WINTER MAINTENANCE AND CYCLEWAYS

A PhD thesis in English

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Abstract

Increasing cycling as a means of personal travel could generate environmental benefits if associated with a corresponding decrease in car-based transport. In seeking to promote cycling in wintertime, it is desirable to understand how important the road surface condition is compared to other factors in people’s decision to cycle or not. In this thesis, the possibility of increasing the number of cyclists by improving the winter maintenance service level on cycleways is examined. The attitudes towards cycling during winter in general, and in relation to winter maintenance of cycleways in particular, is studied through questionnaire surveys. Bicycle measurements are related to weather data from Road Weather Information System, in order to know the influence on cycle flow during winter from different weather factors. Field studies are performed testing unconventional winter maintenance methods, in order to see if a higher service level could be achieved on cycleways and if that would lead to an increase in winter cycling frequency. The field studies are evaluated through road condition observations, measurements of friction, bicycle counts, a questionnaire survey and interviews. A visual method to assess winter road conditions on cycleways is developed, in order to compare the service levels achieved using different winter maintenance methods.

There is a clear difference in mode choice between seasons. With improved winter maintenance service level it could be possible to increase the number of bicycle trips to work during winter with, at the most, 18 %, and decrease the number of car trips with 6 %. However, it could not be concluded with bicycle measurements, that an enhanced service level in fact, generated a higher winter cycling frequency.

To increase cycling during winter, snow clearance is the most important maintenance measure. Skid control is not as significant for the choice of mode but is important to attend to for safety reasons. Winter road condition properties important both with regard to safety and accessibility of cyclists, are icy tracks formed when wet snow freezes, snow depths greater than about 3 cm of loose snow or slush, unevenness in a snow covered surface, loose grit on a bare surface.

Weather factors with negative influence on winter cycling frequency, are temperatures below +5 °C, precipitation and strong winds. Only the occurrence of precipitation, not the amount of rain or snow, is significant for the cycle flow. Low temperatures are more important in reducing the cycle flow than precipitation. Temperatures around 0 °C seem to be extra critical for cyclists, probably due to the larger influence of precipitation and slippery road conditions at these temperatures.

An unconventional method using a power broom for snow clearance and brine or pre-wetted salt for de-icing, provides a higher service level than winter maintenance methods traditionally used, but it is about 2 to 3 times more expensive. The method has great potential in regions, such as southern Sweden, with low snow accumulations but with major ice formation problems. To assess the maintenance service level, the visual assessment method developed and tested in this project is adequate for the purpose, however, further improvements are desirable. As a complement to the visual assessment, a Portable Friction Tester can be used to measure the surface friction on cycleways during wintertime.

Keywords: Cycleways, winter maintenance, maintenance service level, mode choice, winter cycling frequency, winter maintenance equipment, winter road condition assessment, bicycle measurements, friction measurement.
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Preface

This thesis is the final result of almost five years of PhD studies at the Department of Civil and Architectural Engineering, Division of Highway Engineering, at the Royal Institute of Technology (KTH) in Sweden. However, most of the practical work has been performed at the Department of Infrastructure Maintenance at the Swedish National Road and Transport Research Institute (VTI). The PhD project “CDU:R15 – Effects on cycling of road maintenance and operation” (VTI project No. 80265), has been financially supported by the Swedish National Road Administration (SNRA) through the Centre for Research and Education in Operation and Maintenance of Infrastructure (CDU).

A combined steering and reference committee was formed for the project, with Hans Cedermark from CDU as chairman, and Per Wramborg as the SNRA representative. Professor Rolf Magnusson from KTH (now at Dalarna University) was the principal supervisor of the project during the first 3,5 years. Later, Professor Ulf Isacsson at KTH was appointed principal supervisor. Mats Wiklund and Gudrun Öberg were assigned to be the assistant supervisors at VTI. To further supervise the project, the following members, representing different fields of knowledge, were also included in the reference committee: Kenneth Elehed from the municipality of Linköping, Sven Ekman from the municipality of Uppsala, David Eldrot, from the municipality of Gävle, Sonja Forward from VTI, and, for the first year of the project, Björn Malmström from “Cykelfrämjandet”. Meetings with the steering and reference committee were held about twice a year throughout the project.

The composition of the reference committee with representatives from both the scientific and the practical party helped in widening the perspective of the project to not only fulfil the requirements for the PhD dissertation, but also include a viewpoint of the applied sense of the clients.
List of papers

The thesis is based on the following papers:


In the thesis, the above papers are referred to by their respective roman numbers. The studies presented in Paper I through Paper IV, all aimed to gather knowledge and experience in order to carry out and draw the final conclusions from field studies summarised in Paper V.

The vocabulary concerning facilities for cyclists varies in the literature and there seems to be a difference in terminology between American English and British English. In addition, the study is related to several fields of science, and there has been a need to construct definitions specific for this thesis. To avoid confusion, a list of definitions including some of the important words used in the thesis has been assembled. This list can be found before the references.
**Introduction**

In 1998 the Swedish Parliament passed a transport policy decision based on the Bill “Transport policy for sustainable development”, 1997/98:56 (Ministry of Industry, Employment and Communication, 2002). The overall goal of the transport policy is to provide a socio-economically efficient transport system, that is sustainable from an ecological, economical, social and cultural perspective.

Road traffic in Sweden is increasing at a rate of some 1.5 percent per year, and there is no sign of this trend being broken. This course of development leads to added noise, more congestion and vehicle emissions and to a growing demand, that traffic problems must be solved (SNRA, 2002a).

By increasing the bicycle usage for personal travel, a corresponding decrease in car-based transport could be possible. A reduction of motor traffic is especially desirable in urban regions, where the problems with congestion, extensive land use and barrier effects from road constructions are great. From an environmental perspective, it is especially important to reduce the number of short car trips, since they are responsible for a relatively large proportion of the emissions caused by traffic. This is particularly true in winter, when cars are subjected to cold starts. Most people consider, that cycling distances less than 5 km presents no difficulty (Nilsson, 1995; Danish Road Directorate, 1995), but approximately 60% of all passenger journeys in Sweden are shorter than 5 km and more than half of these are made by car (Riks-RVU, 1998). In addition, half of all car trips made in Sweden are shorter than 5 km.

The variation in cycle flows between seasons is large and in Sweden, the flow during summer is nearly three times greater than that during winter (Öberg et al., 1998). The decrease in winter cycling frequency is probably largely due to the less favourable weather conditions. However, road conditions are also important. In seeking to promote cycling, it would be desirable to understand the significance of the maintenance service level compared to other factors in the decision to cycle or not during wintertime.

**Objective**

The main purpose of the PhD project presented in this thesis was to evaluate the possibility of increasing the number of cyclists during winter by improving the winter maintenance service level on cycleways.

The objective can be broken down into the following parts:

- To increase the general knowledge of factors important in the individual decision to cycle or not during winter, and to study regional differences of this matter (Paper I).
- To estimate the potential to increase winter cycling frequency by improved winter maintenance service level of cycleways, by revealing the attitude towards winter cycling (Paper I).
- To examine the influence on cycle flow during winter from different weather factors and indirectly, also considering the influence from different road condition factors (Paper II, and to a certain degree Paper V).

- To develop a visual method to assess winter road conditions on cycleways in order to attain a tool for comparing studies of the service levels achieved using different winter maintenance methods (Paper III).

- To find a suitable method for measurements of friction on cycleways in wintertime as a complement to the visual assessment, in order to compare different road conditions on cycleways (Paper IV).

- To find a winter maintenance method that produces a higher service level on cycleways during winter than conventional methods do, to see to what extent improvements could be done, and if the road users would notice any difference in the level of service (Paper V).

- To see if the increased service level attained using the unconventional method would be more expensive than traditional methods, and to make an estimation of the difference in costs (Paper V).

**Limitations**

The PhD project was limited to facilities for cyclists, not including those for pedestrians, though many of the issues are the same. Furthermore, the project focused on facilities in and near urban areas, where the potential of transferring car trips to bicycles was considered most likely to exist.

This thesis mainly covers winter maintenance on cycleways. Maintenance service levels during summer, including ruts, cracks and irregularities creating a poor road surface condition, also negatively affect winter maintenance, but these features are only discussed briefly.

The disadvantages of using a bicycle for shopping trips and recreational journeys are commonly apprehended. This implies that journeys to work and school, which already have a high percentage of bicycle trips, are those most likely to have the highest potential for increased cycling during winter. Consequently, the studies presented in this thesis focused on bicycle trips to work. Journeys to work and school are also more determined in time and location than other types of trips and are therefore easier to study.

Since all studies within the PhD project presented in this thesis were performed in Sweden, the results are mainly applicable to locations with winter conditions, winter maintenance standards, and attitudes to cycling as in the Scandinavian countries. Still, the results form this study might also be applicable in other countries with similar winter climate.
**Background**

In terms of paved cycleways, or rather footways and cycleways, there are approximately 13,200 km in Sweden, of which 11,000 km are under municipal administration (SALA, 1998a; Bergström, 2000a). This can be compared to the public road network which in Sweden has a total length of about 137,000 km (SNRA, 2000). The actual length of the cycleway network might differ greatly from that mentioned here, since information concerning cycleways is incomplete; for some municipalities there is no available data and figures from others might be inadequate. Also data from the Road Administration are disputable.

**Cycling in Sweden**

In Sweden, in total 11% of all passenger journeys are made by bicycle (Riks-RVU, 1998). This accounts for the total number of trips and not the transport mileage. Only 3% of the passenger transport mileage is done by bicycle compared to 84% by car (Thulin and Nilsson, 1994). The total of 11% is in average over the country for all types of trips and throughout the seasons. In Swedish cities with high cycling frequency, such as Malmö, Lund, Linköping, Uppsala, Västerås, and Umeå, cycling constitutes 25 to 30% of all the personal trips, while it is less than 5% in Stockholm and Norrköping (Berggren, 1998). The amount of passenger journeys made by bicycle in Sweden, is large in relation to that of, for example, America, England or France, but small compared to Denmark and the Netherlands, where about 30% of all passenger journeys are made by bicycle. The differences between countries can to some extent be associated with disparities in climate, although the main reason is probably differences in traditions and attitudes. Also, the size of the city, the spatial planning and the topography are factors explaining geographical differences in cycling (Ljungberg et al., 1987). Finally, the cycle frequency varies between urban and rural areas and can also be related to the size and continuity of the cycleway network (U.S. Dept. of Transportation, 1991).

**Travel behaviour and attitudes to cycling**

The choice of transport mode is affected by attitudes, socio-economic and demographic factors, as well as by a variety of trip-specific factors, such as distance, point of time and weather. Cycling generally decreases with increased age (Riks-RVU, 1998), and a significant decrease in cycling often occurs at the age of retirement, when work trips are no longer needed. Trips to work have a higher share of bicycle trips compared to other types of trips (Riks-RVU, 1998). For example, approximately 9% of all shopping trips and 14 to 15% of journeys to work and school are bicycle trips. These results are not surprising, considering it is more difficult to use a bicycle for shopping trips, when heavy goods have to be transported.

In general, there is no significant difference in cycling between men and women (Riks-RVU, 1998; Brundell-Freij, 1989; Warsén, 1983). However, there are variations within certain ages. Furthermore, some attitudes concerning cycling are related to gender. For example, according to Warsén (1983), winter cycling is perceived more positively by men than by women. The choice of transport mode is of course also associated with the
available alternatives and strongly related to earlier decisions (Forward, 1998; U.S. Dept. of Transportation, 1991; Warsén, 1983). Car owners usually get accustomed to use their car for both short and long trips and hence cycle less than persons without a car. As the choice of transport mode itself, the personal attitude towards cycling is related to lifestyle, life situation and social norms (Forward, 1998). The attitude towards cycling also differs between those who cycle and those who never cycle (Davies et al., 1997).

The major reasons in favour of choosing a bicycle are found to be the exercise it provides, and that it is cheap, quick, easy and environmentally friendly (Forward, 1998; Nilsson, 1995; Warsén, 1983). Furthermore, many people consider cycling to be fun and nice, and that it provides a feeling of freedom. The drawbacks to cycling are its lack of comfort and its strain, the difficulty of carrying a heavy load on a bicycle and ease of theft (Forward, 1998). Some also feel insecure due to increased accident risk riding a bicycle compared to driving a car (Fergusson, Rowell and Shayler, 1993; Warsén, 1983).

**Variation in cycling frequency**

It is difficult to measure bicycle traffic and hence draw conclusions concerning variations in cycling frequency. The random variation in cycle flow is usually large and, in particular during mechanical counts, the dropout is large (Brundell-Freij, 1989). Bicycles are difficult to detect by mechanical detectors, since those are often not sufficiently sensitive, and cyclists often ride two or more abreast in the same lane. In addition, cyclists do not always choose the route they are supposed to and sometimes deliberately go round detectors to avoid them (Bolling, 1995). In wintertime, it is even more problematic to measure bicycle traffic mechanically. Manual measurement methods are more reliable than mechanical counts, but, demand large personnel resources and are therefore rather expensive to perform.

Nevertheless, several studies have been done in order to correlate cycle flow with possible influencing factors. The difficulty in measuring bicycle traffic is mirrored in somewhat differing and contradictory results between various studies. However, some consensus does exist. The cycling frequency is normally higher during weekdays and lower on Saturdays and Sundays (Ljungberg et al., 1987; Bolling, 1999). From Tuesday to Thursday, the variation in cycle flow is normally negligible. However, Fridays seem to have more unstable cycle flows than other weekdays. Of course, holidays and other eventualities also influence the cycle flow. The variation in cycling over the day is characterised by a morning peak between 6 and 9 a.m. and an afternoon peak between 3 and 5 p.m. (Warsén, 1983; Bolling 1999). Of course, this variation is related to customary work and school hours, and differs with location.

Bad weather has been found to be the most common explanation not to cycle (Nilsson, 1995; Warsén, 1983). However, although weather conditions influence cycle flows from one day to another, bad weather plays a less important role when hindering people to cycle regularly (Fergusson, Rowell and Shayler, 1993). It is not only current conditions, that are significant in this respect; weather on the days immediately preceding also affects the cycling frequency (Bolling, 1999). Subsequent days of bad cycling weather produces lower and lower cycle flows. Further, after a long period of
bad weather, several days of good cycling weather are required before the cycle flows are restored to “normal”.

Weather factors affecting cycling frequency negatively are low temperatures, precipitation, fog, and strong winds (Emmerson, Ryley and Davies, 1998; Ljungberg et al., 1987). In some studies (Emmerson, Ryley and Davies, 1998; Bolling, 1999), no correlation between precipitation intensity and cycling frequency could be found, while others (Ljungberg et al., 1987; Öberg et al., 1998) claims, that a heavy precipitation reduces the cycling frequency to a greater extent than light precipitation. According to a British study (Emmerson, Ryley and Davies, 1998), cycle flows are more influenced by the maximum daily temperature than by rainfall. A 1 °C rise in maximum daily temperature gave an approximately 3 % increase in daily cycle flows. However, in some Swedish studies, occasional variations in temperature did not seem to influence the cycling frequency (Bolling, 1999). However, this study did not include any measurements during winter, and the temperature only varied between + 5 and + 21 °C. In another Swedish study (Öberg et al., 1998), cycling frequency reached its minimum in the temperature interval between 0 and –5 °C. However, in this interval the influence of precipitation is large, since it represents an interval where precipitation often occurs.

**Winter cycling and the importance of the road condition**

The variation in cycle flows between seasons is large, and in Sweden the flow during the summer is nearly three times greater than that during the winter (Öberg et al., 1998). As cycling in general, the seasonal difference varies between different parts of Sweden. In the north, the decrease in cycling frequency during wintertime is more significant than in the south of Sweden, and in certain regions, the decrease can be as much as ten times (Ljungberg et al., 1987). The decrease in winter cycling frequency is probably largely due to the less favourable weather conditions, but also to worse road conditions and darkness. In a Swedish survey, 25 % of all planned bicycle trips during winter were replaced by another mode of transport (Wretling, 1996). In 66 % of the cases, the reason given for the change in mode was the slippery road condition, and in 52 % of the cases the temperature. As many as 25 % of the cyclists decided to walk instead, and almost all of them stated, that a slippery road condition was the reason.

Measurements from Gothenburg in Sweden (Öberg et al., 1998) show that during winter, at occasions with mixed road conditions, the cycle flow is reduced by almost 40 %, and under ice and snow conditions, the cycle flow is reduced by half compared to the flow at bare surfaces.

In a Norwegian survey (Giæver, Øvstedal and Lindland, 1998) asking cyclists what would prevent them from using their bicycle during winter, cycleways not cleared from snow was found to be the most important reason. More than 50 % stated, that they would not cycle, if the cycleway was not cleared of snow. Some of the respondents also stated, that a slippery surface would prevent them from using their bicycle, although the majority said it would not affect them. Only a few answered that bad weather, low temperature or darkness would prevent them from using their bicycle during wintertime. However, it should be noted, that the cyclists interviewed in this study frequently used their bicycle in winter. About 65 % of participants stated that they used their bicycle daily or 3 to 5 times a week, disregarding the weather. Giæver, Øvstedal
and Lindland (1998) concluded from their study, that many consider winter cycling a part of their lifestyle. Precipitation, coldness and darkness did not seem to significantly prevent winter cycling. These factors as well as icy road conditions are possible to rule out by using appropriate clothes, lighting, studded tires and helmet, but a snow-covered cycleway generates a problem until it is cleared.

**Bicycle accidents related to road conditions**

Collisions with motor vehicles are the most severe type of bicycle accident, but single accidents are the most common one, but rarely noticed by the police (SNRA, 1999; Nilsson, 1986). According to Nilsson (1986), single bicycle accidents with a share of 30% constitute the single largest group among all traffic casualties reported at hospitals. Of all bicycle accidents reported at hospitals in Sweden, approximately 2/3 are single accidents (Magnusson, 1998; Björnstad, Björnstad and Ohman, 1996). The same proportion was found in both Norwegian (Borger and Frøysadal, 1993) and Danish studies (Binderup Larsen et al., 1991). However, the true amount is probably even greater, since many single accidents never even come to the knowledge of the hospitals. Calculations based on hospital data, indicate that about 20,000 cyclists are injured in traffic in Sweden every year (SNRA, 1999). Of these, about 4,800 are hospitalised. Furthermore, approximately 50 cyclists are killed in traffic in Sweden every year, compared with a total of about 540 persons per year (SNRA, 1999).

Many single accidents among cyclists are caused by poor road conditions. In bare surface conditions, ruts, unevenness and cracks, as well as sand, gravel and other debris are the chief causes. In winter, there is an additional risk due to snow and ice. The accident risk for cyclists and pedestrians increases 5 to 10 times during icy and snowy road conditions compared to bare surfaces (Möller, Wallman and Gregersen, 1991). According to accident data from hospitals in Östergötland (in Sweden), 60% of all bicycle accidents during winter are single accidents due to a slippery surface (Nilsson, 1986b). According to Öberg et al. (1998), ice and snow is the single most important cause of single accidents, where cyclists thought, that the road condition had contributed to the accident (Table 1). Of the cyclists injured in a single accident during winter under ice or snow conditions, 84% thought that the road surface contributed to the accident.

In Umeå, 40% of all bicycle accidents occur in wintertime, between October and April (Björnstad and Björnstad, 1994). Of these accidents, 40% were caused by slippery conditions and 2% by loose grit on the road surface. Also in other studies, grit from winter maintenance has been found to be a safety hazard for cyclists. According to Öberg et al. (1998), 6% of the single accidents among cyclists were caused by grit (Table 1). In a Danish study (Binderup Larsen et al., 1991), 10% of all single accidents were caused by loose grit on the road surface.
Table 1: The significance of road surface conditions for single bicycle accidents (Öberg et al., 1996).

<table>
<thead>
<tr>
<th>Did the road surface contribute to the accident?</th>
<th>Winter, Ice/snow + Mixed road condition</th>
<th>Winter, Bare surface</th>
<th>Other occasions</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yes</td>
<td>84 %</td>
<td>58 %</td>
<td>33 %</td>
<td>42 %</td>
</tr>
<tr>
<td>In what way?:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>* Slippery, ice/snow</td>
<td>68 %</td>
<td>30 %</td>
<td>0 %</td>
<td>13 %</td>
</tr>
<tr>
<td>* Irregularities</td>
<td>5 %</td>
<td>3 %</td>
<td>4 %</td>
<td>4 %</td>
</tr>
<tr>
<td>* High kerbs</td>
<td>2 %</td>
<td>5 %</td>
<td>5 %</td>
<td>5 %</td>
</tr>
<tr>
<td>* Holes in the road</td>
<td>2 %</td>
<td>2 %</td>
<td>2 %</td>
<td>2 %</td>
</tr>
<tr>
<td>* Grit</td>
<td>3 %</td>
<td>8 %</td>
<td>6 %</td>
<td>6 %</td>
</tr>
<tr>
<td>No. of injured cyclists</td>
<td>60</td>
<td>103</td>
<td>427</td>
<td>590</td>
</tr>
</tbody>
</table>

The accidents caused by poor road condition can easily be reduced through improved maintenance and operation and at reasonable low costs (Ardekani et al., 1995). In Umeå municipality in Sweden, efforts to improve winter maintenance of cycleways resulted in a decrease in the number of bicycle accidents during winter, even though the cycling frequency was increased (Hjalmarsson, 1998).

Potential of transferring car trips to bicycle during winter

The transfer of car trips to bicycles would benefit the environment, especially in urban areas, through reduced noise and lower air pollution. In addition to environmental benefits, cycling offers numerous benefits in terms of improved health (Hillman, 1992). Regular exercise increases fitness and can lower cholesterol levels and blood pressure, improve blood circulation and lung function and counteracts overeating (Fergusson, Rowell and Shayler, 1993). Numerous studies indicate, that the rate of coronary heart disease is significantly lower among those, who cycle or walk to work compared to those who go by car. Furthermore, the British Medical Association has proved, that regular exercise has positive effects on mental health by reducing depression, anxiety and stress (Fergusson, Rowell and Shayler, 1993). There is one major advantage of cycling compared to other types of exercise: Cycling is an activity, which is available to the vast majority of the population, including many who are unwilling or unable to take part in sport or active recreation. In addition, cycling provides the opportunity of physical exercise in combination with travelling, for example, cycling to work.

Despite the fact that most people have no difficulty in cycling distances less than 5 km (Nilsson, 1995; Danish Road Directorate, 1995), more than 50 % of these short trips are made by car. Moreover, approximately 60 % of all passenger journeys in Sweden are shorter than 5 km (Riks-RVU, 1998). This implies, that there is a potential of transferring many car trips to bicycle. In addition, the population owning a bicycle but using it infrequently is large (Fergusson, Rowell and Shayler, 1993). According to Nilsson (1995), at least 9 % and at the most 48 % of the short car trips in Sweden can be transferred to bicycle (in total over the year). The decrease in cycling from summer
to winter (Öberg et al., 1998) indicates, that the potential is even greater during wintertime.

Even though bad road conditions affect cycling negatively, it is not certain, that an improved winter maintenance service level on cycleways would lead to more cyclists during winter. If possible, it would be desirable to identify the potential for winter cycling associated with service level. Further studies are needed, such as field studies including bicycle counts related to different road conditions. However, before these studies can be fulfilled, reliable methods to compare different road conditions on cycleways are needed. It is also important to define good road standards on cycleways from a cyclist’s point of view. It is also important to analyse how the level of service can be enhanced and what it will cost. Obviously there are rather complex relationships between improved winter maintenance standards and benefit for the society. An attempt to illustrate such relationships is presented in Figure 1. If the directed edges in the graph were quantified, then it would be possible to carry out cost-benefit analysis for improved winter maintenance standards.

![Figure 1](image)

**Figure 1** Possible relationships between improved winter maintenance standards and benefits for the society.

Winter maintenance requirements on cycleways

Requirements concerning winter maintenance service levels are usually related to snow depth, surface friction, evenness, time to operate and cleared road width with regard to the prevailing weather situation. For example, according to the Swedish general technical description of road operation service levels, “Operation 96 ” (SNRA, 1996), cycleways representing the highest standard must have less than 4 cm of loose snow during snowfall and up to 4 hours afterwards and less than 2 cm in fair weather. Within 2 hours after rain that caused slippery conditions, the cycleway surface must have satisfactory friction, that is, a friction value above 0.25. The friction value is defined as
the average value over a 20-m stretch measured with a “Saab Friction Tester or analogous equipment” (SNRA, 1996). However, the friction value is seldom assessed on cycleways. The above requirements must be fulfilled at 75 % of the total width and at least on 0.5 m. Snow banks are not permitted to be wider than 1 m or higher than 1.1 m on cycleways, and no snow bank is permitted by cycleway crossings (SNRA, 1996).

While the requirements from the Swedish National Road Administration (SNRA) have maximum allowances, the requirements in Swedish municipalities are usually based on starting criteria. For example, in Linköping snow clearance of cycleways should start at a snow depth of 3 cm. Another difference between municipal requirements and the SNRA requirements, is the classification of cycleways in different standard classes. In the municipalities, cycleways are normally divided in two standard classes, regarding cycling frequency and location in relation to housing areas, schools, shopping centres and work places etc. In the requirements by SNRA, cycleways are divided in three standard classes without any concern of cycling frequency. Instead, in this case, the classification roughly depends on the traffic flow and the designation of adjacent roads (SNRA, 1990a). The main reason for this is, that the service level should be high enough to prevent cyclists and pedestrians from choosing nearby roadways instead. In Sweden, the Road Administration is normally responsible for maintaining the cycleways adjacent to highways within the national or regional road network, while municipalities are responsible for cycleways within the local road network. Due to high speeds and traffic flows on the national and regional road network it is, for safety reasons, important that cyclists do not use such roads.

Surveys done by means of questionnaires in a number of municipalities in Sweden show that, while the majority is quite satisfied with present winter maintenance of roadways, they are dissatisfied, when it comes to cycleways (SALA, 1998b). The public view is that winter maintenance of cycleways needs to be greatly improved. However, it is unclear whether this discontent is related to insufficient service level requirements, or if the requirements, in reality, are poorly met.

**Winter maintenance methods used on cycleways in Sweden**

Normally, in Sweden, cycleways are cleared from snow through ploughing. Skid control is almost always performed through gritting, using sand, grit, or abrasives, usually in the 2 to 5 mm size range (Lindmark and Lundborg, 1987; SNRA, 1994). Abrasive, opposed to sand do not need to be heated or mixed with salt to prevent freezing and increase friction even when covered by a thin layer of snow. However, this coarse, rough-edged material creates a problem with punctures in bicycle tyres, and it creates a safety hazard in the spring before it is swept up.

Chemical methods, usually application of sodium chloride (NaCl), are often used on roadways, but rarely on cycleways. Most municipalities stopped using salt on footways and cycleways, after receiving complaints from cyclists concerning rust on cycle chains and from pedestrians, whose clothes and shoes have been stained. Salt contaminates the environment, resulting in damages to vegetation etc. and causes rust and concrete damage. However, it is economical and readily available. Salt can be spread dry, pre-wetted or in solution (brine). Application of brine on roads allows the salt dosage to be reduced considerably, and it is particularly effective as a preventive anti-icing measure.
and for dealing with hoarfrost. Brine is preferred in chemical de-icing of cycleways because cycle traffic is too light for dry salt to work effectively.

The methods and equipment used for cycleway maintenance are usually the same as for ordinary roadways (NVF, 1984). In many cases trucks, tractors, ploughs and sanding equipment are too large and heavy for this purpose and can cause damage to cycleways. It is also difficult for such an equipment to pass through tunnels and narrow passages. However, in recent years a new generation of vehicles more suitable for use on cycleways and footways have become available on the market. These vehicles are light, manoeuvrable and fast 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 provides a good economical situation, since it enables the same vehicle to be used during both winter and summer maintenance operations. Consequently, these smaller vehicles are getting 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.

Winter road condition assessment

During winter, the road condition changes continuously with the weather situation and is also influenced by traffic. Therefore, a subjective visual inspection is the most suitable method to assess road conditions during winter, although this entails considerable manual effort. The road condition observers normally register their results on a protocol specific for the purpose. The protocol and adherent instructions guide the observer, but still in the end the assessment is subjective.

The instructions for observing winter road conditions normally used in Sweden, for research purposes and by the SNRA when monitoring maintenance performance, were developed in the early 1970s at VTI but were not published until 1990 (Möller and Öberg, 1990). They are primarily constructed for observations of surface conditions on roadways, yet the same instructions can and have been used on cycleways. Similar methods are also used in other Nordic countries (Gabestad, 1998; FinnRA, 1994).

Besides instructions on how different road conditions are defined and should be registered on the adherent protocol, an assessment method also includes a description including how, when, where and how many observations should be conducted. The procedures should take into account the purpose of the assessment and the amount of variable factors affecting the surface condition (Gabestad, 1988). For example, frequent precipitation, often changing temperatures around 0 °C and great variations in natural surrounding, in traffic volume and the road structure are reasons for performing observations quite often (Gabestad, 1988).

An important supplement to the visual inspection is measurements of friction. The standard device for measuring friction on roadways in Sweden is the Saab Friction Tester, originally constructed for friction measurements on airport runways (SNRA, 1990b). In this device, based on the fixed-slip principle, the measuring wheel is installed in the rear end of the car. The Saab Friction Tester could, in practice, also be used on cycleways. However, other smaller devices are preferable due to limited space and for the safety of cyclists and pedestrians.
Method

The test site

Most of the studies performed in the PhD project and presented in this thesis were conducted in the city of Linköping, with focus on the largest company in the city, Saab AB. Saab AB was considered suitable for the study not only because it is the largest workplace in the city, but also due to its frequent commuting by bicycle.

Linköping is located in south central Sweden, and the city has about 93 000 inhabitants. Linköping provide a fairly flat, and hence bicycle friendly landscape. In Linköping, the problem with ice formation is major, and, hence, skid control is usually the most important winter maintenance measure on cycleways. Climatic data for Linköping are presented in Table 2, in Paper I. Linköping has a well-developed network for bicycle traffic and a large number of cyclists owing to widespread commuting by bicycle and many cycling students. The total length of the cycleway network in Linköping is about 340 km, representing 2.7 m per inhabitant (SALA, 1998a).

Preparatory studies

To define the issue of the PhD project, a literature review was performed gathering information from earlier studies. Results from the literature review are shortly presented in the preceding chapter, but also in the papers included, when relevant. The complete literature review is available both in English (Bergström, 2000b) and in Swedish (Bergström, 2000a). The literature review, and, in fact, all the studies presented in Paper I through Paper IV, aimed to gather knowledge for the field studies presented in Paper V.

To get background information concerning choice of transport mode when travelling to work and the common view about winter maintenance of cycleways, a questionnaire survey was conducted in 1998 (Paper I). Included in the survey were employees at four major companies in two Swedish cities, Luleå in the north and Linköping in the south of Sweden. Saab AB was one of the companies from Linköping.

In order to examine the influence on winter cycling frequency of different weather factors, cycle flow data for four winter seasons (1 October to 30 April) obtained from the Swedish city of Gävle were correlated with data from the Swedish Road Weather Information System, RWiS (Paper II). The road condition was indirectly considered through weather factors. This study focused on the winter situation, while earlier studies of the variation in cycle flows have mainly considered the situation during summer.

In order to obtain a method to assess winter road conditions on cycleways, a visual method used for roadways (Möller and Öberg, 1990) was modified to better apply to cycleways (Paper III). To find the appropriate modifications needed, winter road condition properties important to cyclists were identified through literature reviews and from comments by cyclists in questionnaire surveys (Paper I) and in roadside interviews. The suggested modifications were also based on personal reflections when performing visual inspections of cycleways in wintertime. The resulting instructions
and the adherent protocol are presented in Appendix A, in Paper III. The developed method was used in the road condition assessment of cycleways to evaluate the unconventional winter maintenance methods tested in the field studies (Paper V).

To supplement the visual assessment, measurements of friction were performed on cycleway surfaces using a Portable Friction Tester (PFT) developed at the Swedish National Road and Transport Research Institute (VTI), originally for the purpose of measuring 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. To analyse its usability for measurements on cycleways in wintertime, the PFT was tested under different winter road conditions (Paper IV). Measurements were also conducted on wetted bare cycleway surfaces.

Field studies

To find a winter maintenance method, that could provide a higher service level than methods traditionally used on cycleways, field studies were performed (Paper V). It was of interest to see to what extent improvements of surface conditions could be achieved, what it would cost, if the road users would notice any difference in the level of service and if it would generate an increase in winter cycling frequency.

At first, to get experience of the problems resulting from certain maintenance methods, a pilot study was carried out in 1999 in Linköping. Traditionally, in Linköping cycleways are cleared through ploughing, and skid control is attained by abrasives in 4 to 8 mm grain 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 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 power broom for snow clearance combined with a brine spreader for de-icing. Using the power 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 Swedish winter climate.

The pilot study was evaluated through road condition observations and measurements of friction. Roadside interviews, catching commuters cycling to or from work to get their opinion of the tested methods, were also conducted in the pilot study. The experience from the pilot study was used to exclude less suitable methods for further testing and as guidance for planning a large-scale study.

During the two following winters, between October 1999 and March 2001, a large-scale study was carried out. In this study a housing area, Ekholmen, within cycling distance (about 5 km) of Saab AB, Linköping was used as a test area. All cycleways
within the housing area of Ekholmen, as well as three major routes from Ekholmen to Saab AB, were included in the test area. The cycleways were given a higher level of service than usual in Linköping by using the front-mounted power broom for snow clearance and brine or on some difficult occasions pre-wetted salt, for de-icing. 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 road surface conditions were conducted after almost each occurrence of snowfall or hoarfrost, using the assessment method developed in Paper III. Observations were done on cycleways within the test area and maintained with the “brine method”, as well as on cycleways used as controls and maintained traditionally. As a complement to the road condition observations, measurements of friction were conducted, in particular during the pilot study, but also during the large-scale study. These measurements were performed with the Portable Friction Tester as described in Paper IV.

The large-scale study was also evaluated through a questionnaire survey performed in spring 2000 to get the road users opinion of the winter maintenance method tested. A total of 829 questionnaires were distributed randomly among employees at Saab AB living in the test area of Ekholmen and by control groups in three other housing areas within about the same cycling distance from Saab AB as Ekholmen. Some of the results from this survey were considered to be a good complement to the questionnaire survey performed in 1998 and were therefore also included in Paper I. Interviews were conducted as a complement to the questionnaire survey, in order to gather opinions concerning the large-scale study from the inhabitants of Ekholmen not working at Saab AB.

Particularly during the second winter, 2000/2001, the large-scale study was also evaluated through bicycle measurements. Both mechanical measurements at a stationary measuring point, as well as manual counts at 5 measuring occasions were conducted. All manual measurements were performed in the morning with the purpose of counting commuters on their way to work. Cycle flows to Saab AB from different housing areas was counted, in order to compare the cycle flows from Ekholmen with that from other parts of the city to see whether the improved service level in the test area of Ekholmen generated a higher cycling frequency from that direction. Naturally, it was not possible to be certain of the starting point and the destination of each counted cyclist. The measuring points chosen coincided to some extent with the cycleway sections observed during the road condition observations.
Results

In this section the results from all the papers included in the thesis are summaries. For more detailed results, the reader is advised to turn to respective Paper. In analysing the results from the questionnaire surveys (Paper I) it was found appropriate to divide the respondents in the following categories of “cyclists” according to their stated choice of mode for their journey to work in summer and winter:

**Winter cyclists** 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.

**Summer-only cyclist** 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.

**Infrequent cyclist** A person who uses a bicycle occasionally, that is less than two cases out of five, when travelling to work.

**Never cyclist** A person who never uses a bicycle for travelling to work, at any time.

Difference in cycling frequency from summer to winter

From the questionnaire surveys (Paper I) a clear difference in mode choice between seasons was found. The largest change between summer and winter was from bicycle to car, although bus trips also increased to a certain degree during wintertime (Figure 2). This implies, that many cyclists do in fact choose between car and bicycle for their journeys to work, indicating that there are environmental benefits to be made, if cycling is increased for personal travel.

![Figure 2](image-url)  
**Figure 2**  
Modal split of journeys to work in summer and winter periods for the two surveys.
The difference in mode choice from summer to winter presented in Figure 2, represents the average difference of the estimating answers by the respondents in the questionnaire surveys (Paper I). It should be noted, that the respondents of the survey of 2000 in general had a shorter travelling distance to work than the respondents of the survey of 1998, which explains the larger number of trips by bicycle and on foot for the survey of 2000, shown in Figure 2. In the surveys, the winter season was defined to last from November to March and the summer season from April to October. Bicycle measurements from four winter seasons in the city of Gävle (Paper II) showed, that December to February had the greatest decrease in cycling frequency of all the months during the winter. The number of cyclists decreased by more than 40 % in comparison with October (Table 3 in Paper II). Pairwise comparisons showed, that there was no significant difference in cycle flows between December, January and February. April showed a significantly higher cycle flow than all the other months and March a significantly higher cycle flow than all months from November through February.

The reasons for the decrease in bicycle usage from summer to winter is, of course, partly related to less favourable weather conditions. According to the bicycle measurements from Gävle related to RWiS data (Paper II), the number of cyclists decreased with air temperature, and was, generally, lower for every temperature interval below +5 °C (Tables 3 and 5 in Paper II). For example, at temperatures between –10 and –15 °C, the number of cyclists was 36 % less than at temperatures between +5 and +10 °C. In the study, air temperature was divided into nine separate intervals of five degrees Celsius, except for temperatures between +1 and –1 °C, that was assigned to an explicit interval. At temperatures above +10 °C, there was no significant increase in cycle flow with temperature. This was partly due to the lower number of observations in these temperature intervals but also indicates that, when temperatures rises above +10 °C, a further increase in temperature does not notably affect the cycle flow. If this is in fact the case, it would explain why, in earlier studies not including measurements in wintertime (e.g. Bolling, 1999), no correlation between temperature and cycle flow could be found.

At temperatures between –1 and +1 °C, the number of cyclists decreased more than at temperatures between –1 and –5 °C. A pairwise comparison proved the difference to be significant. This confirms the hypothesis by Öberg et al. (1998), that temperatures around 0 °C are extra critical for cyclists. The influence of precipitation might be larger in this temperature interval, but the reason for the great decrease in cycling frequency at these temperatures are likely also related to a slippery road condition.

Low temperatures seemed to be even more important in reducing the cycle flow than precipitation (Paper II). At occasions of rainfall or snowfall, the number of cyclists was 13 % less than in fair weather. Only the occurrence of precipitation, not the amount of rain or snow, was significant for the cycle flow. Pairwise comparisons could not distinguish whether snowfall or rainfall had the greatest influence. However, snowfall generally coincides with low temperatures and a winter month, which results in a further decrease in the number of cyclists.

Wind speed was also found to have a negative influence on the cycling frequency during winter (Paper II). For example, at a wind speed of 4 m/s, the number of cyclists was 11 % less than at occasions with no wind. The number of cyclists decreased
continuously with an increase in wind speed. Also, according to comments from the respondents in the questionnaire surveys (Paper I), strong winds were found to be of importance for the choice of mode.

Winter road condition properties of importance for the cycling frequency

As mentioned above, the cycling frequency is low at temperatures around 0 °C, which probably, to some extent, is related to slippery road conditions. According to the measurements from Gävle (Paper II), at occasions of slipperiness due to rain or sleet on a cold surface, the number of cyclists decreased by 27% in relation to occasions of fair weather.

The fact that the winter road condition and not only the weather is important in the choice of mode was also concluded from the questionnaire surveys (Paper I). Cycleways not being cleared from snow was found to be the most important road condition factor for both winter cyclists and others (Table 2). The figures in Table 2 represent the grading done by the respondents in the survey of 1998, according to their personal opinion of the importance of each respective road condition factor, for their choice of mode for the journey to work. Each factor were given a number on a seven-grade scale, where 1 denoted “no importance” and 7 denoted “great importance”. Snow clearance seemed to be a bit more important than skid control for influencing the choice of mode and a lot more important than the occurrence of grit or debris and surface unevenness. The finding that cycleways not being cleared from snow presents the greatest problem for cyclists corresponds to the results from a Norwegian study (Giæver, Øvstedal and Lindland, 1998) mentioned in the background.

<table>
<thead>
<tr>
<th>Road Condition</th>
<th>Winter Cyclists</th>
<th>Summer-Only Cyclists</th>
<th>Never Cyclists</th>
<th>Total Average</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean Std. E.</td>
<td>Mean Std. E.</td>
<td>Mean Std. E.</td>
<td>Mean Std. E.</td>
</tr>
<tr>
<td>Not cleared from snow</td>
<td>4.87 0.22</td>
<td>6.42 0.14</td>
<td>6.04 0.14</td>
<td>5.80 0.10</td>
</tr>
<tr>
<td>Slippery</td>
<td>4.54 0.23</td>
<td>6.31 0.15</td>
<td>5.87 0.16</td>
<td>5.57 0.11</td>
</tr>
<tr>
<td>Occurrence of grit or debris</td>
<td>2.86 0.20</td>
<td>3.91 0.23</td>
<td>4.30 0.17</td>
<td>3.77 0.11</td>
</tr>
<tr>
<td>Cracks or uneven surface</td>
<td>2.88 0.21</td>
<td>3.79 0.24</td>
<td>4.11 0.18</td>
<td>3.67 0.12</td>
</tr>
</tbody>
</table>

The snow depth on the cycleway surface is important, since it is significant for the manoeuvrability of a bicycle. A snow depth less than about 3 cm is usually not a problem for a cyclist to manage, of course related to individual performance and also depending on the consistency of the snow (paper III).

A slippery surface was not considered as important for the mode choice as a cycleway not cleared from snow. However, the difference was marginal (Table 2), and a slippery
surface is critical for the safety of cyclists (Nilsson, 1986; Möller, Wallman and Gregersen, 1991; Öberg et al. 1998). The presence of ice on the road surface almost always creates a slippery condition, and it only takes a small spot with low friction for a cyclist to lose the grip. However, it can be questioned how large that spot has to be in order to be of significance. If it is small enough, it might not be of any importance.

The low importance of cracks and unevennesses for the mode choice, according to Table 2, was surprising, considering that cyclists are very sensitive to an uneven surface, such as, ruts, icy tracks, tracks from ice-cutting blades, potholes or washboards in thick ice or packed snow (Paper III). Comments in the questionnaire surveys indicated, that icy cycle wheel tracks or footprints formed, when wet snow freezes, are what cyclists fear most (Paper I). These icy tracks are considered to be both dangerous and troublesome. All kinds of tracks and unevennesses represent a potential danger for passing manoeuvres and are a larger hindrance for cyclists than for motorists.

Although the occurrence of grit were not considered that important for the choice of mode (Table 2), it is important for the safety of cyclists. Between 2 to 10 % of the single accidents among cyclists are due to slipperiness caused by loose grit on a bare surface (Björnstig and Björnstig, 1994; Binderup Larsen et al., 1991; Öberg et al., 1998). If the amount of grit from winter maintenance is greater than needed, the friction level on the surface decreases instead of increases, which is the fundamental purpose of gritting. This is often the case during mild winters when the general road condition is often bare surface (Paper III).

Preventing bicycle traffic from using the carriageway is considered to be the most important issue in winter maintenance of cycleways (SNRA, 1990a; FinnRA, 1995). Therefore, cycleways must be cleared at the same time as or before adjacent roadways. However, there is a danger in this, since snow can be thrown back on the cycleway, when snowploughs are clearing the roadway. In addition, due to lack of space, snow is often stored in banks between the roadway and the cycleway. Besides reducing the width of the cycleway and thereby obstructing cyclists and pedestrians, in particular when passing each other, snow banks at the edges of a cycleway constitute a problem when melting. Melting water may flow over the cycleway and subsequently freeze, generating a slippery surface.

For the safety and accessibility of cyclists, a high maintenance service level is needed. In the questionnaire surveys, most of the respondents (about 60 %) thought, that winter maintenance of cycleways needed to be improved (Paper I). About 10 % of the respondents thought, that it was satisfactory, and about 30 % were uncertain or without an opinion. Not surprisingly, most of those who were uncertain or without an opinion were those who never cycled to work during winter, which also was the case for those, who were satisfied. The conclusion, that the winter maintenance of cycleways needs to be improved, corresponds with the results from an earlier survey among citizens in twelve Swedish municipalities (SALA, 1998b). In that survey, only 29 % of the respondents were satisfied with winter maintenance of cycleways and footways. Comparatively, 68% of the respondents were satisfied with snow clearance and skid control of roadways in central areas.
Assessment of winter road conditions on cycleways

Before one can study correlations between road condition and cycle flow, reliable and practical methods to assess the winter road condition on cycleways are needed. The instructions and the adherent protocol for assessing the road surface conditions on cycleways during winter, developed in Paper III, proved to be adequate for the purpose. However, further modifications are needed. For example, the amount of grit on the surface and occurrence of tracks from cyclists, were found to be difficult for the observers to assess and must be described more in detail in the instructions. A photo illustrating the road condition should always accompany the observations. Parameters considered important to add are, for example, the road condition on the adjacent roadway and the reason for snow or slush on the surface. Identifying cycleway sections where snow often is thrown up from traffic or during roadway clearing enables actions to be taken to prevent the situation from becoming a problem. For example, a routine can be set up to clear these sections a second time, after the adjacent roadway has been cleared. Perhaps, in some occasions, it can in fact be considered only to clear cycleways after the roadways have been cleared.

It is also beneficial to supplement the subjective visual assessment with objective methods, such as measurements of friction. The Portable Friction Tester, PFT, tested in Paper IV, appears to be a valuable instrument for measuring friction on cycleways. It is handy and small enough to be used even on narrow sections. Using the PFT, the measurements can also be performed without any risk to the road users, i.e. cyclists and pedestrians. The repeatability of the PFT is fairly good, and altered road conditions can be distinguished through the measurements performed using the PFT. Hence, the PFT is a suitable tool for comparing measurements, e.g. for research purposes. However, it is sometimes difficult to interpret the results, particularly when measuring on mixed road conditions, and whenever grit is present. Measurements of friction with the PFT can also be used when monitoring winter road conditions to determine, whether a contracted entrepreneur has achieved the level of service agreed upon.

Both for research purposes and for monitoring reasons there is a benefit in performing the observations in the morning at the time when most of the trips occur, that is, around 7 and in the afternoon before 3:30, to picture the situation for many commuting cyclists.

Improved winter maintenance method for cycleways

The method using a power broom for snow clearance and brine, or pre-wetted salt, for de-icing tested during the field studies in Linköping was found to provide a higher service level than winter maintenance methods traditionally used on cycleways in Sweden (Paper V). In Figure 3, road conditions observed on cycleway sections within the test area during each winter of the large-scale study are compared to those observed on the control sections (Paper V). Cycleway sections observed in the test area are labelled from T1 to T6 while C1 and C2 are the control sections. Not all sections were observed at every occasions, which explains the differing height of the bars.

The road condition observations showed, that the maintenance service level was almost consistently higher in the test area compared to the controls outside the area. Bare surface was found at 52 to 76 % of the observations performed on cycleway sections in
the test area compared to 12 to 17% on the control sections. However, due to the hygroscopic qualities of the salt, the bare surfaces in the test area were often wet. The road condition observations were conducted after, or during, almost each occurrence of snowfall or hoarfrost and, thus, the results in Figure 3, do not represent the road conditions prevailing over the winters. Road conditions representative for the winters of the large-scale study would have had a higher share of bare surfaces, both in the test area and at the control sections outside the area.

Figure 3  Road condition observations performed in the large-scale study (Paper V) at cycleway sections within the test area (T1 to T6) as well as at control sections outside the test area (C1 and C2).

Also measurements of friction showed, that a higher maintenance service level was provided with the method using a power broom for snow clearance and brine, or pre-wetted salt, for de-icing (Paper V and Bergström, 2000b). From questionnaire surveys and interviews, it was also concluded that the cyclists and pedestrians did notice the improved maintenance service level. Almost half (47%) of the interviewees had noticed a difference in the road condition of the cycleways compared to earlier winters.

When asking how well winter maintenance of cycleways had been performed during the winter of 1999/2000, winter cyclists from the test area of Ekholmen were found to be more satisfied compared to winter cyclists in the control areas (Table 3 Paper V). 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 4). Winter cyclists in the control group in Hjulsbro, the first control group in Figure 4, were also to some extent affected by the test, since the last part of their cycle route to Saab AB was located within the test area. The larger the part of the trip to work undertaken on the cycleway network in the test area, the more satisfied with winter maintenance were the respondents.

Also roadside interviews performed in Ekholmen within the large-scale study showed, that the majority thought that road conditions on cycleways in the test area had been good during the winter of 1999/2000 (Paper V).
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 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 was more positive within the test area of Ekholmen than in the control areas. In general, the more a respondent had cycled on the cycleways in the test area, and thus had experienced the use of salt on cycleways, the more positive he/she was to salt on cycleways. In the interviews performed at Ekholmen, the attitude towards salt was even more positive compared to that revealed in the questionnaire survey. In addition, opposed to what was expected, it could not be concluded from the interviews, that dog owners were more negative towards the use of salt on cycleways than others.

The environmental concern was the main reason given by the majority of those that were against the use of salt on cycleways, and in general on roads. Another often stated reason was material damages such as cars or bicycles rusting. In both Ekholmen and Hjulsbro, the two housing areas most affected by the large-scale study, about 58% of the winter cyclists stated, that they have had problems in clearing their bicycles from rust on the chain etc., during the winter of 1999/2000, compared to about 30% in the other control areas (Hackefors and Vasastan).

Another drawback with the method using a power broom for snow clearance and brine, or pre-wetted salt, for de-icing was the increase in costs. The “brine method” was about two to three times more expensive than winter maintenance methods traditionally used on cycleways in Linköping. The increase in costs was mainly related to the more occasions of measures required. In addition, snow clearance using the power broom demanded a slower maintenance speed than during traditional ploughing, which also increased the cost.
Transferring car trips to bicycles through improved winter maintenance

About 40% of the respondents in the two questionnaire surveys stated, that they would cycle more during winter if the maintenance service level of cycleways was improved (Paper I). In Figure 5, the stated willingness to cycle with improved winter maintenance service level is presented for different categories of cyclists.

On basis of those who stated they would cycle more, it was estimated that, with improved winter maintenance of cycleways, it could be possible to increase the number of bicycle trips during winter with about 3 percentage units and decrease the number of car trips with about 2 percentage units. This represents an increase of bicycle trips of, at the most, 18% and a decrease of car trips of up to 6%. This might seem negligible, but already a small decrease of car travel would show environmental effects. Probably only car trips up to 5 km, or perhaps even shorter than 3 km, are transferable to bicycle. Distance seemed to be more significant for the mode choice during the winter period compared to the summer period.

It can be assumed, that improved winter maintenance would only affect winter cyclists and summer-only cyclists. Since infrequent cyclists and never cyclists seldom, or never, cycle to work during summer, they would probably not cycle more to work during winter, if the service level was improved. Obviously, the service level during winter can never be better than that during summer. That argument also leads to the assumption, that winter cyclists and summer-only cyclists would increase their cycling to work during winter, at the most, to the level equivalent to that during summer.

Winter cyclists valued exercise, cost and environmental aspects as the most important factors in the choice of transport mode for the journey to work. Also for summer-only cyclists exercise was important. However, they considered temperature, precipitation

Figure 5  Stated willingness to cycle during winter in case of an improved maintenance service level of cycleways for different categories of cyclists.
and road condition to be of a greater importance. For never cyclists, travel time seemed to be the only really important factor. The grading done by never cyclists (Table 5 in Paper I) indicates, that it is difficult to find any means that could convince them to become winter cyclists. It would probably require a change in attitudes.

In the questionnaire surveys, the respondents were also given the opportunity to mention other factors of importance for their choice of mode when travelling to work. The majority of the comments given in the survey of 1998 concerned the lack of options. Due to long distances and absence of public transport, many respondents were of the opinion that they had no alternative but use of car when travelling to work. A few ones stated that they needed their car at work. Others confessed that they were lazy, and that the car was the most comfortable alternative. Additionally, in the survey of 2000, the freedom and flexibility of choosing time of travelling was mentioned to be important for the mode choice. Also the need to do errands, in particular leaving kids at day-care, was often emphasised.

It was found that winter cyclists did not have access to a car for their journey to work in the same extent as others (Table 4 in Paper I). The reason mentioned for not having access to a car, besides the evident reason of not owning a car or not even having a driving licence, was that the other part in the household used the car for travelling to work. Not having access to a car is probably the main reason for many winter cyclists to cycle to work all year round. This implies that restrictions for the use of cars is likely the measure, that would lead to the largest increase in cycling frequency, although this might be an undesired course of action.

Women are probably harder to convince to cycle more during winter, since typical winter factors, such as icy and snowy road conditions, precipitation, temperature and darkness were more important to them than to men (Paper I). Furthermore, it is likely easier to convince younger age groups to cycle more during winter. Since the accident risk increases with increased age among cyclists (Öberg et. al., 1998), it might not even be desirable to increase winter cycling among elderly.

Although the questionnaire surveys (Paper I) revealed an intention to cycle more if winter maintenance of cycleways was improved, it could not be concluded from the bicycle measurements performed in the large-scale study (Paper V), that a higher maintenance service level generated a higher winter cycling frequency.

Discussion

To be able to meet the environmental goals concerning energy consumption, carbon dioxide emissions, the impacts on health of air pollution and noise, etc., it is of the utmost importance, that environmentally-sound ways of transportation, such as cycling, increases at the expense of car-based transport. In compliance with the Swedish Parliament’s goals for a sustainable environment, the SNRA (Swedish National Road Administration) has drawn up a National Environmental Programme for the period 2002 through 2005 (SNRA, 2002b). One of the areas of focus to reach the environmental goals established in the programme is to “promote walking, cycling and public transport”. The programme does not specify how cycling should be promoted, but enhancing the service level of cycleways could be one way, and that would also raise the status of the bicycle as a mode of transport. Initiating this PhD project has
been one step for the SNRA in taking their assigned responsibility for the development within the road transport sector, and, hopefully, it will lead to further progress in the aim to encourage cycling and gain environmental benefits.

At present, winter maintenance methods of cycleways are often adapted to the prevailing conditions on motor traffic roads. Consequently, they are not necessarily the best methods for bicycle traffic. Since the surface conditions are very important for the safety and accessibility of cyclists, it is important to improve the methods available to better suit their purpose and also to become more cost effective. Perhaps totally new methods could be developed. The winter maintenance method tested in this project provided a higher service level than maintenance methods traditionally used. The higher service level achieved was partly owing to the tougher starting criteria, however mainly thanks to the use of a power broom for snow clearance and brine, or pre-wetted salt, for de-icing. Nevertheless, due to high costs and to the environmental effects from the use of salt, other methods might be more suitable.

For example, new methods for mechanical skid control, such as heated sand, Hottstone, or pre-wetted sand, Friction Maker, might have great potential for use on cycleways. These methods are more durable than abrasives or sand mixed with salt, and when used on cycleways they are likely even more durable than on roadways where traffic finally wears the sand away. However, they require technically advanced equipment not yet available for the use on cycleways. Besides, since these methods require temperatures below 0 °C in order to work properly, they are likely a good alternative in the northern parts of Sweden, but not in the south, in regions with mild winters. In addition, heating sand is very energy consuming, which counteracts the environmental benefits gained by avoiding the use of salt. Different constellations of lime can also be used to increase friction on winter roads. The effect with lime is as good as with grit, but the cost is higher and the lime usually has to be transported long distances. The advantages of using lime instead of grit on cycleways are fewer punctures in bicycle tyres and less material that has to be swept up after the winter (Gävle Highway Department, 1993).

Although gritting is often considered to be an environmentally friendly alternative, it must be kept in mind that it is a natural resource not available in unlimited quantities, and that the production of abrasives consumes energy (Mikkelsen and Prahl, 1998). The use of grit also generates problems with dust particles, and, when a thaw sets in, the grit may end up in the street sewers where it can cause blockages.

The higher service level achieved with the “brine method” (Paper V), compared to traditional methods, can give rise to social benefits. The improved standard might attract more people to cycle, which could bring both health benefits (Hillman, 1992) and environmental benefits. Benefits for cyclists include the absence of abrasives resulting in less punctures and enhanced safety. Thus, the use of salt can be more cost effective, even when the environmental effects have been taken into consideration. Its advantages and drawbacks need to be compared with alternative methods such as the use of abrasives. In particular on certain parts of the cycleway network, where cycling frequency is high or where a lot of accidents occur, a higher level of service is important and the use of the “brine method” is therefore advisable. 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. On the other hand, the advantages of using salt on cycleways seems to become more evident for the road users when experienced directly.
According to the surveys performed in this project, improved winter maintenance on cycleways could lead to a higher winter cycling frequency (Paper I and V). However, bicycle measurements could not verify that the intentions revealed in the questionnaire surveys corresponded with the actual behaviour. The bicycle measurements were conducted only at a few occasions, over a limited period of time. Thus, the results were too limited to detect any significant differences in cycling frequency. In addition, there is likely a detention in effects on cycling frequency from measures such as improved winter maintenance, since it requires a change in behaviour of individuals and the force of habits is strong, and takes time to overcome.

Nevertheless, it is important to realise that many are unwilling to cycle under certain conditions, and therefore it can be difficult to convince others than winter cyclists to cycle more during winter. Winter cyclists seem to be insensitive to other factors than poor road conditions, in their decision to cycle or not. For summer-only cyclists, temperature and precipitation were more important than the road condition, and for never cyclists travel time and need to do errands was the most important factors in the choice of transport mode (Paper I). However, it can be questioned what is “cause and effect” in this case. The ranking of different factors done by different categories of cyclists might actually mirror what factors are considered within the process of mode choice, but it might also only be showing the justification of why a certain mode of transport is used. This means that a person starting to cycle during winter will, gradually, go through a change of attitudes. Therefore, to convince people to try to cycle is an important, early step to increase cycling as a means of personal travel. If that first experience is unpleasant, it is likely that the person will hesitate to cycle again, which is one argument to keep cycleways in good condition. If the city provided a high winter maintenance service level of cycleways, potential cyclists were at least given the chance to cycle instead of driving their cars.

The questionnaire surveys presented in this thesis (Paper I), and the user evaluation conducted by SALA (1998b), all indicated a need to improve the winter maintenance service level of cycleways. The fact that the majority seems to be dissatisfied with present winter maintenance of cycleways is reason enough to make improvements. The improvements might involve the use of better equipment and tougher requirements. However, thorough planning and better strategies are likely more cost effective ways to make improvements. For example, instead of enhancing the overall standard, avoiding “worst case” conditions at certain sections might be more strategic. In a Finnish study evaluating the service level on cycleways during winter, it was concluded that failure to meet the standard requirements often occurred at the same cycleway sections (Hörkkö, 2000). Hence, these critical sections must be identified. Winter maintenance operators usually have rather good knowledge of the location of these sections. However, this knowledge is rarely passed on to higher levels in the organisation, i.e. to planners and clients deciding the maintenance policy.

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 result of snow clearance. In addition, winter hazards are covered with loose snow, making them impossible to discover. Besides a direct
cause of accident, a poor road surface condition attracts cyclists’ attention towards the road surface instead of the overall traffic situation, thus creating a safety risk. A high service level, in general, decreases the accident risk of cyclists, perhaps levelling out the higher number of bicycle accidents that might be related to increased cycling frequency.

For many people, exercise and environmental concern are important reasons to cycle. It is, therefore, essential to keep an interest in environmental issues among the public, and the environmental effects of using a car for personal trips must be recognised. With an increased environmental interest, it might be easier to convince people to cycle instead of driving a car. Furthermore, by increasing the awareness of the health benefits of cycling, it may be possible to convince some inveterate car drivers to cycle instead. However, restrictions for the use of cars is likely the measure that would lead to the largest increase in cycling frequency, although this might be an undesired course of action.

**Further studies**

The knowledge is limited concerning the level of service maintained on the Swedish cycleway network. The public seems to think that winter maintenance of cycleways needs to be improved (Paper I; SALA, 1998b), however, it is unclear if their dissatisfaction is related to insufficient service level requirements, or poor maintenance performance. To reveal that, it would be beneficial to conduct evaluating studies of the prevailing winter maintenance service level.

It is also important to determine the service level required to fulfil the needs of cyclists. Knowledge of what is an adequate road surface standard for cyclists is insufficient. For example, it is necessary to relate friction values measured to what is perceived by cyclists.

Mechanical methods for bicycle measurements need to be further developed for higher reliability even during winter conditions.

Further studies comparing the impact of abrasives and salt on the environment with security and economy are necessary to make the right decisions concerning winter maintenance of cycleways and footways.
Conclusions

To increase cycling during winter, snow clearance was found to be the most important maintenance measure. Skid control was not considered as important for the choice of mode but is very important to attend to for safety reasons. If possible, cycleways should be more frequently cleared from both snow and ice, and the measures should be done earlier in the morning. It is also important to clear continuous routes, not leaving some parts uncleared. The following winter road conditions properties are the most important to attend to, both with regard to safety and accessibility of cyclists:

- Icy tracks formed when wet snow freezes
- Snow depths greater than about 3 cm of loose snow or slush
- Unevenness in a snow covered surface
- Loose grit on a bare surface

A good structure of the pavement is also important in order to achieve a high winter maintenance service level. Also when designing cycleways it is important to consider winter maintenance, since oversights in the design can obstruct the maintenance performance, and hence generate difficulties in obtaining the appropriate service level.

To assess the maintenance service level, the visual assessment method developed and tested in this project proved to be adequate for the purpose, however, further improvements are desirable. As a complement to the visual assessment, the Portable Friction Tester can be used to measure the surface friction on cycleways.

With improved winter maintenance service level it could be possible to increase the number of bicycle trips to work during winter with, at the most, 18 %, and decrease the number of car trips with 6 %. The increase in bicycle trips will mainly be associated with winter cyclists who would cycle more if winter maintenance was enhanced, or summer-only cyclists who would also cycle during wintertime. Men are probably easier to convince to cycle more during winter, since the typical winter factors, road condition, precipitation, temperature, and darkness, were less important to them than to women (Paper I). Furthermore, it is likely easier to convince younger age groups to cycle more during winter. Since the accident risk increases with increased age among cyclists (Öberg et. al., 1998), it might not even be desirable to increase winter cycling among elderly.

Only car trips shorter than 5 km, or perhaps even shorter than 3 km, are possible to transfer to bicycle during winter. Distance seems to be more important in the choice of transport mode during winter than during summer. Weather factors with negative influence on winter cycling frequency, are temperatures below +5 °C, precipitation and strong winds. Only the occurrence of precipitation, not the amount of rain or snow, is significant for the cycle flow. It could not be distinguished whether snowfall or rainfall had the greatest influence. Low temperatures are more important in reducing the cycle flow than precipitation. Temperatures around 0 °C seem to be extra critical for cyclists, probably due to the larger influence of precipitation and slippery road conditions at these temperatures.
The method using a power broom for snow clearance and brine, or pre-wetted salt, for de-icing can provide a higher service level than winter maintenance methods traditionally used on cycleways in Sweden. In particular during spring, in combination with the midday thaw, the “brine method” is efficient for clearing the cycleways. Thus, the method has great potential in regions, such as southern Sweden, with low snow accumulations but with major ice formation problems. Also in regions with a colder climate such as northern Sweden, this method is probably useful during spring and fall when the temperatures are higher and the amount of snow is less.

Using the “brine method”, will be about twice as expensive than a traditional method. However, with a fully implemented method, after a couple of years, it is probably possible to lower the costs. The increase in costs will mainly be associated with the need for more occasions of measures. Using a power broom for snow clearance also means that the operator has to maintain a slower speed than during traditional ploughing, which increases the time to operate and hence further increases the cost.

If we want people to use their bicycles, whenever distance and weather conditions makes it possible, they have to be provided with safe and accessible cycleways. Also, it is important to realise that there are people with no alternative other than bicycle, and they too have the right to a safe and accessible transport system.

**Acknowledgements**

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List of definitions

The vocabulary concerning facilities for cyclists varies in the literature and there seems to be a difference in terminology between American English and British English. To avoid confusion, the following list of definitions including some of the important terms used in the thesis has been assembled. The definitions originate to some extent from literature, but terminology specific for this thesis is also included. Where a reference is not announced the definition is the writer’s own interpretation of an expression.

**Cyclist categories**

*Infrequent cyclist*  A person who uses a bicycle occasionally, that is less than two cases out of five, when travelling to work.

*Never cyclist*  A person who never uses a bicycle for travelling to work, at any time.

*Summer-only cyclist*  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.

*Summer cyclist*  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.

*Winter cyclists*  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.

**Traffic facilities**

*Cycle lane*  A part of a roadway allocated for use by cyclists (Royal County of Berkshire, 1998). The cycle lane is separated from other traffic lanes by road markings (Ljungberg et al., 1987).

*Cycle link*  All links in a cycleway network. A cycle link may consist of a cycleway, cycle lane, or cycle track, in addition to local streets without special cycle arrangements (Ljungberg et al., 1987).

*Cycle track*  A path for cyclists which may be part of a highway adjacent to a carriageway, or a separate highway in its own right, with or without a right of way on foot (Royal County of Berkshire, 1998).

*Cycle route*  The route a cyclist is taking when travelling from point A to point B, which can comprise all kinds of cycle links, including local streets without special cycle arrangements.
**Cycleway**  Refers to any road or path which is designated as being open to bicycle travel, regardless of whether or not it is for exclusive bicycle use. Thus the general term “cycleway” could include cycle routes, cycle lanes and cycle tracks.

**Cycleway/Footway**  A facility alongside a carriageway shared by pedestrians and cyclists. It can either be unsegregated or segregated by level differences, barrier, or white line (Royal County of Berkshire, 1998).

**Footway**  A pedestrian way within the highway boundary, usually adjacent to the carriageway (Royal County of Berkshire, 1998).

**Roadway**  The section of the highway used by vehicles (Royal County of Berkshire, 1998).

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**Winter maintenance**

**Abrasive**  Crushed stone aggregate, generally in 2 to 5 mm size, and the stone material normally used in Sweden today, for the gritting of light traffic lanes.

**Anti-icing**  A bonding inhibitor, for example salt, is applied to the pavement prior to snowpack or ice formation, eliminating the need for de-icing. Anti-icing is generally more efficient than de-icing, but good weather information is necessary to time the chemical application before precipitation starts (Minsk, 1998).

**Bare surface**  The roadway is bare to at least ¾ of the observed road section. A completely bare surface is identical to the pavement surface condition in summer. The bare surface can be Dry, Moist, or Wet. If puddles of water are visible or if windscreen wipers are needed when following another car, even if there is no precipitation, the road surface is considered to be wet. Otherwise it is moist or dry (Möller and Öberg, 1990).

**Black ice**  A thin layer of ice on the road surface. It is called “black” ice, since it is transparent and therefore nearly invisible under most lighting conditions (Minsk, 1998).

**Brine**  A saturated salt solution containing about 20 to 25 % by weight of Sodium Chloride, NaCl, (Öberg, Gustafson and Axelson, 1991).

**Complementary snow clearance**  Finishing snow clearance by complementary work where mechanical equipment has failed to reach. For example, improving sight conditions at crossings and in connection to tunnels by cutting snow banks and removing snow, and to clear the way to push buttons at traffic signals and in stairs and overpasses, etc.
<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
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<tbody>
<tr>
<td>De-icing</td>
<td>A chemical method to break the strong bonds between packed snow or ice and a pavement that has received no bond-prevention treatment (Minsk, 1998).</td>
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<tr>
<td>Graded gravel</td>
<td>Natural granular stone particles washed and processed to get a range of specified sizes (here between 2 and 5 mm).</td>
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<tr>
<td>Grit</td>
<td>Small hard fragments of mineral aggregate for application to a road surface (BSI, 1967). The general term for graded gravel, abrasive, sand etc., used in gritting.</td>
</tr>
<tr>
<td>Gritting</td>
<td>The operation of spreading all kinds of grit, such as, abrasive, graded gravel, sand, etc., on a road surface, to counteract slipperiness caused by frost, snow, etc.</td>
</tr>
<tr>
<td>Hoarfrost</td>
<td>Small water droplets in the air just above the road surface will freeze nearly instantaneously upon contacting a cold pavement and form hoarfrost. Hoarfrost is a light, feathery deposit that is generally not tightly bonded to the pavement, since the contact area is very small (Minsk, 1998). Its colour is usually white.</td>
</tr>
<tr>
<td>Ice and snow conditions</td>
<td>Ice and snow conditions are considered to prevail if at least ¾ of the road section is covered with hoarfrost, ice, snow, or slush from a continuing or earlier snowfall. The condition may also stem from super-cooled rain or moisture that creates ice (Möller and Öberg, 1990).</td>
</tr>
<tr>
<td>Level of service</td>
<td>The combination of operating conditions that may occur on a given lane or roadway when it is accommodating various traffic volumes. A qualitative measure of the effect of a number of factors, which include speed and travel time, traffic interruptions, freedom to manoeuvre, safety, driving comfort and convenience, and operating costs (HCM, 1965).</td>
</tr>
<tr>
<td>Loose snow</td>
<td>Snow on a road surface not yet packed and therefore may be scraped from the pavement by one’s fingers (Minsk, 1998).</td>
</tr>
<tr>
<td>Maintenance</td>
<td>A measure whose object is to restore the properties of structures, facilities, and devices to the level intended at the time of original construction or a later improvement (SNRA, 1990a). Maintenance measures have a residual value at the end of the year, as opposed to operation measures.</td>
</tr>
<tr>
<td>Mixed road conditions</td>
<td>Mixed road conditions are considered to prevail when between ¼ and ¾ of the road section has ice and snow conditions. If less than ¼ of the road section is covered with ice and snow, the road condition is defined as Bare surface and if more than ¾ the road condition is Ice and snow conditions.</td>
</tr>
</tbody>
</table>
**Operation**

The measures necessary to ensure that roads, bridges, and traffic facilities have at all times the functional properties they are designed for (SNRA, 1990a). Operation measures have no residual value at the end of the year.

**Packed snow**

The surface of packed snow is hard and cannot be scraped off without the use of a tool (Minsk, 1998). Packed snow is distinguished from *Thick ice* by its white colour (Möller and Öberg, 1990).

**Patches**

The roadway has *Ice and snow conditions* as well as visible pavement along the roadway. The visible pavement can either be *Bare surface* or covered by *Black ice*. If at least ¾ of the road section consists of one road condition, that condition is considered as the prevailing one (Möller and Öberg, 1990).

**Rut**

A groove or depression formed in a surface layer of a road by wheels of vehicles (BSI, 1967). In winter ruts appear when the roadway is covered with ice, snow, hoarfrost, or slush and wheels have worn the ice/snow layer so that the pavement is clearly visible in the ruts, either as *Bare surface* or through *Black ice*. Ice and snow exists between the ruts. In other words, different conditions occur across the roadway. If the pavement is not visible, the road condition is defined as *Ice and snow condition* (Möller and Öberg, 1990).

**Sand**

A non-cohesive granular material, usually under 2 mm, resulting from the natural disintegration of rocks and consisting mainly of mixtures of irregular or sub-angular and rounded particles.

**Skid control**

Mechanical or chemical measures to provide an increase in friction of a snow- or ice-covered road surface to prevent slipperiness.

**Slag**

The stony product resulting from metallurgical processes (BSI, 1967).

**Slush**

Slush contains more water than *Loose snow*, does not compact, and remains in a soft, loose state on the road surface (Minsk, 1998).

**Snow clearance**

Clearing snow from the road surface, using snowploughs, sweepers, or snowblowers.

**Snow removal**

The large volumes of snow cleared from roads, cycleways etc. may exceed the storage capacity of untrafficked areas. To enhance traffic safety and accessibility, snow masses have to be removed from built-up areas of cities and placed in disposal sites.
**Thick ice**
A surface of *Thick ice* may only be broken by an axe or by another implement (Minsk, 1998). The difference between *Thick* and *Black ice* is characterised by its transparency. The pavement is visible through black ice but not through thick ice (Möller and Öberg, 1990).

**Time to operate**
The time it takes to complete an operation, for example, snow clearance or skid control, after the starting condition is reached.

**Tracks**
Longitudinal depressions or markings on a road surface caused by the passage of vehicles following approximately the same track (BSI, 1967).

**Abbreviations**

- **CDU** Centre for Research and Education in Operation and Maintenance of Infrastructure
- **FinnRA** Finnish National Road Administration
- **KTH** Royal Institute of Technology
- **NVF** Nordic Road Association
- **PFT** Portable Friction Tester
- **SALA** Swedish Association of Local Authorities
- **SNRA** Swedish National Road Administration
- **VTI** Swedish National Road and Transport Research Institute
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