Approach to Optimization of Winter Road Management Operation
by Taxi Probe Data

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Traffic smoothness must be ensured through winter road management. The average travel speed is a key indicator that represents traffic smoothness. In this study, we used taxi probe data to obtain average travel speeds in the Sapporo urban area, Japan for a long period of time, and analyzed the relationship between the average travel speed and various winter weather and road surface conditions. Also, we calculated the monetary value of the increase in average travel speed afforded by snow and ice control operations. We had acquired taxi probe data 6 months from October 1st, 2010 to March 31st, 2011, with the cooperation of a taxi company. Differences in average travel speed between the winter season and the non-winter season have been found to vary depending on weather and road surface conditions. Our survey has found that snow and ice control operations increase the average travel speed of road users. Improved average travel speed increases the benefits for road users. The cost-benefit analysis for snow disposal and hauling for national highways in Sapporo found that the estimated benefits of snow disposal and hauling operations far exceeded the cost of such work operations. This paper proposes an approach to a balance and optimization of winter road management and winter service using the taxi probe data.

<Keywords: taxi probe data, floating car data, winter, travelling speed >
1. INTRODUCTION

In cold, snowy regions, vehicle travel speeds decrease due to snowfall, snow cover, and icy road surfaces. Traffic congestion in winter is a serious problem, particularly in urban areas. In the city of Sapporo (42° North latitude, 141° East longitude), Japan, the annual mean temperature is 8.5°C and the mean temperature in January is –4.1°C. The city is in one of the snowiest areas in the world, having the annual snowfall of about 5 meters. As a large city with inclement winter weather, Sapporo has been facing the need to ensure smooth flow of traffic. Road administrators here are required to assess road traffic conditions accurately and to take adequate winter road management measures.

The authors have been studying methods of practically applying taxi probe data (TPD), i.e. floating car data collected from taxis, such as for monitoring and analyzing winter road traffic conditions. TPD are the data on the time, location (latitude and longitude) and travel speed of taxis, collected at regular intervals by GPS devices. Such devices are usually mounted on taxis for operational control by the company owning the taxies. Analysis of TPD tells us, for example, the route a taxi has travelled, as well as the travel speed for each road section and the time spent on each road section. The authors had been acquiring TPD from 115 taxies from October 1st, 2010 to March 31st, 2011, with the cooperation of a taxi company. The data are used for analysing road traffic characteristics in winter and for assessing winter road management operations.

This paper describes a study that was conducted by utilizing TPD collected on winter roads in the greater Sapporo area. The objectives of this study are to reveal the following:

1) Assessment of travel speeds in the snowy season, as well as in the non-winter season, from the viewpoint of road trafficability;
2) Use of average travel speeds in various road sections for calculating the time lost due to traffic congestion in winter; and
3) Cost-benefit analysis of snow disposal/hauling as an example of a winter road management operation.

2. LITERATURE REVIEW

Previous studies on the balance of winter road management and winter service are following.

Through the SHRP project, Bosely III S.E. showed the reductions in snow and ice control costs resulting from the use of road weather information systems [1]. Hayashiya et al. showed the economic evaluation of snow-removal level by Contingent Valuation Method in Sapporo City of Japan [2]. Strong Christopher K. et.al. showed the cost-effectiveness on winter road maintenance for the 2004 to 2005 winter in the Utah Department of Transportation. According to the result, the benefit-cost ratio was calculated at over 11:1 [3]. Qiu L. and Nixon W. A. showed that maintenance level of service (LOS), Annual Average Daily Traffic Volume (AADT), road class, urban settings all have considerable influence on speed and traffic volume. Based on the results, they recommended appropriate targets for maintenance agencies that accommodate the difference in maintenance outcomes because of a variety of weather conditions, the specifications of road system and various traffic conditions [4]. Laura showed the review results of research on Automatic Vehicle Location (AVL) and Global Positioning Systems (GPS) for winter maintenance. The effectiveness of AVL-GPS was generally found to be favorable [5].

Previous studies using probe-car data have included one on a traffic flow and congestion data collection
system by Yu Liu and Meenakshy Vasudevan et al. [6] [7], another on congestion-related indices by Makimura et al. [8], and yet another on evaluation of road traffic by Tamiya et al. [9]. Michael Chapman and Sheldon Drobot et al. showed the results of diagnosing road weather conditions by probe-car data during April 2009 in the Detroit of Michigan. Through the research, the effectiveness for use of the probe-car data in the field of road weather was shown [10] [11].

However, few studies have used probe-car data to examine how winter weather and road surface conditions and winter road management operations affect winter road traffic. There are no studies that the cost-benefit analysis for winter road management operations using probe-car data.

3. TPD SURVEY

3.1 Outline of the TPD survey

TPD in this study refer to data on the date, time of day (to the precision of seconds), location (latitude and longitude) and travel speed/direction of taxies, collected by GPS devices. The car navigation system of each taxi is connected to a GPS for the purpose of collecting data which the taxi company uses for improving operation of taxies. TPD are collected while taxies are travelling. PDA devices and GPS-equipped cell-phones are also available for collecting TPD, but this study used GPS devices connected with car navigation systems. Data on locations, etc. of a taxi are linked to the corresponding road sections on a digital road map of the car navigation system and recorded on a memory card. The combined daily travel distance of 115 taxies was about 40,000 km. In the TPD acquisition process shown in Figure 1, data are acquired 24 hours a day without interruption. The taxi company cooperating in this study uses the data on taxi locations to provide each taxi with information on optimum travelling routes as well as for taxi dispatch control and other operational management.

![Fig.1 TPD acquisition](image-url)
Table 1 Outline of Taxi Probe-car Data

<p>| | |</p>
<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>Taxies</td>
<td>115 taxies</td>
</tr>
<tr>
<td>Data acquisition device</td>
<td>Car navigation system for taxies (CU-5890 B) + memory card unit</td>
</tr>
<tr>
<td>Data storage device</td>
<td>Compact Flash card</td>
</tr>
<tr>
<td>Data updating cycle</td>
<td>7 seconds</td>
</tr>
<tr>
<td>Data items</td>
<td>Date, time of date (with the precision of seconds), location (latitude and longitude), travel speed/ direction (in 16 directions)</td>
</tr>
<tr>
<td>GPS antenna</td>
<td>Exterior antenna</td>
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</tbody>
</table>

3.2 Analysis of winter road traffic characteristics

The Civil Engineering Research Institute for Cold Region (CERI) uses the Oracle Database format to compile the acquired TPD into a database. Data collected while taxies were not driving (waiting for customers, stopped for a break, stopped to pick up fares, etc.) are excluded before the data are entered into the database. The data in the database are for locations, etc. of taxies while they were moving. The database format for the TPD is shown in Table 2. On the basis of this database, average travel speed (ATS) under different conditions can be obtained by specifying a route, a road section or hours of day, for example.

The authors developed the TPD analysis system. The system is used for calculating ATS under various analysis conditions, and the calculated ATSs are used for analysing winter road traffic characteristics as well as for assessing applied winter road management measures. Here, analysis and assessment are conducted with regard to the following:

1) Annual changes in the ATS by route/road section (peak hours in the morning/evening, 12 hours in the daytime, etc.);
2) Spatial distribution of traffic congestion in Sapporo;
3) Q-V characteristics under different winter road conditions (traffic volume data (Q) obtained from traffic counters are also used);
4) Relationships between the ATS obtained from TPD and road surface/ weather (temperature and snowfall) conditions in winter;
5) Relationships between the ATS obtained from TPD and winter road management operations (snow removal/disposal/hauling, and anti-freezing-agent application);
6) Relationships between the ATS obtained from TPD and road structures (configuration of intersections, cross-sectional geometry, etc.) as well as factors specific to winter (snow mounds and decrease in the effective road width); and
7) Quantitative assessment and cost-benefit analysis of winter road management measures.

Figure 2 shows the major roads in the Urban Sapporo Area. The subject route in this study is the national
highway Route 12 (nine sections from 1011 to 1019).

Table 2 Entry Format for Taxi Probe Data

<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Speed</th>
<th>Direction</th>
<th>……</th>
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</thead>
<tbody>
<tr>
<td>1</td>
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</tbody>
</table>

Fig. 2 Major roads in the Urban Sapporo Area

4. STUDY RESULTS

4.1 Annual changes in ATS

One of the features of studies using TPD is that the data are basically available for 24 hours a day, 365 days a year. Thus, it is possible to understand annual changes in ATS, which is calculated from TPD, for each route, specific hours of day, etc. Figure 3 shows daily changes in ATS for the road sections on which TPD were collected between October 1st, 2010 and March 31st, 2011. The data in this figure were collected in the 12 hours between 7 a.m. and 7 p.m. on various sections of national, prefectural and municipal roads. The figure indicates the following:

1) Between October and November, the ATS was more or less the same: roughly 30 km/h. During this period, the ATS increased slightly at a constant frequency, with this increase falling on Sundays. The ATS also increased on public holidays;
2) The ATS began to decrease in early December, and it stayed at around 25 km/h between December and February;

3) In the winter period, the ATS changed greatly from day to day. Particularly between January 14 and 17, the ATS decreased significantly due to a heavy snowfall event from 5 to 40 cm in the city; and

4) In and after March, when the snow began to melt, the ATS increased gradually.

![Fig. 3 Average travel speeds between October 1, 2010 and March 31, 2011](image)

Figure 4 shows the 12-hour ATS in the daytime on January 17, 2011, when the city had a heavy snowfall. The data were collected on road sections in the inner-city area of Sapporo. Road sections with ATS of 20 km/h or less were found in the entire inner-city area.

Photo 1 shows CCTV footage of the traffic on National Route 12. The road surface is dry in (a) and covered with compacted snow in (b). Figure 5 shows the correlation between the ATS on Section 1012 of Route 12 in the city and the daily snowfall. It is apparent that the ATS decreases remarkably on the days with snowfall.
Fig. 4 ATS in the inner-city area when there was a heavy snowfall
(12-hour ATS on January 17, 2011)
5. BENEFITS OF WINTER ROAD MANAGEMENT OPERATIONS

5.1 Calculation of benefits

During winter, road administrators implement road management operations such as snow removal, disposal/hauling and anti-freezing-agent spraying (Photo 2). The benefits of winter road management operations can be calculated on the basis of the change in daily ATS calculated from TPD. As an example, the benefits of snow disposal/hauling were calculated in this study. In such operations, snow piles at the road shoulders are removed to ensure the effective road width, and the removed snow is transported to snow-dumping sites. This operation is conducted two or three times between January and February on national highways in the city. This study focuses on the snow disposal/hauling because its effects are immediate and relatively persistent.

Fig. 5 ATS and Snow depth (at Section 1012 of Route 12)
(12-hour ATS in the daytime between Jan. 1st, 2011 and Jan. 31st, 2011)

Photo 2 Snow disposal and hauling
(a) Plowing  (b) Hauling
Figure 6 shows a schematic diagram of changes in the travel speed before and after snow disposal/hauling. Snow is removed routinely from the road surface and deposited at the road shoulders. As these snow piles increase in volume and height, the road width and thus the ATS decrease gradually. After snow disposal/hauling, the effective road width is restored and the ATS increases.

![Fig. 6 Change in ATS after snow disposal and hauling](image)

The effectiveness of snow disposal/hauling in increasing the ATS is calculated by Equation (1) below:

\[
V_E = (V_A - V_B) \times N + 2
\]  

(1)

\(V_A\): ATS after snow disposal/hauling (km/h)

\(V_B\): ATS before snow disposal/hauling (km/h)

\(N\): Interval between snow disposal/hauling (days)

Two benefits relate to the change in the ATS after snow disposal/hauling: decrease in travel time (BT), and reduction in travel cost (BR). These two benefits are expressed in Equations (2) ~ (5) below. The benefit of snow disposal/hauling (BH) is obtained by Equation (6):

\[
BT = BT_O - BT_W
\]  

(2)

\[
BT_i = \sum_l \sum_j (Q_{ijl} \times T_{ijl} \times \alpha_j)
\]  

(3)

\(BT\): Total travel cost with snow hauling \(i\) (yen)

\(Q_{ijl}\): Traffic volume of a vehicle type \(j\) on road section \(l\) with snow hauling \(i\) (vehicles/day)

\(T_{ijl}\): Travel time of a vehicle type \(j\) on road section \(l\) with snow hauling \(i\) (min.)

\(\alpha_j\): Basic unit value of time for vehicle type \(j\) (yen/min.-vehicle)

\(W\): With snow hauling \(i\), \(O\): Without snow hauling \(i\)

\(j\): Vehicle type

\(l\): Road section

\[
BR = BR_O - BR_W
\]  

(4)

\[
BR_i = \sum_l \sum_j (Q_{ijl} \times L_i \times \beta_j)
\]  

(5)

\(BR\): Total travel cost with snow hauling \(i\) (yen)

\(BR_W\): Total travel cost without snow hauling \(i\) (yen)
BR: Benefit of reduction in travel cost (yen)

BR: Total travel cost with snow hauling i (yen/year)

Qij: Traffic volume of a vehicle type j on road section l with snow hauling i (vehicles/day)

Ll: Length of road section l

βj: Basic unit of travel cost for vehicle type j (yen/vehicle-km)

BH = (BT + BR) x N / 2  \hspace{1cm} (6)

5.2 Benefits of snow disposal and hauling

The benefits of snow disposal/hauling were calculated on the basis of the changes in the ATS after such operation on Route 12. The data for calculation were collected for the three days before and after the snow disposal/hauling conducted in January 2011. The data on the traffic volume and each vehicle type as a percent of all vehicle types are from the Road Traffic Census Data 2005 [12]. The benefit of decrease in the travel time was obtained by Equations (2) and (3) above. Equations (4) and (5) were used for calculating the benefit of reduction in travel cost. The benefits of snow disposal/hauling calculated by Equation (6) are shown in Table 3. The basic unit value of time by vehicular type (αj) and the basic unit of travel cost by vehicular type (βj) were the data from The Cost-benefit Analysis Manual [13]. The interval between snow disposal/hauling (N) is 21 days, which was calculated from the data in the operational log.

Table 3 Estimated benefits of snow disposal/hauling on Route 12

<table>
<thead>
<tr>
<th></th>
<th>1011</th>
<th>1012</th>
<th>1013</th>
<th>1014</th>
<th>1015</th>
<th>1016</th>
<th>1017</th>
<th>71018</th>
<th>1019</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATS before snow disposal/hauling (km/h)</td>
<td>14.5</td>
<td>14.6</td>
<td>24.5</td>
<td>26.5</td>
<td>26.7</td>
<td>16.8</td>
<td>18.2</td>
<td>27.1</td>
<td>35.0</td>
<td></td>
</tr>
<tr>
<td>ATS after snow disposal/hauling (km/h)</td>
<td>14.2</td>
<td>21.8</td>
<td>28.4</td>
<td>29.7</td>
<td>33.3</td>
<td>27.2</td>
<td>34.3</td>
<td>34.3</td>
<td>30.2</td>
<td></td>
</tr>
<tr>
<td>Road section length (km)</td>
<td>0.4</td>
<td>0.8</td>
<td>1.1</td>
<td>0.7</td>
<td>1.8</td>
<td>2.3</td>
<td>2.1</td>
<td>1.0</td>
<td>3.9</td>
<td>14.1</td>
</tr>
<tr>
<td>Road section traffic volume (vehicles)</td>
<td>36,416</td>
<td>38,140</td>
<td>36,550</td>
<td>30,726</td>
<td>35,155</td>
<td>39,479</td>
<td>39,984</td>
<td>39,984</td>
<td>39,155</td>
<td></td>
</tr>
<tr>
<td>Passenger cars as a % of all vehicles</td>
<td>73.4%</td>
<td>68.6%</td>
<td>71.8%</td>
<td>78.1%</td>
<td>77.4%</td>
<td>77.6%</td>
<td>79.0%</td>
<td>79.0%</td>
<td>79.9%</td>
<td></td>
</tr>
<tr>
<td>Buses as a % of all vehicles</td>
<td>1.9%</td>
<td>2.5%</td>
<td>3.0%</td>
<td>1.9%</td>
<td>1.7%</td>
<td>2.2%</td>
<td>1.6%</td>
<td>1.6%</td>
<td>1.1%</td>
<td></td>
</tr>
<tr>
<td>Small freight trucks as a % of all vehicles</td>
<td>17.9%</td>
<td>21.9%</td>
<td>17.6%</td>
<td>13.2%</td>
<td>13.2%</td>
<td>12.9%</td>
<td>12.0%</td>
<td>12.0%</td>
<td>13.2%</td>
<td></td>
</tr>
<tr>
<td>Standard freight trucks as a % of all vehicles</td>
<td>6.8%</td>
<td>6.9%</td>
<td>7.7%</td>
<td>6.7%</td>
<td>7.6%</td>
<td>7.3%</td>
<td>7.4%</td>
<td>7.4%</td>
<td>5.8%</td>
<td></td>
</tr>
<tr>
<td>Reduction in time (h)</td>
<td>0.000</td>
<td>0.018</td>
<td>0.0062</td>
<td>0.003</td>
<td>0.013</td>
<td>0.052</td>
<td>0.054</td>
<td>0.0077</td>
<td>0.000</td>
<td>0.155</td>
</tr>
</tbody>
</table>

Benefit of reduction in time (BT) (1,000 yen) 0 6,237 2,100 751 3,981 10,136 18,206 2,804 0 52,013

Benefit of reduction in travel cost (BR) (1,000 yen) 0 282 100 41 215 893 962 144 0 2,835

BT+BR (1,000 yen) 0 6,518 2,199 791 4,196 10,029 19,168 2,747 0 54,649

BH= (BT+BR) x N / 2, N=21(1,000 yen) 573,814

5.2.2 Benefit of reduction in travel cost (yen) 0 6,518 2,199 791 4,196 10,029 19,168 2,747 0 54,649

| Snow disposal/hauling operation cost (C) (1,000 yen) | 0 | 4,491 | 6,684 | 2,135 | 8,149 | 10,664 | 7,416 | 4,060 | 21,723 | 65,322 |

5.2.2 Benefit of reduction in travel cost (yen) 0 6,518 2,199 791 4,196 10,029 19,168 2,747 0 54,649

Based on materials for implementation snow disposal / hauling by companies contracted with Sapporo highway office, snow disposal / hauling cost (C) was calculated. The cost-benefit ratio (B/C), which was calculated on the basis of the cost and the total benefit of snow disposal/hauling on Route 12, far exceeds 8.0.
6. CONSIDERATIONS OF ADEQUATE WINTER ROAD MANAGEMENT SERVICE

6.1 Views on the benefits of winter road management operations

In this study, the benefits of snow disposal/hauling were calculated with respect to the improvements over the benefits of routine snow removal and anti-freeze agent application. The effectiveness of snow disposal/hauling operation (a) expressed by changes in travelling speed is shown in Figure 7. The effectiveness of routine snow removal and anti-freeze agent application, shown as (b) in Figure 7, was not assessed in this study. In order to calculate the effectiveness (b), road surface conditions without any winter road management operations would need to be estimated and complete absence of winter road management operations would not be feasible in a city such as Sapporo, because roads would not be trafficable at all if no management measures were taken in winter. The cost-benefit ratio of snow disposal/hauling operation would be enormous if its effectiveness was assessed on the basis of the trafficability on the road surface to which no management measures were applied.

![Fig. 7 Outcome with and without winter road management operations](image)

6.2 Sustainable winter road management

Good trafficability in winter is provided to local residents through the road administrator’s road management. The scope and quality of winter road management operations should be agreed upon by road administrators and the local residents. The cost benefits of winter road management operations, which are accurately calculated on the basis of TPD, are useful in the process of discussing and building a consensus on desirable operations. Sustainable winter road management can be provided according to the following procedure:

1) Road administrators propose target service levels of the winter road management by indicating specific ATSs, together with the cost of the winter road management operations, to local residents;
2) Road administrators and local residents establish consensus on target service levels in terms of ATSs;
3) Winter road management operations are implemented;
4) TPD is used for assessing management performance from the viewpoint of the ATS and the effectiveness of the implemented operations, and
5) The entire process from 1 to 4 above is reviewed.
7. CONCLUSION

The use of TPD for assessing winter road traffic conditions and road management, and the prospects for the use of TPD are summarized here.

1) Because TPD are available from taxies, which operate 24 hours a day, every days during winter in the city of Sapporo, the authors used the TPD to understand the annual changes in the ATS in the city. The ATS greatly decreases in early December, when fallen snow begins to stick, and it gradually increases in mid-March, when the accumulated snow begins to melt. This study confirmed that TPD reveal the changes in trafficability in a city’s extensive road network under various seasonal, weather and road surface conditions.

2) Use of TPD affords more reliable cost-benefit calculation of snow disposal/hauling. According to the calculation for snow disposal/hauling on Route 12 in fiscal 2010, the cost-benefit ratio was much greater than 8.0.

3) The winter road surface, being dry, wet, frozen or covered with compacted snow, changes frequently. Snow removal/disposal/hauling, as well as the amount of snowfall, affect road traffic conditions. TPD are collected from a wide area with no time restrictions; thus they will be very useful for assessing winter road traffic conditions. It is expected that TPD will be used for defining the quality of winter road management service desired by road users as well as for setting the implementation standard of winter road management operations provided by road administrators. In this respect, the use of TPD will contribute to sustainable winter road management service.

The authors will conduct more case studies on assessing the effectiveness of winter road management operations, and will try to understand more precisely how various winter road surface conditions affect the ATS. All these efforts will be directed toward study on sustainable winter road management.
ACKNOWLEDGEMENTS

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