Performance Evaluation of “2+1 Lane” Highway in Hokkaido, Japan: Case Study of Saraki-tomanai Road

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ABSTRACT

Hokkaido, Japan’s northernmost island, sees snowfall for the five months from November to March. The road surface is usually dry, but roads are often covered with compacted snow in winter. A measure to improve existing two-lane highways to “2+1 lane” highways by installing an auxiliary lane has been introduced, toward offering a higher quality of service to road users.

We report the results of performance evaluation before and after “2+1 lane” road improvement using SIM-R traffic flow micro-simulation and field survey. The results show the performance evaluation for various placement intervals of the auxiliary lane. Also, the study addresses Saraki-tomanai Road (L=18 km) of Route 40 in Wakkanai City, Hokkaido. Since 2014, some sections of Saraki-tomanai Road have been in service. A fixed-point survey was conducted in January and August 2014. For measurement results were compared with previously performed by traffic flow micro-simulation results. Two road surface conditions were investigated: dry, and compacted-snow.

The average travel speed and the density of following vehicles were used as evaluation indicators for highway geometric design. As results, with increasing the hourly traffic volumes, performance were found that the average travel speed decreased, and the follower density increased. Moreover, the road performance was lower for the compacted-snow road than for the dry road. It was also found that the installation of an auxiliary lane at a certain interval improved the level of service for this two-lane highway both on the dry road and the compacted-snow road.

<Key words: geometric design, road surface condition, two-lane highway, “2+1 lane” highway>
1. INTRODUCTION

Hokkaido, northern Japan, covers approximately 78,000 km$^2$. National highways in Hokkaido extend for more than 6,675 km. Over 90% of national highways consist of two lanes. Two-lane highways are characterized by the frequent formation of platoons of cars headed by low-speed vehicles, and passing opportunities on two-lane highways are limited. In much of Hokkaido, snow falls for the five months from November to March. The road surface is usually dry but is often covered with compacted snow. With increases in traffic volume, the running performance of vehicles deteriorates somewhat on dry road surfaces and greatly on compacted-snow road surfaces.

On national highways in rural parts of Hokkaido, a measure to improve existing two-lane highways to “2+1 lane” highways (1) by installing an auxiliary lane has been introduced, to offer a better quality of service to road users. Such improvements are known to be more advanced in Europe (e.g., Sweden and Germany) and the United States (2). Efficiently evaluating the running performance of road geometrics of two-lane highways as well as “2+1 lane” highways requires the creation of an appropriate traffic flow micro-simulation.

There have been studies on the evaluation of the structure of “2+1 lane” highways using traffic flow micro-simulation. Andreas Tapani (3) proposed a rural highway traffic flow micro-simulation called “RuTSim”. This model incorporates a model of passing decision-making on two-lane highways and consists of four conditions: passing capability, surrounding traffic, possibility of passing by taking surrounding traffic into consideration, and road traffic regulations. Arne Carlsson and Andreas Tapani (4) used the RuTSim traffic flow micro-simulation to evaluate the road structure of rural two-lane highways and “2+1 lane” highways in Sweden, with average travel speed and the number of following vehicles used as major indicators to evaluate traffic flow. However, it was not possible to simulate winter conditions, such as the winter road surface condition.

In light of the above, the author developed a SIM-R traffic flow micro-simulation program (5) to reproduce traffic flow in response to changes in road surface conditions. The program enables us to deal with changes in road surface conditions, such as the change from the dry surface to the compacted-snow surface. Toward introducing “2+1 lane” highways in Hokkaido, preliminary evaluation of the performance of “2+1 lane” highways has been made using SIM-R. The two simulated road surface conditions were dry (i.e., simulating summer driving) and compacted-snow (i.e., simulating winter driving). The installation interval of the auxiliary lane on the “2+1 lane” highway was varied from 3 km to 10 km.

Road administrator has been constructed the Saraki-tomanai Road of Route 40 in Wakkanai City of Hokkaido as “2+1 lane” highway structure since 2006. As of October 2014, a part of planning for the Saraki-Tomanai Road of Route 40 has been in service.

This paper does the following.

1) It uses SIM-R to evaluate the performance of the “2+1 lane” road structure when dry and when covered with compacted snow.
2) It proposes service levels for dry and compacted-snow road surfaces on two-lane highways and “2+1 lane” highways.

3) It shows the measured performance of the Saraki-Tomanai Road “2+1 lane” highway in Hokkaido as a case study.

2. Research Method

2.1 Models to be applied to SIM-R traffic flow micro-simulation

SIM-R is a traffic flow micro-simulation developed by the Civil Engineering Research Institute for Cold Region of the Public Works Research Institute in 1994. The Herman model, a major car-following model, is expressed by the following Equation 1:

\[
\chi'_{n+1}(t + T) = \alpha \left[ \frac{\chi'(t) - \chi'_{n+1}(t)}{\chi(t) - \chi_{n+1}(t)} \right]
\]  

(1)

\( \chi'_{n+1}(t + T) \): acceleration of following driver \( T \) seconds later  
\( \chi'(t) \): difference in speed between leading and following vehicles (m/s)  
\( \chi_{n+1}(t) \): headway distance between leading and following vehicles (m)  
\( \alpha \): sensitivity value (m/s)  
\( T \): reaction delay of following vehicle (s)

In this model, the headway distance between a leading and a following vehicle is used as the denominator.

However, in an actual car-following situation, the following driver drives while looking at the rear end of the leading vehicle; thus, the inter-vehicle distance found by subtracting the length of the leading vehicle from the headway distance is used for the SIM-R car-following model.

Vehicle equations of motion determines whether the behavior of a certain vehicle is car-following or free travel by comparing its braking stopping distance (6) with the headway distance from the leading vehicle. The behavior is determined to be free travel if the inter-vehicle distance is greater than the braking stopping distance. The braking stopping distance is found using Equation 2.

\[
D = \frac{V}{3.6} t + \frac{V^2}{2gf(3.6)^2}
\]  

(2)

\( D \): braking stopping distance (m)  
\( V \): running speed (km/h)  
\( f \): longitudinal skid resistance coefficient  
\( t \): reaction time (s)  
\( g \): gravitational acceleration (=9.8 m/s²)

Road surface condition differences are reproduced by changing the longitudinal skid resistance coefficient in Equation 2. In this paper, car-following judgment according to the road surface condition is assumed to be a standard of reference whether to fill Equation 2. The longitudinal skid resistance coefficients were assumed to be 0.8 for the dry road and 0.3 for the compacted-snow road. They are based on recent measurement results of
skid resistance tests (7) for various road surface conditions in Japan. Followers are vehicles behind other vehicles at a relatively short headway distance in the traffic flow. The Highway Capacity Manual 2010 (8) uses time headways if no greater than 3 seconds.

The definition of following by HCM2010 is usually assumed based on the results of a measurement with the dry road. The compacted-snow road is slippery than the dry road. Therefore, drivers leave a greater following distance because winter conditions are less safe. Based on the previous research at CERI, time headway as the judgment of the car-following is adopted for less than 4.5 seconds on the compacted-snow-covered road in winter.

The SIM-R free-travel model is based on a configuration in which each vehicle increases its running speed at a certain rate of acceleration (maximum acceleration) until the desired speed is reached.

In addition, a passing model and a lane-changing model of SIM-R, from previous research (5), (9), were found to be valid.

2.2 Indicators to evaluate the performance of two-lane highways
Roads provide drivers with service that should be smooth, comfortable, regular, reliable and safe. Indicators to evaluate the level of service from these various aspects have been developed. The level of service is evaluated through the whole process, from planning and design to operation. This study decided to use the following performance indicators to evaluate the level of service of two-lane highways, in order to provide road users with easy-to-understand indicators.

(1) Average travel speed
Average travel speed (ATS) is one of the two performance indicators used in the existing methodology by the HCM 2010. It is expressed as the average speed of vehicles travelling over a certain section of roadway. Frequently used by transportation engineers, this indicator has the advantage of being easily measured onsite and easily understood by ordinary drivers.

(2) Follower density
The follower density is expressed as the number of following vehicles in a traffic flow for each direction over a unit length of 1 km or more. Van As reported the use of this measure in South Africa as part of the procedure for constructing two-lane highways (10). The follower density is a performance indicator with the major advantage of taking into consideration the influence of traffic conditions efficiency. Although the field measurement of traffic density is difficult, it can be determined by observing traffic volume and speed at follower counting sites. Traffic volume and speed can be measured by using output from a simple traffic counter or other instrument. A study by Nakamura and Catbagan (11) suggested that follower density is an effective indicator of the level of service (LOS) on two-lane highways, based on measurement results of two-lane expressways in Japan.
2.3 Sensitivity analysis of SIM-R

Sensitivity analysis was performed on SIM-R traffic flow micro-simulation for two-lane highways sections where passing is permitted and “2+1 lane” highways. This analysis used road surface conditions, interval of auxiliary lane, auxiliary lane structure and traffic volume as variables. The structures of the highways that were subjected to sensitivity analysis are shown in Figs. 1 and 2. Tables 1 and 2 list the conditions for sensitivity analysis and the items set for simulation, respectively.

![Fig. 1 Highway structures on which sensitivity analysis was performed](image1)

![Fig. 2 Cases of “2+1 lane” highways on which sensitivity analysis was performed](image2)
Table 1 Conditions for sensitivity analysis

<table>
<thead>
<tr>
<th>Item</th>
<th>Sensitivity analysis case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Network length</td>
<td>30km</td>
</tr>
<tr>
<td>Length of each section of auxiliary lane</td>
<td>1.5km</td>
</tr>
<tr>
<td>Intervals between auxiliary lanes</td>
<td>None, 3km, 5km, 7km, 8.5km, 10km</td>
</tr>
<tr>
<td>Hourly traffic volume</td>
<td>100 – 1,000 veh/h</td>
</tr>
<tr>
<td>Surface conditions</td>
<td>Dry surface (f=0.80), Surface covered with compacted snow (f=0.30)</td>
</tr>
<tr>
<td>Simulation frequency</td>
<td>10 times per case</td>
</tr>
<tr>
<td>Time excluded from calculation (Pre-simulation time)</td>
<td>600 seconds</td>
</tr>
<tr>
<td>Simulation time:</td>
<td>3600 seconds</td>
</tr>
</tbody>
</table>

Table 2 Simulation settings

<table>
<thead>
<tr>
<th>Item</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle length</td>
<td>Small vehicles:4.7m, Large vehicles:12.0m</td>
</tr>
<tr>
<td>Maximum acceleration</td>
<td>Small vehicles:6.0km/h/sec, Large vehicles:4.0km/h/sec</td>
</tr>
<tr>
<td>Maximum deceleration</td>
<td>All vehicle types: -17.6km/sec</td>
</tr>
<tr>
<td>Link speed limit</td>
<td>60km/h</td>
</tr>
<tr>
<td>Desired speed distribution</td>
<td>Based on field data</td>
</tr>
<tr>
<td>Traffic data</td>
<td>Based on field data</td>
</tr>
<tr>
<td>Minimum inter-vehicle distance</td>
<td>1.5m</td>
</tr>
<tr>
<td>Sensitivity value</td>
<td>When accelerating 8.2m/sec</td>
</tr>
<tr>
<td></td>
<td>When decelerating 17.0m/sec</td>
</tr>
<tr>
<td>Calculation cycle time</td>
<td>0.5sec</td>
</tr>
</tbody>
</table>

2.4 Measurement Survey

Since 2006, road administrator has been planned and constructed “2+1 lane” highway for Saraki-tomanai Road section (L=18km) on National Highway Route 40 of Wakkanai City in Hokkaido, Japan. As of October 2014, part of a “2 + 1 lane” highway in Wakkanai City had been in service. A fixed camera was placed onsite, and we measured the speed and traffic density of the cross section. Winter snow conditions in January 2014, and for the summer of dry conditions in August 2014, traffic data was measured.

3. Sensitivity analysis results

3.1 Evaluation results for dry road surfaces

The results of the sensitivity analysis for dry “2+1 lane” highways are shown in Fig. 3 for a case with an hourly traffic volume in one direction of 200 vehicles per hour and of 500 vehicles per hour. Average travel speed and the follower density are indicators to evaluate analysis results. Under the dry road surface conditions, when the time headway between two subsequent vehicles is 3 seconds or less, the follower is defined as a following vehicle.

Average travel speed was approximately 68 km/h at a point near where vehicles started to bunch up; however, it decreased to approximately 55 km/h in the case of hourly traffic volume of 200 vehicles per hour, with increasing distance from the start point. Adding an auxiliary lane at certain intervals resulted in increases
in average travel speeds to 65 – 69 km/h on sections with such a lane. In the case of the hourly traffic volume of 500 vehicles per hour, the average travel speed was approximately 63 km/h at a point near where vehicles had started to bunch up; however, it decreased to approximately 52 km/h with increasing distance from the start point. Adding an auxiliary lane at certain intervals resulted in increases in average travel speeds to 57 – 60 km/h on sections with such a lane.

The follower density was very low, around 2 vehicles/km, when the hourly traffic volume was 200 vehicles per hour, regardless of the existence of an auxiliary lane or the distance from the start point. In terms of the level of service provided to road users, it was found that a high level of service was maintained regardless of the installation of an auxiliary lane. In the case of the hourly traffic volume of 500 vehicles per hour, the follower density increased with increase in distance from the start point, and it was approximately 8 vehicles/km on the two-lane highway sections. The addition of an auxiliary lane at certain intervals reduced the density to 4 – 7 vehicles/km.

3.2 Evaluation of compacted-snow road surfaces
The results of sensitivity analysis on “2+1 lane” highways in a compacted-snow surface condition for a case with an hourly traffic volume in one direction of 200 vehicles per hour and for a case of 500 vehicles per hour are shown in Fig. 4. Average travel speed and the follower density are used as indicators to evaluate the analysis results. Under the compacted-snow surface condition, when the time headway between two subsequent vehicles is 4.5 seconds or less, the follower is defined as a following vehicle.

Average travel speed was approximately 59 km/h at a point near where vehicles started to bunch up; however, it decreased to approximately 46 km/h in the case of hourly traffic volume of 200 vehicles per hour, with increasing distance from the start point. Adding an auxiliary lane at certain intervals resulted in increases in average travel speeds to 52 – 58 km/h on sections with such a lane. In the case of the hourly traffic volume of 500 vehicles per hour, the average travel speed was approximately 50 km/h at a point near where vehicles started to bunch up; however, it decreased to approximately 43 km/h with increasing distance from the start point. Adding an auxiliary lane at certain intervals resulted in increases in average travel speeds to 50 – 58 km/h on sections with such a lane.

The follower density was low, 3 – 4 vehicles/km, when the hourly traffic volume was 200 vehicles per hour, regardless of the existence of an auxiliary lane or the distance from the start point. With the case of hourly traffic volume of 500 vehicles per hour, the follower density increased with increase in distance from the start point and it was 10 – 11 vehicles/km on two-lane highway sections. The addition of an auxiliary lane at certain intervals reduced the density to 4 – 8 vehicles/km.
Fig. 3 Sensitivity analysis results
(dry road surface)

Fig. 4 Sensitivity analysis results
(compacted-snow surface)
4. Proposed LOS for cold, snowy regions

Previous research on service level considered neither the influence of the weather nor the changes in the road surface conditions. The service level tends to be set based on observations from dry roads.

The setting service level for the compacted-snow-covered road in winter is preferable. Because it is observed as snow fall for a long term in the cold, snowy region. The setting of the service level is tried for the follower density. The reason is that the follower density is appropriate indicator for a traffic condition and influences of the weather by proper sensitivity. The effective use of follower density as an indicator of service level has been reported by researchers in South Africa, Germany (12) and Japan. Table 3 shows the proposal of the LOS to use follower density for two-lane highways in rural areas.

<table>
<thead>
<tr>
<th>LOS</th>
<th>Follower Density [veh/km•lane]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>≤3</td>
</tr>
<tr>
<td>B</td>
<td>≤6</td>
</tr>
<tr>
<td>C</td>
<td>≤10</td>
</tr>
<tr>
<td>D</td>
<td>≤15</td>
</tr>
<tr>
<td>E</td>
<td>≤20</td>
</tr>
<tr>
<td>F</td>
<td>&gt;20</td>
</tr>
</tbody>
</table>

Table 4 shows the follower density on the dry road and the compacted-snow road for each hourly traffic volume on the two-lane highway and the “2+1 lane” highway (3-km intervals). The value of the follower density in the table is based on the traffic flow micro-simulation results at a point 20 km from the starting point. Through the target of service level is set, a highway design can be decided in consideration of road performances based on road surface condition by the weather characteristic in the region.
### Table 4: Follower density for two-lane and “2+1 lane” highways with dry versus compacted-snow conditions

(Unit: vehicles/km/direction)

<table>
<thead>
<tr>
<th>Hourly Traffic Volume (Vehicles/hour/direction)</th>
<th>Dry Condition in Summer</th>
<th>Compacted-Snow Condition in Winter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2 lane highways</td>
<td>2+1 lane highways (with 3km intervals)</td>
</tr>
<tr>
<td>100</td>
<td>1.1</td>
<td>0.7</td>
</tr>
<tr>
<td>200</td>
<td>2.7</td>
<td>1.8</td>
</tr>
<tr>
<td>300</td>
<td>4.5</td>
<td>2.8</td>
</tr>
<tr>
<td>400</td>
<td>6.3</td>
<td>4.2</td>
</tr>
<tr>
<td>500</td>
<td>8.2</td>
<td>5.4</td>
</tr>
<tr>
<td>600</td>
<td>10.3</td>
<td>7.1</td>
</tr>
<tr>
<td>700</td>
<td>12.2</td>
<td>8.3</td>
</tr>
<tr>
<td>800</td>
<td>14.5</td>
<td>9.9</td>
</tr>
<tr>
<td>900</td>
<td>16.5</td>
<td>11.0</td>
</tr>
<tr>
<td>1,000</td>
<td>18.6</td>
<td>12.8</td>
</tr>
</tbody>
</table>

Note) LOS Colors

<table>
<thead>
<tr>
<th>LOS</th>
<th>Colors</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td></td>
</tr>
</tbody>
</table>
5. Measured survey results

Road administrator has made the construction of Saraki-tomanai Road (L = 18km) on National Highway Route 40 of Wakkanai City in Hokkaido, Japan. Saraki-tomanai Road has been underway in the “2 + 1 lane” road structure. Auxiliary lane of one-way in the three sections is the installed structures. Installation interval of auxiliary lane is about 3 km. The location and photo of “2 + 1 lane” structure are shown in Fig 5. As of October 2014, part of a “2 + 1 lane” highway in Wakkanai City had been in service. Main lane was basically dedicated automobile. In addition, the sub-way has been installed as for light vehicles, such as bicycles, agricultural vehicles.

Traffic survey of “2 + 1 lane” highway for the performance evaluation was carried in winter and summer. Overview of Traffic Survey is shown in Table 5. The traffic survey was carried out by installing a fixed camera at the roadside. In the winter survey, although there was slight snowfall, it had no impact on the investigation.

Table 5 Overview of Traffic Survey

<table>
<thead>
<tr>
<th>Season</th>
<th>Date</th>
<th>Time</th>
<th>Road Surface Condition</th>
<th>Weather</th>
<th>Temp. (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Max.</td>
</tr>
<tr>
<td>Winter</td>
<td>Jan.29, 2014</td>
<td>From 8:00 AM to 3:00 PM</td>
<td>Compacted snow</td>
<td>Snowfall</td>
<td>-9.2</td>
</tr>
<tr>
<td>Summer</td>
<td>Aug.25, 2014</td>
<td>From 8:00 AM to 3:00 PM</td>
<td>Dry</td>
<td>Cloudy</td>
<td>25.0</td>
</tr>
</tbody>
</table>

Average velocity of the cross-section of the 2-hour study day (8:00 to 10:00) is shown in Fig. 6. Case is the winter of compacted snow conditions. "2 + 1 lane" road section, compared with the two-lane road section, was approximately 10 ~ 20km / h higher.
In addition, the measurement results of the follower density are shown in Fig. 7. Case is the winter of compacted snow conditions. In 2 + 1 lane road, as compared to the two-lane road, follower density is lower. From the measured results, LOS had kept the A of the service level.

The measurement results of the follower density for the 2-hour study day (8:00 to 10:00) are shown in Fig. 8. Case is the summer of dry conditions. From the measured results, LOS had kept the A of the service level.
6. Conclusion

(1) Evaluation of the performance of two-lane highways and “2+1 lane” highways with dry versus compacted-snow surfaces

The performance of road structures was showed for two-lane highways and “2+1 lane” highways through sensitivity analysis using the SIM-R traffic flow micro-simulation program. The analysis addressed the two road surface conditions of dry surface and compacted-snow surface. The traffic volume targeted was hourly traffic volume in one direction from 100 to 1,000 vehicles per hour. For “2+1 lane” highway sections, the intervals between auxiliary lanes were 3 km, 5 km, 7 km, 8.5 km and 10 km. It was confirmed that by adding an auxiliary lane to a two-lane highway at a certain interval, i.e., by creating a “2+1 lane” highway, the level of service was improved for each evaluation indicator (average travel speed and follower density) on the dry surface and the compacted-snow surface.

For instance, in the case of the hourly traffic volume of 500 vehicles per hour under the dry surface condition, adding an auxiliary lane at a certain interval resulted in an increase in average travel speed of 10 – 14 km/h, and in a decrease in follower density of 2 – 5 vehicles/km. In the case of the hourly traffic volume of 500 vehicles per hour under the compacted-snow surface condition, adding an auxiliary lane at a certain interval resulted in an increase in average travel speed of 7 – 15 km/h, and in a decrease in follower density of 4 – 8 vehicles/km.

(2) Service level on dry and compacted-snow road surfaces for two-lane highways and “2+1 lane” highways

In evaluating the performance of two-lane highways, as well as of “2+1 lane” highways, in cold, snowy regions, it is essential to take into consideration compacted-snow road surfaces during winter, in addition to normal, dry road surfaces. For both of these highways, the performance is lower with the compacted-snow

Fig. 8 Follower density by observation results
(Dry surface in Summer, Route 40 in Wakkanai City)
road surface than with the dry road surface. It is required to set the target LOS for these highways both in dry and compacted-snow road conditions and to evaluate the performance for the highways geometric design. In this study, the LOS has been proposed using the follower density as indicator.

It is necessary to apply a road structure that satisfies the performance for LOS using the follower density. This study found that it is effective to install an auxiliary lane at intervals of 3 – 5 km when the hourly traffic volume is 600 vehicles per hour. Because it is improved that the service level from D to C both summer and winter. From the viewpoint of improving the LOS, the ideal road design for a highway in a cold, snowy region is that with a short interval of sections without auxiliary lanes between sections installed with auxiliary lanes.

(3) Measurement results for the “2+1 lane” Saraki-tomanai Road
As of October 2014, “2 + 1” part of the Saraki-tomanai Road on National highway Route 40 in Wakkanai City of Hokkaido, Japan has been in service. Traffic measured survey was conducted in January and August 2014. Road surface state was a winter of snow conditions and summer of dry conditions. From the viewpoint of the follower density, in winter and summer both service level A was maintained.

The whole section of Saraki-tomanai road is scheduled to be in service in 2015. Transportation improvement over the full year is expected. “2+1 lane” highway is an efficient road design techniques. We are willing to further advance its effect verification.

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