Effective installation of an auxiliary lane at sag sections to mitigate motorway traffic congestion

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Abstract
Traffic congestion on motorways on weekends and holidays is not unusual in Japan. To mitigate congestion, installation of an auxiliary lane around the bottleneck in the sag section is used as an alternative and effective countermeasure against congestion to correct overuse of the median lane. However, there are no guidelines on effective installation of an auxiliary lane in the sag section to mitigate motorway traffic congestion. This paper uses a microscopic traffic simulation model to study how best to add an auxiliary lane in the sag section of a dual two-lane motorway to mitigate traffic congestion.

Keywords: Congestion countermeasure, auxiliary lane, microscopic traffic simulation, capacity, bottleneck

1 Introduction
Previous studies have shown that sag and tunnel sections on expressways can become bottlenecks that cause congestion (Koshi, 1986). In these sections, when the traffic volume is high enough, a difference in speed develops between vehicles traveling on the outer and inner lanes and the number of vehicles traveling on the inner lane tends to surge. In a previous study (Oguchi et al., 2001), a scheme to add an auxiliary lane to correct the lane use rate and increase the road capacity to counter traffic congestion was introduced and evaluated.

However, although the auxiliary lane scheme has been introduced, no guidelines have yet been set on how long and where the lanes should be installed. Consequently, the structure of an auxiliary lane is decided more or less subjectively in practice. To even out the number of cars traveling on each lane, the auxiliary lane needs to have a certain length, but over-extending the lane will just increase the cost, thus lowering its cost-effectiveness. The most effective location and length of an auxiliary lane should not...
only work to distribute the traffic volume between lanes by a few percent, but also be sufficient to substantially reduce congestion and costs.

In this study, we have sorted existing auxiliary lanes by type and performed microscopic traffic simulations to predict the breakdown flow rate of traffic flow and analyze the effectiveness, to study how to install the auxiliary lanes effectively.

2 Outline of the Study

Figure 1 shows a flowchart of the study. First, the auxiliary lanes in operation were sorted by type and the cases to be studied were selected. Next, road network and traffic data were prepared for the input of a microscopic simulation model used in the study. Various parameters such as the car-following model, lane-changing model, merge/diverge model and so on were calibrated and the simulated traffic flow was examined based on the actual traffic flow observed by vehicle detectors.

Subsequently, simulation runs of each auxiliary lane type were performed to estimate and analyze the traffic flow and study an effective way of installation. A microscopic traffic simulation model was used in this study to estimate the breakdown flow rate of each auxiliary lane type in the sag section.

3 Outline of Traffic Simulation Model

The traffic simulation of the study uses a microscopic model of the periodic scanning method. The vehicle movement model mainly comprises a vehicle generation/extinction model, vehicle’s longitudinal movement (acceleration and deceleration) model and lateral movement (lane-changing) model. The generation/extinction model creates and erases vehicles. The longitudinal movement model comprises free running, car-following behavior based on car-following theory, stop/go, vehicle driving performance (driving power, running resistance and acceleration), acceleration/ deceleration/ stopping at tollgates and deceleration at horizontal curves. The car-following model used in the study is an improved version of a model originally proposed by Koshi (1986) and Koshi et al. (1992, 1993) and identified by Xing (1992), Ozaki (1994) and Xing et al. (1995). The model was proposed to simulate the occurrence of traffic congestion at sag section of motorways.
The car-following model applied in the microscopic simulation model is as follows. The first term shows conventional car-following behavior with respect to relative speed with the leading vehicle, in which time lag and stimulus are assumed to differ for acceleration and deceleration behavior as observed from real car-following data. The second term describes the car-following behavior whereby drivers tend to keep their average desired spacing with speed. The third term reflects driver’s correction behavior with respect to leading vehicle’s behavior. The last term demonstrates the impact of vertical gradient on driver’s car-following behavior. The model parameters were estimated from real car-following observation data.

(1) Driver’s reaction with respect to relative speed with the leading vehicle:

\[ \ddot{X}_{n+1}(t + T^+) = \alpha^+ \left( \frac{\ddot{X}_{n+1}(t)}{S(t)} \right)^{n+} \left[ \dot{X}_n(t) - \dot{X}_{n+1}(t) \right] \quad \text{for acceleration} \]  
\[ \ddot{X}_{n+1}(t + T^-) = \alpha^- \left( \frac{\ddot{X}_{n+1}(t)}{S(t)} \right)^{n-} \left[ \dot{X}_n(t) - \dot{X}_{n+1}(t) \right] \quad \text{for deceleration} \]  
\[ T^+ = \tau^+ + p^+ \ddot{X}_n(t) \]  
\[ T^- = \tau^- + p^- \ddot{X}_n(t) \]  

(2) Driver’s reaction with respect to deflection from their desired spacing with speed:

\[ \ddot{X}_{n+1}(t) = \beta \left[ \frac{1}{S(t)} \right]^1 \left\{ S(t) - f(\ddot{X}_{n+1}(t)) \right\} \]  
\[ f(\ddot{X}_{n+1}) = a_3 \ddot{X}_{n+1}^3 + a_2 \ddot{X}_{n+1}^2 + a_1 \ddot{X}_{n+1} + a_0 \]  

(3) Driver’s correction behavior with respect to leading vehicle’s behavior:

\[ \ddot{X}_{n+1}(t + T) = \gamma \left( \frac{1}{S(t)} \right)^1 \ddot{X}_n(t) \]  

(4) Impact of vertical gradient on driver’s car-following behavior:

\[ \ddot{X}_{n+1}(t) = g \left[ \sin(\theta(t)) - \sin(\theta(t - T_g)) \right] \]  

where,
- \(X_{n+1}\): following vehicle’s acceleration
- \(X_n\): leading vehicle’s acceleration
- \(\dot{X}_{n+1}\): following vehicle’s speed
- \(\dot{X}_n\): leading vehicle’s speed
- \(S(t)\): following vehicle’s spacing with leading vehicle at time \(t\)
  \[ (= X_n(t) - X_{n+1}(t) - L_n) \text{ where } L_n \text{ is leading vehicle length} \]
- \(T^+, T, T_g\): time lag
- \(\theta\): difference of vertical gradient
- \(\alpha^+, \alpha^-, \beta, \gamma, \tau^+, \tau^-, p^+, p^-\): model parameters
The lateral movement model controls overtaking, merging, diverging, weaving, escape running from the outside lane, diverging to the auxiliary lane and selecting the tollgate lane. As for diverging to the auxiliary lane, the diverge probability is assumed to be related with speed so that vehicles move to the auxiliary lane at random for each speed as shown in Figure 2.

**Figure 2:** Diverge rate to auxiliary lane applied in the simulation model

4 Determination of Simulation Cases for Auxiliary Lane Installation

To establish effective installation methods for an auxiliary lane in the sag section, two points have to be answered: longitudinal location patterns, i.e. before or after or straddling the sag bottom; auxiliary lane patterns, i.e. climbing lane or overtaking lane types. The cases studied for simulation runs are combinations of these patterns.

The longitudinal location patterns are further divided into three types as shown in Figure 3: a) the auxiliary lane is installed upstream of the sag bottom; b) the lane is installed downstream of the sag bottom; c) the lane straddles the sag bottom covering the vertical curve. With the upstream type the lane is installed before the sag bottoms out, so that vehicles slowing down because of the upslope could escape to the auxiliary lane beforehand and thus correcting the lane use rate on the upslope. When the auxiliary lane is installed downstream of the sag bottom, vehicles that will slow down at the upslope may escape to the auxiliary lane so that lane use rate at the upslope will be corrected and thus preventing the propagation of shock waves upstream to subsequent vehicles in platoons. The auxiliary lane is installed straddling the sag bottom, to benefit from the merits of both the upstream and downstream types.

**Figure 3:** Longitudinal location patterns of auxiliary lanes

**Figure 4:** Auxiliary lane patterns
Table 1: Auxiliary lane installation cases

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Description</th>
<th>Climbing lane type</th>
<th>Overtaking lane type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-1</td>
<td>500m-long auxiliary lane upstream of the sag bottom</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>1-2</td>
<td>1000m-long auxiliary lane upstream of the sag bottom</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>1-2(O)</td>
<td>1,000m-long auxiliary lane upstream of the sag bottom</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>2-1</td>
<td>500m-long auxiliary lane from 250m upstream to 250m downstream of the sag bottom</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>2-2</td>
<td>1,000m-long auxiliary lane from 500m upstream to 500m downstream of the sag bottom</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>2-2(O)</td>
<td>1,000m-long auxiliary lane from 500m upstream to 500m downstream of the sag bottom</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>2-2'</td>
<td>1,000m-long auxiliary lane from 250m upstream to 750m downstream of the sag bottom</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>2-3</td>
<td>1,500m-long auxiliary lane from 500m upstream to 1,000m downstream of the sag bottom</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>2-3'</td>
<td>1,500m-long auxiliary lane from 250m upstream to 1,250m downstream of the sag bottom</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>3-1</td>
<td>500m-long auxiliary lane downstream of the sag bottom</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>3-2</td>
<td>1,000m-long auxiliary lane downstream of the sag bottom</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>3-2(O)</td>
<td>1,000m-long auxiliary lane downstream of the sag bottom</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>3-3</td>
<td>1,500m-long auxiliary lane downstream of the sag bottom</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>3-4</td>
<td>Auxiliary lane from sag bottom to downstream crest</td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>

Figure 5: Auxiliary lane installation cases

The auxiliary lane patterns considered in this study are shown in Figure 4. They are: the climbing lane type added and closed on the shoulder side, or the overtaking lane type added on the median side and closed on the shoulder side. The climbing lane type aims to allow slower vehicles to escape to prevent any slowdown on the outer lane. The overtaking lane type is used for vehicles wishing to go faster to overtake, so as to reduce the platoon size and increase the average speed on the inner lane. The simple
overtaking lane type that is added and closed on the median side is not addressed in this study because no such type has been in operation on motorways in Japan to date, except for two-lane two-way expressways.

Both longitudinal location and auxiliary lane patterns are combined and a total of 15 cases were selected for simulation runs, as shown in Table 1 and Figure 5.

In the longitudinal location patterns, auxiliary lane lengths were set at 500m (Case x-1), 1,000m (Case x-2) and 1,500m (Case x-3). Moreover, Case 3-4, in which an auxiliary lane is added from the sag bottom to the crest of the upslope, is added in a downstream installation case. This last case is often used in actual applications of auxiliary lanes to mitigate traffic congestion at sag sections. As for the auxiliary lane straddling the sag bottom, the auxiliary lane is set to be basically symmetrical about the sag bottom. However, with lane lengths of 1,000 and 1,500m, Cases 2-2’ and 2-3’, where the auxiliary lanes are moved 250m downstream compared to Cases 2-2 and 2-3 of the same length, are added to study the best ratio for installing a lane before and after the sag bottom.

As for 1000m-long auxiliary lanes, in addition to Cases 1-2, 2-2, 3-2, an overtaking lane type is added so that both climbing lane and overtaking lane types of auxiliary lanes could be compared for the study.

5 Calibration of Traffic Simulation Model to Evaluate Auxiliary Lane Effectiveness

5.1 Preparation of Simulation Data

The purpose of the study is to evaluate the effectiveness of various auxiliary lanes installed at sag sections. To eliminate factors other than sag that may influence the results, a fictional road section model of a 10km-long two-lane straight carriageway with a sag section placed 6km from the start of the section and 1km before the end is used as shown in Figure 6. The sag is assumed as a change of gradient from a 1,000m-long down slope (-4%) and a 2,000m-long upslope (4%). The remaining section is assumed to be level except for the sag section. The vertical alignment of the sag section is taken from a dual two-lane section of the Chuo Motorway near Kobotoke Tunnel, which is one of the most famous bottlenecks in Japan. The horizontal alignment is assumed to be straight, although it differs from that of the real section.

The traffic volume and speed data collected on the inbound two-lane section of the Chuo Motorway near the Kobotoke Tunnel was used to calibrate the microscopic traffic simulation model. The data was taken as a typical example on the weekend, October 30, 2005, at the 40.43kp (kilometer post) using inductive vehicular detectors. The detector data includes a time series of 5-min traffic volume and speed for two vehicle types (passenger cars and heavy vehicles) and also for each different lane and total lanes in one direction. The percentage of heavy vehicles was considered as 9%, taken from the census data for 2005. Data for other days was also examined for the calibration although it is not shown in the paper. OD traffic as an input to the simulation is generated from the upstream end of the 10km-long road section and the generated vehicles move to the downstream end based on the car-following model applied in the microscopic simulation model. Accordingly, traffic volume, individual and average speed and average lane use rate can be predicted at any location of the simulated road section and any time. These predicted traffic flow data are then compared with the observed data to calibrate the simulation model.

However, the bottleneck in the 2-lane section near the Kobotoke Tunnel on the Chuo Motorway is the entrance to the tunnel and sag which is known to cause breakdown in traffic flow or slowing of traffic and ultimately result in traffic congestion on weekends and holidays when traffic demand is high. Data collected near the Kobotoke Tunnel was used to ensure the two-lane sag model would resemble actual traffic conditions. Although the traffic volume, speed reduction and breakdown in flow may be reproduced by the simulation model, the cause of congestion in the simulation may not be exactly the same as that of the actual road section because the effect of the tunnel on the driver’s car-following behavior was not taken into account.
5.2 Calibration of the Microscopic Simulation Model

5.2.1. Traffic Flow at the Sag Section

Whether traffic conditions that lead to congestion were duplicated or not was examined by examining the changes in traffic volume and speed over time and the lane use rate at 250m downstream from the sag bottom. Road conditions during the three-hour period between 1 and 4 pm, when vehicle speed used to start declining, were reproduced for the calibration. Figure 7 shows a comparison of observed and simulated time series of traffic volume and speed and the lane use rate at five-minute intervals, which is the same as the data obtained from vehicle detectors.

Examining the transitions of volume and speed over time, the timings for speed decrease at the sag section in the simulation and on the actual road are the same. This means traffic flow breaks down at the sag at around the same time in both the simulation and observations. In the study, the onset of breakdown
in flow is defined as the transition flow with the directional average speed changing from free flow speed to less than 50 km/h. The timing for slowing down (propagation of congestion) on the upstream side is also about the same. Just before congestion occurs, the traffic volume (breakdown flow) is 700 veh/15-min (2,800 vph), while during congestion, the traffic volume (queue discharge flow) averaged 650 veh/15-min (2,600 vph). As for the lane use rate for the inner lane before congestion occurs, it is 55 - 60% before congestion occurs and drops to an average of 53% during congestion. Figure 7 shows that both observed and simulated traffic volume, average speed and lane use rate are about the same, which means the microscopic traffic simulation model used in the study is of relatively high accuracy to reproduce traffic flow and the bottleneck phenomenon at sag sections. Accordingly, the next section of the paper describes how the microscopic simulation model is applied to study how best to install an auxiliary lane at the bottleneck of the sag section.

5.2.2. Auxiliary Lane Use Rate

The auxiliary lane use rate before congestion was verified spatially by comparing the observation and simulation estimated data of the auxiliary lane and adjacent sections, before and after the auxiliary lane.

Figure 8(a) shows the lane use rates observed at four locations of auxiliary lane and adjacent sections before and after the auxiliary lane. The figure shows that the use rate of the auxiliary lane is about equal to the decrease in the inner lane use rate from just upstream to the end of the auxiliary lane while the outer lane use rate remains unchanged. This means that the auxiliary lane use only comes from the decrease in inner lane use. Watanabe et al. (2005) have analyzed the relation between the auxiliary lane length and the difference between the use rate of the inner lane before and after the auxiliary lane; using the observation data from many auxiliary lanes of the climbing lane type. They have found that the difference is from about 3 to 6%, which means we can estimate the use rate of the auxiliary lane at about 3 to 6%.

Figure 8(b) shows the rate of use for the auxiliary lane estimated through simulations (Case 1-2). The simulation showed that the use rate of the auxiliary lane is about 3 to 5%, which is about the same as the observation result. The parameters used in the simulation were calibrated by repeated runs. In this study, the parameters thus obtained in case 1-2 were used for other auxiliary lanes of the climbing lane type. For the auxiliary lanes of the overtaking lane type, the data collected in the study by Oguchi et al. (2001) in which they analyzed the use rate in a temporary additional lane installed during road works was used as a reference to calibrate the parameters of the simulation model similarly to the climbing lane type.

**Figure 8:** Comparison of observed and simulated lane use rates
6 Simulation Results

In this paper, the effectiveness of the auxiliary lane was evaluated by comparing the increase rate of the breakdown flow rate with the auxiliary lane, which is defined as the ratio of the breakdown flow rate with the auxiliary lane to that without. Figure 9 shows the 15-minute breakdown flow rate and their increase rate obtained from simulations and ratios for the cases described in Table 1 and Figure 5. In case congestion was eliminated by adding an auxiliary lane, traffic demand was increased by 500 vph to cause congestion in simulation, whereupon a breakdown flow rate was obtained.

![Breakdown flow rate estimated from the simulation for all auxiliary lane installation cases](image)

*1. The breakdown flow rate is the 15-minute flow rate just before congestion occurs.
2. The bars in red represent the simulation results of cases in which traffic demand is increased by 500 vph to cause congestion because the original traffic demand has not resulted in congestion.
3. Values shown in () are ratios between each case and no auxiliary lane.

**Figure 9:** Breakdown flow rate estimated from the simulation for all auxiliary lane installation cases

6.1 Longitudinal Location of the Auxiliary Lane Installed at the Sag Section

6.1.1. Auxiliary Lane Installed Upstream of the Sag Bottom

When an auxiliary lane is added upstream of the sag bottom, the ratio of breakdown flow rate with an auxiliary lane to that without, at the start of the congestion, is estimated at between 1.07 and 1.09 in Cases 1-1, 1-2 and 1-3, which means the breakdown flow rate is predicted to increase by 7 - 9% with the addition of an auxiliary lane. An auxiliary lane added upstream of the sag bottom is only effective to a certain degree of less than 10% and the length of the auxiliary lane does not increase the breakdown flow significantly.

6.1.2. Auxiliary Lane Installed Downstream of the Sag Bottom

With the 500m-long auxiliary lane (Case 3-1), the ratio is 1.09 and was slightly effective. With lanes of 1,000m or longer (Cases 3-2, 3-3, 3-4), the ratio is between 1.21 and 1.22, indicating a comparative increase in traffic volume during congestion. However, compared with the 1,000m-long auxiliary lane
(Case 3-2), both the 1,500m-long auxiliary lane (Case 3-3) and the 2,000m-long auxiliary lane extended to the crest (Case 3-4) show little difference.

6.1.3. Auxiliary Lane Installed Straddling the Sag Bottom

With the 500m (Case 2-1) and 1000m (Case 2-2) auxiliary lanes, the ratio is between 1.09 and 1.10, indicating that the results differ little to the point when the auxiliary lane is installed on the upstream side of the sag bottom.

However, when the 1,000m-long auxiliary lane is moved 250m downstream (Case 2-2’), the ratio increases to 1.21 and the effectiveness soars. This shows that with the 1000m-long auxiliary lanes, it is more effective to install the lane from around the starting point of the vertical curve. With the 1,500m-long auxiliary lanes (Cases 2-3, 2-3’), when the lane is extended 500m downstream (Case 2-3’), the ratio is 1.23, which slightly exceeds Case 2-2, whose ratio is 1.21, indicating that extending beyond 500m downstream of the end point of the vertical curve farther downstream does not increase the effectiveness of the lane that much. With Case 2-3, the lane is extended 250m on both upstream and downstream sides of the sag bottom from Case 2-2’. In this case the ratio is 1.25 and slightly exceeds Cases 2-2’ & 2-3’. This shows that extending to the upstream side till around the starting point of the vertical curve is slightly more effective than extending the lane downstream. However, no major difference in effectiveness was found in either case, compared with adding 1,000m-long lanes.

6.1.4. Summary of the Longitudinal Location of the Auxiliary Lane Installed at the Sag Section

It can be seen from the results of 6.1.1 to 6.1.3 that auxiliary lanes 1,000m or longer are preferable and most effective when they extend from around the start of the vertical curve to 500m downstream from the end of the same. Extending the lane beyond 1,500m shows no further improvement in effectiveness. These findings agree with previous study results (Xing et al., 1995) that, before congestion begins, vehicles first start to lower their speed and a shock wave develops from around the end of the vertical curve to several hundred meters downstream. Accordingly, the auxiliary lane needs to cover the section where the shock wave develops and needs not extend farther to upstream beyond there and even to the downstream crest.

6.2 Auxiliary Lane Patterns

When comparing 1,000m-long auxiliary lanes of both the climbing lane and overtaking lane types (Cases 1-2, 2-2, 3-2), it is seen that the breakdown flow rate with an auxiliary lane of the overtaking lane type that is installed on the median side is comparatively larger than the auxiliary lane of the climbing lane type installed on the shoulder side. This is because the overtaking lane type auxiliary lane enables vehicles to travel at high speeds to overtake slower vehicles near the start of the bottleneck area and at the end of the auxiliary lane, the vehicles traveling on the auxiliary lane need not change lanes, making traveling more efficient and safer. This type of auxiliary lane is most effective to correct the over use of inner lanes and imbalanced lane use because the use rate of the overtaking type auxiliary lane starts from zero at the auxiliary lane that is the median lane. However, because all vehicles traveling on the outer lane have to change lanes to move to the inner lane and more vehicles need to change lanes in this case, safety concerns may arise. Accordingly, it is advisable to make the auxiliary lane (or 3-lane section) as long as possible. Note is needed that the overtaking lane type auxiliary lane discussed in the paper is not the same as normal one, which adds and closes on the median side.
7 Conclusion and Future Issues

A sag section bottleneck of a dual two-lane motorway is studied through microscopic traffic simulations to determine how best to install an auxiliary lane to mitigate congestion.

Auxiliary lanes of 1000m or longer are preferable when installing lanes at sag sections. The breakdown flow rate tends to increase more when the auxiliary lane is installed to cover the vertical curve and approximately 500m beyond the end of the vertical curve, rather than before the sag bottom. In other words, the auxiliary lane is most effective when installed from the start of the vertical curve to 500m downstream from the end of the same, with little benefit of any further extension.

When comparing auxiliary lanes of both the climbing lane and overtaking lane types, the breakdown flow rate with an auxiliary lane of the overtaking lane type, as installed on the median side and closed on the shoulder side, is comparatively higher than with an auxiliary lane of the climbing lane type installed on the shoulder side. This type of auxiliary lane is most effective to correct the over use of inner lane and imbalanced lane use. However, because all vehicles traveling on the outer lane have to change lanes to move to the inner lane and more vehicles need to change lanes in this case, a concern about safety may arise. Accordingly, it is advisable to make the auxiliary lane (or 3-lane section) as long as possible.

In future, the findings obtained in this simulation study should be validated on the actual road network. One method would be to use an actual auxiliary lane, adjust its length by restricting travel and study the effects on traffic flow. There is also a need to improve the accuracy of the microscopic simulation model by applying the findings of field validation tests. In addition, the effectiveness of the normal overtaking lane type auxiliary lane that is added and closed on the median side should also be evaluated and compared with the two types discussed here in this paper.

References