Roadside Environment

Forestry should be thought of as a process rather than a steady state. While one effect of the roadside exposure to de-icing salt is a lower yield from forestry, a possibly more important long-term consequence may manifest itself when reforestation is to take place. The seedlings and young plants are much more sensitive to salt exposure than are older trees. Reforestation may therefore be virtually impossible in a zone of up to several tens of metres from the road. This extends in many places beyond the road reserve area and, hence, may affect the land next to the road. If reforestation is made impossible the landowner is subjected to a forced change of land-use (Figure 5), which probably will

lead to a different situation concerning the legislative possibilities to claim for damages, than do the impact of diminished growth in the roadside.

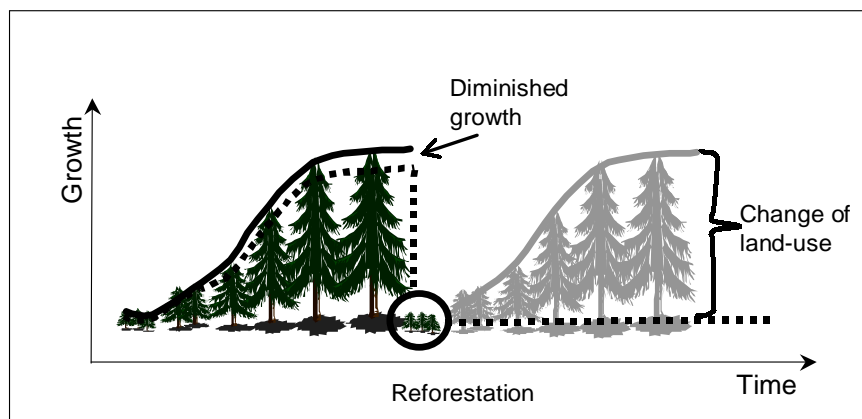


Figure 5 Implications for forestry, seen as a process

Sweden has a long tradition of monitoring salt concentrations in groundwater. Starting already in the late 1970's, Bäckman has been monitoring sodium and chloride concentrations in observation wells as influenced by de-icing salt. Long-term increases have been documented (Bäckman 1980, 1997). The same result has been obtained in long-term monitoring of chloride concentrations in municipal groundwater supplies (Knutsson et al. 1998; Rosén et al. 1998). Likewise, a long-term increase trend was documented by Thunqvist (2000) compiling data from up to 23 Swedish municipal groundwater plants for the period 1954–1999. By compiling data from 13 000 private drilled wells, Olofsson and Sandström (1998) found that wells located close to major roads had increased concentration of chloride.

The salt that has percolated through the road construction, or roadside and reached the soil or groundwater will to a large extent be transported with the groundwater to the surface waters and then follow the water cycle to the sea. In that sense this is – in a very long time-scale – a geochemical cycle of salt, extracted from the seas or rocks, placed on the roads and then returning to the seas again. On the road surface, most effects are desired and in the seas salt is at least not harmful. The important issue is what happens in between (Thunqvist, 2000).

4. Monitoring the system

Robinson et al. (1998) have stated that: “A key challenge for the road manager is to find ways in which to describe the problems and impacts of road maintenance that can be understood by the politicians and the general public”. One could also state that a crucial challenge for the scientific community would be to find key parameters and indicators of the system's different compartments that can be understood and utilised by the road managers (Blomqvist, 2001b). A system that is used by the European Environmental Agency (EEA) as a generic tool to support understanding of complex environmental systems is the DPSIR model (Towards a transport and environment reporting mechanism ‘TERM’ for the EU, 1999). This system is used for facilitating communication and is based on indicators of the different compartments. Societal needs and activities can be viewed as driving forces (D) that lead to a pressure (P) on the environment. The pressure may change the state (S) of some compartments of the environment. This, in turn, can lead to impacts (I) on a system such as human health or nature. Finally, the society will respond (R) in some way to combat the problem in one or several of the earlier stages in the model (Figure 5).

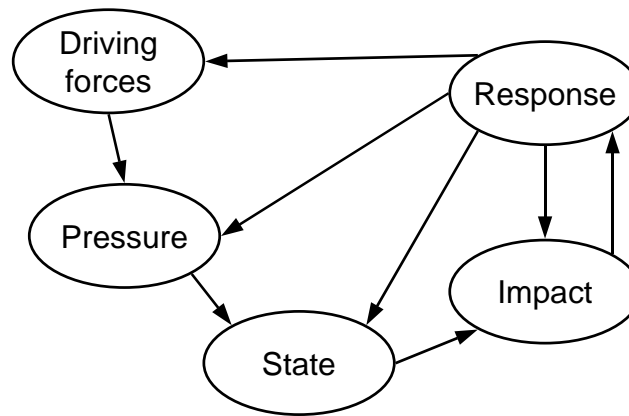


Figure 5 The DPSIR Framework For Reporting On Environmental Issues

Using the DPSIR-model (figure 5), the use of de-icing salt and damage to vegetation could be described as follows. The need for transportation (D) leads to a roadside exposure to salt (P), which alters the state of the vegetation (S), thereby leading to different impacts (I), which may require some kind of response (R) from society (Figure 6).

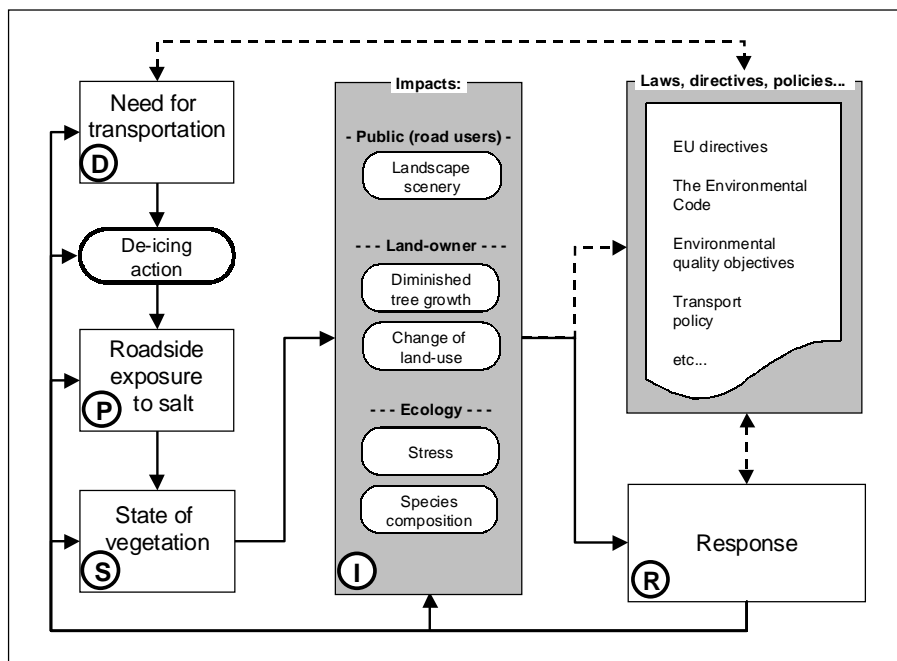


Figure 6 The System Of De-icing Action And Damage To Vegetation As Illustrated By The DPSIR model.

The impacts have been divided into different spheres of interest where the interest of the public as road users is threatened by the impaired landscape scenery. The interest of the rural landowners can be threatened by the diminished tree growth or the forced change of land-use that may occur if reforestation is made impossible in the salt exposed environment. The vegetation as part of the ecosystem can be influenced by being stressed and as a result there may be a change in the species composition of the roadsides.

By adding two new compartments to the original DPSIR model, the model is made suitable to be used for identifying the involved processes. The two new compartments are the first oval between the driving force and pressure (figure 6) which represents the activity that is induced by the driving force, causing the pressure. In this case it is the actual de-icing measure taken. The other new compartment in figure 6 is the box of laws, directives, policies, regulations, contract conditions, etc. These are partly a result of the needs within the society (e.g. need for transportation is manifested in some of the goals

of the transport policy), but it can also be used as a toolbox of the society to respond to all of the stages in the DPSIR model.

In most cases it is important to find useful indicators as early in the system as possible, especially when the environmental effect is delayed in time, as for instance regarding contamination of ground water resources. In that case an early warning could be reached.

By assigning adequate indicators to the different levels of the DPSIR model, the road keeper will not only strengthen his scientific understanding of the ecological effects, but also increase his possibilities to take appropriate measures to improve the sustainability of the system. The road keeper needs also to know the environmental utility of the responses he has taken.

6. Ongoing research

Research at the Swedish National Road and Transport Research Institute (VTI) in Linköping, Sweden is currently addressing the issue of roadside exposure to salt and the development of indicators of different components within the system as described above, both regarding groundwater contamination and damage to vegetation.

7. Acknowledgement

This paper is based on the results of the licentiate thesis “Air-borne transport of de-icing salt and damage to pine and spruce trees in a roadside environment”(Blomqvist, 1999) and PhD thesis “De-icing salt and the roadside environment: Air-borne exposure, damage to Norway spruce and system monitoring” (Blomqvist, 2001). They are results from the project “Influence of De-icing salt on Roadside Vegetation” (VTI Project No 80131) performed at VTI during 1996–2001. The work has been financed by the Swedish National Road Administration through the Centre for Research and Education in Operation and Maintenance of Infrastructure (CDU) at the Royal Institute of Technology (KTH) in Stockholm and by the Swedish National Road and Transport Research Institute (VTI) in Linköping, Sweden.

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WEATHER DESCRIPTIONS AND COMPENSATION MODEL FOR WINTER ROAD MAINTENANCE

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Abstract

A good compensation model for regulating costs for winter road maintenance between client and contractor requires two well-functioning sub models.

- A sub model that describes the weather during the winter season.
- A sub model that links the weather descriptions to the need to take measures/set in resources.

The basis for the weather descriptions are data collected from the individual stations in the Swedish National Road Administration system for road weather information, RWiS. Through using special definitions, the data are translated into eight weather situations at an hourly level. Examples of weather situations are snowfall, drifting snow and risk of slipperiness caused by rain or sleet on a cold roadway.

The hour-by-hour weather descriptions are then summarised into clearly defined weather occurrences, for instance drifting snow during 6 hours or a snowfall lasting 20 hours with a snow depth of 10 cm. The final result of weather descriptions for a winter is a number of clearly defined weather occurrences.

The compensation model is based on the number of weather occurrences for each RWiS station chosen as representative for a certain maintenance area. Starting from each weather occurrence the number of so-called resultant weathers is calculated being the basis of compensation. In this step the connection is made between weather and the need to take measures.

Background

A good compensation model (payment model) for regulating costs for winter road maintenance between client and contractor, based on winter conditions, requires two well-functioning sub models.

- A sub model that describes the weather during the winter season.
- A sub model that links weather descriptions to the need to take measures/set in resources.

Weather Situations

Weather descriptions are based on raw data from individual stations in the Swedish National Road Administration system for road weather information, RWiS. The following raw data are used.

- Air temperature.
- Road surface temperature.
- Relative humidity.
- Dew point temperature.
- Precipitation type.
- Precipitation quantity.
- Wind speed.

With the aid of specific definitions, these raw data are translated from the RWiS to the eight weather situations below on an hourly basis.

- Snowfall (S).
- Drifting snow (D).
- Slippery surface due to rain or sleet on a cold road (SSP).
- Slippery surface due to damp/wet roads freezing (SSF).
- Slippery surface due to light hoar frost (SSH1).
- Slippery surface due to heavy hoar frost (SSH2).
- Specific weather, type 1, i.e. drifting snow with high wind speed (SW1).
- Specific weather, type 2, i.e. snowfall with high snow intensity (SW2).

The following are two examples of definitions for translating raw data into weather situations:

Drifting snow (D).

- Snow likely to drift should be present (as in a specific definition).
- The average wind speed should be 5 m/s or above.

Slippery surface due to light hoar frost (SSH1).

- Road surface temperature must be at least 0.5 °C lower than the dew point temperature.
- Road surface temperature must be below + 1.0 °C.

Weather Situations On An Hourly Basis

An example of hourly weather situations is given in table 1 below. The situations are for an operating area where three RWiS stations, 307, 312 and 320, have been selected as representative.

Station	Weather	Hour																							Snow depth (mm)	
		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	
Date: 28 Nov.																										
307	Weather situation													S	S		S	S	S	S	S	S	S	S	S	
307	Snow depth (mm)	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0.2	0	3.5	4.8	5.8	8.5	5.8	8.8	9.9	8.2	5.8	62
312	Weather situation													S			S	S	S	S	S	S	D	D	D	
312	Snow depth (mm)	0	0	0	0	0	0	0	0	0	0	0	0	0.2	0	0	0.2	1.0	1.6	4.8	4.8	9.0	7.1	5.9	6.6	41
320	Weather situation														S		S	S	S	S	S	S	S	S	S	
320	Snow depth (mm)	0	0	0	0	0	0	0	0	0	0	0	0	0	2.1	0	1.3	4.0	5.6	7.1	5.1	2.4	3.5	9.8	9.7	51
Date: 29 Nov.																										
307	Weather situation	S	S	S	S	S	S	S							S	S	S	S	S	S				S	S	
307	Snow depth (mm)	5.0	4.6	5.5	5.9	6.0	3.8	0.6	0	0	0	0	0	0	0.3	0.8	1.6	0.2	0.2	1.5	0	0	0	1.4	2.4	40
312	Weather situation	D	D	S	S	S	S	S							S	S	S	S	S	S	S	S		S	S	
312	Snow depth (mm)	5.0	3.1	3.4	4.2	2.3	6.1	2.3	0	0	0	0	0	0	0.2	0.6	1.1	0.8	0.5	0.3	0.8	0.2	0	0.4	1.0	32
320	Weather situation	S	S	S	S	S	S	S						S	S	S	S	S	S	S	S			S	S	
320	Snow depth (mm)	6.6	9.5	5.8	7.8	9.8	5.6	1.5	0	0	0	0	0	0.5	0.5	1.2	0.5	1.7	0.5	1.4	2.8	0	0	0.3	2.4	58
Date: 30 Nov.																										
307	Weather situation	S						S	S	S				S	S	S										
307	Snow depth (mm)	1.1	0	0	0	0	0	0.4	1.5	2.1	0	0	0	0.7	0.3	0.2	0	0	0	0	0	0	0	0	0	6
312	Weather situation	S	S					S	S	S	S					S										
312	Snow depth (mm)	1.0	0.3	0	0	0	0	1.0	0.8	1.6	0.3	0	0	0	0	0.2	0	0	0	0	0	0	0	0	0	5
320	Weather situation	S			S		S	S	S	S	S					S	S									
320	Snow depth (mm)	1.0	0	0	0.5	0	0.2	0.8	1.1	2.1	0.2	0	0	0	0	1.0	0.8	0	0	0	0	0	0	0	0	8

Table 1 72-hour Weather Situations At Hourly Intervals For An Operation Area.

The weather description table reveals that a relatively heavy snowfall (S) started at approximately 12.00 on 28 November and continued for around 20 hours, i.e. until 07.00 the next morning. At station 312 drifting snow (D) occurred for 5 hours around midnight at the same time as it snowed.

After a break of around 6 hours, it started snowing again. This time in the form of light snowfall that continued for around 24 hours, although this stopped several times. When this snowfall had ended, between 8 and 12 cm of snow had fallen, depending on the individual RWiS stations.

Payment Model

The payment model is based on weather occurrences, not on specific hours with certain weather situations. Examples of weather occurrences are a snowfall between 06.00 and 12.00 or slippery surface due to hoar frost between 01.00 and 05.00. The payment model is based on weather occurrences because for example, an occurrence of hoar frost for four hours is not equivalent to four separate hours of hoar frost on four different days. The first four-hour hoar frost may perhaps call for just one salting run while the four separate hours would probably need four runs.

The starting point for payment calculations is the weather situations on an hourly basis set out above. These weather situations at hourly intervals are first merged together into weather occurrences. Each weather occurrence then generates one or several so-called resultant weathers that form the basis for payment. The calculations are done for one RWiS station at a time and then summarised for the whole maintenance area. It is at this stage that a relation is set up between weather and need for action. It must be stressed that **one** resultant weather does not equal **one** action to be taken, e.g. a salting run or a ploughing run.

The following rules apply when resultant weather calculations are performed.

Calculation Order For Different Weather Situations

1. Specific weather, type 1 (SW1).
2. Specific weather, type 2 (SW2).
3. Drifting snow (D).
4. Snowfall (S).
5. Slippery surfaces of all types (SSP, SSF, SSH1, SSH2).

Demarcation Of Weather Occurrences

The following method for the demarcation of weather occurrences applies for all weather situations except SW2.

The first hour during winter with the current weather situation, generally called W, is identified. The last hour during this first occurrence of W is identified. This is found when there is a break of at least 6 hours until the next hour of W. The following weather occurrences with W during the winter season are demarcated in the same way. See illustration 1 below.

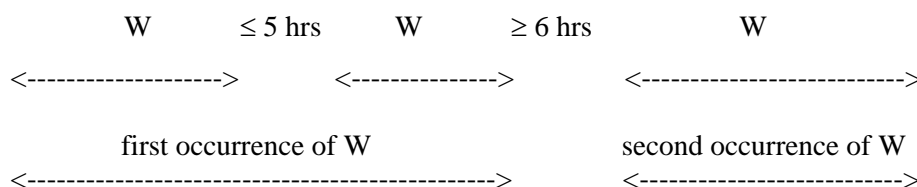


Illustration 1 Demarcation Of Weather Occurrences Of Weather Type W.

Specific Weather Type 1 (SW1)

1. All hours with SW1 during the current calculation period are demarcated as weather occurrences according to the method given in illustration 1.
2. How long the SW1 occurrences found last is determined in the following way. If SW1 occurs $\geq H_{SW1}$ hours consecutively then specific weather type 1 arises. Otherwise there are just intermittent hours of SW1.
3. The SW1 occurrences that meet the time period requirements are shown under the heading “Resultant weather, SW1”. This states the start and finish times for each occurrence.
4. During the time period when an SW1 occurs and H_{SW1} after hours thereafter no calculations are done for weather of types drifting snow, snowfall and slippery surface, (payment for the SW1 weather plus the subsequent H_{SW1} after hours takes precedence). If however several SW1 or SW2 occurrences arise within H_{SW1} after hours after an SW1 occurrence ends, the end time point is extended.

Specific Weather Type 2 (SW2)

1. Weather occurrences of type SW2 are calculated and how long they lasted is determined for each RWiS station with the aid of a specific procedure. The calculations are done such that the snow intensity shall amount to not less than I_{SW2} cm/hr for not less than H_{SW2} hrs. The SW2 occurrences are given under the heading “Resultant weather, SW2” where the start and end time point is given for each occurrence.
2. During the course of an SW2 occurrence and H_{SW2} after hours afterwards no calculations are done for weather of types drifting snow, snowfall and slippery surface (payment for SW2 weather and the following H_{SW2} after hours takes precedence). However if there are several SW2 or SW1 occurrences within H_{SW2} after hours after an SW2 occurrence ends, the end time point is extended.

Drifting Snow (D)

1. All hours with D during the current calculation period are demarcated as weather occurrences in accordance with the method in illustration 1.
2. If D arises $\geq H_{DRIFT}$ hours in succession during the course of the D-occurrence the time period requirement for drifting snow is met, i.e. drifting snow occurs. For instance, as SW1 is a heavier type of D, a 4-hour combination of situations D, D, SW1, D can be counted as drifting snow.
3. Each D-occurrence that meets the duration requirement is divided into 4-hour intervals (the last 4-hour interval can be between 1 and 4 D hours) and the number of intervals is calculated. The amount of snow in each 4-hour interval is calculated. The intervals that have both $\leq 0,3$ cm of snow and do not have D or SV1 hours are discounted. The remaining intervals are shown in four classes under the heading “Resultant weather, drifting snow”.

The classes are defined according to the following amounts of snow d (cm).

- $0,0 \leq d \leq 0,3$
- $0,3 < d \leq 1,0$
- $1,0 < d \leq 2,5$
- $2,5 < d$.

Snowfall (S)

1. All hours with S during the current calculation period are demarcated as weather occurrences according to the method in illustration 1.
2. Each occurrence of S is divided into 4-hour intervals (the last 4-hour interval can be between 1 and 4 S hours) and the number of intervals is calculated. The amount of snow in each 4-hour interval is calculated. The intervals that have $\leq 0,3$ cm of snow are discounted. The remaining intervals are shown in three snow quantity classes under the heading “Resultant weather, snowfall”.

The snow quantity classes are defined by the following amounts of snow d (cm).

$$0,3 < d \leq 1,0$$

$$1,0 < d \leq 2,5$$

$$2,5 < d.$$

Slippery Surface Occurrences Of Type SSP, SSF, SSH1 And SSH2

1. When snowfall or drifting snow occurs and up to 6 hours after such weather, no demarcation is done for slippery surfaces. Nor during the occurrence of SW1 or SW2 and up to H_{SW1} after resp. H_{SW2} after hours thereafter is any demarcation made for the occurrence of slippery surfaces. The following tests are done for the remaining periods.
2. When demarcating occurrences of slippery surfaces, all types of slippery surface, i.e. SSP, SSF, SSH1 and SSH2 are classed the same.
3. All hours of slippery surface weather during the current calculation period are demarcated as occurrences of slippery surfaces according to the method in illustration 1.
4. The duration of the resultant weather is linked to the type of slippery surface weather, H_{SSP} , H_{SSF} , H_{SSH1} and H_{SSH2} hours.
5. The slippery surface type during the first hour in the first occurrence of slippery surface (generally called type SS1) is identified. The duration of this type is H_{SS1} hours. An interval of H_{SS1} hours is set out from the first hour of such inclusive. A test is done to see if some type of slippery surface weather shorter than H_{SS1} hours occurred within the interval. If no such type is found then a resultant weather of type SS1 has occurred. This is shown under the heading “Resultant weather, slippery surface type SS1”.
6. Otherwise the interval is shortened by one hour at a time and new tests are done until no slippery surface type shorter than the length of the interval is found within the interval. Then a resultant weather of the slippery surface type with the shortest duration within the interval (generally called type SS2) has been found. This is shown under the heading “Resultant weather, slippery surface type SS2”.
7. The slippery surface type in the first hour after the resultant weather found and shown according to the above is identified and steps 5 and 6 are repeated until the first slippery surface occurrence is resolved. The next occurrence of slippery surface is dealt with in the same way.

Implementation

Regulating the costs between client and contractor for winter road maintenance has previously been done in accordance with three principles.

1. Payment has been based on the resources used such as ploughing hours, amount of salt spread etc.
2. The contractor has been paid for the stretch cleared, e.g. number of kilometres ploughed and number of kilometres salted/sanded etc.
3. Payment has been based on different types of so called weather days, e.g. days with snowfall and days with icy roads.

With the aid of the payment model described above, payment will be based on the same basic data that the contractor uses to decide what action to take.

Before the start of the tendering procedure of winter road maintenance in an operating area, a number of RWiS stations are selected that are representative for the operating area in question and that will form the basis for payment. Three or four stations are normally selected. These can be within or outside the boundaries of the operating area.

Data from different RWiS stations can be combined. For instance, one can choose to get temperature and precipitation from one RWiS station and wind speed from another.

A number of parameters are then set that are included in the eight different weather situations (see page 1) and also govern the resultant weather. Examples of such parameters are:

- Lowest snow intensity for SW2 to arise, I_{SW2} [cm/hr].
- Shortest duration for triggering SW2 payment, H_{SW2} [hrs].
- Lowest wind speed for drifting snow to be declared, V_{DRIFT} [m/s].
- Shortest duration to trigger drifting snow payment, H_{DRIFT} [hrs].
- Length of resultant weather SSP, H_{SSP} [hrs].

The resultant weather is determined for a “normal” winter in the operating area with the help of historic data from a number of winter seasons. The number of SW1, S, SSP, SSH1 etc. is then listed. As a part of the tendering procedure the contractor sets prices for each of them.

It should be added that in first hand the payment model described above covers snowploughing and salting actions. The need for sanding measures is normally regulated according to some other payment model.

PREDICTING STEADY STATE CONCENTRATIONS OF CHLORIDE IN GROUNDWATER AND SURFACE WATER.

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Abstract

A road in operation with its traffic can pose a serious pollutant threat to groundwater and surface water in its vicinity. Examples of pollutants are salt for deicing and dustbinding; metals from corrosion of vehicles and wear of road surface and tires; hydrocarbons from the wear of road surface, tires, exhaust, oils; and hazardous goods discharged in the case of an accident. In Sweden about 300000 tonnes of sodium chloride are used annually by the Swedish National Road Administration for deicing purposes. In addition the local municipalities also use salt for deicing purposes. The use of studs improve the friction but increase the wear and the grinding effect on winter roads. The wear of a wet surface is reported to be two to seven times the wear of a dry surface, and hence, the grinding effect may be further increased by the use of deicing salt.

The movement of pollutants from the road to the surrounding environment will involve run-off from roads, airborne spreading, infiltration from road construction and road area. The chloride ion is a good tracer. It is conservative and highly soluble and not subjected to retardation or degradation. A small part of the sodium may be retained in soil but almost all of the deicing salt will be either infiltrated and found in groundwater or form runoff and be found in surface water. Other, non-degradable road-related substances may be retained in soil to a greater extent. Eventually, all pollutants from roads, which are not subjected to degradation, will be transported either to surface water or to groundwater.

In this paper a method is presented by which the steady state concentration of chloride in groundwater and surface water due to the use of deicing salts can be calculated. The calculations are based on digital data for catchment areas, net recharge (precipitation with the deduction of evapotranspiration), background deposition and road network with deicing salt application rates. All data are processed and presented with the GIS-tool Arcview. The method makes it possible to scan an area, e.g. a country, in order to make the decisions on what areas to protect and which measures to adopt. The method can also be used to predict the steady state concentrations of other road related pollutants.

Introduction

A road in operation with its traffic can pose a serious pollutant threat to groundwater and surface water its vicinity. Examples of pollutants are salt for deicing and dustbinding; metals from corrosion of vehicles and wear of road surface and tires; hydrocarbons from the wear of road surface, tires, exhaust, oils; and hazardous goods discharged in the case of an accident. In Sweden about 300000 tonnes of sodium chloride are used annually by the Swedish National Road Administration for deicing purposes of national roads (Thunqvist 2000). In addition the local municipalities also use salt for deicing purposes.

The major roads in Sweden are deiced with 10-20 tonnes of sodium chloride per kilometre annually. On the road the effects of the salt are desired, and in the ocean a high salt concentration is

natural. However, on their way the sodium and the chloride ions will pass through an environment where the natural concentration of salt is low, involving an impact on the environment (Figure 1).

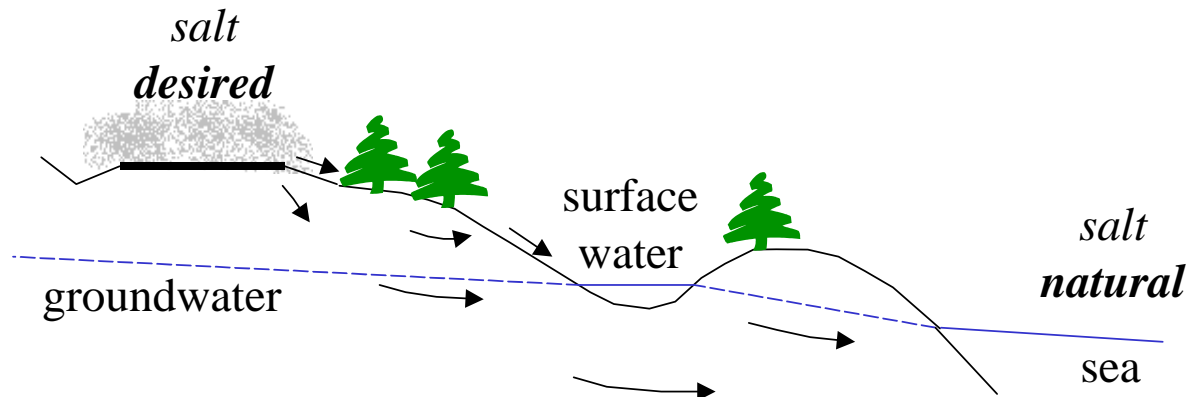


Figure 1. The movement of deicing salt from road to sea.

The chloride ion is a good tracer. It is conservative and highly soluble and not subjected to retardation or degradation. A small part of the sodium may temporarily be retained in soil but almost all of the deicing salt will by infiltration or runoff reach groundwater and surface water. Several Swedish investigations show that the chloride concentrations in both groundwater and surface water have increased in the vicinity of roads (e.g. Bäckman & Folkesson 1995, Olofsson & Sandström 1998, Thunqvist 2000). The movement of pollutants from the road to the surrounding environment will involve run-off from roads, splash, airborne spreading and infiltration from road construction and road area. Other, non-degradable road related substances may be retained in soil to a greater extent, but they will eventually reach groundwater or surface water. There are also several investigations which show that heavy deicing salt application increases metal mobilisation (Amrhein et al 1994, Bauske & Goetz 1993, Norrström & Jacks 1998).

The Swedish Environmental Code (SFS 1998:808, ch.2) states that everyone is required to possess the knowledge of the impact of one's activities and to implement protective measures in order to prevent impact on the human health and the environment. A simple and robust model to estimate the concentration of chloride in recharge water based on different salt application rates would be a first step towards that knowledge. It is of importance that the data are easily accessible and the processing tool well known.

This paper shows how such a simple model can be used to predict chloride concentrations in water due to application of deicing salt. If it is possible to scan an area, e.g. a county, it is possible to make the decisions on what areas to protect and which measures to adopt. The limitations of the model and how the results can be refined by the use of more data or by the use of a more sophisticated model is discussed.

Background

There are different ways of combining the data which give different precision in identifying water in the vicinity of roads where there is a risk for high chloride concentrations. The simplest way is to combine the maps of the road network with maps of the hydrogeological conditions and maps of lakes and watercourses in order to identify risk areas. The result is a rough indication of where conflicts of interest exist between roads and groundwater/surface water. This method has been used by the Swedish National Road Administration in order to identify where the consequence of a road accident would be serious for a water supply (Vägverket 1995). However, the investigation has been limited to national roads and to municipal water supplies of a certain capacity. The actual number of important aquifers and lakes/watercourses in conflict with deiced roads is much greater. Furthermore, only the different sites of conflicting interest are listed - the increase in chloride concentration for different areas is not calculated. In Figure 2 the digital maps of the main roads are combined with digital maps showing the main aquifers in the county of Västmanland. Historically roads in Sweden were built on

good soil material high in the landscape. Thus, the roads are often built on the major eskers (which are also important aquifers) since they provided the necessary requirements.

The winter road maintenance categories are A1 to A4, B1 and B2. The A-roads are deiced regularly, where category A1 is the largest road with the most frequent recurring deicing operations. The B1-roads are deiced occasionally, although sand with a small amount of deicing salt added is used more frequently, and on the B2-roads even less deicing salt is used.

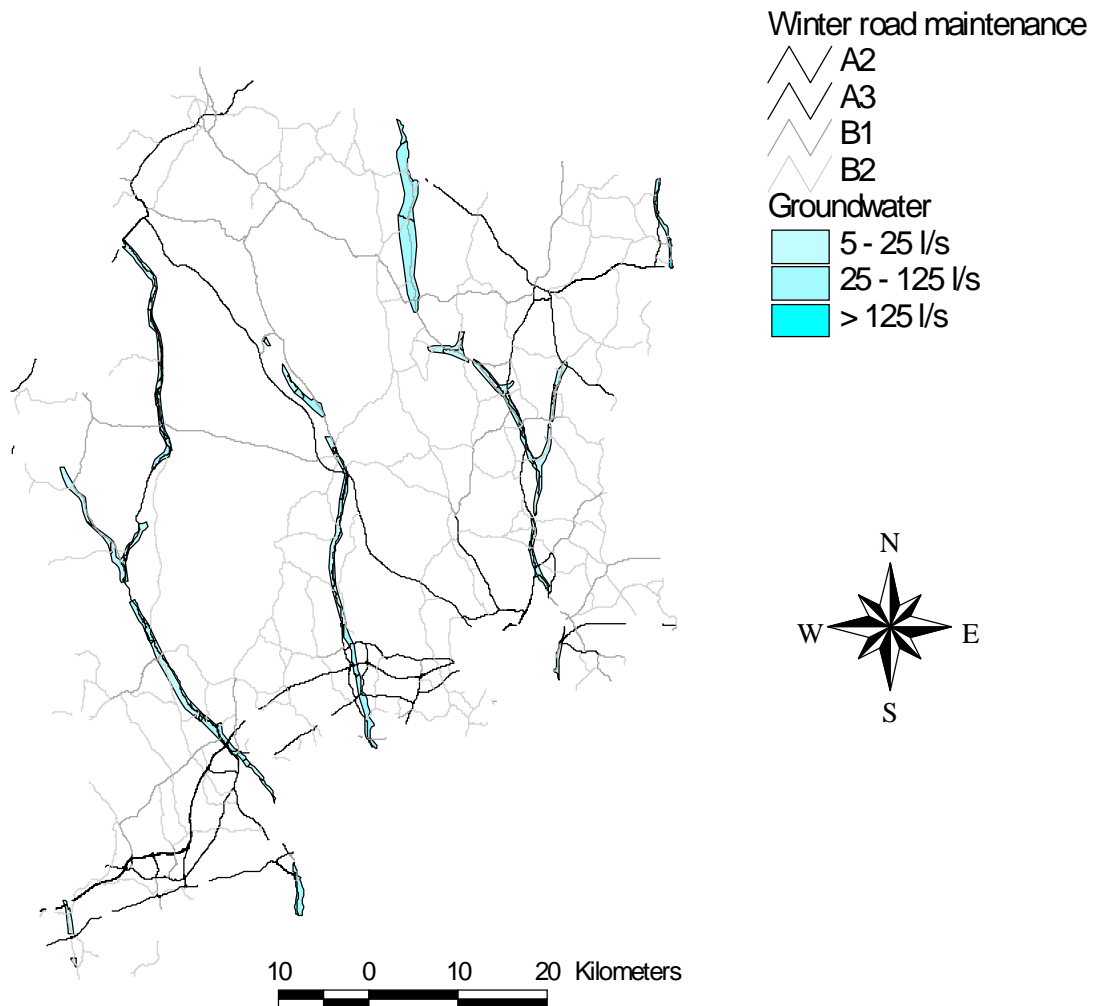


Figure 2. Intersections between major roads and major aquifers in Västmanland, Sweden.

A more general method is to apply the annual amount of deicing salt within the area and the annual net recharge to the catchment areas within the investigated area (Huling & Holocher 1972, Howard & Haynes 1993, Thunqvist 2000). In Sweden the National Swedish Meteorological and Hydrological Institute has estimated the catchment areas for the whole of Sweden and they are available in digital form. If it is assumed that deicing salt application has occurred sufficient time for steady-state conditions to be established, the average chloride concentration in the discharge will be the same as in the net recharge. During the first years of deicing salt application the chloride concentration in the recharge will be much higher than in the discharge. Hence, chloride will

accumulate in the storage and the concentration will increase. On conditions that the salt application is invariable the chloride concentration in discharge will eventually be the same as in recharge (steady state). The increase in concentration as a function of time is an exponential curve (Figure 3). The calculated chloride concentration from road salt is then added to the natural background deposition for the area.

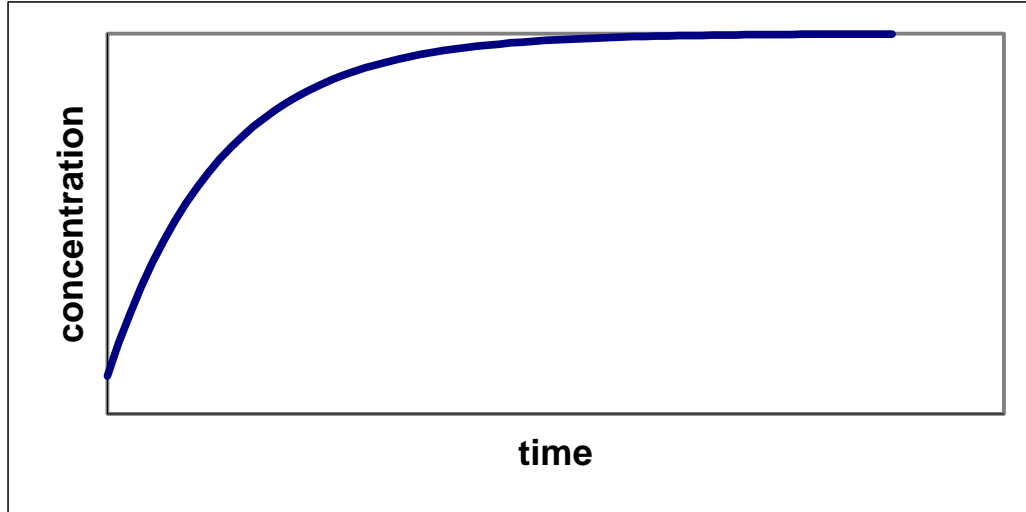


Figure 3. The exponential function for a complete-mix box model.

Methods and Materials

The average concentration in net recharge can be calculated as the annual average amount of chloride applied divided by annual net recharge for the area plus the natural background deposition.

$$[Cl]_{tot} = \frac{\frac{M_{Cl}}{M_{NaCl}} * m_{salt}}{(P - E)A} + [Cl]_{dep}$$

In order to make these calculations for a region the necessary digital data are:

- Maps showing the catchment area obtained from the Swedish Meteorological and Hydrological Institute (SMHI) or digital elevation data from which the catchment areas are obtained by the use of a Geographical Information System e.g. Arcview.
- Net recharge obtained from maps made by the Swedish Meteorological and Hydrological Institute.
- Natural deposition of chloride (considering the difference in deposition for different land use) in the area from the Swedish Environmental Protection Agency (SEPA 2000).
- National road network, the different road categories and the average amount of deicing salt applied for each category obtained from the National Swedish Road Administration.

All data are processed and presented with the GIS-tool Arcview.

Information on net recharge from SMHI is based on the annual average for the period 1961-1990. The natural background deposition values are calculated from deposition values 1985-1989 (SEPA 2000). Deicing salt application is based on annual average values for the period 1995-1999.

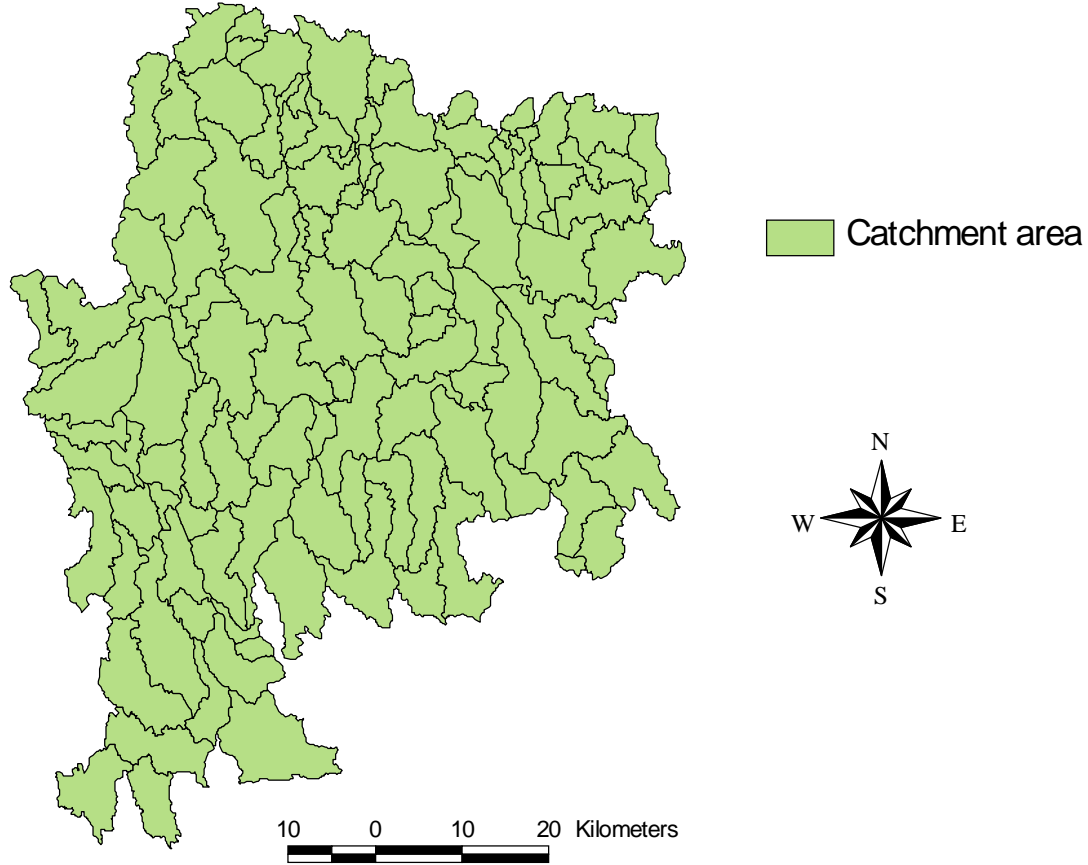


Figure 4. Catchment areas of Mälaren in the county of Västmanland

The calculations have been made for the Swedish county of Västmanland. In Figure 4 the catchment areas of Mälaren are shown with a mean sub catchment area of 34 km². The calculated chloride concentration is an average value for the recharge water in every sub catchment area. However, the chloride concentration in discharge water for a sub catchment area is a function of the concentration in recharge in the area and the concentration in water from areas upstream the basin [1].

$$[Cl]_i = \frac{\frac{M_{Cl}}{M_{NaCl}} \sum \left(\frac{m_{salt}}{(P-E)A} + [Cl_{dep}] \right) A_i}{\sum A_i} \quad [1]$$

Result

In Västmanland the annual net recharge varies between 200 and 300 mm, and the background deposition contributes to a chloride concentration of 2 mg/l in recharge water. In Figure 5 the average calculated chloride concentration in recharge is shown for all sub catchment areas of Mälaren within the county of Västmanland. The amount of deicing salt applied (in tonnes per kilometre and season) for the different road categories is 12 tonnes for A2, 11 tonnes for A3, 4 tonnes for B1 and 1 tonne for B2. There are no A1 or A4 roads within the county.

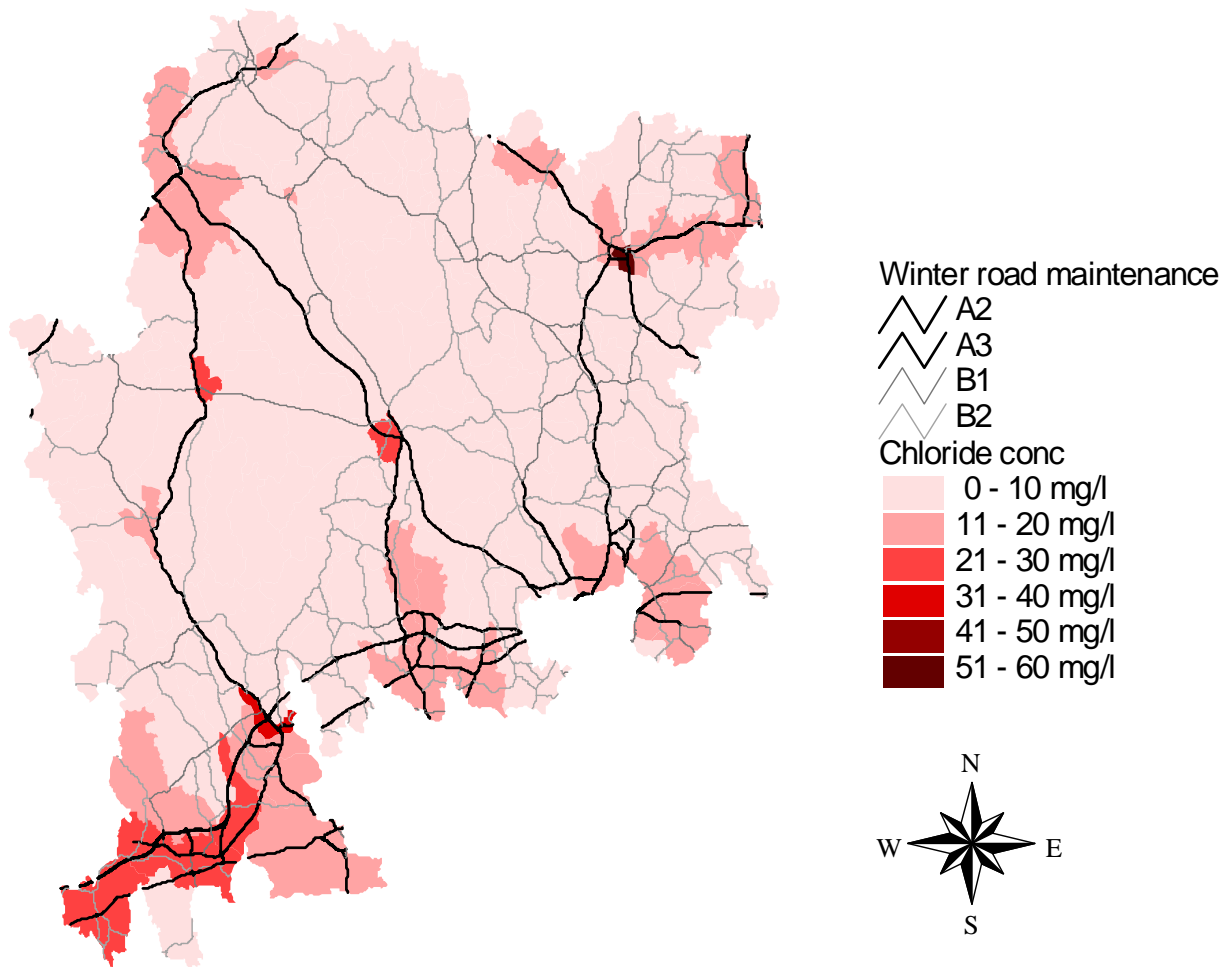


Figure 5. Average chloride concentration in recharge water in sub catchment areas in Västmanland, Sweden.

Discussion

The method shows the environmental effect of deicing salt application on a larger scale. The seasonal variations and the local spatial variations may influence the actual concentration. To calculate the average steady state concentrations is to simplify a complex event in order to estimate the effects.

Originally the calculations were county based. However, in order to calculate concentrations in a particular sub catchment area the calculation must begin at the watershed and hence, the calculations were change to be catchment area based. As mentioned above the calculated chloride concentration is an average value for the recharge water in every sub catchment area and the chloride concentration in discharge water for a sub catchment area is a function of the concentration in the recharge in the area and the concentration in water from areas upstream the basin. In reality the closest representation of this value would be the chloride concentration in a lake or in a large spring close to the outflow from the sub catchment area. As a part of the National Monitoring Programme, the SLU University in Uppsala investigates the status of some lakes every fifth year. In the three most recent investigations the chloride concentration has been measured. In order to evaluate the method, the calculated chloride

concentration in each sub catchment area was compared to the measured chloride concentrations in lakes close to the outflow from the respective sub catchment area. The calculated chloride concentration was consistent with the measured values.

Another possible way to appreciate the effects of deicing salt is to start with measured values and estimate the contribution from other sources. How large is the contribution from road salt compared to other sources of chloride (e.g. relict salt, saltwater intrusion, sewage, landfills, fertilisers etc). The presented method only considers deicing salt application and background concentration. Other sources may be of equal or larger importance locally. However, the greatest impact of deicing salt may be for areas where the chloride concentration already is increased due to other factors.

In order to estimate the chloride concentration with more precision it is necessary to consider the direction of the water flow. Upstream a road only fresh water will infiltrate or form runoff. Immediately downstream the road the chloride concentration in infiltrating water or surface water will be the highest. The location of the road within the catchment area will be of importance for the obtained chloride concentration. If the road is located further downstream the dilution effect will be much greater than if the road is located “higher up” in the system with only a small amount fresh water contribution.

The contamination will be quite high for small areas with many major roads. If the area is “higher up” in the system, the concentration in discharge water from the area will be high. If the area is closer to the outlet the dilution effect may reduce the concentration to lower levels.

When calculated chloride concentrations are compared with the measured concentrations especially in urban areas it is important to remember the differences in urban and rural environment. In the rural environment the road can be considered a line source. In the urban environment the use of deicing salt is more evenly distributed since not only the Swedish National Road Administration but also municipal and private property owners use salt for deicing purposes. Hence it is more accurate to consider the average application in g/mm^2 (Howard & Haynes 1993). Furthermore the amount of paved surfaces and the drainage water system in an urban environment will affect the water distribution within the catchment area.

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NON-EXHAUST PARTICLES IN THE ROAD ENVIRONMENT – A LITERATURE REVIEW

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1. Abstract

Non-exhaust particles in the road environment originate from wear of asphalt road pavement, mainly caused by the use of studded tyres, and corrosion of vehicle components such as tyres and brakes. Other sources are road maintenance, road equipment and particles originating in the road surroundings. This literature survey aims at giving an overview of the current knowledge about airborne particles from these different sources in the context of characteristics and emissions as well as health and environmental effects.

2. Introduction

Particles related to road traffic have over the last few decades become an important issue among scientists, the reason being the often-recurrent indications of relationships between airborne particles and effects on health and the environment. A recently published study shows that particles related to road traffic are responsible for about 3 % of the total mortality in France, Austria and Switzerland (Kunzli et al., 2000).

Due to their small size and their ability to adsorb toxic components in the exhaust gas, exhaust particles have been the main focus for research. In the road environment though, particles from several other sources occur. Particles generated through wear of vehicles and pavement, added through maintenance measures or transported to the road environment from the surroundings, make up a large fraction of road dust. All these particles accumulated on the road surface can be re-suspended by the action of passing vehicles (fig.1.).

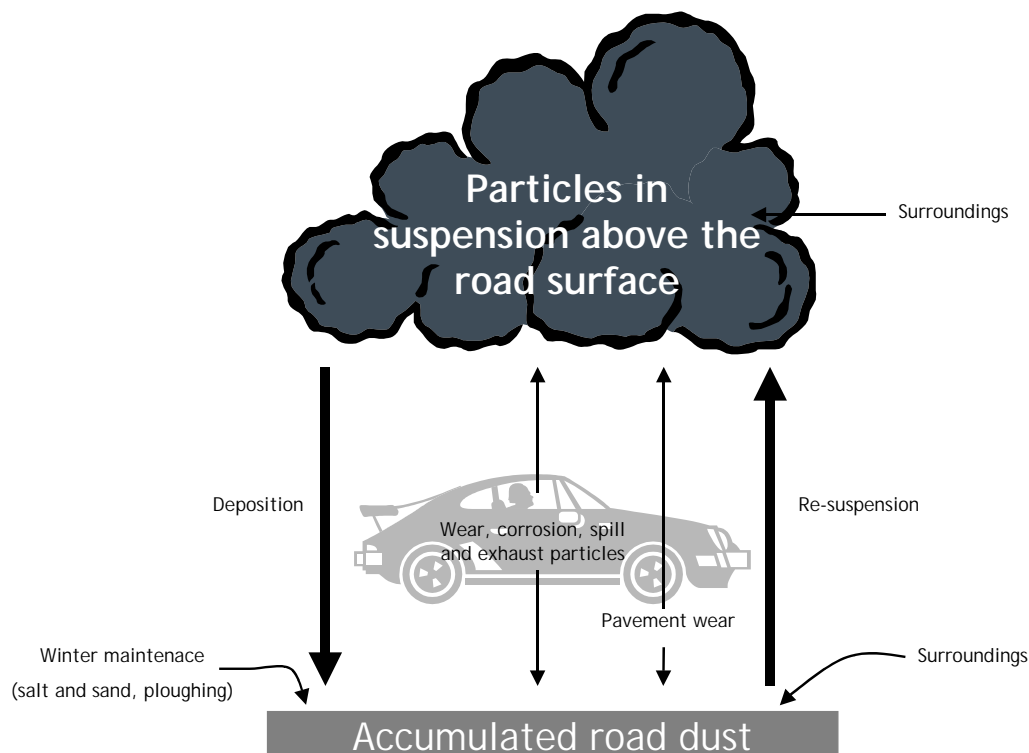


Figure 1. Schematic illustration of sources and fluxes of particles in the road environment.

The concentration of particles in the air is usually measured with respect to mass or number per volume of air. Mass distribution, chemistry and physical properties are also important aspects when describing the characteristics of particles. When the importance of particle size became apparent a standardised measure for inhalable particles was constructed called PM₁₀. Roughly, this is the fraction of particles smaller than 10 µm in diameter. This standard is commonly used throughout the world and also in the relatively few Swedish cities that measure particles on a regular basis. As interest has shifted towards even smaller particles, the standard has been supplemented with PM_{2.5}, to measure particles smaller than 2.5 µm.

This literature survey aims to summarise current knowledge of sources, emissions and health and environmental effects of non-exhaust particles in the road environment. These are generally larger than exhaust particles, but a significant fraction occur within PM₁₀ and also PM_{2.5}.

3. Particle sources

Wear particles in the road environment have mainly three sources; tyres, brakes and pavement, but also incorporate wear from other movable parts in vehicles. For Swedish conditions, pavement wear during the winter months, when studded tyres are used, is the main source of wear particles.

3.1 Tyres

Depending on quality demands and area of use, tyres consist of a variety of mixtures of rubber polymers. Latex, as well as synthetic rubber, such as e.g. isoprene rubber, is used to obtain the desired properties of elasticity, heat resistance and friction (Ahlbom and Duus, 1994). More latex is used in bus and truck tyres, due to higher friction demands. Rubber mixtures vary greatly between manufacturers and also between summer, winter and studded tyres, making it difficult to generalise the chemistry of tyre wear particles (Johansson, 2000).

Tyres also consist of a large number of chemicals added during manufacture. Reinforcing agents, vulcanisers, accelerators, activators, colour pigments, softeners, dispersing agents, anti-oxidants, anti-ozonants, stabilisers etc are used during production (Rogge et al., 1993). In literature, tyres are often mentioned as a main source of zinc in the road environment (Rogge et al., 1993). This is due to the relatively large amount of zinc oxide used as an activator to make the accelerators more efficient during manufacture.

Also, PAH (polycyclic aromatic hydrocarbons) occurs in relatively large amounts in tyres. Very different information on the concentration of substituted and non-substituted PAH in tyres is reported in literature. (Ahlbom and Duus, 1994) report 7000 µg g⁻¹, while in a Swedish survey, (Lindgren, 1998) has measured between 33 and 93 µg g⁻¹ in three ordinary tyres. Measured in wear particles, (Takada et al., 1991) reports 31-71 µg g⁻¹.

The size distribution of tyre wear particles is difficult to generalise. (Kobriger and Geinopolos, 1984) and (Noll et al., 1987) claims a mean diameter of 20-25 µm, while (Kumata et al., 1997) reports a bimodal distribution with peaks at 0,4-0,5 µm and 5-7 µm. These results imply that a considerable proportion of the wear particles are airborne and inhalable.

Studded tyres, commonly used in Sweden during winter, are made of the same types of rubber mixtures as other tyres. The studs were initially made of steel, but due to the large wear they caused to road pavements, they are nowadays made of light metals or plastic. The number of studs and the stud force have also been decreased (Jacobson and Hornvall, 1999a).

3.2 Brake linings

Similarly to tyres, brake linings are very heterogeneous in composition and manufacturer-dependent. The friction materials contain binders, fillers, fibres of glass, plastic, steel, organic or inorganic material or metals. Metals are also used as heat conductors (Rogge et al., 1993). Table X shows the metal content of the most common brake linings for cars making up approx. 60% of the Swedish car fleet (Westerlund, 1998).

An important feature of brake lining particles is their small size. Using a brake dynamometer (Garg et al., 2000) showed that 63% of the wear particles were smaller than 2.5 µm (PM_{2.5}), i.e. respirable.

3.3 Pavement

The most important wear associated with the use of studded tyres is pavement wear. This depends on the weight, number and composition of the studs, the flow, composition and speed of the traffic, climatic conditions, road geometry, pavement composition to mention a few factors. The percentage and quality of the stone material and the properties of the asphalt itself are of great importance. In Sweden, high quality pavements with a high percentage of very hard porphyry and quartzite (about 95% in the surface) have gradually replaced pavements with less resistant local rock material on the heavily trafficked roads (Jacobson and Hornvall, 1999b).

The high cost of maintenance related to pavement wear has caused many countries to prohibit the use of studded tyres. In Japan and Norway, regulations have also been based upon the health aspects of the road dust. In Japan studs are prohibited. Before the restrictions, the concentration of airborne dust could vary between $30 \mu\text{g m}^{-3}$ in summer and $400 \mu\text{g m}^{-3}$ in winter (Takishima et al., 1987). The current restrictions are questioned though, since the climate of Hokkaido involves very icy roads, which has affected the number of traffic accidents negatively (Norem, 1998). In Norway, the “Road grip project” (Krokeborg, 1997; Larssen and Haugsbakk, 1996) has so far resulted in stud restrictions in Oslo.

The particles formed through pavement wear reflect the asphalt composition. In Sweden about 95% is rock material and 5% bitumen. This oil product contains asphaltenes (5-25%), saturates (5-20%), cyclic compounds (45-60%) and resins (15-25%) (Gonzàles Arrojo, 2000). The PAH content is very small and not considered a main source of PAH in the road environment (Lindgren, 1998). The size of the pavement wear particles varies, but is generally regarded as being fairly large. According to (Bækken, 1993) only about 2% are smaller than $36 \mu\text{m}$. Japanese studies on the other hand state a size interval of about 5-50 μm (Amemiya et al., 1984). This particle size depends mainly upon the properties of the rock material in the pavement, so a large variation is to be expected between countries and regions.

3.4 Salt and sand

About 200,000 – 400,000 tons of de-icing salt was added to Swedish roads annually between 1991/92 and 1995/96. The salt is re-suspended as wet or dry aerosol by passing vehicles and can be transported hundreds of meters from the road. The effects of these salt droplets and particles have been described exhaustively in literature (Blomqvist, 1999), but information about their characteristics is unfortunately very rare.

3.5 The road as source for PM_{10} and $\text{PM}_{2.5}$

Many studies make no attempt to distinguish between particle sources, but concentrate on describing concentrations of the PM_{10} and/or $\text{PM}_{2.5}$ fractions.

In Norway, before the regulation of studded tyre use, (Larssen, 1987) measured PM_{10} concentration to $55 \mu\text{g m}^{-3}$ in dry conditions and $10 \mu\text{g m}^{-3}$ in wet and therefore concluded that road wear particles contributed $45 \mu\text{g m}^{-3}$ in dry conditions. In a later study, (Larssen and Haugsbakk, 1996) found that in dry conditions, the road dust depot does not grow due to a balance between produced and re-suspended particles. The contribution of road dust to mean annual PM_{10} and $\text{PM}_{2.5}$ concentrations in Norwegian cities has been shown to be high along roads and streets. The contribution to highest mean diurnal concentration is significant both in city centres and along roads and streets (tab. X) (Larssen and Hagen, 1997).

Results from countries where studded tyres are not allowed shows that in spite of this, road dust often contributes a substantial proportion of PM_{10} or $\text{PM}_{2.5}$. (Schauer and Cass, 2000) determined the concentration of road pavement dust to 0.5-1 g m^{-3} during severe air pollution episodes in California, USA. Also in the USA, (Noll et al., 1987) found that tyre rubber particles made up approximately 35%, limestone 54% and silicates 10%, both important road building materials, of road dust collected in business districts in Argonne and Chicago. (Chow et al., 1996) estimated that the road dust contributed to 25-27% of urban PM_{10} concentrations as compared to a 30-42% contribution from exhaust particles.

4. Emissions

4.1 Non-exhaust Particles

Emission factors for tyres in literature range from 0.006 to 0.36 g km⁻¹. Using a road simulator (Rogge et al., 1993) estimated the wear to 0.006-0.09 g km⁻¹ and tyre. Swedish investigations in co-operation with the police authorities, a local traffic company and tyre manufacturers calculated the emissions to 0.09 g km⁻¹ for a car and 1.0 g km⁻¹ for a bus (Table 1) (Lindström and Rossipal, 1987).

Table 1. Emissions from tyres (*Lindström and Rossipal, 1987*).

Component	Car	Bus
	<i>g km⁻¹</i>	<i>g pbkm⁻¹</i>
Rubber	0,05	0,7
Carbon black	0,03	0,3
Process chemicals, Activators, Accelerators	0,011	0,1
Sulphur	0,002	0,02
Total	0,09	1,0

Total emissions from tyres in Sweden has been calculated by (Ahlbom and Duus, 1994), see Table X). These figures has been criticised by STRO (Scandinavian Tyre and Rim Organisation) who claim that the calculations do not account for tyre tread and therefore overestimates the emissions (Johansson, 2000). (Ahlbom and Duus, 1994) also calculated the PAH emissions connected to tyre wear and concluded that these, 28 µg km⁻¹, are about six times as high as the contribution from exhaust from a car with a catalytic converter, 5 µg km⁻¹. For Sweden the total amount is 14 tonnes PAH per year. STRO on the other hand, have calculated the emissions to 284-470 kg y⁻¹.

Table 2. Emissions from tyres (Ahlbom and Duus, 1994)

Component	Total annual emissions in Sweden (tonnes)
Polymeres	5 000
Black carbon	2 500
Oil	2 000
Zinc oxide	150
Stearin acid	70
Sulphur	100
Accelerators	50
Anti oxidants	100
Other	30
Totalt	10 000

In a recently published brake dynamometer investigation (Garg et al., 2000), brake lining emissions were calculated to 3.2-8.8 mg km⁻¹. Early work by (Cha et al., 1984) supports these figures. (Westerlund, 1998) estimated the contribution from brake lining wear to metals in the Stockholm environment and found that about 3,900 kg of copper, 900 kg of zinc, 560 kg of lead as well as a few kg of chromium and nickel were added each year from cars, buses and trucks. About 80% of the brake lining wear could be attributed to cars.

Emissions of airborne, inhalable particles from pavements are difficult to handle from literature. The pavement source contribution is often hidden in terms like “road dust”. Even in Norway, where great efforts are made to measure PM₁₀ concentrations in i.e. Oslo, the contributions from long range

transport and local wood burning disturbs the possibilities to calculate pavement emissions (Larssen, 2000). The pavement wear caused by studded tyres has in Sweden decreased from about 30 g vkm⁻¹ in the 80ies to about 10 g vkm⁻¹ today. This sums up to about 110 000 tonnes each year.

4.2 Exhaust Particles

The main particle emissions related to vehicle exhaust come from diesel engines. As the attention paid to the health effects of these particles has increased, the development of cleaner diesel engines has accelerated. (Lenner and Karlsson, 1998) compiled particle emission figures from 19 different sources to be used in a quantitative model (Table 3). The figures presented here might therefore be somewhat out of date due to engine development.

Table 3. Emissions of exhaust particles (mg km⁻¹) (Lenner and Karlsson, 1998). W cat. = without catalytic converter (figures in brackets are standard deviations).

<i>Car</i>				<i>Heavy truck</i>		
W cat.	Cat.	New cat.	Diesel	< 16 t	> 16 t	Bus
16 (2)	2,4 (0,5)	1,4 (0,3)	279 (56)	630 (227)	1080 (430)	830 (274)

5. Health and Environmental Effects

A very extensive literature deals with the relationships between airborne particle concentrations and public health. This study mainly concentrates on literature that discusses the coarser fraction of inhalable particles (> 2.5 µm), but some information about smaller fractions has been included for comparison. Of special importance for human health is the inhalable fraction. Both their ability to enter more or less deep into the respiratory system and their ability to adsorb toxic substances, such as PAH and heavy metals, to their surface make them highly interesting to health scientists.

During the late 1990s, American studies have shown that latex particles from tyre wear contain allergens which might be coupled to an increased risk of latex allergy and asthma (Miguel et al., 1996; Williams et al., 1995). The studies have their background in the increasing over-sensitivity to latex in society, the causes of which are not yet clear. (Williams et al., 1995) found that 53% of the latex particles found in Denver air were inhalable and that their mean size was 6-7 µm. Chemical analyses suggested the particles originate from tyre wear. (Glovsky et al., 1997; Miguel et al., 1996) extracted latex allergens from tyre wear particles in Los Angeles and suggested the particles were a potentially important factor for latex allergy and asthmatic symptoms associated to air pollution.

The health effects of particles related to the use of studded tyres have mainly been studied in Japan. As early as the mid-1980s, (Morikawa, 1985) related the road dust concentrations to respiratory symptoms among asthmatic children and (Ikeda et al., 1986) to the frequency of upper respiratory symptoms. (Watanabe et al., 1990) studied the concentration of elements in the lungs of feral pigeons and found significantly higher concentrations of Si, Al, Pb and Ti in pigeons living in cities where studded tyres were used.

Many highly resistant Swedish pavements are based upon rocks containing high concentrations of quartz (mainly quartzite and porphyry). Quartz dust is well known to induce silicosis among for example miners, and quartz is regarded as one of the most toxic minerals. In Norway, ongoing research on PM₁₀ particles from road tunnels shows that particles containing the minerals quartz, amphibole, chlorite and epidote induced a much higher production of interleukin-6 and -8 in human lung epithel than did particles containing plagioclase (Hetland et al., 2000). (Murphy et al., 1998) compared particles of crystalline quartz, amorphous quartz, from diesel exhaust and black carbon and their impact on rats' lungs. Somewhat surprisingly, he found more damages from crystalline quartz and amorphous quartz no effects from diesel or black carbon particles. This should imply a surface structure or chemical effect. As opposed to this, many studies rather imply a particle size effect, i.e. the chemistry or structure is not important (Camner, 2000).

Epidemiological studies relate inhalable particle concentrations to mortality, morbidity, lung cancer, asthma, respiratory symptoms and coughs, usually in urban areas and to a greater extent among sensitive populations such as children, asthmatics and elderly people. Extensive compilations of current knowledge has been made by e.g. (Vedal, 1997) and (Areskoug, 2000).

Commonly, literature implies that fine and ultra-fine particles ($< 1 \mu\text{m}$) show stronger relationships to health effects than do coarser fractions. The increase in mortality is generally 0.5-1.0% per $10 \mu\text{g m}^{-3}$ increase in PM_{10} concentration. Hospital admissions due to short term exposure increases by 0.5-3.0%, which confirms a relationship to particle concentration. The relationship is often stronger for symptoms in the lower respiratory tract than in the upper and also stronger for elderly people but also for children (Areskoug, 2000).

Despite the fact that most studies stress the importance of the fine fractions, quite a large number of exceptions exist. (Pekkanen et al., 1997) found that ultra-fine particles were not more strongly related to variations in peak expiratory flow rate (PEFR) than were PM_{10} or black smoke particles. A study made in Cochella valley in USA where coarse particles with a geologic origin contribute to a very large fraction of PM_{10} show that PM_{10} was significantly associated to all used measures of mortality (Ostro et al., 1999). On the other hand, (Schwartz et al., 1999) saw no such signs in a similar study. In Mexico City, (Castillejos et al., 2000) found that $\text{PM}_{10-2.5}$ had a stronger effect on mortality (4.07% associated with a $10 \mu\text{g m}^{-3}$ concentration increase) than PM_{10} (1.83%) and $\text{PM}_{2.5}$ (1.48%). A probable explanation might be the presence of biogenetic material in the $\text{PM}_{10-2.5}$ fraction.

Except for the health effects, non-exhaust particles affect public comfort by dirtying cars, sidewalks, house fronts, windows and even insides of houses.

Literature on the environmental effects of road dust particles as such is scarce. Most of it deals with the road as a source of pollution for the roadside environment (Bækken, 1993; Bækken and Jørgensen, 1994; Bjelkås and Lindmark, 1994; Gjessing et al., 1984; Kobriger and Geinopolos, 1984; Lygren and Gjessing, 1984; Sansalone et al., 1995). Particles from pavement wear contribute to the structure and composition of the roadside soils. The accumulation of material might amount to as much as 1.5 cm y^{-1} . Roadside soils diverge strongly from adjacent soils both regarding size distribution and chemical properties. High pH, high content of base cat-ions and heavy metals are characteristic features of these soils (Bækken, 1993).

Some studies concern the effects of particles on vegetation. Particles on the surface of leaves and needles have been shown to cause stress and therefore reduced growth due to increased temperature, blocked stomata and the hygroscopic properties of some particles (Farmer, 1993; Flückiger et al., 1978). Effects on limnic systems include high, and sometimes toxic, concentrations of PAH and heavy metals in lake sediments (Bækken and Jørgensen, 1994), but also first flush effects, where the particle depot accumulated on a road causes high concentrations of toxic compounds in streams during rainfall.

De-icing salt, which can be transported to the roadside environment as an aerosol or as dry dust, also affects vegetation negatively, which is a very visible problem in Sweden as Norway spruce and Scots pine along salted roads often turn brownish in spring due to the salt (Blomqvist, 2001). Salt deposited on leaves and needles causes osmotic stress causing dessication. The salt has also been shown to accumulate in ground water reservoirs with a hydrologic connection to road environments (Thunqvist, 2000).

6. Discussion

The sources for non-exhaust particles, judging from this literature survey, are many and their interplay complicated. Information about emissions and characteristics of more diffuse sources, like corrosion and biogenic material deposited on the road, has not been found in literature.

A critical report on tyre wear in Sweden (Ahlbom and Duus, 1994) has caused a debate, where the STRO claim the report to be incorrect and exaggerated in many respects. Nevertheless the debate has led many tyre manufactures to develop winter tyres without HA-oils, which is used as an argument in commercials. In summer tyres, the HA oils are more difficult to omit, since they are responsible for a large part of the grip properties (Johansson, 2000). Very varying information is reported about the properties of tyre particles. Both small quantities of inhalable particles as well as rather large proportions of respirable particles are reported, which might be a result of the large variation in materials, wear conditions and measurement methods.

Studded tyres and the related pavement wear are the particle source most thoroughly investigated in conditions similar to those in Sweden. In our neighbouring country, Norway, studded tyres have

been the subject of much debate and major research for two decades. The focus has been on health effects, and an economic investigation during the “Veggreppsprosjektet” (Road grip project) showed that restrictions in the four largest cities in Norway were profitable to society (Krokeborg, 1997). So far, only Oslo has introduced the restrictions since 1999. Studded tyre use is now about 30% as compared to 70% before the restrictions. Due to large variations in seasonal weather it is too early yet to determine any effect on PM₁₀ concentrations (Hagen and Haugsbakk, 2000).

There are a few studies on brake linings and their contribution to pollution. Most of these show that particulate heavy metals are the main cause of concern. An important aspect from a health point of view is that brake lining particles are very small and therefore potentially more dangerous to health.

For Swedish conditions the three most important emission sources for non-exhaust particles are, in order of magnitude, pavement wear (about 110,000 tonnes), tyre wear (about 10,000 tonnes) and brake lining wear (about 1,000 tonnes). The total amount of these particles emitted during a year is in the same order of magnitude as that of exhaust particles, but seasonal effects of climate, local sources, maintenance actions etc make the emissions very uneven both temporally and spatially.

Health surveys dealing with particle effects are common and usually based upon measurement of PM₁₀ and/or PM_{2.5}, which are measures produced for this specific purpose. The results of these studies show a rather scattered picture of how PM relates to toxicological or epidemiological effects. There is a consensus that particle size matters and that there is a specific particle effect, but what this effect really involves is still not clear. A part of the problem definitely lies in the PM methodology. PM₁₀ or PM_{2.5} says nothing about size distribution below 10 or 2.5 µm and nothing about chemical or physical properties, i.e. surface area, of the particles. According to (Camner, 2000), there is a gap between toxicology and epidemiology, since the effects shown in epidemiological studies, with effects on populations at rather low PM concentrations can not be verified in toxicological experiments where it takes much higher concentrations to cause the same medical symptoms. Regarding environmental effects of particles, these are seldom related to particles as such, but rather to pollution from PAH or heavy metals.

7. Conclusions and research needs

The international literature on non-exhaust particles and their effects is quite extensive. The information about particle emissions and particle characteristics displays a very large variation though, depending on investigation quality, methods and extent as well as geographical variations. The material is often based on short-term measurements seldom valid for other geographic locations or during other time intervals. For Swedish conditions, the following approximations might be considered:

Wear

Total in Sweden

- Pavement 110 000 t y⁻¹
- Tyre 10 000 t y⁻¹
- Brake linings 1 000 t y⁻¹

Emissions

- Pavement wear from studded tyre use <10 g km⁻¹
- Tyre car 0,006 - 0,36 g km⁻¹
truck, bus approx. 1 g km⁻¹
- Brake lining wear 0,0032 - 0.0088 g km⁻¹
- Re-suspension 0,13 - 6 g km⁻¹
- Exhaust car with catalytic converter 0.0014 - 0.0024 g km⁻¹
car (diesel) 0,279 g km⁻¹
heavy truck (>16 tonnes, diesel) 1,08 g km⁻¹

Health effects

Toxicological aspects

- Tyres allergy and asthma from latex particles?
relatively high PAH content
relatively large percentage of PM₁₀
- Pavement wear important source for PM₁₀ in the road environment
mineral composition and surface properties?
- Brake lining wear large percentage of PM₁₀
especially important in cities?

Epidemiological aspects

- Few other measures than PM₁₀ and PM_{2.5} are studied
- Wear particles mainly in the coarse fraction PM_{10-2.5}
- Many studies show a higher correlation of health effects to PM_{2.5} but there are also studies indicating higher correlation to PM_{10-2.5}
- Not only a particle effect. Chemistry and surface properties probably also important.

To be able to thoroughly investigate the relations between non-exhaust, as well as exhaust, particles and health- and environmental effects it is essential to complete PM measurements with measurements giving more information on chemical characteristics, particle size distribution and maybe also surface characteristics. Characterisation should be made on source specific particles to be able to make reliable source apportionments in field measurements as well as risk assessments. More field data covering a greater temporal and spatial variation are needed to improve knowledge about variations in particle concentration, composition and characteristics.

At VTI (National Swedish Road and Transport Research Institute) efforts to characterise particles from pavement and tyre wear using the VTI road simulator are being made. The road simulator offers the possibility to study “pure” wear particles since it is situated inside a building. Ongoing projects deal with emission factors for inhalable wear and re-suspension particles to be used in emission models and an inventory of road cleaning methods effective for particle removal. Future particle research efforts at VTI are planned to include spatial and temporal variations and model validation studies in the field.

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WINTER INDEX BY USING RWIS AND MESAN

an Operational Mesoscale Analysis System

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1. Abstract

In today's road administrations it is very important to keep track of costs and the amount of chemicals and abrasives used in winter road maintenance. Variations in snow and ice conditions from year to year make it difficult to compare figures. In order to tackle this problem, the Swedish National Road Administration (SNRA) has developed a new Winter Index.

The Winter Index is based on data from our 680 Road Weather Information System (RWIS) stations as well as data provided by the Swedish Meteorological and Hydrological Institute (SMHI). Basically, we use the former for information on the air and road surface temperatures, humidity, wind and type of precipitation and SMHI data for the amount of precipitation. The RWIS data is collected every half-hour and the SMHI data every third hour. To calculate the amount of precipitation, SMHI uses a model called Mesan, which is an operational Mesoscale Analysis System. This model subdivides Sweden into a 22 by 22 kilometre grid net, and calculations are performed for each grid individually.

The system provides data on slippery roads, snowfall and snowdrifts expressed in number of occasions; e.g., two icy road surface occasions will be registered if it is known that a skid control measure will be effective for 5 hours, and the RWIS data shows that there still is a risk of slippery roads after 6 hours. The same principle applies to snowfalls and snowdrifts. The system can detect four kinds of slippery surfaces ranging from light frost to freezing rain, and three kinds of snowfall and snowdrift, from light to heavy.

The amount of material used and the cost involved is entered in the final step of the calculation. This provides a good basis for comparing salt consumption from year to year. When calculating the Salt Index in this model, the length of road treated with salt, type of road (standard class) and our "Guidelines for Salt" are used. A Salt Index of 1.0 indicates that the contractor (or county, regional, or national road manager) has used the optimum salt dosage.

The system is also a good tool for benchmarking costs.

2. Background

When following up winter road maintenance, an important parameter for being able to compare costs and material consumption is knowing what the winter was like compared to other winters. Formerly, salt consumption was recorded in terms of tonnes per kilometre, and costs in terms of SEK per kilometre. Needless to say, figures varied from winter to winter, but it was difficult to determine exactly why. Previously, we used SMHI weather statistics in Sweden, but these statistics are based on atmospheric measurements, and as such are not directly connected to road climatology. Typical parameters obtained through this type of follow-up are days of snowfall and days of predicted hoar frost formation.

The SNRA owns 681 RWIS stations located throughout the country. An original idea was to use the data that has been stored in these stations



over the years. There would have been two advantages to this: firstly, since RWIS data is used by contractors as a trigger factor for initiating action, road maintenance measures and follow-up parameters coincide well. Further, no additional cost is involved since this data is the property of the SNRA.

However, what we want at the SNRA are parameters that reflect the predicted number of times when snow ploughing or skid control action is needed. We have therefore chosen follow-up parameters to show this. The new Winter Index can be used both for cost and salt consumption follow-up, and as a payment basis for contracted winter road maintenance. The procedure for paying contractors is described in paper no. 22 under topic #1, which also gives a more detailed description of how the Winter Index is calculated.

3. Bases and theories behind the Winter Index

As mentioned earlier, we want an index that reflects reality, i.e., one that is related to the measures actually carried out. Hence, every weather situation that would entail winter maintenance action has been divided into time periods. The weather situations studied are snowdrifts, snowfall and the risk of slippery road surfaces (hoar frost formation). This is done in hierarchical order. In other words, the system first searches for snowdrifts. In the absence of such, it searches for occasions of snowfall. If neither of these situations is found, the system then searches for occasions of slippery road surface conditions.

Snowdrifts are divided into four categories (d = snow depth in cm)

$$0.0 \leq d \leq 0.3$$

$$0.3 < d \leq 1.0$$

$$1.0 < d \leq 2.5$$

$$2.5 < d.$$

Further, the duration of a measure is calculated as 4 hours; i.e., if a snowdrift lasts between 0.5 and 4 hours, it is counted as one occasion, and as two if it lasts between 4 and 8 hours, as three if it lasts between 8 and 12, etc.

Snowfall is divided into three categories (d = snow depth in cm)

$$0.3 < d \leq 1.0$$

$$1.0 < d \leq 2.5$$

$$2.5 < d.$$

Four hours is the presumed duration of a measure here as well, and the calculation procedure for the number of occasions is the same as for snowdrifts.

There are four different categories of slippery surface.

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

Slippery surface due to damp/wet roads freezing over (HT).

Slippery surface due to light frost (HR1).

Slippery surface due to heavy frost (HR2).

A measure is presumed to last between 3 and 6 hours, depending on the category of slipperiness and the time of year.

4. Calculating occasions of snowfall conditions

Snowfall is divided into 4-hour periods. The reason behind this is that our winter road maintenance specifications stipulate different action completion times for different types of road (standard classes), and 4 hours was considered to be a suitable average. The division into different snow depth categories also complies with the specifications.

To exemplify this, class $0.3 < d \leq 1.0$ signifies a snowfall where it is expected that it will only be necessary to use salt to melt the snow, whereas class $2.5 < d$ signifies snowploughing on the low volume traffic network.

5. Calculating occasions of slippery road conditions

Occasions of slippery surface conditions are those where RWIS data would theoretically mean hoar frost formation. This means that the figures are directly related to road climatology and not atmospheric measurements, which is the usual way of measuring.

6. Weather presentation

Weather situations can be presented in tables or as graphs at a resolution that shows either the entire country, each winter maintenance region or each production and maintenance district. The following graphs are examples of weather situations in Sweden during the winters between 1996/97 and 2000/2001.

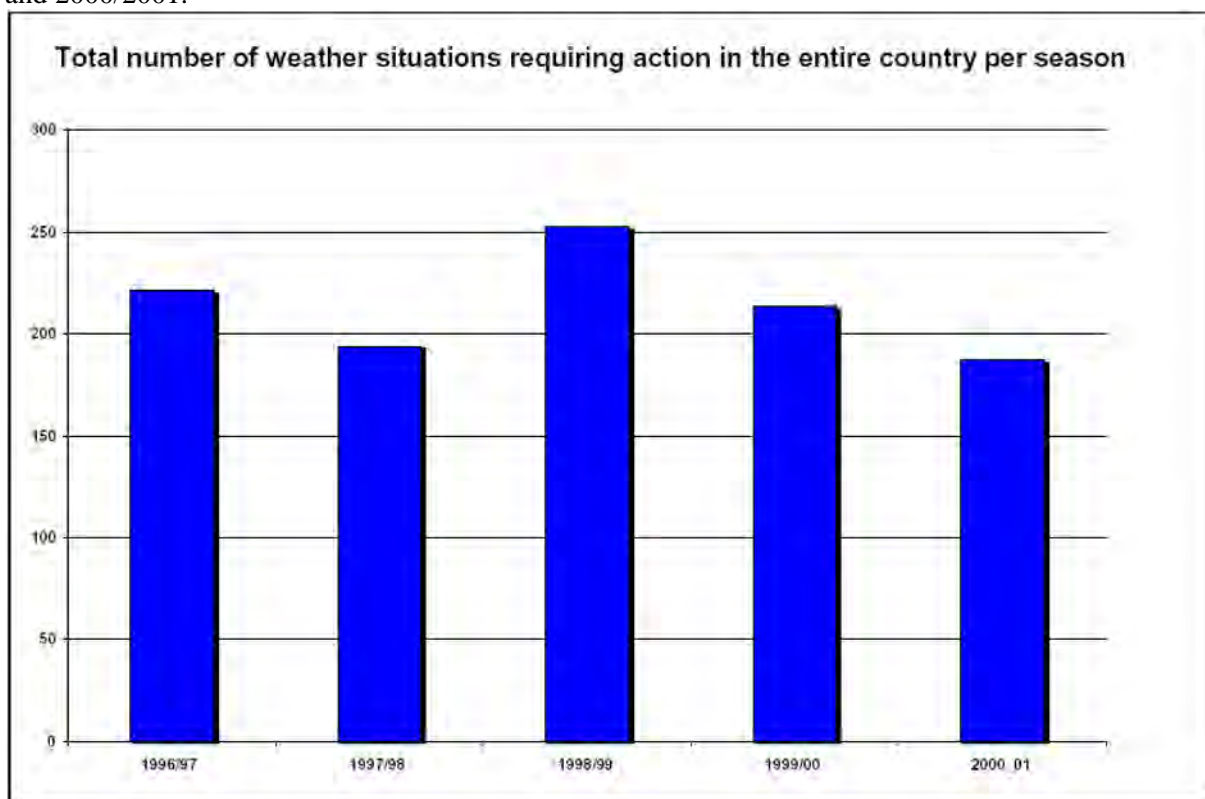


Diagram 1, Total number of weather situations requiring action in the entire country per season

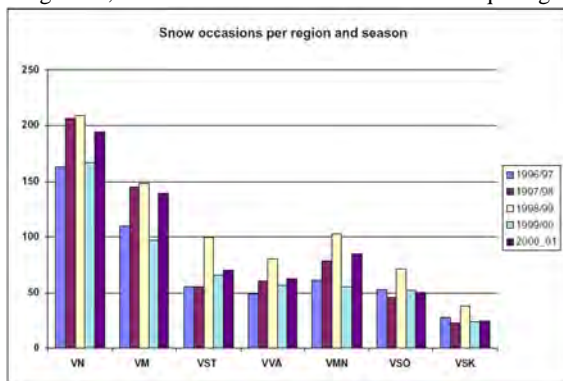


Diagram 2, Snow occasions per region and season

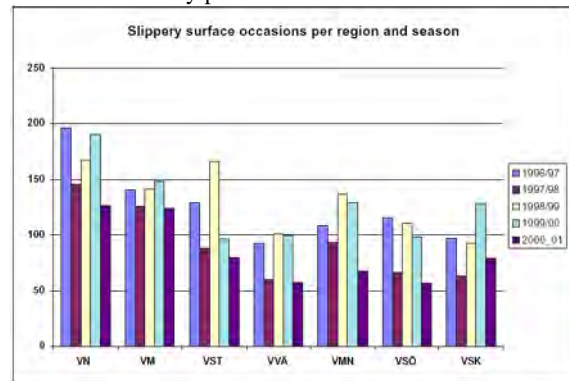


Diagram 3, Slippery surface occasions per region and season

7. Presentation of the salt index

The salt index is calculated on the basis of the weather data above, taking into consideration the length of the road network treated with salt and the recommended salt dosage for different weather conditions. The salt dosage values used in the calculation model are based on the SNRA's Guidelines for De-Icing, which is an official document that describes different salting methods and dosages based on different conditions. For instance, a salt solution shall be used in connection with light frost (HR1). During other weather situations, pre-wetted salt is permitted. The table below shows the recommended salt dosage in grams per metre 2-lane road for different weather situations.

Type of slipperiness				Snowfall amount of snow (cm)		
HR1	HR2	HT	HN	SNOW1 0.31-1.00	SNOW2 1.01-2.50	SNOW3 2.51-
24	36	48	60	36	90	120

Table 1. Recommended salt dosage in grams per metre 2-lane road during different weather situations.

Based on this, the salt index is calculated as follows:

⇒ salt consumption during the period for the area in question.

⇒ km of road treated with salt. For motorways and 4-lane roads, both directions are counted.

⇒ number of HR1, HR2, HT, HN, snowfall and snowdrift occasions as per the following table for the area in question.

$$\text{Salt index} = \left(\frac{\left(\frac{\sum \text{Salt consumption, kg}}{\sum \text{Length of road salted, km}} \right)}{(\text{HR1} * 24) + (\text{HR2} * 36) + (\text{HT} * 48) + (\text{HN} * 60) + (\text{SNOW1} * 36) + (\text{SNOW2} * 90) + (\text{SNOW3} * 120)} \right)$$

The salt index can be presented in tables or as graphs at a resolution that shows either the entire country, each winter maintenance region or each production and maintenance district. The following graphs are examples of weather situations in Sweden during the winters between 1996/97 and 2000/2001.

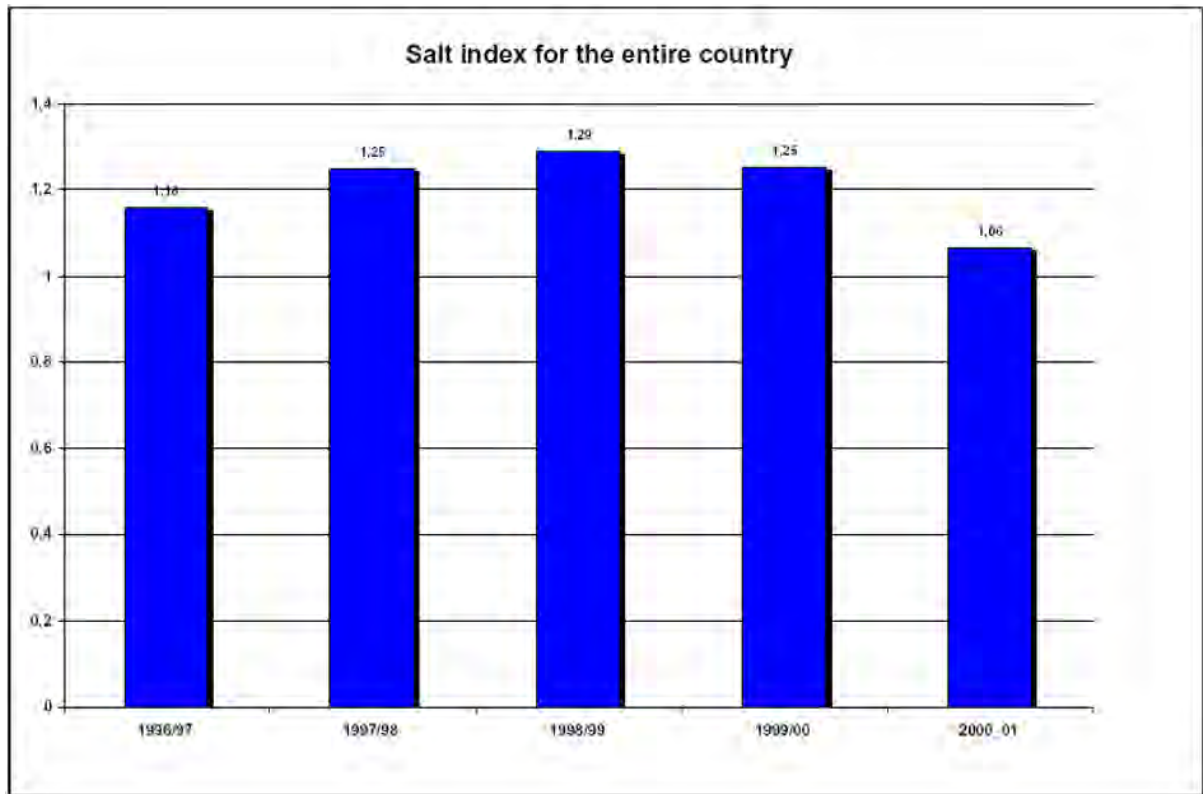


Diagram 4. Salt index for the entire country

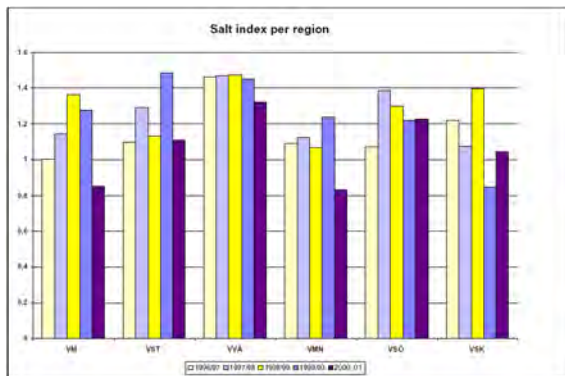


Diagram 5. Salt index per region

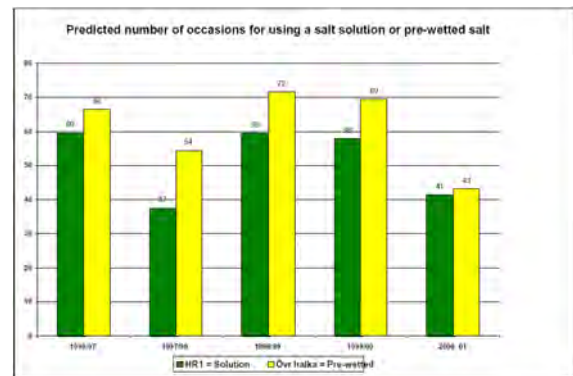


Diagram 6. Predicted number of occasions for using a salt solution or pre-wetted salt

Diagram 6 is intended to show that it probably is also possible to follow up how the contractor has complied with the recommendations concerning the use of different methods for different conditions. Since more and more skid control vehicles are being equipped with GPS, which also records salt dosage and method, this follow-up can probably be done automatically in the future.

8. The future

In preparation for the coming winter, 2001 – 2002, further testing will be done to determine if we have used the right parameters in our evaluation. There is a some uncertainty concerning the figures in the SNRA's Guidelines for De-Icing.

Moreover, we will be developing a similar system to follow up costs for winter road maintenance. At present, 100% of winter road maintenance is contracted in open competition, and the SNRA does not have any ploughs or skid control equipment of its own. This would appear to make it even more important today to follow economic trends.

Considering today's demands on environmentally sound and rational road management, it is essential to have follow-up tools that indicate whether or not we are making improvement. This is important for ecologically sound development (it is not only in Sweden that the use of salt on roads has come into question) as well as to show our principal – the Ministry of Industry Employment and Communication – as well as road users that we are taking these matters seriously.