# Optimal Winter Speed Limit

by Suthipun Thanesuen, Seiichi Kagaya, Ken-etsu Uchida, and Toru Hagiwara

This study aims to determine 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 accident cost 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. In conclusion, we found that our model was reliable and the results were appropriate and sustainable for the 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 covering 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 (VSLs) set up by the police department to inform drivers of the recommended speed limits are only available on expressways.

Figure 1: Maximum Depth of Snow (Dec. 2005-April 2006)
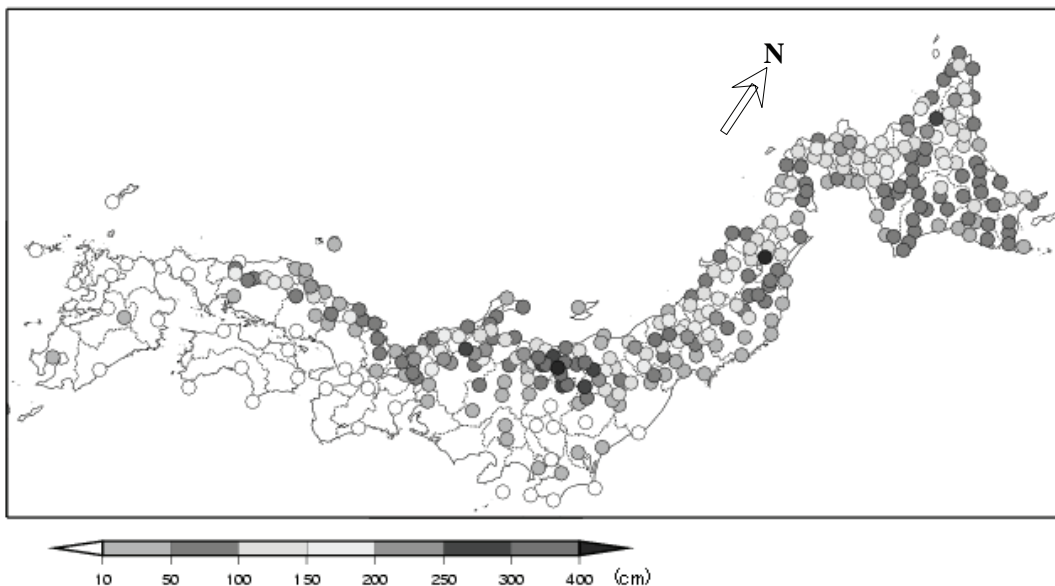
Data source: Japan Meteorological Agency (2006)

From *Best Practices for Road Weather Management Version 2.0* (USFHWA 2006), 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 mile (0.16 kilometer), the speed limit is reduced to 45 mph (72.4 km/h) and traction tires made a requirement.

Even though the use of a DMS or VSL sign is the best way to enhance safety levels, setup 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 those that exist over most of Hokkaido, due to low traffic volume. As mentioned above, for economic reasons, the traditional posted speed limit signs should be employed in winter.

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 because there are more summer months (seven) than winter months (five), and the amount of travel is higher in the summer months. However, the average number of accidents per month in winter was higher than that in summer from 1998 to 2004, as shown in Table 1. Moreover, from the statistical data, 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 (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 Accidents			Average Number of Accidents 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

Data Source: CERI (2006)
Remarks: Winter period is from November to March; five months per year in total.

LITERATURE REVIEW

Previous studies done by other researchers have shown that the introduction of winter speed limits would enhance road 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% reduction in accidents in the first two-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 reducing speed limits in winter tend to agree that the main purpose in doing so is to reduce the number of accidents.

Räsänen and Peltola (2005) proposed the introduction of seasonal speed limits for heavy vehicles. 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 could further promote traffic safety.

Figure 2: Winter Roads in Hokkaido

a) Urban National Highway

b) Rural National Highway

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 (TRB 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). The winter speed limit should be changed depending on 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.

Elvik (2002) proposed the recent estimations of optimal speed limits on public roads in Norway and Sweden. He applied the concept that the optimal speed limits are those that minimize the total costs of transportation for society. The cost components were costs of travel time, vehicle operating costs, road accident costs, costs of traffic noise, and cost of air pollution. The same concept of Elvik (2002) was also applied to a previous speed limit study developed by the authors (Thanesuen et al. 2007b). However, the effects of road and traffic conditions, which were not included in Elvik's study (2002), were introduced to the previous work, including this study, after a cost analysis was applied.

In the previous speed limit study developed by Thanesuen et al. (2007b), a cost analysis and effects from road and traffic conditions were applied to determine the optimal speed limits in summer. The results were compared with the 85th percentile speed and speed limits according to road characteristics. It was found that this method was superior to other methods because it included the important criteria to determine speed limit, i.e. time, safety, pollution, and fuel consumption (shown as part of VOC). Moreover, the results from the previous study were considered to be appropriate to the actual road and traffic conditions. Although the same method was applied 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 in the effect of road and traffic conditions.

Until now, there is not yet any accepted method for determining the speed limit in winter, and the only measure is a 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, a method is proposed for determining the optimal winter speed limit by applying a cost analysis and the effects of traffic signal density, and 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.

Additionally, to ensure the reliability of the model, a sensitivity test was also applied to observe changes when costs increased. The paper addressed three research questions as follows:

1. Which cost component and factors 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

Before proceeding to the details of methodology, the concept of this study is explained first. The concept is that speed limit has an influence on the average speed. Also, the difference between them is derived from the effects of traffic signal density and traffic congestion. Therefore, to obtain the optimal winter speed limit, a *cost analysis* was applied first to determine the optimal average speed and then the *effects of road and traffic conditions* were introduced, which included the effects from traffic signal density and traffic congestion. The study flowchart is shown in Figure 3. The details of each part are discussed in the next section.

Figure 3: Study Flowchart
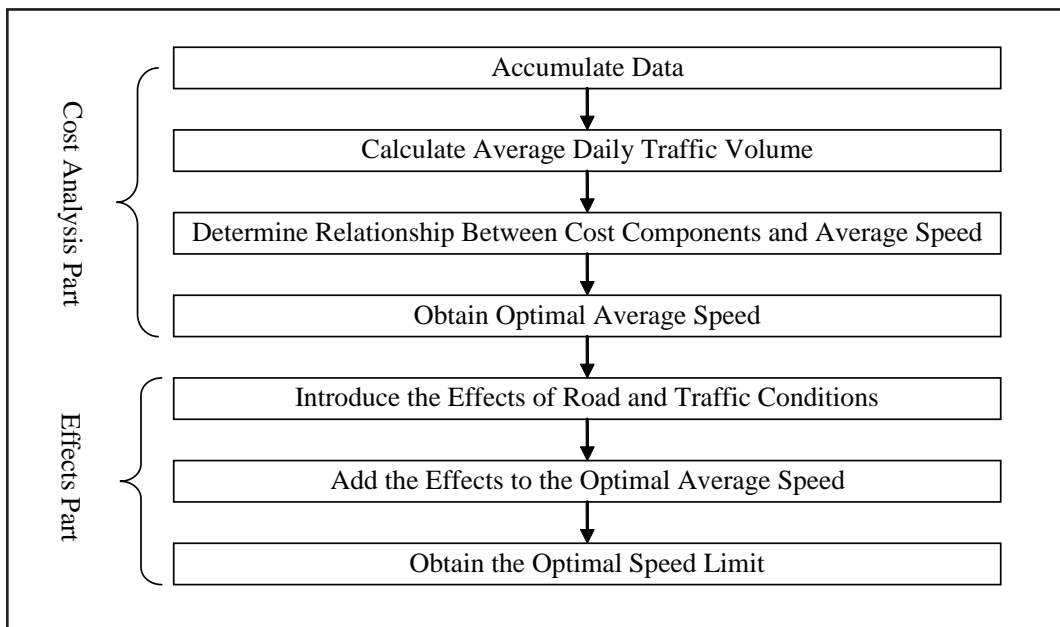
Cost Analysis

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 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 of the year 1999 (MLIT 1999). Therefore, an estimate 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 (traffic volume in summer was not used here because the total traffic volume in summer was lower than that in winter.)

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

Data Source: Ministry of Land, Infrastructure and Transportation (1999)

Then, the relationship between each cost component and average speed was determined. Cost components consisted of:
- 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 assumed to indicate the optimal average speed. The details of the cost components are as follows.

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 an 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. To determine the VOT, the VOT per person was calculated on the basis of the wage level and converted into the VOT per vehicle by multiplying the number of passengers per vehicle and adding the rental charge per vehicle. In the case of truck, the VOT value has been calculated in a similar way. However, the equivalence of inventory interest of freight cargoes has also been included. Then, VOT was expressed as the unit of monetary value (yen) per unit time per vehicle. From this, VOT depends on the number of passengers in the vehicle, purpose of travel, and the basic wage of people in the area concerned. From the *Cost Benefit Analysis Manual* (BPR 2004), 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 11, 2006).

After the average daily traffic volume (Table 2) and VOT were obtained, the VOT of each vehicle type was divided by speeds (every 10 km/h, ranging from 10 to 120 km/h) to obtain the travel time costs of each vehicle type at each average speed (yen/veh/km). Then, the obtained values were multiplied by the average daily traffic volume from Table 2 and summed up to obtain the total travel time cost of each average speed. Finally, travel time cost curves were plotted, as shown in Figure 4a.

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 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 4b.

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 methods of reducing their emission; through the application of the optimal speed limit, for example, would be of great value. The amount emitted and cost of such was determined by the Committee for Guidelines for the Evaluation of Road Investment Projects (JRI 2000), as shown in Table 3.

Table 3: Emission of Pollution for Each Traveling Speed

Traveling Sped (km/h)	NOx (g/km/day)	CO_2 (g-c/km/day)	Noise Level (dB(A))
10	$(0.34a_1+3.79a_2)Q$	$(99a_1+237a_2)Q$	
20	$(0.20a_1+3.33a_2)Q$	$(67a_1+182a_2)Q$	
30	$(0.24a_1+2.87a_2)Q$	$(54a_1+155a_2)Q$	
40	$(0.20a_1+2.41a_2)Q$	$(46a_1+137a_2)Q$	40+A
50	$(0.21a_1+2.16a_2)Q$	$(42a_1+127a_2)Q$	
60	$(0.23a_1+1.90a_2)Q$	$(40a_1+122a_2)Q$	
70	$(0.25a_1+2.10a_2)Q$	$(39a_1+123a_2)Q$	42+A
80	$(0.27a_1+2.29a_2)Q$	$(40a_1+129a_2)Q$	43+A

a_1: ratio of passenger car, a_2: ratio of heavy vehicle, Q: traffic volume (veh/day)

$A = 10*\log(a_1+4.5a_2)+10*\log(Q/24)$

g-c: gram-carbon, and dB(A): unit of sound level pressure. **Data Source:** Japan Research Institute (2000)

- 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) (JRI 2000). The unit ton-C denotes the weight of carbon contained in the corresponding carbon dioxide (CO_2). As the price (yen/ton-c) and amount

Figure 4: Cost Components

a) Travel Time Cost

b) Vehicle Operating Cost

c) Carbon Dioxide

d) Nitrogen Oxide

e) Noise Pollution

f) Accident Cost
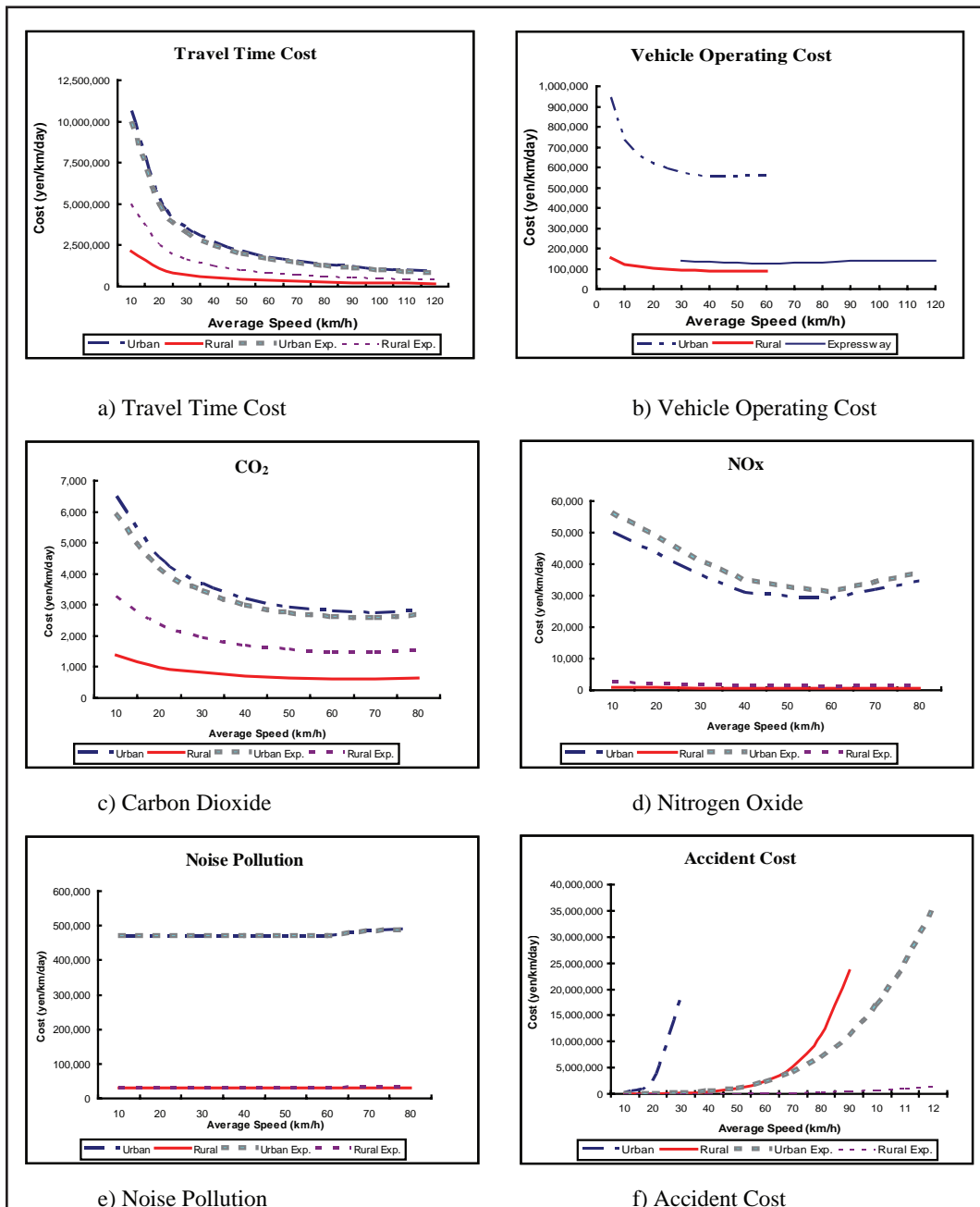
of CO_2 (g-c/km/day) were not in the same unit, in order to obtain CO_2 cost (yen/km/day) the unit conversion from gram-c (g-c) to ton-c was required by dividing 10^6(g-c/ton-c), as shown in equation 1. From the calculation, the cost was high at low speed, and started to decrease as speeds increased, reaching a minimum cost at 70 km/h. Cost again began to increase at speeds above 70km/h, as shown in Figure 4c.

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

- 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 (USEPA 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 dollars/ton) for urban and rural areas, respectively (JRI 2000). As the price (yen/ton) and amount of NOx (g/km/day) were not in the same unit, in order to obtain NOx cost (yen/km/day), the unit conversion from grams (g) to tons is required by dividing 10^6(g/ton), as shown in equation 2. The minimum cost obtained was at 60 km/h, as shown in Figure 4d.

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

- Noise Pollution

Noise pollution can be defined as unwanted or offensive sounds that unreasonably intrude upon 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 was 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 165,600 yen/dB(A)/year (20,000 and 1,375 US dollar/dB(A)/year) for urban and rural areas, respectively (JRI 2000). The dB(A) is the unit of sound pressure level. The noise cost was the per day cost but price of noise level was the per year cost so the unit conversion from year to day was required by dividing by 365 (days/year). The results shown in Figure 4e were obtained from the following equation 3.

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

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.

To reveal the relationship between accident cost and average speed, accident data is required. In Japan, the number of fatalities has been the most important factor in the evaluation of all road safety projects. When the Japanese government initiates a road project, its target is primarily to reduce fatalities. Therefore, only fatalities were employed to reveal the relationship between accident cost and average speed. From the national statistics in 2003 (STAT 2003), Hokkaido had the highest number of fatalities (391) among the 47 prefectures in Japan. 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 four fatalities on expressways.

Recently, many methods have been used to determine the relationship between accident cost and average speed; e.g., linear model, logistics model, power model, 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). Moreover, Elvik (2005) also studied the evaluation of the power model of the relationship between speed and road safety. He concluded that the results were broadly supportive of

the power model. The power model (Nilsson 2004) was proved to be able to reveal the relationship between speed and road safety. Therefore, it 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 of 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, the power model was applied to determine the relationship between accident cost and average speed. To apply the power model, the number of fatal accidents and fatalities and the average speed of each road should be obtained first. From the road traffic census for the year 1999 (MLIT 1999), the average speeds of each road (v_0 in equation 4) 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, equation 4 from Nilsson's power model was applied. Then, the number of fatalities after average speed changes (z_1) can be predicted when average speed after speed changes (v_1) (every 10 km/h, range from 10 km/h to 120 km/h) are inserted in equation (4). At this step, the number of fatalities at each average speed was predicted. After that, the number of fatalities at each average speed was multiplied by fatality cost (36,163,000 yen or 314,500 US dollars, (BPR 2004)) and the result was divided 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 (MLIT 2004). The accident cost for each average speed and the relationship between accident cost and average speed was obtained, as shown in Figure 4f.

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

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 speed changes
v_1 : average speed after speed changes

The exponential function was also applied to determine its relationship; however, it was obvious that the relationship determined by the power model gave more appropriate optimal speed limits than the exponential function did. The power model estimated optimal speed limits that were not too low and not too high for the road conditions in Hokkaido. Moreover, the power model has been widely applied to many studies related to speed-safety topics (e.g. Elvik et al. 2004, Elvik 2005). Even though only the fatalities were considered in the analysis as mentioned above, the non-fatal accidents were also examined to observe how they affected the results. However, the result showed that the optimal average speed on urban national highways was too low to be viable, i.e. 10 km/h, while others remained the same. Therefore, the non-fatal accidents were excluded from the analysis.

Optimal Average Speed. After the relationships between all cost components and average speed were obtained, the next step was to sum the individual total costs to determine the optimal average speed as shown in Figure 5. It could be identified 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 due to the high number of accidents, especially on the urban national highways. However, the road condition in winter is rather severe (see Figure 2). Therefore the optimal average speeds are quite suitable but may be too low in case of some roads which have good road conditions even in winter. Consequently, further detailed work is required.

Figure 5: Summation of Cost
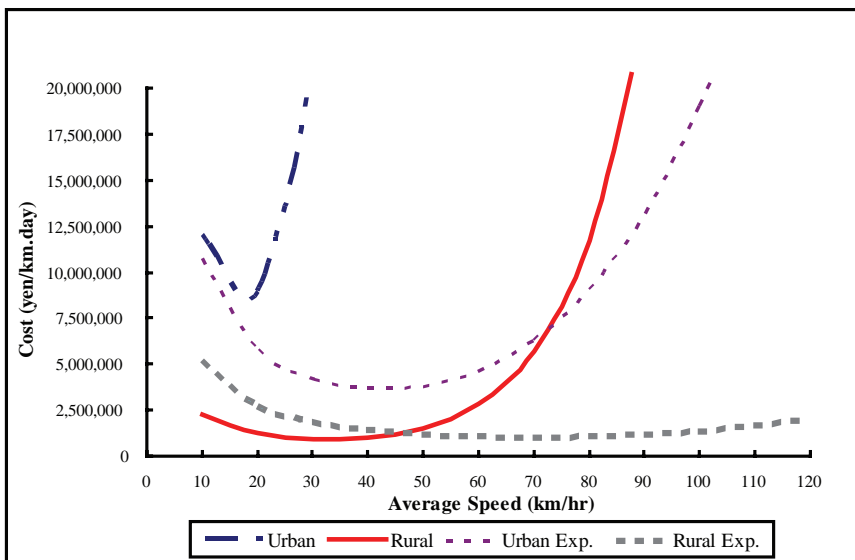
In terms of optimal total cost, the urban national highways had the highest cost as they had the highest accident cost as well as the largest traffic volume. In decreasing order of cost, urban national highways were followed by urban expressways, rural expressways, and rural national highways. However, looking at the total costs of rural national highways, urban expressways, and rural expressways, it was 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. From Thanesuen et al. (2007b), only the effects of traffic signal density and traffic congestion were included; however, the present study is more complicated due to the complex interplay of conditions on winter roads.

Effects of Road and Traffic Conditions

Normally, many factors affect driving speed, but the most influential factors are traffic signals and traffic congestion. However, in winter, in addition to 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 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 MLIT (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 to be a linear function, as shown in equation (5). He showed the skid number (or coefficient of friction * 100) in range, i.e. icy road (0-23), snow-compacted road (23-45), wet road (45-68), and dry road (68-100). After this step, it is still difficult to find the exact value of the coefficient of friction between tires and road surface. Thus, coefficients of friction from many studies in Hokkaido were applied in this study, including Shirakawabe (1990), Uchida et al. (2002), and Nakatsuji et al. (2005), as shown in Table 4. These values were also justified that they were appropriate to the road conditions. However, in the future studies, its average value should be determined by field experiment and reapplied to this model.

(5) $Y = 1219.75 + 5.2987X$

where Y : Road capacity (passenger cars/hr/lane)
        X : skid number (or coefficient of friction * 100)

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	Powder snow with icy on the bottom	0.23[1]
10	Powder snow with icy on the bottom	0.23[1]
11	Dry	0.70[3]
12	Wet	0.60[1]
13	Sherbet (crushed ice)	0.45[1]

Remarks: The categories for road conditions followed those used in the MLIT (1999).
1)   Taken from Shirakawabe (1990), [2] taken from Uchida et al. (2002), [3] taken from Nakatsuji et al. (2005)

After road capacity was calculated allowing for the effect of road slipperiness, the effect of weather was introduced, which causes a further reduction in capacity. From TRB (2000), light snow was shown to reduce road capacity by 5 to 10%. Heavy snow significantly influences the speed-flow curve, which suggested a 30% drop in capacity. The capacities of each road section were then calculated to adjust in terms of 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 were represented as a v/c ratio (v: traffic volume, c: capacity).

The next step was the accumulation of other data; i.e., those for traffic signal density and actual average speed in peak hour (to account for 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 can be expressed by the following equation.

(6)   Average Speed (V_{avg}) = Speed Limit (SL) – Effects of road and traffic conditions (y)

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

To obtain the optimal speed limit from the optimal average speed, the effects (y_i) in equation 6 should first be obtained. These effects can be obtained from the difference 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, it was assumed that the relationship between difference in speed and effects of road and traffic conditions and traffic signal density could be determined by regression analysis. In the regression analysis, a trial and error method was used to obtain the regression equation that had the highest R^2 value and the coefficients of each parameter that showed the highest absolute t-stat value. The absolute t-stat values of all parameters were higher than 1.96 which meant that the parameters had statistically significant impacts on the effects of road and traffic condition (y_i). The effects are shown in equation 7. R^2 values of all roads were likely to be accepted in this study. However, it was obvious that the R^2 value of urban expressways was relatively low as well as the absolute t-stat values (<1.96) of friction (*f*) and weather (*W*). The possible reason is that traffic volume was predicted from autumn data as discussed in the cost analysis section, not the actual collected data. Therefore, in the future, actual traffic volume in winter corresponding with speed data should be collected to improve the model.

(7)
$$
\begin{cases}
y_1 = 27.466 - 0.868x_1 - 35.988x_2^{\;3} + 1.704W & R^2 = 0.45 \\[2mm]
y_2 = 15.460 - 3.182x_1 + 0.378x_1^{\;2} + 57.877x_2 - 69.305x_2^{\;2} - 22.199f & R^2 = 0.31 \\[2mm]
y_3 = 14.09 - 9.750f + 0.245W & R^2 = 0.06 \\[2mm]
y_4 = 7.643 + 213.252x_2^{\;2} - 263.657x_2^{\;3} & R^2 = 0.48
\end{cases}
$$

where y_i : effects of road and traffic conditions (km/h)

x_1 : traffic signal density (average traffic signal density from MLIT (1999) for urban and rural national highways are eight and three signals per km, respectively)

x_2 : volume-capacity ratio

W : weather condition number (obtained from Table 5)

f : coefficient of friction between tires and road surface

From equation 7, it is obvious that weather condition had an influence on the speeds on urban national highways (y_1) and urban expressways (y_3) while friction had an influence on the speeds on rural national highways (y_2) and also urban expressways (y_3). Only on urban expressways the relationship between volume-capacity ratio (x_2) and speed could not be found so the actual traffic volume was unobtainable. This could affect the quality of model, as it appears in equation 7 that R^2 is quite low for urban expressways.

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

(8) $SL_{opt.} = y_i + V_{opt.avg.}$

where $SL_{opt.}$: optimal speed limit

y_i : effects from traffic signal density and traffic congestion

$V_{opt.avg.}$: optimal average speed

RESULTS

The optimal winter speed limits ($SL_{opt.}$) 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	$SL_{opt.}$
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	15.16	55.16
Rural Expressways	70	1,208	5,724	0.21	0.13	7	14.66	84.66

DISCUSSION

From this study, it is 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 results but less significantly than accident cost. As the accident cost was determined by power function, the factors that influenced accident cost were the actual average speed and the number of fatal accidents and fatalities. If the mean speed and number of fatal accidents change, the accident cost will change accordingly. The least influential cost component in the cost analysis was CO_2 emission cost due to the low cost per unit.

Second, based on 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 causing 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 the questionnaire survey (Thanesuen et al. 2007a). About 1,000 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. The questionnaire was divided into two parts. In the first part, general personal information (i.e. age, gender, car ownership, travel distance per year) were inquired. In the second part, the trade-off analysis was applied to determine the preferable speed limits on Hokkaido roads in both summer and winter. An example of the questionnaire for urban national highways is shown in Table 7. From the questionnaire analysis, the results showed 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. For 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. For this reason, 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.

Table 7: Questionnaire Example

Urban National Highway (Example of route: Route 5, Sapporo-Otaru, Urban Area, with 4 –lane)

Condition A		Percentage			Condition B	
Speed Limit	**Accident Rate**	**A**	Indifference	**B**	**Speed Limit**	**Accident Rate**
					<30 km/h	<0.20
					30 km/h	0.20-0.59
50 km/h	1.00				40 km/h	0.60-0.99
					60 km/h	1.41-1.80
					>60 km/h	>1.80

Remark: There were five cases to compare in each road, two conditions were compared. The answer could be A, B, or indifference in each case. For the accident rate, Nilsson's power model was applied (Thanesuen et al. 2007a).

Finally, a sensitivity analysis was applied in this study to observe the effect of changes in cost on the results. The accident cost and time cost were focused for this analysis as they had the most influence on the optimal speed limit. For accident cost, it was 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 remained unchanged. Then, the fatality cost was further increased by 240%, only the optimal speed limit on urban national highway was decreased by 10 km/h. 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 more sensitive to increases in cost, while the optimal speed limit on urban national highways shows little sensitivity to cost increases. From this, the model can be regarded as reliable. Here, only the increases in costs were considered as an examination of costs to date shows a rising trend, suggesting they will have high possibility to increase in the future.

CONCLUSION

Due to the noticeably high number of accidents in winter on Hokkaido roads, the winter speed limit should be addressed to enhance road safety. In this study, a cost analysis method was applied to determine the optimal average speed, and then the effects of road and traffic conditions (i.e. traffic signal density, traffic congestion, weather conditions, and road slipperiness) were introduced to determine the optimal winter speed limit. The calculation showed that it is possible to apply the derived speed limits to all road and traffic conditions, except for urban expressways for which the optimal speed limit obtained was too low to be viable. These optimal speed limits would be applicable for both cars and trucks. It is quite difficult to apply differential speed limits for cars and trucks on Hokkaido roads as most Hokkaido roads are two-lane highways. If the differential speed limit is applied, traffic congestion is likely to occur.

Moreover, a sensitivity analysis was conducted to investigate the results when costs (VOT and fatality cost) were increased. The analysis suggested that the model is reliable and these speed limits can be sustained in the long term as costs of components are not expected to change significantly from year to year. Moreover, the results also corresponded to those of the road users according to questionnaire survey findings, with the exception of urban expressways.

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 of missing or unavailable data; e.g., driver behavior and traffic volume on urban and rural expressways. Therefore, more data should be collected to improve the results. Nevertheless, road users (from the questionnaire survey) agreed that the optimal speed limits obtained in this study are appropriate, except that for urban expressways.

Recently, the Japanese Police Department has announced that it would reconsider speed limits in summer because the existing speed limits have been unchanged for a long time. It is anticipated that optimal speed limit could be applied for improvement in terms of road safety, so this method will be proposed as it has included 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 the results of this model with the available dynamic message signs or variable speed limit (VSL) 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 the future studies, the better quality data and driver behavior in winter will be collected to improve the model. Moreover, a spot speed study in winter will be conducted to obtain information on speed distribution. With this data the model results can be compared with other well-known methods for setting speed limits; i.e., the 85th percentile speed. As this study is the first step of a speed limit study in winter, the next step would be to consider each road section individually.

References

Aarts, L.T. "Speed, Speed Distribution, and the Chance of Road Crashes." *SWOV Report R-2004-9*, SWOV, Netherlands, 2004.

Berthelot, C. F., G. A. Sparks, T. Blomme, L. Kajner, and M. Nickeson. "Mechanistic-Probabilistic Vehicle Operating Cost Model." *Journal of Transportation Engineering* 122(2), (1996): 337-341.

Bureau of Public Road (BPR). *Cost Benefit Analysis Manual.* Ministry of Land, Infrastructure and Transportation (MLIT), Japan, 2004.

Civil Engineering Research Institute (CERI). *Traffic Accident Analysis on Hokkaido Roads*, 2006. http://www2.ceri.go.jp/jiko/ (accessed November 1, 2006)

Department of Environment and Conservation (DEC). *Chapter 1: Atmosphere – 1.7 Noise Pollution*, 2006. http://www.epa.nsw.gov.au/soe/97/ch1/15_1.htm (accessed November 14, 2006).

Elvik, R. "Optimal Speed Limits: Limits of Optimality Model." *Transportation Research Board 1818*, (2002): 32-38.

Elvik, R. "Speed and Road Safety: Synthesis of Evidence from Evaluation Studies." *Transportation Research Board 1908*, (2005): 59-69.

Elvik, R., P. Christensen, and A. Amundsen. *Speed and Road Accidents: An Evaluation of the Power Model.* TOI report no. 740/2004, Institute of Transport Economics, 2004.

Japan Meteorological Agency (JMA). *Snow Data*. http://www.data.kishou.go.jp/mdrr/snc_now/index.html (accessed November 7, 2006).

Japan Research Institute (JRI). *Guidelines for the Evaluation of Road Investment Projects*. Japan, 2000.

Ministry of Land, Infrastructure and Transportation (MLIT). Annual Road Statistics Year 2004. Japan, 2004.

Ministry of Land, Infrastructure and Transportation (MLIT). Road Traffic Census Survey Year 1999. Japan, 1999.

Nakatsuji, T., I. Hayashi, A. Kawamura, and T. Shirakawa. "Inverse Estimation of Friction Coefficients of Winter Road Surface: New Considerations of Lateral Movements and Angular Movements." *Transportation Research Record 1911*, (2005): 149-159.

Nilsson, G. "Traffic Safety Dimensions and the Power Model to Describe the Effect of Speed on Safety." *Bulletin 221.* Department of Technology and Society, Lund Institute of Technology, Lund, Sweden, 2004.

Peltola, H. "Seasonally Changing Speed Limits: Effects on Speeds and Accidents." *Transportation Research Record 1734*, (2000): 46-51.

Räsänen, J. and H. Peltola. "Seasonal Speed Limits and Heavy Vehicles." *NORDIC Road And Transport Research, No.2/3* (2005): 22-23.

Robinson, A. B., S. L. Baliunas, W. Soon, and Z. W. Robinson. *Environmental Effects of Increased Atmospheric Carbon Dioxide. Petition Project*, 1998. http://www.oism.org/pproject/s33p36.htm (accessed November 14, 2006).

Shirakawabe, H. "Analysis of Factors that Influence on Intersection Capacity." Graduate Thesis. Hokkaido University, 1990.

Statistics Bureau and Statistical Research and Training Institute (STAT). Ministry of Internal Affairs and Communications. *Road Traffic Accidents by Prefecture* (2003). http://www.stat.go.jp/data/nenkan/pdf/y2625000.pdf. (accessed July 14, 2005).

Thanesuen, S., S. Kagaya, K. Uchida, and T. Hagiwara. "Evaluation of Speed Limit on Hokkaido Roads" Submitted for *Journal of the 7th Eastern Asia Society of Transportation Studies Conference*, Dalian, China, 2007a.

Thanesuen, S., S. Kagaya, K. Uchida, and T. Hagiwara. "Optimal Speed Limit by Cost Analysis Including Effects of Road and Traffic Conditions in Hokkaido." *Proceeding of TRB 86th Annual Meeting*, Washington D.C., 2007b.

Transportation Research Board (TRB), National Research Council. *Managing Speed: Review of Current Practice for Setting and Enforcing Speed Limits.* Committee for Guidance on Setting and Enforcing Speed Limits, Special Report 254, Washington, D.C., 1998.

Transportation Research Board (TRB). *Highway Capacity Manual (2000) (Metric Units)*. National Research Council, Washington, D.C., 2002.

Uchida, K., S. Kagaya, and S. Keiichi. "Study of Overtaking on Slippery Two-lane Road." *Proceeding of 11th PIARC Winter Road Congress*, Sapporo, Japan, 2002.

U.S. Environmental Protection Agency (USEPA). *Air & Radiation – Basic Information – Six Common Air Pollutants – Nitrogen Dioxide*, 2006. http://www.epa.gov/air/urbanair/nox/chf.html (accessed November 14, 2006).

U.S. Federal Highway Administration (USFHWA). *FHWA Road Weather Management – Best Practices Version 2.0. U.S. Department of Transportation*, 2006. http://ops.fhwa.dot.gov/Weather/best_practices/1024x768/right_main.htm (accessed November 10, 2006).

Acknowledgements

Suthipun Thanesuen (corresponding author) is a doctoral student in the Laboratory of Infrastructure Planning and Design, Hokkaido University. He started his degree in October 2004 and plans to finish in September 2007. His research is primarily on speed limits. Now he is doing a collaborative research on revising speed limits on Hokkaido roads with the Civil Engineering Research Institute for Cold Region, PWRI, Hokkaido.

Kagaya Seiichi is a professor in the Laboratory of Infrastructure Planning and Design. He is a supervisor of Suthipun Thanesuen. His research subjects are transportation planning, transportation policy, and transportation sustainability.

Ken-etsu Uchida is a researcher in the Laboratory of Infrastructure Planning and Design. His research is primarily on transportation models and cost benefit analysis.

Toru Hagiwara is an associated professor in the Laboratory of Infrastructure Planning and Design. His research is primarily on traffic safety on Hokkaido roads.