Analysis on Rural Highway Design using Traffic Micro-Simulation in Cold Regions

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Abstract

A sensitivity analysis was undertaken using a traffic flow micro-simulation program “SIM-R” to evaluate the effectiveness of “2+1 lane highway” sections, which were built by adding an auxiliary lane to rural two-lane highways, in a cold, snowy region. The road surface conditions analyzed were dry and covered with compacted snow. As evaluation indicators, average travel speed, the percentage of following vehicles and the density of following vehicles were used. As a result, the evaluation found that the installation of an auxiliary lane at certain intervals improved the level of service on two-lane highways.

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Keywords: Service level, road surface condition, two-lane highways, “2+1 lane” highways, follower density

1. Introduction

Evaluating the performance of two-lane two-way highways is a complicated task due to their unique operating behaviors. On most highways, two lanes of traffic move in opposite directions; therefore, there are interactions between vehicles travelling in the same lane and those in the on-coming lane. For instance, drivers have to pass slower vehicles in front in order to maintain their desired speed. However, on two-lane highways, passing opportunities are limited. Accordingly, this type of road is characterized by the frequent formation of platoons of cars headed by low-speed vehicles.

Hokkaido is located in the northern part of Japan and covers an area of approximately 78,000km\textsuperscript{2}. The total length of national highways stretching over Hokkaido is 6,550 km. In terms of road structure, over 90\% of national highways consist of two lanes. Hokkaido is a cold, snowy island, where winter, a season when snowfall is recorded, lasts for approximately five months from November to March. Therefore, road surfaces are usually dry but frequently covered with compacted snow. The running performance of vehicles deteriorates with an increase in traffic volume on dry road surfaces, and it further decreases on compacted-snow-covered road surfaces during winter.

On national highways in rural parts of Hokkaido, a measure to improve existing two-lane highways to “2+1 lane” highways by installing an auxiliary lane has been introduced to offer a better quality of service to road users.

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It is widely known that road improvement with the use of “2+1 lane” highways is further developed in European countries, including Sweden and Germany, as well as in the United States. In order to efficiently evaluate the running performance and road structure of two-lane highways as well as “2+1 lane” highways, the creation of an appropriate traffic flow micro-simulation is demanded.

There have been studies on the evaluation of the structure of “2+1 lane highways” using traffic flow micro-simulation. Andreas Tapani (2005) 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 the four conditions: passing capability, surrounding traffic, possibility of passing by taking surrounding traffic into consideration, and road traffic regulations. Arne Carlsson and Andreas Tapani (2006) used the RuTSim traffic flow 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. Other two-lane traffic flow simulations include the Two-Lane Passing (TEOPAS) model (Mc Lean 1989) developed by the Midwest Research Institute and Traffic on Rural Roads (TRARR) (Hotban et al. 1991) developed by the Australian Road Research Board. Unfortunately, there were no studies on traffic flow simulations that take into account weather and specific road surface conditions.

The authors developed a SIM-R traffic flow micro-simulation program to reproduce traffic flow responding to changes in road surface conditions. This program enables us to deal with changes in road surface conditions such as dry and compacted-snow-covered. The reproduction of traffic flow responding to changes in road surface conditions with the use of SIM-R was verified based on the field data collected at three sections of national highway in Hokkaido. Verification of the passing model and lane-changing model were carried out. This paper aims to reproduce the traffic flow of two-lane highways as well as “2+1 lane” highways using SIM-R traffic flow simulation and achieve the following objectives:

1) To evaluate the performance of “2+1 lane” road structure on dry and compacted-snow-covered road surfaces.
2) To clarify the validity of each of the following indicators: average travel speed, the follower percentage and the follower density.
3) To suggest an ideal road structure for national highways in cold, snowy regions

Introduction

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. In the United States, the Highway Capacity Manual 2000 (HCM 2000) published by the Transportation Research Board summarizes their views on the level of service. The HCM uses two factors – average travel speed (ATS) and percentage of time-spent-following (PTSF) – as indicators to evaluate the level of service on two-lane highways. The level of service is evaluated through the whole process, from planning and design to operation stages. In the planning and design stage, a decision is made on the number of lanes to be needed to achieve the target service level in consideration of design traffic volume. In the operation stage, a check is made to see whether the target service level has been met.

The previous study conducted by Brilon et al. took up examples of rural two-lane highways in Germany and discussed the evaluation of highway performance based on German experiences. The previous study by Armed Al-Kaisy and Sarah Karjala reviewed the literature on various indicators of performance of two-lane highways and discussed the advantage of each indicator. Taking these previous studies into account, this study decided to use the following performance indicators to evaluate the level of service of two-lane highways in order to provide easy-to-understand indicators for road users.

1) Average travel speed

Average travel speed (ATS) is one of the two performance indicators used in the existing methodology by the HCM. This is expressed by the average speed of vehicles travelling over a certain section of roadway. Frequently used by transportation engineers, this indicator has the advantage of being easy to measure on site and easily understood by ordinary drivers.
(2) Follower percentage
Followers are vehicles behind other vehicles at a relatively short headway distance in a traffic flow. The follower percentage shows that of vehicles traveling at short headways. This performance indicator can be measured on site easily and used in the HCM as a surrogate measure in the field for PTSF. The HCM uses time headways no greater than three seconds.

(3) Follower density
The follower density is expressed by 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. Unlike the follower percentage, the follower density is a performance indicator with the major advantage of taking into consideration the influence of traffic conditions in terms of efficiency. Although the field measurement of traffic density is difficult, it can be determined by observing traffic volume and speed at follower percentage measurement sites. Traffic volume and speed can be measured by using output from a simple traffic counter or other instrument. The previous study conducted by Nakamura and Catbagan suggested that measuring the follower density is effective as an indicator for the level of service (LOS) of two-lane highways based on measurement results of two-lane expressways in Japan.

3. SIM-R traffic flow micro-simulation

3.1 Models to be applied to SIM-R

SIM-R is a traffic flow simulation developed by the Civil Engineering Research Institute for Cold Region, PWRI in 1994. It determines whether the behavior of a certain vehicle is car-following or free travel by comparing its stopping-sight distance with the headway distance from the leading vehicle. The behavior is determined to be free travel if the inter-vehicle distance is greater.

The stopping-sight distance is found using Equation (1). Road surface condition differences are reproduced by changing the longitudinal skid resistance coefficient in the equation. In this paper, it is assumed to be a standard of reference whether to fill Equation (1) on following judgment according to the road surface condition.

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

\(D\) : stopping-sight distance (m)
\(V\) : running speed (km/h)
\(f\) : longitudinal skid resistance coefficient
\(t\) : reaction time (s)
\(g\) : gravity acceleration (=9.8m/s^2)

The Herman model is one of the major car-following models and is expressed by the following Equation:

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

\(\chi''_{n+1}(t+T)\) : acceleration of following driver \(T\) seconds later (m/s^2)
\(\chi'(t) - \chi'_{n+1}(t)\): difference in speed between leading and following vehicles (m/s)
\(\chi''(t) - \chi''_{n+1}(t)\): 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 the leading and following vehicles is used as the denominator. However, as the following driver drives while looking at the rear end of the leading vehicle during an actual car-
following situation, the inter-vehicle distance found by subtracting the length of the leading vehicle from the headway distance was used for the SIM-R car-following model.

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

For the passing model on two-lane highway sections where passing is permitted and the lane-changing model on “2+1 lane” highway sections, measurement was made on the highways shown in Table 1 to collect field data and the situation was additionally reproduced using SIM-R to verify the effectiveness of each model.

### Table 1 Highways used to verify the models and field data

<table>
<thead>
<tr>
<th>Road Type</th>
<th>Name</th>
<th>Road Surface Condition</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two-lane highway</td>
<td>National Highway R275</td>
<td>Dry</td>
<td>10 days (From Jul.11, 2007 to Jul.21, 2007)</td>
</tr>
<tr>
<td></td>
<td>Shintotsukawa</td>
<td>Compacted Snow</td>
<td>10 days (From Jan 11, 2008 to Jan., 2008)</td>
</tr>
<tr>
<td>Two-lane plus auxiliary lane highway</td>
<td>National Highway R244</td>
<td>Dry</td>
<td>8 days (From Aug.27, 2008 to Sep.4, 2008)</td>
</tr>
<tr>
<td></td>
<td>Abashiri</td>
<td>Compacted Snow</td>
<td>1 day (From Jan. 15th, 2009)</td>
</tr>
</tbody>
</table>

### 3.2 Sensitivity analysis of SIM-R

Sensitivity analysis was performed on SIM-R traffic flow micro-simulation of the structures of two-lane highways sections where passing is permitted and “2+1 lane” highways. For this analysis, road surface conditions, lane operations, auxiliary lane structure and traffic volume were used as variables.

The structures of highways on which sensitivity analysis was performed are shown in Figs. 1 and 2. Tables 2 and 3 list conditions for sensitivity analysis and items set for simulation, respectively.

![Fig. 1 Highway structure on which sensitivity analysis was performed](image-url)
Fig. 2 Cases of “2+1 lane” highways on which sensitivity analysis was performed

Table 2 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>Total length 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 – 500 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</td>
<td>600 seconds</td>
</tr>
<tr>
<td>Simulation time</td>
<td>3600 seconds</td>
</tr>
</tbody>
</table>

Table 3 Items set for the simulation

<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>Other 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>
4. Sensitivity analysis results

4.1 Evaluation results for dry road surfaces

The results of the sensitivity analysis of “2+1 lane highways” in the dry road condition for a case with an hourly traffic volume in one direction of 100 vehicles per hour and that of 500 vehicles per hour are shown in figs. 3 and 4, respectively. Average travel speed, the follower percentage and the follower density are indicators to evaluate analysis results. Under dry road surface conditions, when time headway between two subsequent vehicles is three seconds or less, the follower is defined as a following vehicle.

Average travel speed was approximately 70 km/h at a point near where vehicles had started to bunch up; however it decreased to approximately 57 km/h, in the case of the hourly traffic volume of 100 vehicles per hour, with increasing distance from the start point. Adding an auxiliary lane at certain intervals resulted in an increase in average travel speed to 67 – 69 km/h on sections with an auxiliary lane. In the case of the hourly traffic volume of 500 vehicles per hour, average travel speed was approximately 65 km/h at a point near where vehicles had started to bunch up; however it decreased to approximately 53 km/h with increasing distance from the start point. Adding an auxiliary lane at certain intervals resulted in an increase in average travel speed to 62 – 66 km/h on sections with an auxiliary lane.

The follower percentage increased with distance from the start point and was approximately 70% on two-lane highway sections in the case of the hourly traffic volume of 100 vehicles per hour. However, the percentage decreased by adding an auxiliary lane at certain intervals. It was found that the shorter the interval, the greater the effect of the auxiliary lane. Also with the case of the hourly traffic volume of 500 vehicles per hour, the percentage rose with an increase in the distance from the start point and was approximately 88% on two-lane highway sections. Adding an auxiliary lane at certain intervals resulted in a decrease in the percentage.

The follower density was very low, around 1 vehicle/km, when the hourly traffic volume was 100 vehicles per hour, regardless of the installation of an auxiliary lane or 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 an increase in distance from the start point, and it was approximately 8 vehicles/km on two-lane highway sections. The addition of an auxiliary lane at certain intervals reduced the density to 4 – 6 vehicles/km.
Fig. 3 Sensitivity analysis results
(Hourly traffic volume: 100 veh./h on dry road surfaces)
Fig. 4 Sensitivity analysis results
(Hourly traffic volume: 500 veh./h on dry road surfaces)
4.2 Evaluation of compacted-snow-covered road surfaces

The results of the sensitivity analysis of “2+1 lane highways” in a compacted-snow-covered road surface condition for a case with an hourly traffic volume in one direction of 100 vehicles per hour and that of 500 vehicles per hour are shown in figs. 5 and 6, respectively. Average travel speed, the follower percentage and the follower density are used as indicators to evaluate analysis results. Under compacted-snow-covered surface condition, when time headway between two subsequent vehicles is 4.5 seconds or less, the follower is defined as a following vehicle.

[(1) Average travel speed]

![Average travel speed graph](image1)

[(2) Follower percentage]

![Follower percentage graph](image2)

[(3) Follower density]

![Follower density graph](image3)

Fig. 5 Sensitivity analysis results
(Hourly traffic volume: 100 veh./h on compacted-snow-covered surfaces)
Average travel speed was approximately 60 km/h at a point near where vehicles had started to bunch up; however it decreased to approximately 50 km/h, in the case of the hourly traffic volume of 100 vehicles per hour, with increasing distance from the start point. Adding an auxiliary lane at certain intervals resulted in an increase in average travel speed to 57 – 59 km/h on sections with an auxiliary lane. In the case of the hourly traffic volume of 500 vehicles per hour, average travel speed was approximately 50 km/h at a point near where vehicles had started to bunch up; however it decreased to approximately 42 km/h with increasing distance from the start point. Adding an auxiliary lane at certain intervals resulted in an increase in average travel speed to 50 – 56 km/h on sections with an auxiliary lane.
The follower percentage rose with an increase in the distance from the start point and was approximately 80% on two-lane highway sections in the case of the hourly traffic volume of 100 vehicles per hour. However, the follower percentage decreased by adding an auxiliary lane at certain intervals. It was found that the shorter the interval, the greater the effect of the auxiliary lane. In the case of the hourly traffic volume of 500 vehicles per hour, the percentage rose further with an increase in the distance from the start point and was approximately 96% on two-lane highway sections. Adding an auxiliary lane at certain intervals resulted in a decrease in the percentage.

The follower density was low, around 2 vehicles/km, when the hourly traffic volume was 100 vehicles per hour, regardless of the installation of an auxiliary lane or distance from the start point. With the case of hourly traffic volume of 500 vehicles per hour, the follower density increased with an increase in distance from the start point and it was approximately 11 vehicles/km on two-lane highway sections. The addition of an auxiliary lane at certain intervals reduced the density to 5 – 7 vehicles/km

5. Conclusion

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

The performance of road structures was evaluated for two-lane highways and “2+1 lane” highways through sensitivity analysis using a SIM-R traffic flow micro-simulation program. Two road surface conditions – dry and compacted-snow-covered – were included in the analysis. The traffic volume targeted was hourly traffic volume in one direction from 100 to 500 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 two-lane highways at certain intervals, namely by introducing “2+1 lane” highways, the level of service was improved for each evaluation indicator – average travel speed, the follower percentage and the follower density, both on dry and compacted-snow-covered road surfaces. For instance, in the case of the hourly traffic volume of 500 vehicles per hour under dry surface condition, adding an auxiliary lane at certain intervals resulted in an increase in average travel speed for 9-13km/h, in a decrease in follower percentage for 20-35%, and in a decrease in follower density for 2-4 vehicles/km. In the case of the hourly traffic volume of 500 vehicles per hour under compacted-snow-covered surface condition, adding an auxiliary lane at certain intervals resulted in an increase in average travel speed for 8-14km/h, in a decrease in follower percentage for 15-45%, and in a decrease in follower density for 4-6 vehicles/km.

(2) Effectiveness of evaluation indicators that demonstrate road performance

As indicators to evaluate the performance of two-lane highways and “2+1 lane” highways, average travel speed, the follower percentage and the follower density were used and the effectiveness of each indicator was investigated. Based on the sensitivity analysis results of the traffic flow micro-simulation in this study, it was clarified that these three evaluation indicators contributed to the evaluation of the level of service on roads. However, high follower percentages were observed even with low hourly traffic volumes, in good road surface conditions and with relatively high average travel speed. However, the follower density was low when hourly traffic volume was low, the road surface condition was good and average travel speed was relatively high. On the other hand, in high hourly traffic volume and poor road surface conditions covered with compacted snow, the density was high when average travel speed was relatively low.

Accordingly, the follower density is believed to be an appropriate and well-balanced indicator to evaluate the performance of two-lane highways as well as “2+1 lane” highways. The follower density can be set from the relational equation “k = V/Q” (k: density, V:average travel speed, Q:traffic volume) as a targeted value of the LOS. It is effective to assume the follower density to be a service target value, to set of each at the dry road surface and the compacted-snow-covered surface conditions, and to evaluate the design of intervals and extensions for the auxiliary lane.

(3) Ideal highway structure for cold, snowy regions

For evaluating the performance of two-lane highways as well as “2+1 lane” highways in cold, snowy regions, it is essential to take into consideration compacted-snow-covered road surfaces during winter in addition to normal, dry road surfaces. The performance of both of these highways is lower on compacted-snow-covered road surfaces compared to that on dry road surfaces. It is required to set the target LOS for these highways both in dry and
compacted-snow-covered road conditions and evaluate the performance that the highways are expected to
demonstrate. It is necessary to apply a road structure that satisfies the performance required for each highway by
using evaluation indicators such as the follower density. Through this study, it is effective to install the auxiliary
lane by 3- 5km intervals in the case of the hourly traffic volume of 500 vehicles per hour. On the other hand, there
is no necessity to install it in the case of the hourly traffic volume of 100 vehicles per hour. An ideal road design for
highways in a cold, snowy region requires a short interval between installed auxiliary lanes in the certain traffic
section from the viewpoint of improving the LOS.

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