Vehicle Speed and Flow in Various Winter Road Conditions

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Continuous measurements of traffic and weather variables were undertaken at five road sites in central Sweden during the winter of 1998–1999. Visual observations of the state of the roads were made at the same time. Traffic measurements, with the vehicles grouped into three categories, included vehicle speed and flow. Data were aggregated as average values per hour. Weather data were gathered from Road Weather Information Systems stations of the Swedish National Road Administration close to the observation sites. The data included precipitation (rain or snow), intensity (mm/h), risk of slipperiness due to hoarfrost and other similar conditions, air temperature, road surface temperature, wind force, and wind direction. Observations were made on weekdays from 6 a.m. to 8 p.m. Observational frequency of road states varied from twice per day to once per hour depending on the situation. The road states were classified into one of 18 categories depending on road surface characteristics. A new data analysis method was developed whereby traffic data for hours of normally similar traffic conditions were compared. Any observed differences could therefore be assumed to be associated with different weather or road conditions. The method takes into account daily, weekly, and seasonal variations in speed and flow. The analysis resulted in data for the average speed and flow for any particular road state compared with averages for bare road conditions. For speed, significant, systematic, and plausible differences were established. Road surface conditions, however, were shown to have no systematic influence on traffic flow, suggesting that weather is probably a more important factor.

To meet drivers' needs for safety and accessibility, road networks must be kept in good condition. Pavement should be even and free of ruts, cracks, and other damage. To maintain good friction in winter, roads must be clear of ice and snow. However, with the limited resources available to road administrators, these goals cannot always be achieved, and priorities must be established regarding what actions to take when, where, and how. To optimize maintenance actions (or at least enable making sufficiently good choices), administrators use management systems that require an assessment of the effects of road conditions and maintenance efforts on road users.

Winter conditions imply snow and ice on the road surface, which lead to considerable socioeconomic consequences mainly as a result of increased accident risk, reduced accessibility, and increased vehicle cost. Environment is also affected primarily as a result of salting actions. The relationship between weather, traffic, maintenance actions, and road conditions is illustrated in the Winter Model flowchart (Figure 1).

The Winter Model consists of submodels for assessing the state of the road, its effects and their appraisement, and road maintenance optimization. For some of the submodels, relevant variables and effect relations are known, but there are many areas in which far more knowledge is required, knowledge that can only be obtained by assiduous effort.

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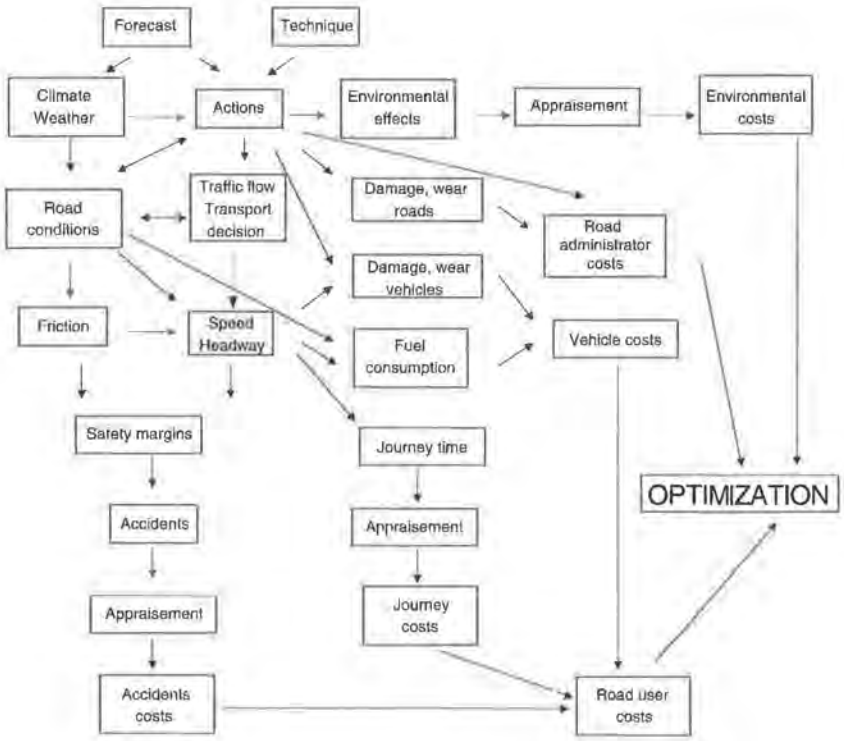


FIGURE 1 Winter Model for optimizing winter road maintenance: relation among different effects.

The most practical way to develop the Winter Model is to study the submodels individually. This approach takes into account the needs of the main sponsor of this project, the Swedish National Road Administration (SNRA), which is providing long-term financing for the project.

One important submodel, which is also useful alone, describes the relationship between weather, traffic, maintenance actions, road condition, and vehicle speed and flow, as shown in Figure 2.

The effect of roadway ice and snow on traffic speed and flow is not well understood, mainly because conditions vary and may exist only for a short period. A successful assessment of these effects calls for very close monitoring of the road state and the weather. The winter road surface state cannot be described by one uniform condition; a number of ice and snow states for the road have to be defined. In addition, the difficulties of measuring vehicle speed and flow are considerable. In Sweden, traffic measurements are

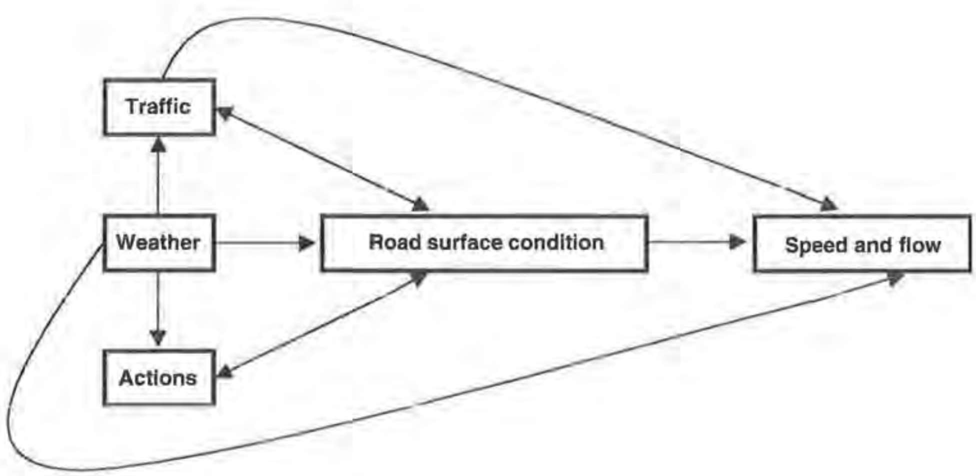


FIGURE 2 Relation among traffic, weather, actions, road surface, and speed and flow.

generally carried out using rubber tube sensors, which are not suited to winter conditions. Until now, the quality of data has been too poor to support any detailed analysis.

Hypothesis

In winter, the road surface may be covered with snow and ice. This cover is subject to influence by the weather, maintenance measures, and traffic. The properties of the ice and snow cover (such as its appearance, extent, texture, and friction) influence drivers' behavior. This effect can be measured by variations in vehicle speed and flow. Other important factors influencing driver behavior are precipitation and visibility.

Measuring vehicle speed and flow while simultaneously monitoring weather and road surface conditions will yield data that can be used to develop reliable models for estimating effects.

Method

Selection of Sites

The goal of this project is to study representative roads all over Sweden, an undertaking that will last several years. For the first year (represented in this paper), the intention was to choose sites where there existed a high possibility of frequent icy and snowy road conditions so that data capture routines, database management, and analysis methods could be tested. The roads were preferably to be nonsalted and have fairly low traffic volumes.

For practical and financial reasons, the number of sites was restricted to five. All sites were two-lane roads located in central Sweden. Data describing the sites are shown in Table 1.

Traffic Data

The SNRA's standard equipment for measuring traffic data was used for this project. However, to ensure good performance under any road surface condition, standard tube sensors were exchanged for inductive loop sensors. There was a loss of accuracy in vehicle classification, but this was a minor disadvantage compared to the added reliability of the system. Vehicle speed and flow were recorded as average hourly values. Three vehicle categories were distinguished: private cars, trucks with no trailer (including buses), and trucks with trailer. Data were collected separately for the two road directions.

Weather Data

SNRA has about 660 Road Weather Information Systems (RWIS) stations across Sweden. On average there is one weather station per 150 km of national road. There were no significant obstacles in finding suitable stations for each of the different road categories involved in this project.

Raw data from RWIS required only light processing. The data were acquired hourly by air temperature, road surface temperature, precipitation quantity, wind direction, wind force, and weather situation (fair, rainfall, snowfall, blowing snow across the road, or risk of slipperiness due to freezing rain or frost).

Traffic and weather data were transmitted by cellular phone to SNRA and forwarded to the National Swedish Traffic and Transport Research Institute (VTI) via the Internet.

Road Surface Observations

Two observers were trained for each observation site. Depending on the weather and road surface conditions, the observers were to note road conditions from twice per day to once per hour. The state of the road was broadly defined as either changeable or steady. Changeable conditions prevailed when there was precipitation, when the road was wet or moist or covered with soft snow, slush, hoarfrost, or black ice. Under these circumstances observations were made every hour (from 6 p.m. to 8 a.m.). Steady conditions prevailed in fair weather and when the road was dry and bare, or if the road was covered with hard-packed snow or thick ice. In the case of a steady state, only two observations per day were necessary.

TABLE 1 Data for the Five Sites, Winter 1998–1999

	Width (meters)	Speed limit (km/h)	AADT	Skid-control
Site #1	8.8	90	2000	Salt
Site #2	9.0	90	3130	Sand
Site #3	7.0	90	2000	Sand
Site #4	7.0	70	2680	Sand
Site #5	8.5	110	1000	Sand

Observations were made on only one lane of road. Five separate strips on the lane and two on the shoulder (as shown in the roadway cross section in Figure 3) were observed. More specifically, these strips were the outer and inner halves of the shoulder, the edge of the lane, the right rut, between the lane ruts, the left rut, and the middle of the roadway. Each strip was 100 m long. During each roadway observation the average condition of the 100-m strips were recorded. If the width of the shoulder was less than 1 m, no notes were taken for it. Observations were made from right to left as seen from the driving direction.

The strips were described in terms of bare pavement (dry, moist, or wet) or different kinds of snow or ice (soft snow, slush, hard-packed snow, thick ice, black ice, or hoarfrost). The thickness of soft layers was also measured, as was the width of ice or snow strips between the ruts and along the middle of the road.

Data Processing and Analysis

A custom-made database manager was developed for loading traffic, weather, and observed data into the database. The observed data were processed before loading, which involved applying a set of rules to categorize the conditions of the 100-m strips into 18 specified road states. Essentially these states were bare surface (dry, moist, or wet), hoarfrost, black ice, hard-packed snow, thick ice, soft snow, and slush. Rutted conditions were also defined. In the ruts the pavement must be visible and must be described as either bare pavement or black ice. Outside the ruts there were other kinds of ice or snow layers. The specified states may be viewed as a standard description of winter road surface conditions in Sweden and Norway. The traffic data were prepared before being loaded into the database by calculating the average speed for both directions and summing the two flows.

Instead of relying on the usual regression analysis, a new method of evaluation was developed. The underlying concept was to match pairs of hours in which only the weather and surface conditions differed. Each member in a pair should have close to equal traffic conditions (speed level and number of vehicles). Consequently, daily, weekly, and seasonal variability of traffic flow had to be taken into account. Daily variation was accommodated by comparing one particular hour with the same or adjacent hours on another day (e.g., the 9th hour on a Tuesday would be matched with the 8th, 9th, and 10th hour on a following Thursday). The weekly variation was considered by combining comparable days, such as Mondays and Thursdays, into one group; designating Fridays as their own group; and combining Saturdays, Sundays, and holidays as a last group. Seasonal variation was accommodated by limiting the time span for comparisons to a maximum of 14 days before the current day. The variability of the traffic was assumed to be applicable only for levels of speed and flow; accordingly, the differences between two different weather and surface conditions are presumed to be the same throughout the season. Each site was analyzed separately.

Theoretically, 153 different pairs are possible. Each member is primarily identified by its surface condition. A number of other attributes are attached to the member: date, hour, weather conditions, average speed and number of vehicles in each vehicle class, and a code for daylight or darkness. Briefly, the statistical analysis comprised a regression analysis of the result of all matched pairs and relating the differences to the speed at dry, bare surface conditions. Before performing the analysis, the data had to be prepared using sophisticated mathematical and statistical methods to eliminate redundant matches and weight data of members joined by more than one member. This statistical method will soon be published separately.

Results

The output from the analysis was hourly mean speed and flow for wet, icy, or snowy road surface states, expressed as divergences from the dry, bare surface condition. An

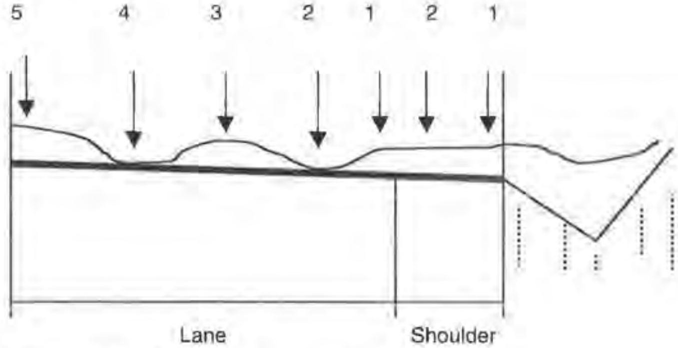


FIGURE 3 Observed strips on the roadway.

TABLE 2 Average Speed at Dry, Bare Surface Conditions

	Private cars	Trucks with no trailers	Trucks with trailers
Site #1	100.1	90.7	82.5
Site #2	98.6	89.6	83.9
Site #3	93.4	83.4	81.0
Site #4	77.3	78.8	74.4
Site #5	101.0	91.2	82.3

estimate of speeds at dry, bare states is shown in Table 2 as a 24-h average.

Results for the different road surface states are shown in Tables 3 and 4 for speed and flow, respectively. The tables comprise mean values and 95 percent confidence intervals for private cars. R stands for rutted conditions, B denotes bare surface in the ruts, and BI denotes black ice. "Hard" means that hard-packed snow or thick ice surrounds the ruts, and "Soft" indicates soft snow or slush. Finally, "Misc" (for "Miscellaneous") means that both soft and hard layers were found outside the ruts.

Speed

Some results were based on few observations, as can be seen by the large confidence intervals. However, most of the speeds at the different states of the road showed significant differences from the speed at bare road surface. There is great variation among the mean values; however, clear tendencies toward systematic divergences between different winter conditions can be noticed. For example, soft snow or slush generally results in greater speed reduction than black ice or hoarfrost. Rutted conditions with

TABLE 3 Speed Divergences from Dry, Bare Surface Conditions (Significant Values in Boldface)

Surface	Site #1	Site #2	Site #3	Site #4	Site #5
Moist	**-0.9 ± 0.9**	**-3.7 ± 1.3**	-1.1 ± 2.0	**-1.6 ± 1.2**	4.6 ± 7.9
Wet	**-3.0 ± 0.9**	**-4.1 ± 1.6**	**-3.5 ± 3.5**	0.2 ± 0.8	**2.6 ± 1.9**
Hoarfrost	**-7.3 ± 3.7**	-2.4 ± 3.3			-3.7 ± 13.6
Black ice		**-4.5 ± 1.2**	**-7.9 ± 2.7**	**-1.3 ± 0.5**	**-5.8 ± 2.1**
Hard snow	**-14.0 ± 3.0**	**-16.0 ± 3.1**	**-9.4 ± 1.7**		**-6.2 ± 3.3**
Thick ice					
Soft snow	**-12.5 ± 1.9**		**-7.9 ± 3.4**		
Slush	**-11.3 ± 1.9**	-4.3 ± 9.5	**-11.2 ± 8.2**		
R(B, Hard)	**-6.4 ± 3.3**	**-5.8 ± 1.4**	**-5.6 ± 1.3**	**-2.7 ± 2.4**	**-7.0 ± 5.6**
R(B, Soft)	**-5.9 ± 1.1**	**-7.9 ± 1.5**	**-2.0 ± 2.7**		0.3 ± 6.1
R(B, Misc)	**-2.1 ± 1.4**	**-1.4 ± 1.0**	**-1.8 ± 1.5**	-0.3 ± 1.3	**-7.5 ± 2.8**
R(BI, Hard)		**-7.2 ± 1.0**	**-8.0 ± 1.3**	**-2.7 ± 1.2**	**-4.5 ± 1.2**
R(BI, Soft)	**-5.2 ± 2.3**	**-10.6 ± 1.3**	**-9.2 ± 2.7**	**-3.4 ± 0.9**	**-7.4 ± 2.2**
R(BI, Misc)		**-5.2 ± 2.3**	**-7.9 ± 1.6**	**-3.6 ± 1.1**	**-3.1 ± 1.5**

TABLE 4 Flow Divergences from Dry, Bare Surface Conditions (Significant Values in Boldface)

Surface	Site #1	Site #2	Site #3	Site #4	Site #5
Moist	**11.9 ± 10.0**	–0.9 ± 12.0	0.4 ± 16.0	**35.6 ± 18.3**	–2.4 ± 23.0
Wet	**15.1 ± 11.0**	10.6 ± 15.3	**47.9 ± 28.2**	**26.7 ± 12.7**	**10.5 ± 5.4**
Hoarfrost	17.2 ± 43.5	–24.4 ± 30.3			7.6 ± 39.6
Black ice		**–27.0 ± 11.5**	**–30.3 ± 20.4**	**14.4 ± 7.1**	3.2 ± 6.1
Hard snow	33.6 ± 34.8	**53.8 ± 28.8**	**–16.2 ± 14.1**		1.3 ± 9.8
Thick ice					
Soft snow	**–36.2 ± 22.7**		**–42.5 ± 27.4**		
Slush	–15.7 ± 22.3	15.4 ± 88.5	–22.4 ± 78.0		
R(B, Hard)	–12.0 ± 38.5	–7.8 ± 13.1	**–30.0 ± 10.2**	21.7 ± 37.1	4.1 ± 16.4
R(B, Soft)	**12.9 ± 12.4**	12.6 ± 13.9	–2.1 ± 22.1		2.6 ± 17.9
R(B, Misc)	**16.6 ± 15.9**	**–27.0 ± 9.7**	**–44.4 ± 11.8**	–12.6 ± 20.5	**–8.4 ± 8.0**
R(BI, Hard)		**–32.0 ± 9.6**	**–38.7 ± 10.3**	**19.5 ± 18.6**	**–7.8 ± 3.4**
R(BI, Soft)	–14.1 ± 27.5	–4.2 ± 12.2	–11.7 ± 21.6	**27.4 ± 13.7**	–1.1 ± 6.5
R(BI, Misc)		**–26.0 ± 21.5**	–5.8 ± 12.9	**30.6 ± 16.7**	**–12.9 ± 4.2**

black ice in the ruts lead to greater speed reductions than bare surface in the ruts. Moist or wet surfaces are generally associated with only slight speed reductions.

The analysis lacks any estimation of the influence of weather conditions. So far this influence has been studied in only a couple of case studies (see the section on case studies below).

Flow

In Table 4, flow divergences are given as the number of vehicles per hour. (A better measure would be the ratio of the numbers at prevailing conditions and at bare surface conditions). Differences in flow do not appear related to surface conditions. It is thus concluded that road states have very little influence on the decision to make a trip, especially for the roads in this study, many of whose users are long-distance ski tourists. The weather may well prove to be a more important factor.

Case Studies

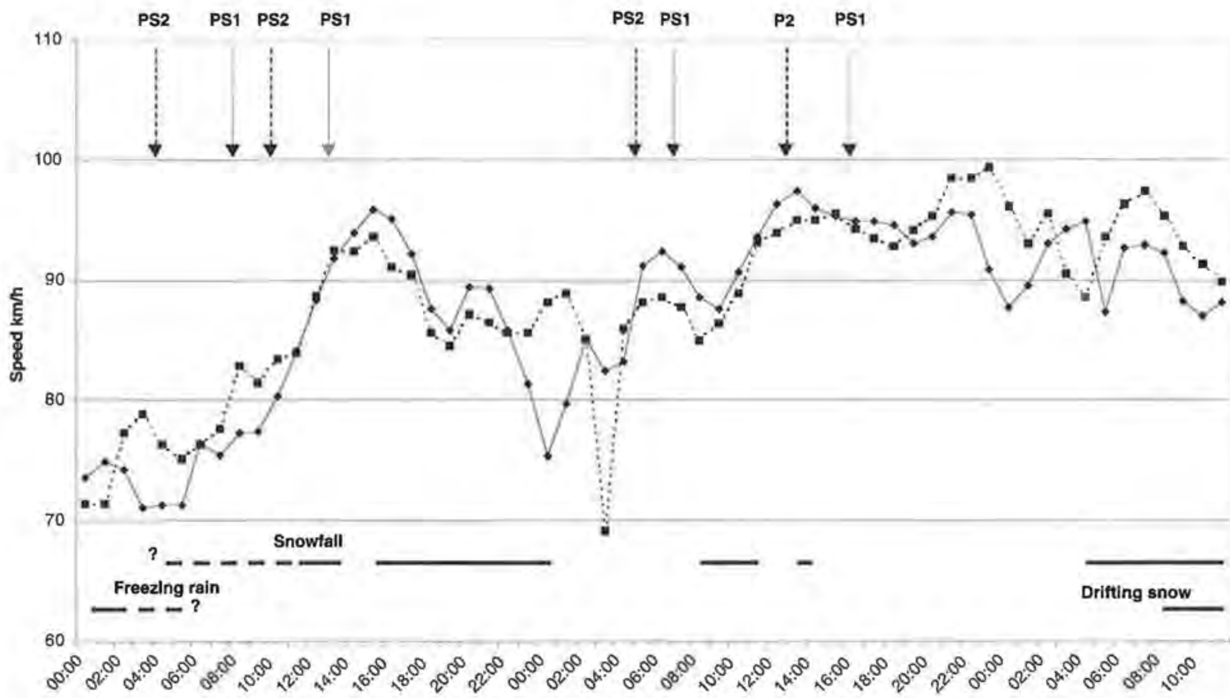
The data acquisition method and its close monitoring of traffic, weather, and road surface conditions meant that it was possible to follow the course of events during adverse weather conditions. This opportunity was twice utilized. One such event is shown in Figure 4. Here the observations of road conditions were extended so that 36 h of consecutive observations were obtained during the worst hours. The hourly average speed of private cars is plotted for each direction, together with weather data such as snowfall and blowing snow due to vehicle movement. Plowing and salting actions are also plotted in Figure 4 for the time they occurred at the observation site. It is possible to follow the speed adaptation to changing surface conditions, snowfall, visibility, snow control measures, and other factors.

To isolate the effect of weather, a small study was carried out for two successive days: the first had fair weather, and the second had snowfall as well as blowing snow due to vehicle movement. As can be seen in Table 5, significant speed differences in both directions were recorded.

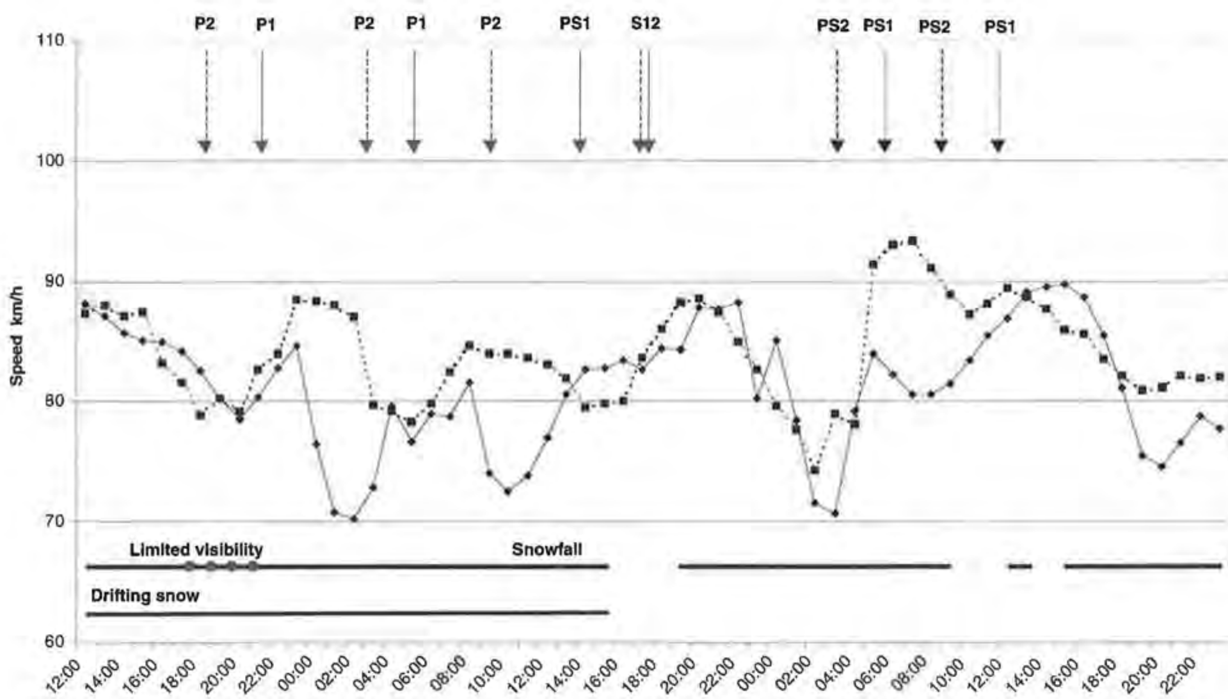
CONCLUSIONS

The methods for data acquisition, storage, and evaluation proved to work very well, thereby reinforcing intentions to successively extend surveys across Sweden.

The first results concerning speed reductions at different road states might, with some caution, be interpreted as follows:



(a)



(b)

Legend: Direction 1: continuous line, direction 2: dashed line
Px: plowing in direction x, Sx: salting in direction x
PSx: combined plowing and salting in direction x.

FIGURE 4 Hourly average speed at Site 1 for private cars during intense snowfall: (*a*) March 1–3, 1999; and (*b*) March 3–5, 1999.

TABLE 5 Weather Influence on Average Speed of Private Cars

Date	Hours	State of the road	Weather	Average speed	
				Dir. 1	Dir. 2
Feb 18 1999	9 – 18	Dry, bare	Fair	92.0	91.6
Feb 19 1999	9 – 18	Dry, bare	Snowfall, blowing snow	80.7	84.1

- The reduction for moist or wet bare surface is not unambiguous. For private cars the indicated reductions are 2 km/h for moist surfaces and 3 km/h for wet surfaces.
- For conditions with hard-packed snow, hoarfrost, or black ice, and rutted conditions with black ice in the ruts, the decrease for private cars is about 7 to 9 km/h.
- For conditions with soft snow or slush the corresponding value is 10 to 12 km/h.
- For rutted conditions with bare surface in the ruts, the corresponding value is 4 to 6 km/h.
- Trucks with no trailer generally have lesser speed reductions than private cars (about 2 to 4 km/h), whereas trucks with trailer reduce speed even less (by only 1 or 2 km/h).

ACKNOWLEDGMENT

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