Traffic Simulation of a Rural 2+1 Highway in Hokkaido, Japan

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ABSTRACT
This paper investigates lane-changing behaviors on a 2+1 highway section using a SIM-R traffic flow micro-simulation program. Since 2005, the authors have been observing the behaviors of vehicles moving from the main lane to a left-hand auxiliary lane and back to allow following vehicles to overtake on a section of Nat’l Highway 38 in Shiranuka, Hokkaido. Based on the observation results, the authors have modified the SIM-R to include lane-changing behaviors (giving way and overtaking).

1. Introduction
Hokkaido is a snowy island that extends from 42° to 45°N. Lat. Automobile travel speeds are reduced in winter by snowstorms and snowy and icy road surface conditions. This causes economic losses, and such losses from traffic congestion are particularly great in urban areas. Toward addressing this, road administrators must clearly understand the road traffic conditions in all seasons and establish road condition forecasting methods. To accurately reproduce traffic conditions and evaluate future road conditions, in 1996 the authors developed a traffic flow micro-simulation called SIM-R. SIM-R is capable of simulating traffic flow for uninterrupted sections and for signalized sections, and of forecasting and evaluating summer and winter road traffic conditions.

In recent years, road managers have been examining service level improvement by the development of “2+1 highways,” in which some sections of existing two-lane highways are installed with an auxiliary lane. Such improvement has been considered for national highways in rural Hokkaido, because it is cheaper and faster to add an additional lane only on sections where it is needed rather than on the entire route. Under these circumstances, an appropriate traffic simulation program for rural 2+1 highways has been called for. Existing studies\(^1\)\(^2\) have attempted to formulate a lane-changing model and an approach to reproduction of rural traffic behaviors. Yet, such models are not designed for traffic flow simulation of rural 2+1 highways. Since 2005, the authors have been observing the behaviors of vehicles moving from the main lane to a left-hand auxiliary lane and back to allow following vehicles to overtake on a section of Nat’l Highway 38 in Shiranuka. The authors have worked to improve the SIM-R traffic flow simulation program based on the observation results, toward reproducing and evaluating traffic flow on a 2+1 highway section.

This paper discusses:
(1) the summer survey results of vehicle behaviors on an experimental auxiliary-lane section (2+1 highway section) of Nat’l Highway 38 in Shiranuka;
(2) lane-changing behaviors (giving way and overtaking) reproduced by the SIM-R traffic flow simulation program; and
(3) examination of the simulation results.

![Figure 1. Hokkaido and Shiranuka Town](image1)

**2. Study approach**

**2.1 Vehicle behaviors observed on Nat’l Highway 38 in Shiranuka**

Nat’l Highway 38 is a major national highway that crosses Hokkaido east-west. Shiranuka Town is west of Kushiro, a large city in eastern Hokkaido. The road section surveyed is a left-hand auxiliary-lane section (L = 1.605 km) on Nat’l Highway 38 in Shiranuka. The survey was carried out for the ten days from 7:00 on Friday, August 12, to 7:00 on Sunday, August 21, 2005. The surveyed section was equipped with simple traffic counters (STC-2100P; Sumitomo 3M) to obtain data on speed, vehicle position and traffic volume of small vehicles (passenger cars) and large vehicles (trucks) in each lane. As Figure 2 shows, simple traffic counters were placed at ten locations from A to J. A video camera was installed at a fixed point to record vehicle behaviors of changing from the main lane to the left-hand auxiliary lane and back.

![Figure 2. Section with a left-hand experimental auxiliary lane (Nat’l Highway 38 in Shiranuka)](image2)

**2.2 Simulation**

(1) Simulation parameters

On the basis of the abovementioned observations regarding vehicle behaviors on Nat’l Highway 38 in Shiranuka, three simulation parameters were examined.

1) Traffic volume by vehicle type (small or large) in each lane

   This was measured using simple traffic counters. The data were used to determine the simulation duration and traffic volume data, including the ratio of large vehicles, for simulation development.

2) Speed distribution in each lane

   This was measured using simple traffic counters. The data were used in two simulation cases: one for all traveling vehicles, and one for only free-traveling vehicles.

3) Ratio of following vehicles

   This was obtained through the following inequality:
Time lag behind preceding vehicle (min.) × Speed of subject vehicle (m/min.) < Minimum braking distance of subject vehicle (m)  \hspace{50pt} \text{Formula 2.1}

Vehicles traveling as expressed by the above inequality are defined as \textit{following vehicles}. All others are defined as \textit{free-traveling vehicles}.

(2) Modification to SIM-R simulation of lane-changing behaviors

The SIM-R simulation program was modified to reproduce traffic behaviors (giving way and overtaking) on a 2+1 highway section.

(3) Simulation run

Using the improved SIM-R program, traffic conditions of the 2+1 highway section (left-hand auxiliary lane) on Nat’l Highway 38 in Shiranuka were reproduced for comparison with the results of the abovementioned field survey.

3. Results of field survey on Nat’l Highway 38 in Shiranuka

3.1 Speed distribution

A field survey was conducted for all vehicle types using simple traffic counters on the auxiliary-lane section (2+1 highway section) of Nat’l Highway 38 in Shiranuka for the ten days from August 12 to 21, 2005. During the survey period, the surveyed road surface was mostly dry and the average daily traffic volume in the observed lane was 10,130 vehicles on weekdays and 11,815 vehicles on weekends. Large vehicles accounted for 13% of the daily traffic volume. Figure 3 shows the hourly traffic volume during the survey period. It is about 600 - 800 vehicles during daytime (7:00-17:00) and more than 1,100 vehicles during the peak time on August 13, 2005.

The average speeds of traveling vehicles at each observation point in both lanes are shown in Figure 4. The speed distributions of small and large vehicles at Point J (main lane) are shown in Figure 5. Those at Point E (main lane, midpoint of the 2+1 section) are shown in Figure 6. Those at Point F (left-hand auxiliary lane, midpoint of the 2+1 section) are shown in Figure 7. These diagrams suggest the following tendencies.

1) The average speed of all vehicles is about 66 km/h at Point G (main lane, start of the 2+1 section) and Point H (left-hand auxiliary lane, start of the 2+1 section).
2) When Point E and Point F are compared, the average speed of large vehicles is about 13 km/h higher in the main lane than in the auxiliary lane, and the average speed of small vehicles is about 6 km/h higher in the main lane than in the auxiliary lane.
3) The observed speed distribution at Point E (main lane) revealed an average speed of small vehicles of 76 km/h and an 85th-percentile speed of 87 km/h. This indicates variation in speeds.

![Figure 3. Hourly traffic volume (Point I)](image)

![Figure 4. Average speed of each observation point on National Highway 38 in Shiranuka](image)
3.2 Utilization of the left-hand auxiliary lane

Based on video images taken by a fixed camera, the traffic volume on the 2+1 highway section was analyzed. The analysis was conducted on 1,004 vehicles (806 small, 198 large) traveling between 10:00 and 12:00 on Thursday, August 18, 2005. The traffic volume in the left-hand auxiliary lane was analyzed.

1) Vehicles using the left-hand auxiliary lane: 49% of all vehicles (traveling independently: 11%; leading a platoon: 22%; following in a platoon: 12%; and overtaking on the left lane: 4%).

2) Vehicles using the main lane: 51% of all vehicles

Broken down by vehicle type, 38% of the small vehicles and 94% of the large vehicles used the left-hand auxiliary lane.

Most of the large vehicles use the left-hand auxiliary lane.

4. Improvements to the SIM-R traffic flow simulation program
4.1 Basic model for vehicle behaviors
(1) Car-following model

Hermann’s model, described by the equation below, is a typical car-following model. Our SIM-R program is based on it. The original model, however, does not take vehicle length into account; instead, it assumes that the following vehicle uses the front end of the preceding vehicle to determine the minimum space headway, although in fact, a following vehicle uses the rear end of the preceding vehicle. Also, we determined that the vehicle length has to be considered more carefully when a vehicle is following or stopped. Thus, the vehicular gap (space headway minus the length of preceding vehicle) is substituted as an input variable in this car-following model.
There is enough space in the target (left-hand auxiliary) lane.

Requirements for considering a change to the left-hand auxiliary lane

Change Left

Change Right

Requirements for finalizing the decision to change to the left-hand auxiliary lane

NO

YES

1. There is a following vehicle.
2. The following vehicle is traveling fast enough.
3. There is enough space in the target (left-hand auxiliary) lane.
4. The left-hand auxiliary lane has enough distance before it ends.

NO

YES

(2) Free-traveling model

Basically, it is assumed that, in free traveling, each vehicle accelerates at its maximum acceleration until it reaches its desired speed.

4.2 Modifications to the simulation of lane-changing behavior

(1) Flowchart of lane changing in the left-hand auxiliary-lane section

The process of lane-changing behavior on a road with a left-hand auxiliary lane is shown in Figure 8.

Figure 8. Process of lane changing in a left-hand auxiliary-lane section

(2) Vehicle behaviors on a road with a left-hand auxiliary lane

(i) Changing from the main lane to the left-hand auxiliary lane

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

Formula 4.1

\[
\chi''_{n+1}(t + T): \text{acceleration of following vehicle at time plus } T \text{ seconds (m/s}^2) \\
\chi'_{n}(t) - \chi'_{n+1}(t): \text{difference in speed between preceding vehicle and following vehicle (m/s)} \\
\chi_{n}(t) - \chi_{n+1}(t): \text{Space headway (m)} \\
\alpha: \text{sensitivity coefficient (m/s)} \\
T: \text{lag in reaction by following vehicle (s)}
(a) Requirements for considering a change to the left-hand auxiliary lane

Parameters governing the decision whether to change from a main lane to a left-hand auxiliary lane in the SIM-R traffic flow simulation program were modified as follows:

1) Distance from following vehicle \( D \) Minimum braking distance of following vehicle (following vehicle is in a platoon)

It is assumed that a given vehicle decides to move into the left-hand auxiliary lane when a following free-traveling vehicle reaches it or when the vehicular gap between them becomes less than the minimum braking distance of the following vehicle.

2) Desired speed of following vehicle \( B_1 \) Desired speed of subject vehicle \( B_2 \) (km/h)

It is assumed that a subject vehicle is likely to decide to move into the left-hand auxiliary lane when the desired speed of the following vehicle exceeds that of the subject vehicle. (The following vehicle will rapidly close, tailgate or flash its high beams.) It is also assumed that a subject vehicle is unlikely to move into the left-hand auxiliary lane when the desired speed of the subject vehicle exceeds that of the following vehicle.

Therefore, the difference in desired speed between the subject vehicle and the following vehicle (speed difference) was used for simulation.

The speed difference \( B_1 \) in the above inequality is a parameter used in reproducing the real traffic flow.

(b) Requirements for finalizing a decision to change to the left-hand auxiliary lane

Requirements for finalizing a decision to change to the left-hand auxiliary lane were determined as follows.

1) Expected vehicular gap to the preceding vehicle \( D_1 \) in Figure 9) and from the following vehicle \( D_2 \) in Figure 9) in the left-hand auxiliary lane when the subject vehicle has changed into the auxiliary lane \( D \) minimum vehicular gap.

It is assumed that a subject vehicle finalizes its decision to change into the left-hand auxiliary lane when the expected minimum vehicular gap to the preceding vehicle and from the following vehicle in the left-hand auxiliary lane when the subject vehicle has changed into the left-hand auxiliary lane will be secured. The required minimum vehicular gap between the preceding and following vehicles after lane changing is calculated in the following formula.

\[
D_1 \geq \frac{V_0^2}{2gf} + (V_0 - V_1) + L_0 \quad \text{and} \quad D_2 \geq \frac{V_2^2}{2gf} + (V_2 - V_0) + L_0 \quad \text{--------- Formula 4.2}
\]

\( D_1 \): Distance between preceding vehicle and subject vehicle (m)
\( D_2 \): Distance between subject vehicle and following vehicle (m)
\( V_0 \): Speed of subject vehicle (km/h)
\( V_1 \): Speed of preceding vehicle (km/h)
\( V_2 \): Speed of following vehicle (km/h)
\( f \): Coefficient of sliding friction in the longitudinal direction
\( L_0 \): Vehicular gap after stopping (= 1.5 m)
\( t \): Response time (= 2.5 sec)
\( g \): Gravitational acceleration (= 9.8 m/s²)

Figure 9. Calculation of minimum vehicular gap
2) The following vehicle is able to overtake the subject vehicle before the end of the left-hand auxiliary lane.

Consideration of whether a following vehicle is able to overtake a subject vehicle before the end of the left-hand auxiliary lane is added to the requirements of lane-changing behavior. This is to reproduce the behaviors of vehicles that cannot change into the left-hand auxiliary lane because they finalize that decision toward the end of the 2+1 section. Such behavior is determined according to the following inequality.

\[
\text{(Expected vehicular gap from a following vehicle in the main lane to the subject vehicle that has changed into the left-hand auxiliary lane and reached the desired speed, when the subject vehicle reaches the end of the left-hand auxiliary lane)} > \text{minimum vehicular gap}
\]

(ii) Re-entering the main lane from the left-hand auxiliary lane
(a) Requirements for considering reentering a main lane

Parameters governing the decision whether to re-enter the main lane from the left-hand auxiliary lane in the SIM-R traffic flow simulation program were modified as follows:
- After changing to a left-hand auxiliary lane, the subject vehicle travels through to the end of the lane.
- The subject vehicle re-enters the main lane if a slower vehicle is traveling ahead in the left-hand auxiliary lane.

As a basic rule, a vehicle that has moved into the left-hand auxiliary lane keeps traveling in that lane to its end. If a slower vehicle travels ahead in the left-hand auxiliary lane, the decision of the subject vehicle on whether to re-enter the main lane follows the overtaking algorithm.

(b) Requirements for finalizing the decision to re-enter the main lane

Requirements for re-entering the main lane were set as follows.
- Distances to preceding and from following vehicles in the main lane  \( \geq \) minimum vehicular gap.
- In a situation where the subject vehicle joins a platoon, the following vehicle must reduce its speed to secure the minimum vehicular gap.

The minimum vehicular gaps to the preceding vehicle and from the following vehicle in the main lane required for re-entering the main lane are the same as those when the subject vehicle has changed into the left-hand auxiliary lane.

In a situation where the subject vehicle joins a platoon in the main lane, it is assumed that the following vehicle reduces its speed to maintain the minimum vehicular gap.

To secure a large enough vehicular gap from a following vehicle, the subject vehicle activates its turn indicator so that the following vehicle reduces its speed. When the minimum vehicular gap between the subject vehicle and the following vehicle is obtained, a maneuver to re-enter the main lane is executed.

(3) Flowchart of lane changing in the right-hand auxiliary-lane section

The process of reproducing lane-changing behavior on a road with a right-hand auxiliary lane is shown in Figure 10.

(4) Vehicle behaviors on a road with a right-hand auxiliary lane
(i) Changing to the right-hand auxiliary lane
(a) Requirements for considering a change to the right-hand auxiliary lane

1) Distance to preceding vehicle  \( \geq \) Minimum braking distance of subject vehicle (Subject vehicle is following.)

It is assumed that the subject vehicle decides to change to the right-hand auxiliary lane when the subject vehicle starts following after free traveling, i.e., the vehicular gap becomes less than the minimum braking distance of the subject vehicle.
2) Desired speed of subject vehicle - Speed of preceding vehicles $\Delta B_2$ (km/h)

It is understood that, when there is a platoon, a subject vehicle does not start overtaking unless all the vehicles in that platoon can be overtaken in a single overtaking maneuver. Therefore, it is assumed that the target of overtaking is the lead vehicle in the platoon (in Figure 11). The speed difference $B_2$ in the above inequality is a parameter for reproducing the real traffic flow.

Figure 10. Process of lane changing in a right-hand auxiliary-lane section

Figure 11. Preceding vehicles including the lead vehicle in the platoon
5. Simulation run
5.1 Simulation requirements
(1) Traffic data
Traffic data obtained between 10:00 and 11:00 on the morning of August 13, 2005 were employed in the simulation analysis. Based on field observation results, it is assumed that the traffic volume was 1,100 vehicles/hour and that large vehicles accounted for 7.7% of all vehicles. The distribution of desired speeds was obtained from speed data of independent free-traveling vehicles collected at Points E and F, which are at the midpoint of the left-hand auxiliary-lane section (Figure 12). The speed distributions of all vehicles and independent free-traveling vehicles are shown in Figure 13.
(2) Other parameters

The coefficient of sliding friction used to calculate braking distance was set at 0.60 for dry road surface and 0.31 for wet road surface. This simulation assumed a dry road surface. Other parameters are listed in Table 1, and the requirements for simulation running are in Table 2.

### Table 1. Other simulation parameters

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<td>Max. acceleration</td>
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<td></td>
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<td>Large vehicle</td>
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<td>Computing cycle time</td>
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### Table 2. Simulation running requirements

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<td>Simulation repetitions¹</td>
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<tr>
<td>Initialization time (pre-simulation time)²</td>
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<tr>
<td>Simulation time</td>
<td>3,600 sec. 60 min.</td>
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</table>

¹Simulation repetitions: Because each simulation run produces a different traffic pattern which affects the survey result, the simulation result is the average of five runs.

²Initialization time: Time before start of simulation.

5.2 Simulation results

Based on the above conditions, simulations were run to present the current traffic conditions of the 2+1 highway section on Nat’l Highway 38 in Shiranuka. The survey section was a section with a left-hand auxiliary-lane and a dry road surface. The simulation results are collated in Figure 14, from

![Figure 12. Percentile values of desired speed (Points E and F on Nat’l Highway 38 in Shiranuka)](image1)

![Figure 13. Speed distribution (Points E and F on Nat’l Highway 38 in Shiranuka)](image2)
which the following have been determined:
1) Regardless of the desired speed difference \( B \), the slope of the line approximating the correlation was within 1±0.1 and the correlation coefficient \( R^2 \) exceeded 0.9 for traffic volume at all observation points. This indicates that the reproducibility is high.
2) The speed distribution in summer was accurately reproduced at Points G and H. However, reproducibility was slightly lower for Points E and F.
3) The highest reproducibility was at a speed difference of 10 km/h or less.

![Graphs showing speed distribution](image)

(2) Speed distribution

Figure 14. Simulation results
(Nat’l Highway 38 in Shiranuka)

6. Summary

The findings of this survey are summarized here.

(1) A survey on vehicle behaviors on an auxiliary-lane section (2+1 highway section) of Nat’l Highway 38 in Shiranuka was carried out for ten days in August 2005. A simple traffic counter was installed at ten observation points. At the midpoint of the auxiliary-lane section, the average speed of all vehicles surveyed was highest both in the main and the left-hand auxiliary lanes. The average speed of all vehicles in the main traffic lane was 10 km/h greater than that in the left-hand auxiliary lane. The average speed of small vehicles was 6 km/h greater in the main traffic lane than in the left-hand auxiliary lane, and that of large vehicles was 13 km/h greater in the main traffic lane than in the left-hand auxiliary lane. Based on two hours of video images taken by fixed video camera, the use of the left-hand auxiliary lane was analyzed. Vehicles that used the left-hand auxiliary lane accounted for 49% of all vehicles (independent traveling: 11%, leading a platoon: 22%, following in a platoon: 12%, overtaking: 4%). The remaining 51% used the main lane. As for large vehicles, 94% of them traveled in the left-hand auxiliary lane.

(2) Three parameters were used in the SIM-R traffic flow simulation program: traffic volume in each lane for two vehicle types, distribution of desired speed for each lane, and ratio of following vehicles.

(3) Vehicle behaviors on roads with a left-hand auxiliary lane and a right-hand auxiliary lane were closely examined. Changing into the left-hand auxiliary lane and re-entering the main lane were simulated from the vehicular gap between a preceding vehicle, the subject vehicle and a following vehicle.
traveling in the left-hand auxiliary lane. For a right-hand auxiliary lane, changing into the right-hand auxiliary lane and re-entering the main lane were simulated. Based on the results, the program to simulate lane-changing behaviors was modified. Using the modified program, a traffic simulation analysis was carried out for the auxiliary-lane section (2+1 highway section) of Nat’l Highway 38 in Shiranuka (dry road surface in summer). The correlation coefficient for simulated and observed spot traffic volume was 0.9 at all points. The reproducibility was high. However, reproducibility of the speed distribution varied from point to point.

(4) Further examination is being conducted on lane-changing behaviors for summer (dry road surface) conditions. We plan to further modify the program based on the results. In Hokkaido, it is necessary to run a traffic simulation for winter road surface (ice and compacted snow) conditions. We will conduct a field survey on winter vehicle behaviors while modifying the program for winter lane-changing behaviors and implementing a simulation analysis.

Acknowledgments
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