OPTIMAL WINTER SPEED LIMIT

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ABSTRACT

Nowadays, there is no exact method for determining the optimal speed limit in winter and the problems associated with winter speed limit has not yet been addressed in Hokkaido. Therefore, this study aims at determining the optimal winter speed limit through the application of a cost analysis and by analysis of effects of road and traffic conditions. Initially, a cost analysis of travel time costs, vehicle operating costs, pollution costs, and cost of accidents was applied to determine optimal average speed on the basis of the minimum total cost. Then, the effects of road and traffic conditions were calculated by regression analysis. Finally, the optimal winter speed limits were achieved by adding those effects to the optimal average speed. For the purpose of reliability, we applied a sensitivity analysis to the model. We found that our model was reliable and the results are appropriate and sustainable long term.

INTRODUCTION

In Hokkaido, the winter season is relatively long, lasting about six months per year, and during winter there is a lot of snow on the roads, as shown in figure 1. This figure shows the maximum depth of snow cover on the roads in Japan from December 2005 to April 2006. It is obvious that all areas of Hokkaido, the northern island of Japan, are covered by snow during winter. Therefore, road users, both drivers and pedestrians, face many problems during the winter season, including slippery roads, poor visibility, adverse weather, and narrower-than-usual roads and walkways. Drivers experience difficulty driving and also judging a safe driving speed. They usually drive at speeds in accordance with their judgment and experience, which makes driving in winter risky. However, to date, the winter speed limit has not yet been addressed on roads in Hokkaido or Japan. At present, dynamic message signs (DMS) or variable speed limits (VMLs) set up by the police department to inform drivers of the recommended speed limits are only available on expressways.

From Best Practices for Road Weather Management Version 2.0 (FHWA), the speed limit is reduced on the basis of prevailing road, weather, and traffic conditions and is communicated to drivers by dynamic message sign (DMS) or variable speed limit (VSL) sign. For example, in Washington State, if there is heavy rain or snow with compacted snow/ice on the roads and visibility of less than 0.1 mi. (0.16 km.), the speed limit is reduced to 45 mph (72.4 km/h) and traction tires required.

Even though the use of a DMS or VSL sign is the best way to enhance safety levels, set-up and maintenance costs are relatively high. These signs can be best employed on major roads, such as expressways or urban highways, but they may not be cost efficient on minor rural roads, such as exist over most of Hokkaido, due to low traffic volume. As mentioned above, for economic reasons, traditional posted speed limit signs should be employed in winter.

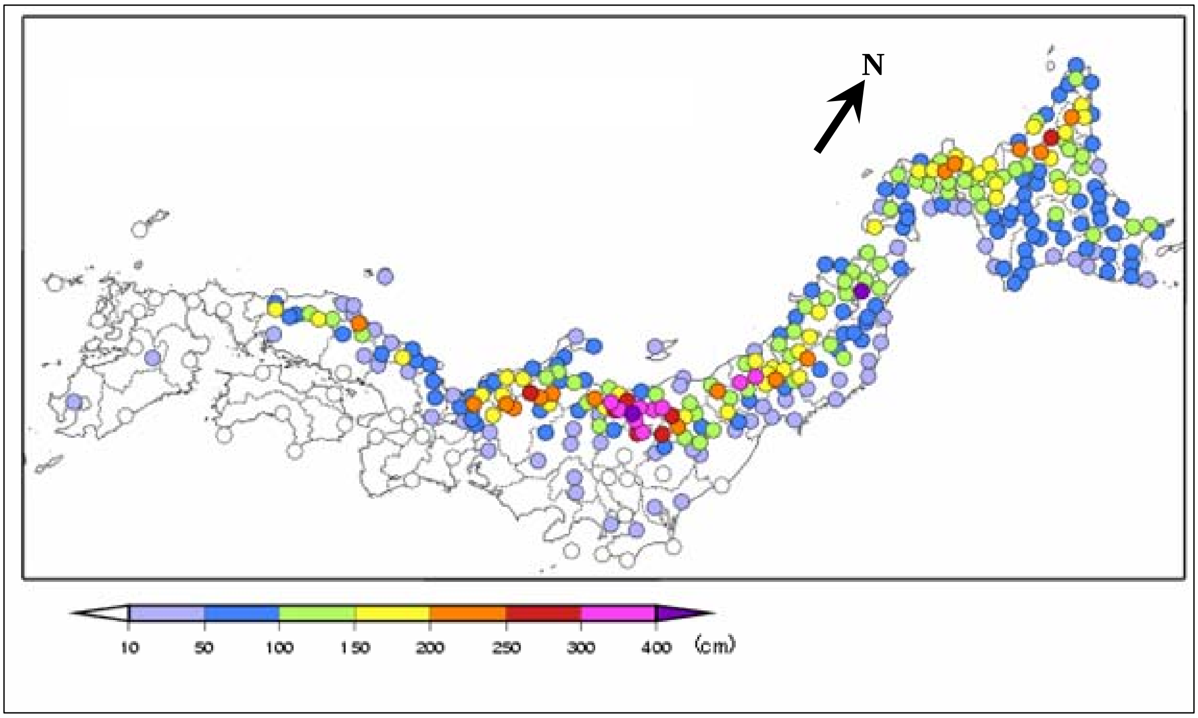


Figure 1 Maximum Depth of Snow (Dec. 2005-April 2006) (JMA)

From a traffic accident analysis for Hokkaido (CERI 2006), it is obvious that the total number of accidents in winter is lower than that in summer, as shown in table 1. However, the average number of accidents per month in winter was higher than that in summer from 1998 to 2004. Moreover, from the statistical data, most of the accidents in winter are likely to result in slight injuries because slippery roads are the main cause of accidents in winter. Even though most people drive carefully and seldom drive at high speed due to traffic jams and narrowed lane width from accumulated snow (see figure 2), accidents generally occur as braking is difficult in such conditions. Therefore, a reduced winter speed limit would be an effective solution.

Table 1 Number of Accidents

Year	Total Number of Accident			Average Number of Accident per Month		
	Summer	Winter	Total	Summer	Winter	Total
2004	15,163	12,681	27,844	2,166	2,536	2,320
2003	16,121	12,690	28,811	2,303	2,538	2,401
2002	16,221	12,453	28,674	2,317	2,491	2,390
2001	16,804	13,727	30,531	2,401	2,745	2,544
2000	16,964	13,842	30,806	2,423	2,768	2,567
1999	16,131	13,435	29,566	2,304	2,687	2,464
1998	15,652	12,501	28,153	2,236	2,500	2,346

Remarks: Winter period is from January to March and from November to December; 5 months per year in total.

Figure 2 A Winter Road in Hokkaido (Urban National Highway)

Some studies have shown that the introduction of winter speed limits has enhanced road safety. Räsänen and Peltola (2005) proposed the introduction of seasonal speed limits for heavy vehicles. And as the summertime speed limit of 100 km/h is generally reduced to 80 km/h during winter months in Finland, they concluded that lowering the speed limit during wintertime on the road sections could further enhance traffic safety.

Peltola (2000) found that the reduction of 100 km/h speed limits to 80 km/h during winter months in Finland resulted in a 14 percent reduction in accidents in the first 2-year study, and follow-up research suggested an even greater reduction in accidents. He concluded that lower wintertime speed limits resulted in a beneficial effect in terms of safety, and appeared to have a positive effect even on roads with a fixed 100 km/h speed limit. Many studies on lowering speed limits in winter tend to agree that the main purpose in doing so is to reduce the number of accidents.

The primary purpose of speed limits is to regulate driving speeds to achieve an appropriate balance between travel time and risk for road class or specific highway section (Committee for Guidance on Setting and Enforcing Speed Limits 1998). However, safety—more specifically, avoidance of crashes and mitigation of crash outcomes—is the most important reason for imposing speed limits. Therefore, to reduce the number of accidents in winter, the winter speed limit should be regulated. Nevertheless, until now, there has been no best solution for setting winter speed limits because road conditions in winter vary considerably. Some sections of roads are covered with snow while other parts are covered with ice, so the coefficient of friction between tires and the road surface (f) varies. Though it is difficult to define the specific coefficient of friction for either icy roads or roads covered with compacted snow, it is possible to define the coefficient as a range; i.e., f = 0.00-0.23 for icy roads and f = 0.23-0.45 for snow-compacted roads (Shirakawabe 1990). We reason that the winter speed limit should increase or decrease in proportion to the coefficient of friction between tires and the road surface. For example, the speed limit on an icy road should be lower than that on a snow-compacted road.

As mentioned by many researchers, there is not yet any accepted method for determining the speed limit in winter, and only the measure is the reduction of speed limits; e.g., a decrease of 10 km/h for snow, of 20 km/h for heavy snow and so on. Therefore, in this paper, we propose a method for determining the optimal winter speed limit by applying a cost analysis and the effects of traffic signal intensity, traffic congestion caused by the reduction in road capacity due to accumulated snow and slippery roads. Moreover, the optimal winter speed limits are compared with the recommended winter speed limits from a questionnaire survey distributed in October 2006. These optimal winter speed limits are then evaluated to assess their appropriateness to road and traffic conditions.

In our previous speed limit study (Thanesuen et al. 2006), we also applied a cost analysis and effects from road and traffic conditions to determine the optimal speed limits in summer. We compared our results with the 85^{th} percentile speed and speed limits according to road characteristics and realized that this method was superior to other methods. Moreover, the results from the previous study were considered to be appropriate to actual road and traffic conditions. Although we applied the same method to determine the optimal speed limit in summer and winter, the determination of the optimal speed limit in winter is much more difficult as road conditions in winter are more variable. The effect of slippery roads was included as an effect of road and traffic conditions.

Additionally, to ensure the reliability of the model, a sensitivity test was also applied to observe changes when costs increased. We also addressed three research questions to develop a better understanding in our study as follows:

1. Which cost component and factors that have the most influence on the results in the cost analysis?
2. Are the optimal winter speed limits appropriate to road and traffic conditions?
3. How are the results affected if component costs change?

METHODOLOGY

To obtain the optimal winter speed limit, we divided study into two sections; the first was a *cost analysis* to determine the optimal average speed and the second was a study of the *effects of road and traffic conditions*, which included the effects from road and traffic conditions and traffic signal intensity to obtain the optimal winter speed limit.

Cost Analysis

In this study, four types of roads in Hokkaido were examined; i.e., urban national highways, rural national highways, urban expressways, and rural expressways. Initially, the average daily traffic volumes on Hokkaido roads were to be determined, as shown in table 2. Unfortunately, the traffic volumes on urban and rural expressways for winter were not available from road traffic census survey figures from the year 1999. Therefore, an estimation was made on the basis of the following assumptions:

- the ratio between traffic volume on "*urban expressways*" for winter and summer was equal to the ratio between traffic volume of urban highways for winter and summer
- the ratio between traffic volume on "*rural expressways*" for winter and autumn was equal to the ratio between traffic volume of rural highways for winter and autumn (we did not use traffic volume for summer here because the total traffic volume in summer was lower than that in winter.)

Then, the relationship between each cost component and average speed was determined. Cost components were:

- Travel time cost
- Vehicle Operating Cost (VOC)
- Emitted pollution cost (i.e., CO_2, NOx, and noise pollution)
- Accident cost

Here, the cost unit was yen per kilometer per day. After the relationship between total cost and average speed was obtained, the minimum cost was taken to indicate the optimal average speed. The details of the cost components are as follows.

Table 2 Average Daily Traffic Volume in Winter

	Average Daily Traffic Volume (veh/day)				
	Car	**Bus**	**Small Truck**	**Truck**	**Heavy Veh. Ratio**
Urban Highways	16,600	400	6,000	2,100	0.10
Rural Highways	2,700	100	1,000	900	0.21
Urban Expressways	14,600	600	3,000	2,900	0.17
Rural Expressways	6,000	200	2,500	2,400	0.23

Travel time cost. From the primary purpose of speed limits mentioned above, travel time is known to be an important factor in determining an appropriate speed limit. The appropriate speed limit should be not so low that road users waste time on the road, nor should it be so high that road users face increased risk of accidents.

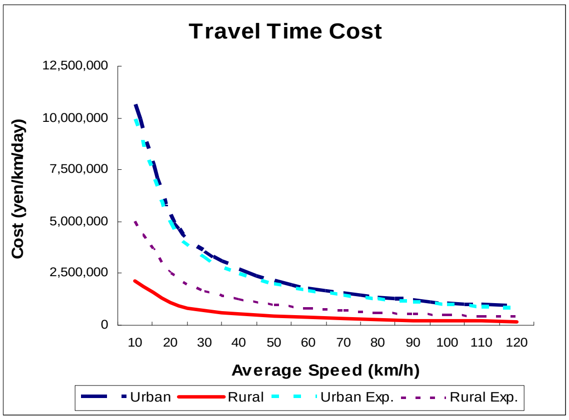
To determine the relationship between travel time cost and average speed, a value of time (VOT) was obtained from the Cost Benefit Analysis Manual (BPR 2004). VOT is the expression of time transformed into a monetary value, has and is shown as the unit of monetary value per unit time per vehicle. VOT was derived from an analysis of the questionnaire survey. VOT depends on the number of passengers in the vehicle, purpose of travel, and the basic wage of people in the area concerned. The VOT in Japan is 3,771.6 yen/hr/veh for a car (US$31.43), 31,184.4 yen/hr/veh for a bus (US$259.87), 3,408.6 yen/hr/veh for a small truck (US$28.41), and 5,246.4 yen/hr/veh for a truck (US$43.72). (US$1 = 120 yen, as of October 11th, 2006)

After we obtained the average daily traffic volume and VOT, the VOT of each vehicle type was divided by speed to obtain the cost of each average speed and then multiplied by the average daily traffic volume in table 2. Finally, we plotted the results to obtain the travel time cost curves shown in figure 3a.

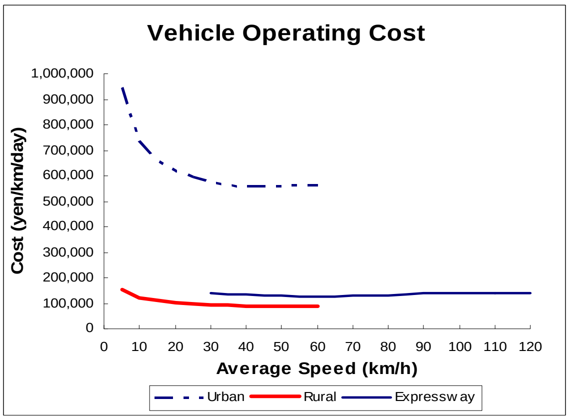
Vehicle Operating Cost (VOC). VOC is the cost associated with owning, operating and maintaining a vehicle, including fuel consumption, tire wear, maintenance and repair, oil consumption, capital depreciation, license and insurance costs, and operator labor and wages.

It is a direct function of the mechanical relationships of vehicle characteristics, road geometrics, road surface type, road surface condition, environmental factors, and vehicle speed (Berthelot, et al. 1996).

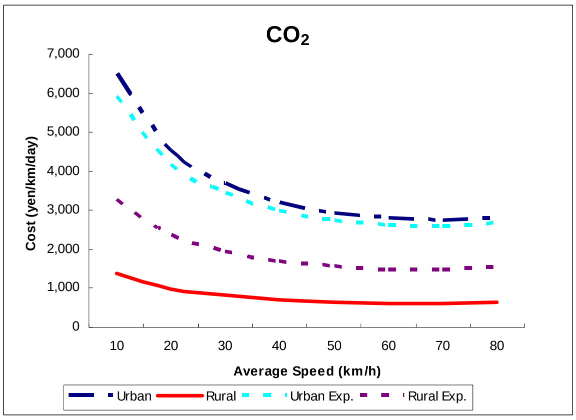
From the Cost Benefit Analysis Manual (BPR 2004), it is obvious that larger vehicles had a higher VOC and driving at very high or very low speeds had led to a high VOC. In this calculation, the minimum values for VOC were observed at 50 km/h for highways and at 60 km/h for expressways, as shown in figure 3b.



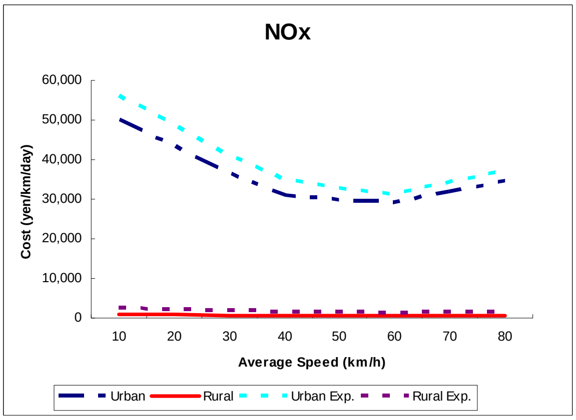
a) Travel Time Cost



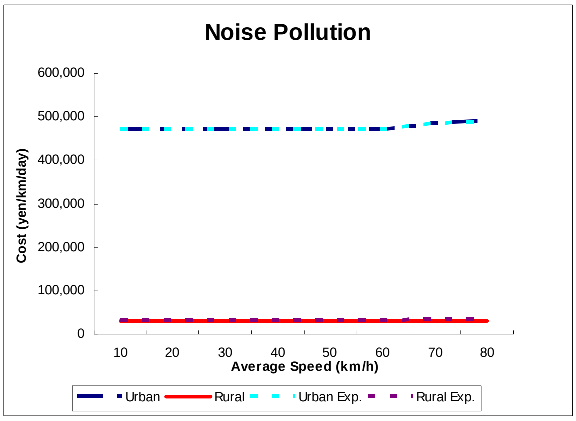
b) Vehicle Operating Cost



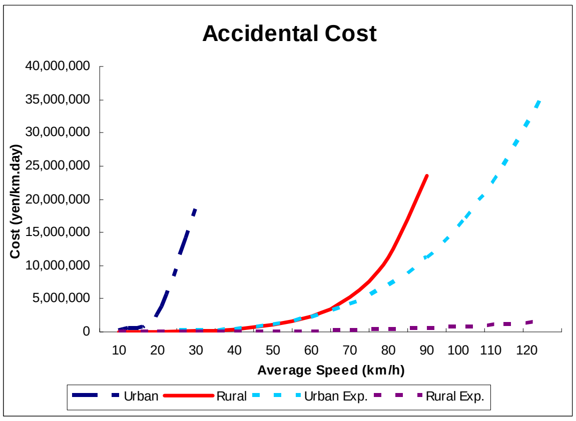
c) Carbon Dioxide



d) Nitrogen Oxide



e) Noise Pollution



f) Accident Cost

Figure 3 Cost Components

Emitted pollution cost. Here, three pollutants were considered; i.e., CO_2, NOx, and noise pollution. At present, the emission of these pollutants, which are harmful to humans and the ecosystem, continue to increase. Therefore, some method of reducing their emission; through the application of the optimal speed limit from this study, for example, would be of great value. The amount emitted and cost of such was determined by the Committee for Guidelines on the Evaluation of Road Investment, as shown in table 3.

- Carbon Dioxide (CO_2)

Carbon dioxide is thought to cause "global warming" resulting in severe increases in the earth's atmospheric and surface temperatures with disastrous environmental consequences. CO_2 levels have increased substantially since the Industrial Revolution, and are expected to continue to do so. It is reasonable to believe that humans have been responsible for much of this increase (Robinson et al. 1998).

From table 3, the emission of CO_2 depended on traffic volume and average speed. The price of CO_2 was 2,300 yen/ton-c (19.17 US dollar/ton-c). From the calculation, the cost was high at low speed, and started to decrease as speeds increased, reaching a minimum cost at 70 km/h. Cost again began to increase at speeds above 70km/h, as shown in figure 3c. Equation 1 shows the calculation method.

CO_2 cost (yen/km/day) = Amount of CO_2 (g-c/km/day) * Price (yen/ton-c) / 10^6(g-c/ton-c) (1)

- *Nitrogen Oxides (NOx)*

This is a generic term for the various nitrogen oxides produced during combustion. It is one of the main ingredients involved in the formation of ground-level ozone, which can trigger serious respiratory problems. Moreover, it contributes to the formation of acid rain and to nutrient overload that deteriorates water quality (EPA 2006).

From table 3, the emission of NOx depended on traffic volume and average speed. The prices were equal to 2,920,000 yen/ton and 200,000 yen/ton (24,333 and 1,667 US dollar/ton) for urban and rural areas, respectively. The minimum cost obtained was at 60 km/h, as shown in figure 3d. The calculation is shown in equation 2.

NO_x cost (yen/km/day) = Amount of NOx (g/km/day) * Price (yen/ton) / 10^6(g/ton) (2)

- Noise Pollution

Noise pollution can be defined as unwanted or offensive sounds that unreasonably intrude upon our daily activities. It has many sources, most of which are associated with urban development; roads, air and rail transport, industrial noise, and neighborhood and recreational noise (DEC 2006).

From table 3, it is obvious that the noise level depended both on traffic volume and traveling speed. Noise levels remained constant and only increased above 60 km/h. The prices were 2,400,000 and 165,000 yen/dB(A)/year (20,000 and 1,375 US dollar/dB(A)/year) for urban and rural areas, respectively. The results shown in figure 3e were obtained from the following equation (3)

:

Noise cost (yen/km/day) = Noise Level (dB(A)) * Price (yen/dB(A)/year) / 365 (days/year) (3)

Table 3 Emission of Pollution for Each Traveling Speed

Traveling Speed (km/h)	NOx (g/km/day)	CO_2 (g-c/km/day)	Noise Level (db(A))
10	(0.34a1+3.79a2)Q	(99a1+237a2)Q	40+A
20	(0.29a1+3.33a2)Q	(67a1+182a2)Q	
30	(0.24a1+2.87a2)Q	(54a1+155a2)Q	
40	(0.20a1+2.41a2)Q	(46a1+137a2)Q	
50	(0.21a1+2.16a2)Q	(42a1+127a2)Q	
60	(0.23a1+1.90a2)Q	(40a1+122a2)Q	
70	(0.25a1+2.10a2)Q	(39a1+123a2)Q	42+A
80	(0.27a1+2.29a2)Q	(40a1+129a2)Q	43+A

a1: ratio of passenger car, a2: ratio of heavy vehicle, Q: Traffic volume (veh/day)

A= 10*log(a1+4.5a2)+10*log(Q/24)

Accident cost. From the primary purpose of speed limits, accident cost is introduced to the cost analysis to limit the speed to a safe range. Generally, there is a correlation between speed and the severity of an accident; i.e., the severity of an accident tends to be greater when driving at higher speeds.

In order to reveal the relationship between accident cost and average speed, accident data is required. In Japan, since the number of fatalities has been the most important factor in the evaluation of all road safety projects, only fatalities were employed to reveal the relationship between accident cost and average speed. From the national statistics in 2003 (STAT 2005), Hokkaido had the highest number of fatalities (391) among the 47 prefectures in Japan. As we are concerned with the optimal winter speed limit, only the 94 fatalities that occurred in winter (January-March and November-December) on national highways and expressways were included in the analysis. There were 24 fatalities on urban national highways, 56 fatalities on rural national highways and 4 fatalities on expressways.

Recently, many methods have been used to determine the relationship between accident cost and average speed; e.g., linear models, logistics model, power models, and so on. However, based on studies that focused on the relationship between average speed on a particular road section and crash risk, it was concluded that this relationship was best described by a power function (Aarts 2004). Moreover, several other mathematical functions may describe the relationship between speed and road safety, but the generality and simplicity of the power model makes it superior to other models (Elvik et al. 2004). Therefore, the power model (Nilsson 2004) was applied in this study. It showed that the relative change in the number of accidents or accident victims is a function of the relative change in the mean speed of traffic, raised to an exponent. There are at least five advantages to this model, as follows:

- The model is easy to derive and is symmetric. It can be used for both increases and decreases in speed.
- The model isolates and estimates the effect of changes in speed on safety.
- The model can be used in all environments for which an average speed measurement and representative injury accident statistics are available.
- The model takes into account whether the accident statistics are presented in terms of injury accidents and/or injured (fatal accidents and fatalities).
- The model is quite independent of the form of speed measurement used as it is based on relative speed change. It is of course important to use the same method/presentation in the analysis.

In this study, we applied the power model to determine the relationship between accident cost and average speed. To apply the power model, the number of fatal accidents and fatalities and the mean speed of each road should be obtained first. From the road traffic census for the year 1999, the mean speeds or average speeds of each road were 18.1 km/h on urban national highways, 39.1 km/h on rural national highways, 68.5 km/h on urban expressways, and 81.9 km/h on rural expressways. After that, we simply applied equation 4 from Nilsson's power model. Then, we multiplied the number of fatalities at each average speed by fatality cost (36,163,000 yen or 314,500 US dollars) and divided the result by the length of each type of road; i.e., 544 km., 5933 km., 38.3 km., and 462.6 km. for urban national highways, rural national highways, urban expressways, and rural expressways, respectively (as of April 2004). The accident cost for each average speed and the relationship between accident cost and average speed was obtained, as shown in figure 3f.

$$z_1 = y_0\left(\frac{v_1}{v_0}\right)^4 + \left(z_0 - y_0\right)\left(\frac{v_1}{v_0}\right)^8 \qquad (4)$$

Where z_1 : number of fatalities after average speed changes
z_0 : number of fatalities before average speed changes
y_0 : number of fatal accidents before average speed changes
v_0 : average speed before change
v_1 : average speed after change

We also applied the exponential function to determine its relationship; however, it was obvious that the relationship determined by the power model gave a higher accident cost than did the exponential function. Moreover, the results obtained from the cost analysis seem to be more appropriate if the power model was applied. Even though Nilsson mentioned that the power model underestimated the effect of speed on the number of fatalities, it did not appear to do so in this case.

Optimal average speed. After the relationships between all cost components and average speed were obtained, the next step was to sum the individual totals to determine the optimal average speed as shown in figure 4. It was obvious that the curve of the urban national highways increased sharply after the minimum value was reached, due to high accident costs, while the others increased only slightly. The optimal average speeds were 20, 30, 40, and 70 km/h for urban national highways, rural national highways, urban expressways, and rural expressways, respectively. These optimal average speeds were relatively low. In terms of optimal total cost, the urban national highways had the highest cost as they had the highest accident cost as well as the largest traffic volume and the highest accident cost. In decreasing order of cost, urban national highways were followed by urban expressways, rural expressways, and rural national highways. However, looking at the total costs of rural national highways, urban expressways, and rural expressways, we observed that the minimum costs and the costs at 10 km/h higher than optimal average speeds varied less than 10%. Therefore, it was possible to apply the higher average speed as the new optimal average speed.

After we obtained the optimal average speed from the cost analysis, the next step was to assess the effects of road and traffic conditions. As these effects influence driving speed, these effects should be included when determining the optimal speed limit. In our previous speed limit study (Thanesuen et al. 2006), only the effects of traffic signal intensity and traffic congestion were included; however, the present study is more complicated due to the complex interplay of conditions on winter roads.

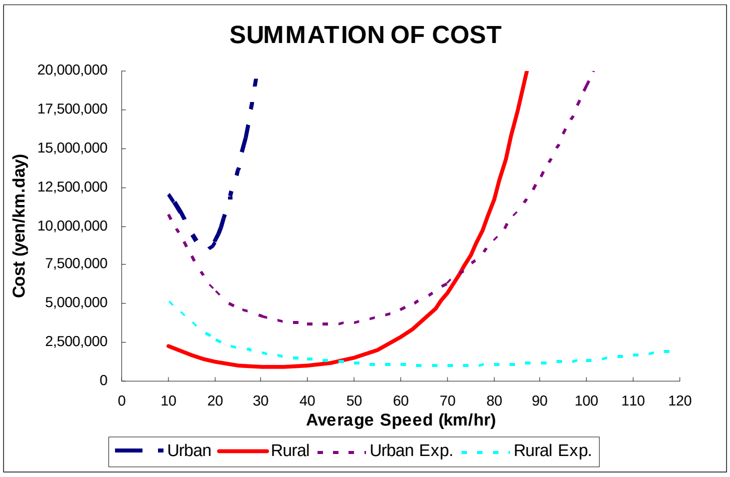


Figure 4 Summation of Cost

Effect of road and traffic conditions

Normally, there are many factors that affect driving speed, but the most influential factors are traffic signals and traffic congestion. However, in winter, besides these factors, we must take into account the slipperiness and narrowing of roads, adverse weather (or poor visibility), driver nervousness, and so on. Therefore, to determine a winter speed limit from the optimal average speed, the effects that these factors have on speed need to be taken into account. As road slipperiness, adverse weather and accumulated snow on the roadway are functions of road capacity, these effects are included in the effect of traffic and road conditions. Therefore, the road capacities according to these effects were determined first. However, the accumulated snow data in the road traffic census (1999) was incomplete and difficult to apply, so only the effect of road slipperiness and adverse weather were involved in the calculation of road capacity.

Shirakawabe (1990) studied the effect of road slipperiness on capacity in Sapporo, Hokkaido and found its relationship as a linear function, as shown in equation (5). The coefficients of friction between tires and road surface are shown in Table 4.

$$Y = 1219.75 + 5.2987X \tag{5}$$

where Y : Road capacity (pcus/hr/lane)

X : skid number (or coefficient of friction * 100)

After we had calculated road capacity allowing for the effect of road slipperiness, we introduced the effect of weather, which causes a further reduction in capacity. From Highway Capacity Manual 2000, light snow was shown to reduce road capacity by 5 to10 percent. Heavy snow significantly influences the speed-flow curve, which suggested a 30 percent drop in capacity. The capacities of each road section were then calculated to adjust for the effect of road slipperiness and then of adverse weather. The weather conditions are listed in table 5, and ordered from good (sunny) to bad weather conditions (very heavy snow). The results of the adjustments for traffic congestion due to road slipperiness and adverse weather for each road section are represented as a v/c ratio (v: traffic volume, c: capacity).

Table 4 Coefficient of Road Friction between Tires and Road Surface

No.	Road Condition	Coefficient of Friction
1	Very slippery Snow-Compacted Road	0.23[1)]
2	Very Slippery Icy (> 1 mm thickness)	0.13[1)]
3	Very Slippery Icy (< 1 mm thickness)	0.13[1)]
4	Snow-Compact	0.37[2)]
5	Icy (> 1 mm thickness)	0.18[2)]
6	Icy (< 1 mm thickness)	0.18[2)]
7	Powder Snow	0.45[1)]
8	Grain Snow	0.45[1)]
9	Power Snow with Icy on the bottom	0.23[1)]
10	Power Snow with Icy on the bottom	0.23[1)]
11	Dry	0.70[3)]
12	Wet	0.60[1)]
13	Sherbet	0.45[1)]

Remarks: The categories for road conditions followed those used in the road traffic census for the year 1999.

[1)] taken from Shirakawabe (1990)

[2)] taken from, Uchida et al. (2002)

[3)] taken from Nakatsuji et al. (2005)

Table 5 Weather Conditions

Weather	No.
Sunny	1
Cloudy	2
Rainy	3
Foggy	4
Sleet	5
Little snow	6
Snow	7
Heavy Snow	8
Very Heavy Snow	9

The next step was the accumulation of other data; i.e., those for traffic signal intensity and actual average speed in peak hour (as we wanted to know the effect of traffic congestion) on the road section. As an average speed is a function of the speed limit and the effects of road and traffic conditions, it means that

$$\textit{Average Speed } (V_{avg}) = \textit{Speed Limit } (SL) - \textit{Effects of road and traffic conditions } (y) \qquad (6)$$

In order to obtain the optimal speed limit from the optimal average speed, the effects (y) in equation 6 should first be obtained. These effects can be obtained from the difference in speed between speed limit and actual average speed. Therefore, the differences in speed of each road section were determined by subtracting actual average speed from the posted speed limit. Here, we assumed that the relationship between difference in speed and effects of road and traffic conditions and traffic signal intensity could be determined by regression analysis. In the regression analysis, a trial and error method was used to obtain the coefficients of each factor that showed the highest R^2 value and the highest absolute *t-stat* value of each coefficient. The effects are shown in equation 7. However, the effects from road and traffic conditions on urban expressways (y_3) were not obtained by regression analysis because the R^2 value was very low. Rather, we obtained the effects directly by subtracting the actual average speed from the posted speed limit of each road section and then averaging them.

$$\left.\begin{array}{ll} y_1 = 27.466 - 0.868x_1 - 35.988{x_2}^3 + 1.704W & R^2 = 0.45 \\ y_2 = 15.460 - 3.182x_1 + 0.378{x_1}^2 + 57.877x_2 - 69.305{x_2}^2 - 22.199f & R^2 = 0.31 \\ y_3 = 11.49 & \\ y_4 = 7.643 + 213.252{x_2}^2 - 263.657{x_2}^3 & R^2 = 0.48 \end{array}\right\} \quad (7)$$

where x_1 : traffic signal intensity (8 and 3 signals per km for urban and rural national highways)
x_2 : volume-capacity ratio
W : weather condition number (obtained from table 5)
f : coefficient of friction between tires and road surface

After we substituted the average values in equation 7, the effects (y) were obtained. Finally, the optimal winter speed limits were obtained by applying equation 8.

$$V_i = y_i + V_{opt.avg.} \quad (8)$$

where V_i : optimal speed limit
y_i : effects from traffic signal intensity and traffic congestion
$V_{opt.avg.}$: optimal average speed

RESULTS

The optimal winter speed limits (V_i) are shown in table 6. These speed limits are for icy roads (f = 0.13) with falling snow (W = 7). On urban national highways, it was obvious that the effects of road and traffic conditions were very large due to the high volume-capacity ratio. Rural national highways had the lowest optimal speed limit, followed by urban national highways, urban expressways, and rural expressways.

Table 6 Optimal Speed Limits

	$V_{opt.avg}$	Volume	Capacity	x_2	f	W	y_i	V_i
Urban Highways	20	2,760	5,155	0.54	0.13	7	26.93	46.93
Rural Highways	30	570	2,320	0.25	0.13	7	16.47	46.47
Urban Expressways	40	2,406	5,523	0.44	0.13	7	11.49	51.49
Rural Expressways	70	1,208	5,724	0.21	0.13	7	14.66	84.66

DISCUSSION

From this study, is it clear that the cost component that most influenced the results was accident cost. Obviously, on urban national highways, the curve of total cost followed the same trend as that of accident cost. The accident cost increased sharply after 20 km/h and from that point the optimal average speed on urban national highways was relatively low. Besides accident cost, travel time cost also affected the resulted but less than accident cost. As the accident cost was determined by power function, the factors that influenced accident cost were mean speed or average speed and the number of fatal accidents and fatalities. If the mean speed and number of fatal accident change, the accident cost will changed accordingly. The least influence cost component in the cost analysis was CO_2 due to the low cost per unit.

Second, based on our driving experience, we realized that only optimal speed limits on urban national highways and rural expressways were appropriate. This meant a speed limit that was neither too low nor too high. But the optimal winter speed limits on other roads were relatively low, especially on urban expressways, because the road conditions are quite good even in winter. However, as discussed before, the minimum costs and the costs at 10 km/h higher than optimal average speeds varied by less than 10%. Therefore, the optimal winter speed limit on rural national highways and urban expressways could be increased about 10 km/h; i.e., to 56.47 km/h and 61.49 km/h, respectively, thus making them more acceptable and more appropriate to public needs. Nevertheless, the optimal speed limit on urban expressways was still not acceptable as an appropriate speed limit. It was too low and, therefore, the public would not be likely to pay the tolls.

Moreover, we compared the optimal speed limit with the recommended winter speed limit from our questionnaire survey. About 1000 questionnaires were distributed in Sapporo and the neighboring cities (Otaru, Ebetsu, Teine, and Chitose) via post boxes during October 2006. To date, 130 questionnaires (13%) have been returned. The purpose of the questionnaire survey was to determine public opinion regarding speed limits in Hokkaido both in summer and winter. From the questionnaire analysis, we found that about 50% of the respondents recommended a 50 km/h winter speed limit on urban and rural national highways and an 80 km/h winter speed limit on urban and rural expressways. From comparison, the optimal speed limits obtained from our study agreed with the speed limits recommended by the respondents or road users, except for the optimal speed limit on urban expressways. From this, we can imply that these optimal winter speed limits are appropriate to road and traffic conditions, except for the optimal speed limit on urban expressways.

Finally, a sensitivity analysis was applied in this study to observe the effect of changes in cost on our results. We focused on accident cost and time cost for this test as they had the most influence on the optimal speed limit. For accident cost, we found that the optimal speed limit on rural expressways only was decreased by 10 km/h when fatality cost was increased by 50%. Even if fatality cost was increased by 100%, the optimal speed limits on other roads were unchanged. For time cost, only the optimal speed limit on urban expressways was increased by 10 km\h when time cost was increased 26%. When time cost was increased by 40%, the optimal speed limit on rural expressways was increased by 10 km/h. These results indicate that optimal speed limit on rural expressways is likely to be sensitive to increases in cost, while the optimal speed limit on urban national highways shows little sensitivity to cost increases. From this, our model can be regarded as reliable. Here, we considered only the increase in cost as an examination of costs to date shows a rising trend, suggesting they will continue to increase in the future.

CONCLUSION

As the number of accidents in winter on Hokkaido roads is still high, we speculated that the winter speed limit should be addressed to enhance road safety. In this study, we applied a cost analysis to determine the optimal average speed and then we introduced effects of road and traffic conditions (traffic signal intensity, traffic congestion, weather conditions, and road slipperiness) to determine the optimal speed limit. The results were appropriate to road and traffic conditions, except for urban expressways for which the optimal speed limit obtained was too low to be viable. Moreover, we applied a sensitivity analysis to observe the results when costs were increased and found that our model is reliable and that these speed limits can be sustained for many years as costs are not expected to change greatly from year to year. As the optimal speed limits were derived from the cost analysis, we suggest that the optimal speed limits can contribute to greater road safety, energy efficiency and a healthier roadside environment.

However, when examining the effects of road and traffic conditions, the R^2 values were relatively low which made the results unviable. This may have been because some data were missing or unavailable; e.g., driver behavior and traffic volume on urban and rural expressways. Therefore, more data should be collected to improve our results. Nevertheless, we and other road users (from the questionnaire survey) agree that the optimal speed limits obtained in this study are appropriate, except that for urban expressways.

Recently, the Japanese Police Department announced that it would reconsider speed limit in summer because the existing speed limits have been unchanged for a long time. We feel it would be better to apply new winter speed limits on Hokkaido roads to enhance the road safety, so we plan to purpose this method as it already includes important factors for determining speed limits. As the variable message signs are good for maintaining appropriate speed limits under changing conditions, thus reducing accidents, it would be better to combine this model with the available dynamic message signs or variable speed limit signs to enhance road safety. Additionally, speed enforcement and management should be emphasized to further improve road safety. However, the best way to reduce the number of road accidents is to improve winter road management.

In future studies, we plan to collect better quality data and to study driver behavior in winter to improve our model. Moreover, we would like to develop a spot speed study in winter to obtain information on speed distribution. With this data we can compare our results with other well-known methods for setting speed limits; i.e., the 85th percentile speed.

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