Economic Impact of Winter Road Maintenance on Road Users

RASHAD M. HANBALI

State and local governments spend significant amounts of both human power and money annually on snow and ice control programs. On the basis of previous studies expenditures to counteract adverse road surface conditions during snow and icy conditions consume as much as 33 percent of some state highway maintenance budgets. These poor road surface conditions exist for only 4 to 8 percent of the total time that these roads are used. Expenditures of this magnitude have traditionally been justified through improved road user benefits, usually increased safety and decreased traffic delay. An important objective of evaluating the effectiveness of winter road maintenance operations (salting, plowing, and following a bare pavement policy) is determination of the economic impact of such operations on road users from a safety standpoint. The approach taken in evaluating the financial benefits of removing the adverse road surface conditions during snow and icy conditions is to compare the savings (benefits) to the costs expended in deriving them. It is concluded that winter road maintenance operations result in average direct savings to road users of 45 and 20 cents per vehicle kilometer of travel on two-lane highways and multilane freeways, respectively. The costs of winter road maintenance operations are offset by the benefits within the first 35 min after establishing bare pavement.

During winter, snow and ice on streets, roads, and highways cause hazardous driving conditions. Failure to act and deice roads effectively and as soon as possible creates general threats to the health and safety of the members of the community. Reducing the level of effort for snow removal and ice control has immediate consequences on traffic delay, traffic volumes, traffic congestion, and the public's image of the state department of transportation. Without close attention to the effective removal of snow and ice from streets, roads, and highways during periods of snow and icy conditions, local economies will suffer, traffic accidents will escalate, and most activities of individuals, industries, utilities, schools, and governments are handicapped in social and economic ways. This paper analyzes and evaluates the economic impacts of winter road maintenance operations (salting, plowing, and following a bare pavement policy) on road users in three states (New York, Illinois, and Wisconsin) and shows any cost savings per vehicle kilometer of travel (VKT).

BACKGROUND

A methodology was prepared for selecting the test sections and reviewing the exposure data, winter maintenance operations records, and traffic accidents on all of the selected test sections in the three states (*1,2*). The methodology covered the traffic accidents that were reported to have occurred during the research periods on two-lane highway test sections totaling 1,600 lane-km in New York (Wayne and Tompkins counties), Wisconsin (Walworth County), and Illinois (Ogle and Lee counties) and on multilane divided (freeway) test sections totaling 400 lane-km in New York (Cortland and Monroe counties), Wisconsin (Walworth County), and Illinois (Ogle County). In addition to the traffic accident data detailed information was also available on winter road maintenance operations, including the date, the operation route, times of salt applications, state of the weather, the time of day, and so on. A very time consuming before-and-after method was used to analyze these data. After determining the hour that the deicer (salt) application (just preceding the establishment of bare pavement) occurred (zero hour), hourly intervals were taken backwards and forwards (up to 12 hr in each direction) (*1,2*). The incident of each reported traffic accident was determined by time, severity, location, and traffic density. These data were then used to work out traffic accident rates and cost rates for every elapsed time (12, 11, . . . , 1) before establishing bare pavement and its conjugate after. An illustration of the compilation approach is presented in Figure 1. The reduction in traffic accident rates from before to after were found to be statistically significant (*2*). The methodology was presented in detail in an earlier paper (*2*).

ECONOMIC ANALYSIS

After confirming that the reduction in traffic accident rates from before to after were statistically significant (*1,2*) at the selected level of confidence (99 percent, 95 percent, or both), it is appropriate to conduct the economic analysis for winter road maintenance and its impact on traffic accident occurrence. Conclusions on costs and benefits documented in other studies and serving the purpose of the present analysis were reviewed.

Literature Review

A benefit-cost analysis study is one that identifies both the beneficial effects and the cost effects of winter road maintenance operations and that quantifies all effects in term of dollars. Comparisons can then be made to determine whether the economic benefits exceed the costs. The costs of winter road maintenance can be classified as follows:

1. Direct costs, that is, expenditures made by a government agency to remove snow and ice:
   –Labor,
   –Equipment,
   –Materials, and
   –Administration.

Bureau of Traffic Engineering, City of Milwaukee, 841 North Broadway Street, Room 909, Milwaukee, Wis. 53202.

STEP ONE:
- For each sub-event; two points of time need to be identified:
  - The approximate time of establishing the policy's goal on the testing section "**P**"; and
  - The hour that the deicer application (just proceeded the establishment of the policy's goal) occurred is called zero hour "**0**".
- Take hourly intervals backwards and forwards (up to 12 hours) from "**0**", and identify each interval's traffic volume and accidents.

HWY Section	Sub-event	Sub-events *(shaded cells below)* based on hour of the day																							
1	1	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	0	17	P	19	20	21	22	23	24
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	2	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	0	P	23	24
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
87	3979	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
		0	2	P	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24

STEP TWO:
- Hourly intervals are now defined by relative hours (n; where n = -12, -11, ..., -1, +1, ..., +11, +12) before and after the "**0**";
- For all sub-events; categorize and total traffic accidents, and calculate and total VKmT per each relative hour (n); and
- Calculate the traffic accident rates for each elapsed time (Z Hours; where Z = 12, 11, ..., 1) before and its conjugate after.

HWY Section	Sub-event	Sub-events *(shaded cells below)* based on relative hour (n)																							
		Before (-)												0	After (+)											
1	1	12	11	10	9	8	7	6	5	4	3	2	1	0	1	2	3	4	5	6	7	8	9	10	11	12
1	2	12	11	10	9	8	7	6	5	4	3	2	1	0	1	2	3	4	5	6	7	8	9	10	11	12
•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
87	3979	12	11	10	9	8	7	6	5	4	3	2	1	0	1	2	3	4	5	6	7	8	9	10	11	12
Hourly Total		Categorized traffic accidents & VKmT for each n												0	Categorized traffic accidents & VKmT for each n											
Accident Rates		For each elapsed time (Z hours) from the zero hour												0	For each elapsed time (Z hours) from the zero hour											

FIGURE 1 Compilation approach for two-lane test sections.

2. Indirect costs, that is, expenditures resulting from the procedures or conditions used for winter road maintenance:
   - –Damage to vehicles from deicing materials,
   - –Damage to pavements and structures from deicing materials,
   - –Property damage and deaths resulting from accidents between winter maintenance equipment and vehicles,
   - –Costs to the user to remove snow and ice from driveways, and
   - –Other indirect costs.

In all studies conducted so far the direct costs are of primary interest. It has also been found that it is an extremely expensive operation to get accurate estimates of indirect costs. Minimizing the direct costs while achieving the desired appropriate level of service is a major goal in most highway departments. In the Snow Belt states every highway agency has been trying to make winter road maintenance operations as cost-effective as possible. Safe winter driving conditions must be provided to the public; at the same time expenditures must be kept to a minimum, since winter road maintenance operations do not provide any lasting improvement to the highway system. Labor represents the largest class of expenditure in highway maintenance activities. The level of winter road maintenance can vary from one unit of government to another, as well as within a unit of government; the expenditures including all of the direct and indirect costs vary accordingly. Each county or state can calculate the range of expenditures for direct costs at the end of each winter season. This range depends mainly on the number of snowstorms, the actual depth of snow, the water content of the snow, the duration of the storms, temperature, prevailing wind, and other factors.

The benefits that accrue as a result of the open roads in winter can be classified as follows:

1. Direct benefits, that is, road user savings from using the road during snow and ice conditions:
   - –Vehicle operating cost reduction;
   - –Travel time reduction; and
   - –Avoidance of property damage, personal injury, or loss of life.
2. Indirect benefits, that is, those benefits derived from the community:
   - –Availability of community services (hospitals, postal services, schools, police, and fire protection), and

–Maintenance of business (industry, government, personal income).

Many of the benefits are intangible. The most commonly claimed road user benefits have been increased safety and decreased traffic delays, particularly in urban areas. These benefits are the most recognized and immediately apparent during snow conditions. Changing the level of service or the level of effort for snow and ice removal and control have immediate effects on road users' safety, travel time, traffic volumes (which can be altered), traffic congestion, and public acceptance.

Vehicle Operating Costs

In reality and as a result of an effective snow and ice control policy, there have been many savings in vehicular operating costs. For vehicles some savings are generally converted to time savings by driving at increased speeds, with a probable increase in fuel and tire costs (*3*).

Fuel Consumption

All fuel consumption economic estimates for vehicles on snow- and ice-covered highways were derived from Claffey's work (*4*).

1. Road surface. Claffey (*4*) considered the road surface condition to be an important variable affecting average vehicle fuel consumption. The average operating pavement speed during snow and icy conditions was converted to fuel consumption in liters per kilometer (gallons per mile). The excess fuel consumption per kilometer (mile) multiplied by highway length yielded the total number of liters (gallons) of fuel consumed in excess of normal fuel consumption. Fuel consumption varies with travel speed, and this has been accounted for in Claffey's work, as shown in Table 1 (*4*).
2. Type of vehicle. In Claffey's work (*4*) additional fuel consumption was applied only for passenger car vehicles, light trucks, and vans. For estimating additional fuel consumption it was assumed that large trucks did not contribute to traffic volumes during snow.
3. Level of service. The level of service would affect the fuel consumption rate of vehicles traveling through snow and ice conditions. In a given snowstorm the snow and ice control policy set for the level of service would form the basis for the best estimate of road surface conditions. Modification of the level of service affected the economics of fuel consumption by causing corresponding changes in pavement condition (*4*).

Tires, Oil, and Vehicle Maintenance

During snow and ice conditions vehicle operating expenses such as those for tires, oil, and vehicle maintenance have not been studied or included in any research to date. These expenses are usually a function of distance and are not time driven (*3*). As a result of changing the level of service, the changes in these expenses are considered to be insignificant.

Fixed Operating Costs

Fixed operating costs (insurance, depreciation, taxes) are yearly expenditures and are not a function of time or distance driven (*3*).

Travel Time

As a result of snow or ice on pavement the vehicle traveling time on a given highway segment increases. For a given highway trip the vehicle traveling time with snow and ice on the pavement must be compared with the normal vehicle traveling time under dry pavement conditions. Normal trip times have been related to the type of highway, traffic volume, capacity ratios, sight distance, time of day, and many other variables (*5*). The magnitude of the delay for any one vehicle is given by (*6*)

$$\text{Delay} = \text{trip length} \times \left(\frac{1}{\text{snow speed}} - \frac{1}{\text{normal speed}}\right) \qquad (1)$$

The total delay for all vehicles traveling on a given roadway segment can be calculated from

$$\text{Total delay} = \frac{\text{mean delay} \times \text{AADT} \times M_i \times D_j \times H_k \times V_r \times L}{\text{average trip length}} \qquad (2)$$

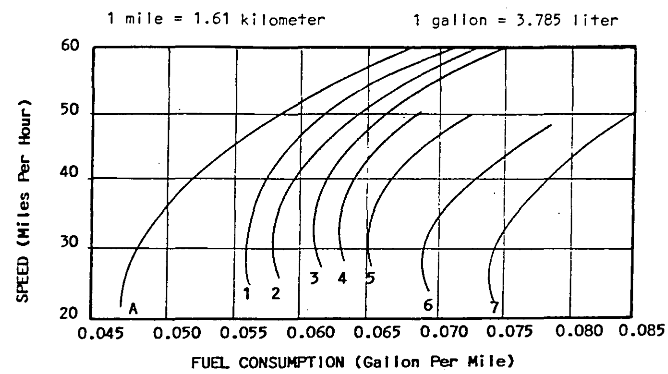
where

AADT = average annual daily traffic,
M_i = traffic monthly factor for month i of year,
D_j = traffic daily factor for day j of week,
H_k = hourly index for hour k of day,
V_r = volume reduction factor because of snow, and
L = roadway segment length.

It has been the custom in highway economics studies to price travel time in dollars, so that the figures could be used in the economic analysis. No publication so far has determined the value of travel time in a scientific manner. The basic work was done by Claffey (*4*) in 1960 and 1961. The result of Claffey's work (*4*) was the value of \$1.42/hr for a passenger car. Later two more studies were published by Thomas and Thompson (*7*) and Lisco (*8*). The study of Thomas and Thompson (*7*) followed the same procedure used by Claffey (*4*), but with a much improved mathematical model. The study of Lisco (*8*) was done in the Chicago Loop area, and it compared the cost of driving vehicles with riding the rapid transit rail system. The study of Lisco (*8*) used a mathematical model almost identical to that used in the study of Thomas and Thompson (*7*). The study of Thomas and Thompson (*7*) concluded a value of about \$2.80/person-hr, and the study of Lisco (*8*) concluded a value of \$2.50/person-hr. These two values in dollars per hour of travel time represent highly selective conditions (peak urban hours). The AASHTO *Manual of User Benefit Analysis of Highway and Bus-Transit Improvements* (*9*) presented a chart that can be used to obtain estimates of travel time value once the time savings per trip for a particular highway are known. However uncertainties over the exact time saved by cumulative improvements may be so great that it becomes a needless refinement to select the exact point on the curve that corresponds to the

TABLE 1 Passenger Car Fuel Consumption in Snow Belt States under Snow and Icy Conditions (*4*)

(a) Passenger Car Fuel Consumption in Snow Belt States under Snow & Icy conditions



A = Dry Pavement.
1 = Very Slippery Hard-Packed Snow and Ice.
2 = Hard-Packed Snow and Ice with irregular bumpy wippled surface.
3 = 12 mm. (1/2 inch) new snow on hard-packed snow.
4 = 19 mm. (3/4 inch) new snow on hard-packed snow.
5 = 25 mm. (1.0 inch) new snow on hard-packed snow.
6 = 38 mm. (1.5 inch) new snow on hard-packed snow.
7 = 50 mm. (2.0 inch) new snow on hard-packed snow.

(b) Correction Factors to Adjust Passenger Car Fuel Consumption for Snow & Icy Conditions

Speed (Km/Hr)	Dry Pavement	Very Slippery Hard-Packed Snow	Hard-Packed Snow & Ice with Bumpy Surface	New Snow on Hard-Packed Snow (mm)				
				12	19	25	38	50
32	1	1.23	1.30	1.36	1.43	1.47	1.51	1.60
48	1	1.16	1.20	1.28	1.32	1.35	1.45	1.54
64	1	1.11	1.14	1.20	1.23	1.28	1.40	1.48
80	1	1.06	1.10	1.12	1.18	1.24	1.34	1.45
96	1	1.04	1.08	1.10	----	----	----	----

Note: Correction factors are designed to be applied to values obtained from Claffey's charts and the above table (a).

estimated cumulative time savings for each curve. A conservative value of travel time per hour of $3.00 (1975 U.S. dollars) per passenger car was generally used throughout the AASHTO manual (*9*). This estimate was derived from a value of $2.40/person-hr and 1.25 persons/vehicle. For trucks the manual used a travel time per hour of $7 to $8/truck on the basis of 1975 truck driver wages and fringe benefits.

Accident Costs

Motor vehicle accident costs are an important component in benefit-cost evaluations of highway safety improvements. Among the attempts that were made in the last decade to provide comprehensive estimates of motor vehicle accident costs is a 1984 study by Miller et al. for FHWA (*10*). That study did not express accident costs in a form that can be directly used in benefit-cost analyses. In a paper published later accident costs from the cost data presented in the study by Miller et al. (*10*) and accident data from five states were developed by McFarland and Rollins for FHWA (*11*). These accident costs can be used directly with state accident data, thereby facilitating the use of state-of-the-art accident cost estimates in benefit-cost analyses of highway safety improvements.

Winter Maintenance Costs

The complexities of obtaining accurate cost records for municipal, county, and state governments are so great that an early decision was made to restrict the current study to cost records available from each testing area's department of transportation. The level of winter road maintenance can vary from one unit of government to another as well as within a governmental unit. Total cost information for winter road maintenance for each participating county was provided by the highway department authority in the respective state. These costs are based on the expenditures and direct costs of the winter road maintenance program during the winter season of each county's testing period. Figure 2 presents the winter road maintenance cost for each test area (the participating areas are not identifed in Figure 2) as the cost, in U.S. dollars per lane kilometer per average snowstorm (total snowfall divided by total number of snow and ice storms for each participating area).

METHODOLOGY

An assessment of the combined effects of winter road maintenance operations (salting, plowing, and following a bare pavement policy) on cost and traffic accident reduction was performed to determine whether the economic benefits exceed the costs and to show any cost savings per vehicle kilometers of travel.

Benefit-Cost Analysis

The computation of winter road maintenance benefits requires an estimate and calculation of the savings that would accrue to the highway users (direct benefits) and to the community (indirect benefits).

Winter Road Maintenance Benefits

In calculating the winter road maintenance benefits it is necessary to understand the following points:

1. The savings accruing from winter road maintenance are normally called benefits;
2. Winter road maintenance benefits are either difficult to measure in terms of dollars or border on being intangible; and
3. Almost all indirect winter road maintenance benefits are intangible; that is, the ability to assess a dollar value is impractical or cumbersome.

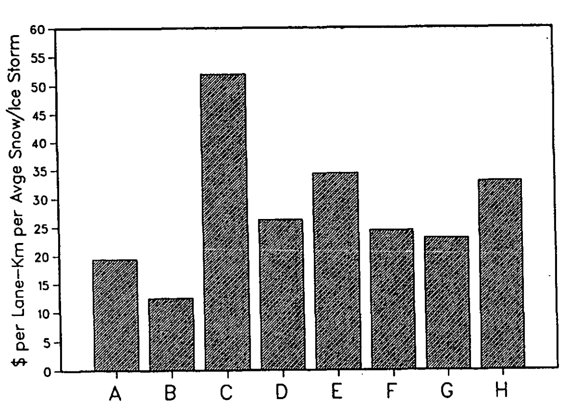


FIGURE 2 Average unit cost for winter road maintenance.

To strengthen the computation in this analysis all previous methods used in other research projects for computing road improvement benefits were studied. The road user savings considered for computing the direct benefits of winter road maintenance in this analysis were as follows:

1. Road user safety. As a result of winter road maintenance the primary benefit accrues from the reduction in the before traffic accident rates to its conjugate after. Two estimates of traffic accident costs (1980 and 1990) were presented earlier: the 1980 McFarland and Rollins (*11*) estimate for FHWA, which was updated to the year 1990, and the 1990 National Safety Council estimate (*12*). During the course of the present study a third 1991 FHWA estimate based on 1988 U.S. dollars and updated to the year 1990 was considered for accident cost calculations (*12*). The 1991 FHWA estimate based the costs of motor vehicle crashes on the allocation of scarce highway safety resources to maximize benefits and evaluated proposed safety regulations. The costs included medical expenses, emergency services, workplace costs, travel delay, property damage, and administrative and legal out-of-pocket expenses. It also included cost of wages and household production and cost of pain, suffering, and lost quality of life. On the other hand the other two estimates based their costs only on medical expenses, wage loss, insurance administration cost, and motor vehicle property damage. The 1991 FHWA estimate [$2,950,000/fatal accident, $75,400/injury accident, and $4,900/property damage only (PDO) accident] was used throughout the present study as the basis in traffic accident cost-related calculations. The road user safety benefit calculations are based on the traffic data discussed, analyzed, and evaluated in earlier papers (*1,2*). It should be noted that each winter road maintenance operation was studied very carefully. On the basis of winter road maintenance records provided by highway authorities, the approximate time of establishing their policy's goal (bare pavement) for each subevent (winter road maintenance operations on one test section to counteract snow and icy conditions during any one snowstorm) was determined. The deicer (salt) application that just preceded the establishment of the policy's goal was used for the analysis. For each subevent the hour that the deicer (salt) application occurred is called the zero hour. Traffic accident rates for each elapsed time (Z hr, where Z = 12, 11, 10, . . . , 1) before the zero hour and its conjugate after were calculated. Figure 1 illustrates the compilation approach for two-lane sections. To determine the effect of winter road maintenance on traffic safety, a comparison between each elapsed time's (Z hr) traffic accident rate before and its conjugate after was conducted. Figures 3 and 4 present a summary of the analysis results. The following example illustrates the procedure for the road user safety benefit calculations:

$$\text{Accident rate reduction}_{\text{categ},Z} = \text{rate}_{\text{before},Z} - \text{rate}_{\text{after},Z}$$

$$\text{Accident rate reduction}_{\text{inj},4} = 4.99 - 0.58$$
$$= 4.41 \text{ traffic accidents (injury)}/10^6 \text{ VKT}$$

$$\text{Accident rate reduction}_{\text{PDO},4} = 2.96 - 0.45$$
$$= 2.51 \text{ traffic accidents (PDO)}/10^6 \text{ VKT}$$

$$\text{Road user safety benefit}_4 = 4.41 \times 75{,}400 + 2.51 \times 4{,}900$$
$$= \$345{,}000/10^6 \text{ VKT}$$

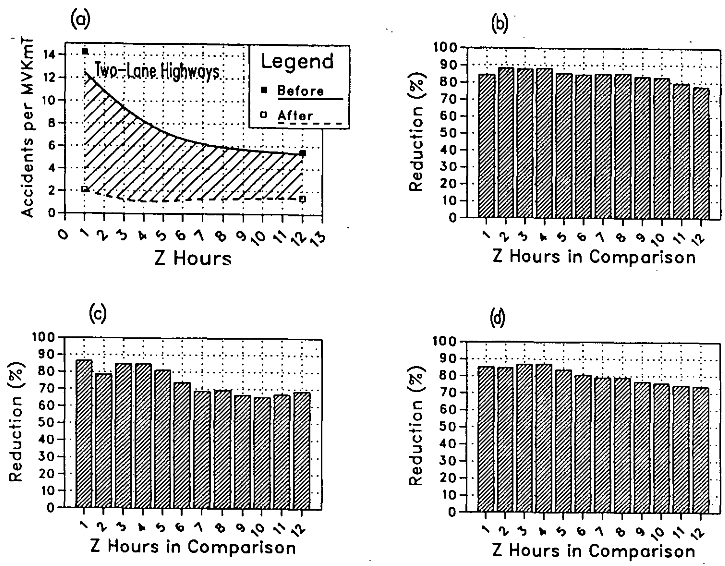


FIGURE 3 All traffic accident rates and their reductions from before to after on two-lane undivided testing sections: *a*, all traffic accident rates; *b*, injury rate reductions; *c*, PDO rate reductions; *d*, all accident rate reductions.

In addition to the road user safety benefit, AASHTO has summarized the benefits to road users in the form of reduced vehicle operating costs, decreased travel time, and increased comfort and convenience (*13*). The most important factor in determining these benefits as a result of winter road maintenance during snow and icy conditions is the running vehicle speed. Before predicting the speed of vehicles on the test sections during the winter period researched, it is necessary to know the conditions of the roadway before and after establishing bare pavement. As an example assume that present snow and ice maintenance operations were performed adequately during a snowstorm that lasted 6 hr and that the snowfall was about 50 mm (2 in.). Before the start of the storm state highway department trucks are loaded with a deicer (in the present study, salt) and are standing by. As soon as there is an indication that snow will stick, salt is applied to the roadways in the respective areas. During the first hour of the storm there

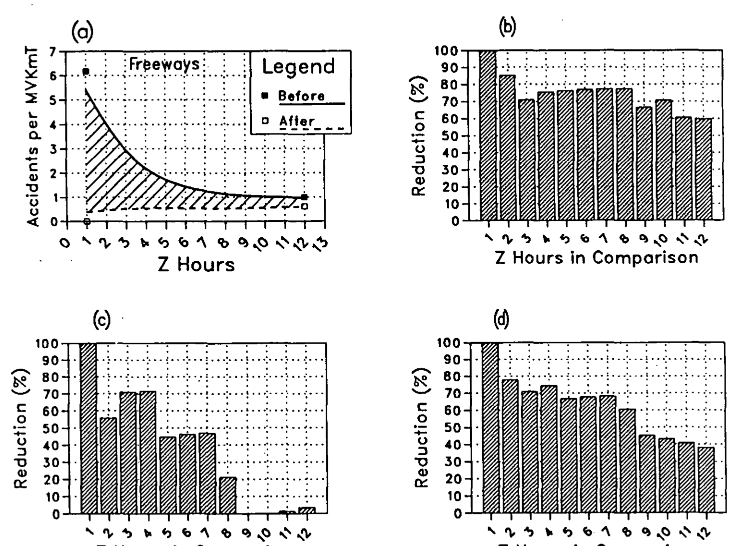


FIGURE 4 All traffic accident rates and their reductions from before to after on multilane divided testing sections: *a*, all traffic accident rates; *b*, injury rate reductions; *c*, PDO rate reductions; *d*, all accident rate reductions.

may be some accumulation of snow and this will tend to slow traffic. However the salt takes effect after this period and the pavement becomes wet and clear. Under light storm conditions [less than 50 mm (2 in.) of snow] the pavement generally remains clear throughout the entire storm after the first salt application. Traffic is able to maintain speed at all times except during the first hour.

Assume that nothing is done to the roadways. Once snow has started to fall on the test sections more would stick and accumulate. Under heavy traffic this would probably pack very fast and within 0.5 hr an ice crust would form. Traffic would slow considerably and the accumulated snow and ice would become quite rough. This would tend to slow traffic even more. Traffic would not be able to maintain normal speed during or after the storm. Traffic would be restricted to 32 to 48 km/hr (20 to 30 mph) on this icy road surface in comparison with a normal speed of 56 to 72 km/hr (35 to 45 mph) on two-lane rural highways and a normal speed of 40 to 56 to 90 to 105 km/hr (25 to 35 to 55 to 65 mph) on multilane rural freeways. A similar circumstance could be pictured for the various priority highways and different storm conditions. If temperatures remained low and nothing was done to remove ice from the pavement, the ice could remain on the highway for weeks.

A previous study (*6*) reported that the average ranges of vehicle speed reduction during snow and icy conditions were 18 to 42 percent and 13 to 22 percent on two-lane highways and freeways, respectively. In the present study, and to be conservative, the average vehicle speed reductions as a result of snow and icy conditions for two-lane rural highways and multilane rural freeways are 25 percent [16 km/hr (10 mph)] and 15 percent [15 km-hr (10 mph)], respectively, of their average normal speeds [65 and 100 km/hr (40 and 60 mph)]. Time savings are also generated from driving at normal speeds. Time savings or time losses associated with winter road maintenance can be valued within a marketable concept.

2. Vehicle operating cost. Snow and icy conditions restrict vehicle movement in a variety of ways, depending on the actual condition of the ice or snow on the pavement. The roadway surface condition has an effect on the vehicle operating cost. A slippery road surface or a road covered with snow and ice would tend to increase the vehicle operating cost. Snow, and particularly ice, increases fuel consumption by causing slippage of the traction wheels, which in turn produces engine revolutions without corresponding vehicle movement.

On the basis of the data presented in Table 1 the vehicle fuel consumption cost savings accruing from winter road maintenance operations on roadways were calculated as follows.

–By using Claffey's charts (*4*) presented in Table 1 the average operating vehicle speeds were converted to fuel consumption in liters per kilometer (0.435 gal/mi) as follows: [the conservative assumption is that the average snow accumulation is 12 mm (0.5 in.)]:

$$\text{Normal average vehicle speed, 40 mph} = 0.053 \text{ gal/mi} = 0.023 \text{ L/km}$$

$$\text{Adjustment because of snow } (0.053 \times 1.2) = 0.063 \text{ gal/mi} = 0.027 \text{ L/km}$$

$$\text{Normal average vehicle speed, 60 mph} = 0.068 \text{ gal/mi} = 0.029 \text{ L/km}$$

$$\text{Adjustment because of snow } (0.068 \times 1.1) = 0.075 \text{ gal/mi} = 0.032 \text{ L/km}$$

–The operation cost savings per vehicle kilometer was calculated by multiplying the excess fuel consumption in liters per vehicle kilometer

$$\Delta\text{LPK} = \text{LPK}_{\text{snow}} - \text{LPK}_{\text{normal}}$$

by the average fuel cost per liter during the test period [on the basis of the data obtained from the consumer price index (CPI) reports (1989 to 1991) for the average prices of gasoline during the months of the test period] and as follows:

$$\text{CPL} = \frac{\sum_{M=1}^{3-8} (\text{gasoline price} \times \text{VKT})_{M,\text{area}}}{\sum_{R=1}^{R=2} \text{VKT}_R} = \$0.50/\text{L}$$

where

CPL = average cost per liter of fuel (\$/L),
R = northeast or north-central region, and
M = testing period month.

The following example illustrates the procedure for the vehicle operating cost calculations:

$$\Delta\text{LPK} = 0.027 - 0.023 = 0.004 \text{ L/km}$$

$$\text{Fuel consumption savings} = 0.004 \times 0.5 \approx \$0.01/\text{VKT (conservative)}$$

3. Travel time. Severe weather conditions such as those resulting from snow- and ice-covered pavements increase the time of vehicle travel on a given highway section. Snow travel delay is the additional time required in an average trip beyond the normal travel time. The economic value of increased travel time on a highway section resulting from snow and ice is tempered by several variables, including type of vehicles, normal time delays, trip purpose, time of day, and increased fuel consumption. The procedure for determining the travel time savings that accrue from the winter road maintenance operations on the roadways is as follows:

–A conservative \$3.00 value of time savings per hour based on a 1975 estimate was obtained from the AASHTO manual (*9*). This value was updated to the year 1990 by using the gross national product (GNP) deflator:

$$\text{Time saving}_{1990} = \$3.00 \times \frac{\text{cost of market basket}_{1990}}{\text{cost of market basket}_{1975}} = \$3.00 \times 131.40/59.30 = \$6.65/\text{hr (conservative)}$$

and the CPI:

$$\text{Time saving}_{1990} = \$3.00 \times \frac{\text{cost of budget}_{1990}}{\text{cost of budget}_{1975}} = \$3.00 \times \frac{130.70}{53.80} = \$7.28/\text{hr}$$

Economists often consider the GNP deflator to be a better measure of overall inflation in the economy than the CPI. The CPI is based on the budget of a typical urban family. By contrast the GNP deflator is constructed from a market basket that includes every item in the GNP, that is, every final good and service produced by the economy. Thus in addition to prices of consumer goods, the GNP deflator includes the prices of airplanes, lathes, and other goods purchased by business. It also includes government services (*14*).

–On the basis of Equations 1 and 2 the following equation was generated and used to calculate the reduction in vehicle travel time (prevented delay) after the zero hour of salt spreading that was considered and used

$$\text{Average delay}\left(\frac{\text{hr}}{\text{VKT}}\right) = \frac{1}{\text{snow speed}_{\text{avg}}} - \frac{1}{\text{normal speed}_{\text{avg}}}$$

–The total savings value in travel time per vehicle kilometer of travel was calculated on the basis of the following equation:

$$\text{TTS} = \text{TSV}_{1990} \times \text{TS}$$

where

TTS = travel time saving value ($/VKT),
TSV_{1990} = updated time saving value ($/hr), and
TS = vehicle travel time saved per (hr/km).

The following example illustrates the procedure for the travel time saving calculations:

$$\text{Average delay} = 1/48 - 1/65 = 0.00545 \text{ hr/VKT}$$
$$= 20 \text{ sec/VKT (30 sec/VMT)}$$

$$\text{TTS}_{\text{GNP}} = 6.65 \times 0.00545$$
$$= \$0.036\text{/VKT (conservative)}$$

Winter Road Maintenance Costs

The computation of winter road maintenance costs requires an estimate and calculation of:

1. Expenditures made by a government agency to remove snow and ice from highways, roads, and streets (direct costs), and
2. Expenditures that result from the procedures or conditions utilized for winter road maintenance (indirect costs).

In calculating the winter road maintenance costs it is necessary to understand the following points:

1. The primary interest in most previous economic studies is the direct costs; and
2. It is a complicated and extremely costly operation to estimate accurate values for indirect costs.

The winter road maintenance direct cost used in the present analysis is the expenditures (labor, equipment, material, and administration) made by the government agency in each participating area to counteract snow and icy conditions on roads and highways. The direct cost was provided as a total cost rate [dollars/lane-kilometer (lane-mile)/average snowstorm] by the authorities in the highway department of each respective participating area. The average direct cost of winter road maintenance per lane-kilometer (lane-mile) per average event was calculated on the basis of the data presented in Figure 2, the length of the test sections, and the following equations:

$$\text{TDC}_p = \text{CR}_p \times \text{TL}_p \times \text{No. of Events}_p$$

$$\text{ADC (\$/lane-km/event)} = \frac{\sum_{p=1}^{4-5} \text{TDC}_p}{\sum_{p=1}^{4-5} (\text{TL}_p \times \text{No. of Events}_p)}$$

where

TDC_p = total direct costs during this study period in p area ($);
CR_p = cost rate of winter road maintenance in p area ($/lane-km/average snowstorm);
TL_p = total testing sections length in p area (lane-km);
ADC = average direct cost ($/lane-km/average event);
z = elapsed time after winter road maintenance (hr); and
p = for undivided highways, Wayne, Tompkins, Walworth, Ogle, or Lee county; for divided highways, Monroe, Cortland, Walworth, or Ogle county.

The following procedure illustrates the calculations (CR_{1-5} = cost rate not identified, but based on data presented in Figure 1) for the direct cost:

$$\text{TDC}_{\text{Walworth}} = \text{CR}_1 \times 116.3 \times 2 \times 14 = \$3{,}256.40\ \text{CR}_1$$

$$\text{TDC}_{\text{Wayne}} = \text{CR}_2 \times 101.8 \times 2 \times 46 = \$9{,}365.60\ \text{CR}_2$$

$$\text{TDC}_{\text{Tompkins}} = \text{CR}_3 \times 100.9 \times 2 \times 63 = \$12{,}713.40\ \text{CR}_3$$

$$\text{TDC}_{\text{Ogle}} = \text{CR}_4 \times 79.0 \times 2 \times 8 = \$1{,}264.00\ \text{CR}_4$$

$$\text{TDC}_{\text{Lee}} = \text{CR}_5 \times 19.3 \times 2 \times 6 = \$231.60\ \text{CR}_5$$

$$\text{TDC}_{\text{All}} = \$920 \times 10^3$$

$$\text{ADC (\$/lane-km/average event)}_{\text{two-lane}} = \frac{920 \times 10^3}{13{,}415.5 \times 2 \times 1.61}$$
$$= \$21.5\ (\$34.3)$$

$$\text{ADC (\$/lane-km/average event)}_{\text{freeway}} = \$37.0\ (\$59.3)$$

Road Users' Savings

On the basis of the preceding two sections the direct benefits and direct costs per vehicle kilometer of travel after winter road maintenance operations for both two-lane highways and freeways are presented in Figures 5 (*top*) and 6 (*top*), respectively. Accordingly direct road users' savings (traffic accident severity reduction, travel time, and fuel consumption reduction) on both types of highways were generated and are presented in Figures 5 (*bottom*) and 6 (*bottom*). The author believes that these curves can be useful for future benefit-cost analyses and in determining road users' direct savings for areas that use similar winter road maintenance operations.

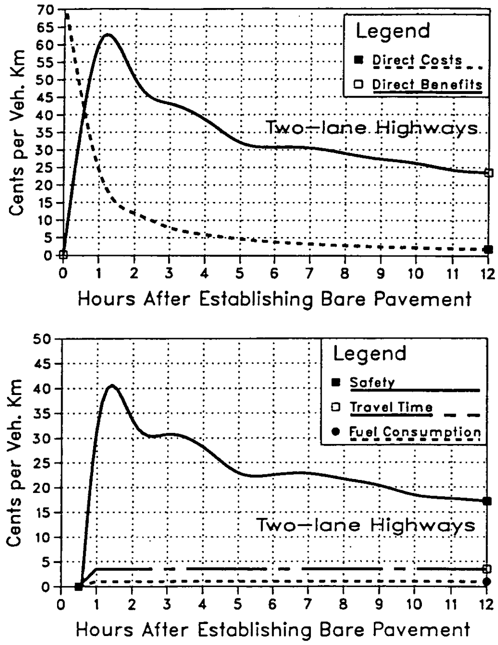


FIGURE 5 Direct benefits, costs (*top*), and savings (*bottom*) of winter road maintenance operations on two-lane highways.

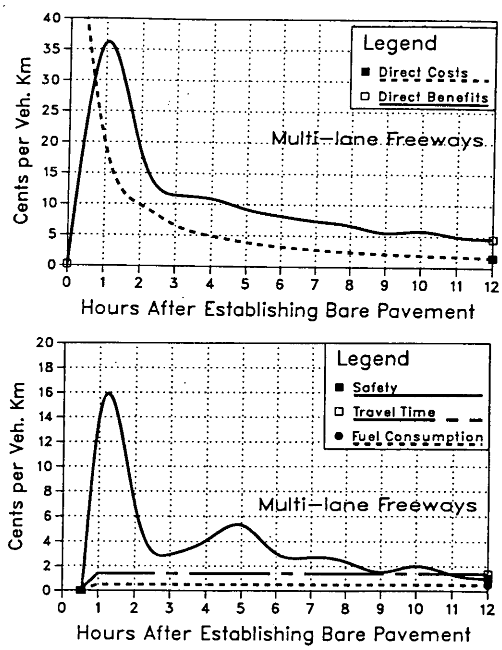


FIGURE 6 Direct benefits, costs (*top*), and savings (*bottom*) of winter road maintenance operations on multilane divided freeways.

direct savings for areas that use similar winter road maintenance operations.

Benefit-Cost Ratio

On the basis of winter road maintenance benefits and costs that were calculated in the preceding three sections, the benefratio was calculated to determine how much the road users receive as savings (in dollars) for every dollar spent on winter road maintenance operations.

The benefit-cost ratio (*B/C*) of direct benefits and direct costs of winter road maintenance operations was calculated for each *Z* hr after establishing bare pavement (zero hour) on the basis of the following equation:

$$\left(\frac{B}{C}\right)_{\text{direct},Z} = \left(\frac{\text{\$ of winter road maintenance direct benefits}}{\text{\$ of winter road maintenance direct costs}}\right)_Z$$

The following example illustrates the procedure for (*B/C*) ratio calculations:

Road user safety savings = \$0.345/VKT

Fuel consumption savings = \$0.010/VKT

Travel time savings = \$0.036/VKT

Total VKT during the first 4 hr after = 15,682,250

Total winter road maintenance direct cost = $\$920 \times 10^3$

$$\left(\frac{B}{C}\right)_{\text{direct},4} = \left[\frac{(0.345 + 0.010 + 0.036) \times 15{,}682{,}250}{920 \times 10^3}\right]_4 = 6.50$$

and conclude that during the first 4 hr after establishing bare pavement (zero hour) the average road users' savings were \$6.50 for each \$1.00 spent on winter road maintenance operations.

RESULTS AND CONCLUSIONS

Before 1991 several extensive European studies (*15*) measured the impact of winter road maintenance operations (and its economic benefits) on road users' safety. In the United States no such study up to the date of the present research has documented how effective winter road maintenance operations are on road users' safety.

The maximum benefit of a policy for dealing with snow and ice problems would be to achieve a bare pavement condition as quickly as possible. The optimum snow and ice policy varied from one participating area to another, but they were all similar in establishing bare pavement as soon as possible.

The primary objective of the present study was to compare and evaluate the direct benefits and direct costs accrued through winter road maintenance operations (salting, plowing, and following a bare pavement policy) during snow and icy conditions on highways. It was possible to do a benefit-cost analysis on the basis of the direct benefits and the direct costs. The results and conclusions reached are as follows:

Two-Lane Undivided Highways

On the basis of a representative average case ($Z = 4$), the following conclusions were reached.

Conclusion One

Winter road maintenance operations on two-lane highways reduce traffic accident costs by 88 percent and the average traffic severity by 10 percent.

1. The traffic accident cost rate before was $390,000/10^6 VKT (MVKT) [$625,000/10^6 vehicle mi of travel (MVMT)];
2. The traffic accident cost rate after was $46,000/MVKT ($74,000/MVMT);
3. The average traffic accident severity before was $49,000/accident; and
4. The average traffic accident severity after was $44,000/accident.

Conclusion Two

Winter road maintenance operations on two-lane highways cause direct economic benefits to the users much more than direct economic costs:

1. During the first 4 hr after salt spreading (zero hour) the average road users' savings were $6.50 for each $1.00 spent on winter road maintenance operations in direct costs;
2. The average direct winter road maintenance costs are offset by the average direct winter road maintenance benefits as soon as 71 vehicles have driven over a deiced two-lane highway; and
3. The winter road maintenance service pays for itself within the first 25 min after establishing bare pavement.

Multilane Divided Freeways

On the basis of a representative average case (Z = 2) the following conclusions were reached.

Conclusion Three

Winter road maintenance operations on freeways reduce the traffic accidents cost by 85 percent and the average traffic severity by 30 percent.

1. The traffic accident cost rate before was $196,000/MVKT ($316,000/MVMT);
2. The traffic accident cost rate after was $30,000 per MVKT ($49,000/MVMT);
3. The average traffic accident severity before was $57,500/accident; and
4. The average traffic accident severity after was $40,500/accident.

Conclusion Four

Winter road maintenance operations on freeways cause direct economic benefits to the users two to three times the amount of the direct economic costs:

1. During the first 2 hr after salt spreading (zero hour) the average road users' savings were $2.00 for each $1.00 spent on winter road maintenance operations in direct costs;
2. The average direct winter maintenance costs are offset by the average direct winter road maintenance benefits as soon as 280 vehicles have driven over a deiced two-lane highway; and
3. The winter road maintenance service pays for itself within the first 35 min after establishing bare pavement.

Both Types of Highways

Conclusion Five

During snow and icy conditions the ratio of accident and cost rates on two-lane highways in comparison with those on multilane freeways are (a) approximately 2 times in the period prior to establishing bare pavement and (b) approximately 1.5 times in the period after establishing bare pavement.

Conclusion Six

Winter road maintenance operations reduce accident and cost rates from before to after establishing bare pavement by ≥80 percent.

Conclusion Seven

Traffic accidents severity is (a) greater on icy freeways than on icy two-lane highways by 17 percent and (b) lower on deiced freeways than on deiced two-lane highways by 8 percent.

Conclusion Eight

Winter road maintenance operations on highways cause direct savings to the users (Figures 5 and 6) in the after period. (a) The average direct savings to a two-lane highway user is 45 cents/vehicle-km of travel, and (b) the average direct savings to a multilane freeway user is 20 cents/vehicle-km of travel.

RECOMMENDATIONS

On the basis of the results and conclusions presented in this paper the author recommends the following:

1. The direct economic impact of different procedures and policies for winter road maintenance operations on road users should be studied and evaluated by using the methodology described in this paper.
2. More research on investigating the indirect economic impact of winter road maintenance operations on road users should be conducted.
3. More research on measuring the impact of different weather conditions on vehicle fuel consumption and air quality should be conducted.
4. A policy on proper computerization of winter road maintenance records, which will simplify and ease computations of the economic impacts, should be adapted.

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