A STUDY ON TRAVEL TIME IMPACT OF AUTOMATED TRUCK LANE ON INTERCITY EXPRESSWAYS USING HYBRID SIMULATOR

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1. Introduction

Truck transport has significantly promoted economic growth in Japan as the intercity expressway network expanded. However, two obvious deficiencies for truck transport compared with coastal shipping have been pointed out: higher labor intensity and limited scope for productivity improvement. Despite this, truck transport still accounts for a great proportion of intercity freight transport in Japan. Just-in-Time (JIT) production is believed to be one major factor driving this high proportion of truck usage. JIT can meet this customer demand by producing goods of perfect quality with zero lost time, while eliminating waste and so on. However, this kind of production requires freight transport that is able to deliver goods of appropriate quality and quantity to the right place at right time. Trucks are ideal for such small-lot cargo and delivered at high frequency. Given this background, and considering the future prospect of growth in demand for truck transport, it is likely that traffic flows will become less homogeneous, while efficiency and safety are likely to decrease. Consequently, innovations of the truck transport are required to realize more efficient and eco-friendly logistics systems.

Tomei-Meishin expressway is a main artery of Japan, and connects three main metropolitan areas (Tokyo area, Chukyo area and Hanshin area). The majority of freight movements among these metropolitan areas are along the Tomei-Meishin expressway. A second expressway linking the same areas (named New Tomei-Meishin Expressway) will come into use in 2020. In order to analyze the potential safety and efficiency improvements delivered by a new logistics system called an automated truck lane (ATL), it is assumed that one lane of the expressway is dedicated to automated trucks. By making the trucks automated, there should be opportunities for more efficient transport and environment improvement; by providing a dedicated lane, vehicle interactions can be avoided for high reliability and safety. Moreover, with no drivers needed for automated truck operations, the problem of labor scarcity may be overcome. Previous studies[1)-2)] have focused on how traffic flows would change if one lane of New Tomei-Meishin Expressway was set aside as an ATL. They have mainly involved basic analyses of the impacts on the expressway itself and assume a fixed demand. However, the impact of ATL systems over a wide area should be evaluated because ATL will likely affect not only the traffic flow in the ATL itself but also traffic on other expressways and ordinary road network.

In order to effectively evaluate ATL performance on New Tomei-Meishin Expressway in this manner, we construct a hybrid simulator which combines a mesoscopic simulator for the ordinary road network over a wide area and a microscopic simulator for car-following and lane-changing behavior on the expressway network[3)-4)]. This hybrid simulator can be used to analyze changes in traffic flows and travel time over a wide area resulting from introduction of ATL.

2. Hybrid simulator

The aim of this paper is to model changes in traffic flow induced by introduction of ATL on New Tomei-Meishin Expressway, so the hybrid meso-micro simulator must be able to model traffic on a large-scale road network. Generally, the impact of introducing ATL would require precise modeling of passenger vehicle and truck speed changes as traffic volume and traffic composition change. The usual approach is to adopt instantaneous speed, vehicle type, and vehicle spacing as the main factors in modeling behavior such as car-truck following and lane-changing.

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A mesoscopic simulator alone is only able to provide the average speed of a group of vehicles on link and cannot effectively evaluate the impact of an ATL. Moreover, it is important to accurately model the relationship between cars and trucks, since an ATL system will cause a change in the percentage of trucks in the traffic flow. In mesoscopic simulations, the concept of passenger car equivalent (PCE) is generally adopted to reflect this relationship. However, it is difficult to calibrate the value of the PCE parameter under various road and traffic flow situations on a large-scale road network. Hence, a microscopic model is adopted to simulate the detailed relationship between passenger vehicles and trucks on the intercity expressway network. On the other hand, microscopic simulators is not cost effective for simulating in detail the behavior of large-scale road networks because of the computing time and parameter calibration required. For this reason, vehicle behavior on the ordinary road network is modeled using a mesoscopic simulator.

To meet the specific research requirements of this work, therefore, an integration framework that combines microscopic and mesoscopic models is designed for the development of a hybrid simulator. The proposed framework consists of a common module, meso and micro simulators, as shown in Figure 1.

(1) Mesoscopic simulator

The mesoscopic simulator models the movement of vehicles on the ordinary road network and provides basic information about vehicles entering the expressway. All origin and destination points are nodes on ordinary road links. Simulation is initiated at the mesoscopic simulator, which calls the common module to calculate link travel time and provide dynamic route information for the overall road network using the dynamic user optimum (DUO) assignment method. Two types of vehicle — passenger vehicles and trucks — are considered in the study. The movement unit is a vehicle package containing a maximum of five vehicles. The time-driven method is used to deal with the movement of vehicles and the scanning time step is 15 seconds. Travel speed is calculated using the k-v equation of traffic flow.

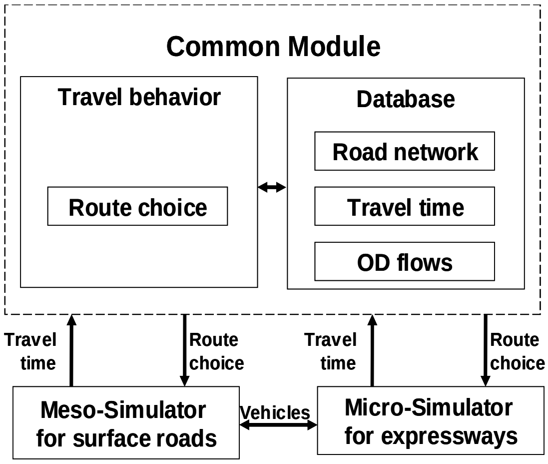


Figure 1: Framework of hybrid simulator for ATL system

PCE is used to quantify the impact of trucks. PCE value of 1.73 is used, as estimated from road traffic census data. The link entry/exit capacity at each time step is used to control the flow of traffic from one link to another. If the number of vehicles moving from the current link to the next link exceeds the current link exit capacity or the next link entry capacity, a queue of vehicles is formed to represent traffic congestion.

(2) Microscopic simulator

The microscopic simulator deals with the movement of vehicles on the expressway network and provides real-time results of link performance to the common module for the calculation of route choice. The scanning time step is 0.5 seconds and the length of cars and trucks is set at 5m and 13.5m, respectively. According to a previous study[5)] and taking into account the expressway speed limit, the range of desired passenger vehicle speed is 90–120km/h and that of trucks is 80–90km/h in this paper. The network of expressways used in this study is the one anticipated to be in place in 2020, when New Tomei-Meishin Expressway is expected to be completed. The simulator is capable of modeling basic microscopic behavior, including car-following, lane-changing, on- and off-ramps, merging and diverging procedures.

The basic microscopic simulator is the FRESIM model. This was selected on the basis of insights gained from a previous study[6)-7)] comparing several popular car-following models. That study concluded that the FRESIM car-following model replicates the field data more closely than other models when the driver sensitivity factors are finely calibrated. To precisely simulate the impact of the ATL system, the microscopic simulator also includes truck-following and modified lane-changing models so as to incorporate car-truck interactions; these are based on the car-following and lane-changing logic of the FRESIM model.

a) Car following model

The basic FRESIM following model uses a new set of values to represent driver sensitivity factors. The desired acceleration of the following vehicle is calculated according to driver preferred time headway and relative speed. The model used in the hybrid simulator is expressed as follows.

$$H = L_l + \beta \left\{ qV_f + bq\left(V_l - V_f\right)^2 \right\} \tag{1.a}$$

Where H is the spatial headway between leading and following vehicles, L_l is the lead vehicle length, q is the driver sensitivity factor for the following vehicle (a time headway expression for drivers), V_f is the speed of the following vehicle at time t, V_l is the speed of the leading vehicle at time t, and b is a calibration constant defined as follows.

$$b = \begin{cases} 0.1 & \text{if } V_l < V_f \\ 0 & \text{otherwise} \end{cases} \tag{1.b}$$

Previous studies have indicated that car drivers dislike following close behind trucks and so the headway for following a car is lower than the headway for following a truck. The following model uses the parameter β to represent the different spatial headway according to lead vehicle type. The value of coefficient β is estimated from simulator results in a previous study[8]. In that study, the subjects followed cars about 10% closer than they follow trucks. Hence, β has a value of 1.1 in the case of a car following a truck and 1.0 for other cases.
The acceleration can be expressed as follows.

$$a = \frac{2\left\{x_l^{t+T} - x_f^t - L_l - V_f^t(\beta q + T) - b\beta q\left(V_l^{t+T} - V_f^t\right)\right\}}{T^2 + 2\beta q T} \tag{2}$$

Where, a is the acceleration of the following vehicle, T is the simulation time step, x_l^{t+T} is the lead vehicle position at the end of time step (T), x_f^t is the following vehicle position at the beginning of the time step. The distance traveled by the vehicle during the time step is calculated according to the above acceleration and the reaction time.

b) Lane-changing model

The lane-changing model is another important component of car-truck interactions. Drivers make discretionary lane changes to obtain a more favorable position and/or a higher speed. The motivation of the car driver also is affected by car-truck interactions. A car-driver behavior survey indicates that drivers are more willing to change lanes when they are following a truck. Therefore, the FRESIM lane-changing "desire" component is modified and modeled as follows.

$$d = \begin{cases} 100 & , v \le v_i \\ \min\left[100\left\{1 - \dfrac{v - v_i}{v_0 - v_i} + c\dfrac{1.5 - q}{1.5 - 0.6}\right\}, 100\right] & , v_i < v < v_f \\ 0 & , v \ge v_0 \end{cases} \tag{3}$$

Where v_i is a speed level below which the driver is highly motivated to change lanes, v_f is the desired free-flow speed, v is the current speed of the vehicle that is changing lanes, q is a driver sensitivity factor ranging from 1.5 to 0.6 (the smaller the value of q, the greater the motivation to pass a truck), and c is a coefficient. In the case of a car following a truck, this paper assume a value of 0.38 for c, so that when q=1, the probability of the driver changing lanes is about 20%, even if the truck ahead is traveling at the free-flow speed. For other cases, c is 0.

3. Validation of hybrid simulator

(1) Road networks

Road networks are based on the allocation network of the central regional development bureau of Japan's Ministry of Land, Infrastructure and Transport, with adjustments to take into account the opening of New Tomei-Meishin Expressway in 2020. The network is shown in Figure 2. The number of overall road links is 15,489, with 1,077 for expressways.

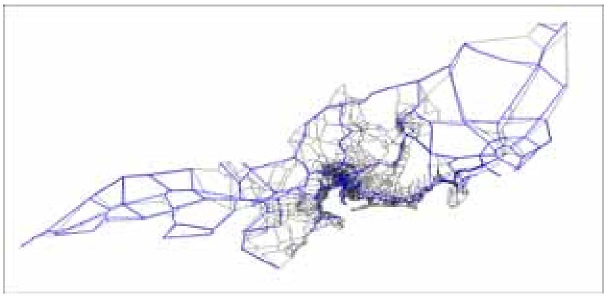


Figure 2: Overall road network in the simulation

(2) OD data

The hybrid simulator uses OD demand data for 2020 based on future OD demand predicted by the central regional development bureau for 2030. Data is obtained by multiplying by a cut-rate which is calculated using the 20th reference data of Promotion Committee for the Privatization of the Four Highway-Related Public Corporations[9].
The departure time distribution for each OD pair is created from the departure time distribution obtained by aggregating traffic census master OD data from 1999. The departure time distribution for OD pairs to be added in future is based on the distribution table of OD pairs in the same region. Zone is mainly based on the "B" zone of traffic census within the scope of central regional development bureau. Some zones located in North of Kanto and west region of Kinki are appropriately integrated. The number of zones is 946.

(3)Validation of hybrid simulator

The reproducibility of the simulator is validated by comparison of observed and simulated traffic link volumes. The simulated volumes are generated using OD demand data and road network data for 1999. The correlation coefficients for the whole network and for the expressway network are calculated both to validate the simulator. The correlation coefficients are 0.771 and 0.776 respectively. Given that the simulated network is the complete road network of Japan, the correlation is good and indicates that the hybrid simulator has the ability to model the actual data. As such, it is suitable for analyzing the ATL system.

4. ATL evaluation

(1) Change of travel time

In order to analyze the impact of ATL on travel time, we calculate the dynamic link mean travel time over a day. The sum of link travel times on New Tomei-Meishin Expressway in the down direction between Ebina South JCT and Kobe JCT (a distance of 512km) is used. Three cases are simulated for comparison. The "base case" is the initial design case of four to six lanes serving two-way traffic, while the "all six lanes" case consists of six general-purpose lanes serving two-way traffic of mixed trucks and passenger vehicles. The "ATL + four lanes" case has automated trucks on the inner two lanes and normal trucks and passenger vehicles on the other four lanes.

The traffic situation resulting from the simulations is shown in Figure 3. Mean travel speed in the base case is between 60 and 95km/h. Compared with the actual travel speed (76.7km/h) on the Tomei-Meishin Expressway (Tokyo IC to Nishinomiya IC) calculated using traffic census data during the rush hour in 2005, the simulation gives a somewhat lower speed. In order to enhance the accuracy of the simulator, careful calibration of drivers' desired speeds and the car-following models' parameters is required, while models that take into account vehicle behavior according to a detailed description of traffic conditions are required. These are questions to be solved in the future.

In Figure 3, travel speeds in the all six lanes case are much higher over the whole region, while in "ATL + four lanes" case they are still higher. This means that the effect of reducing the proportion of trucks is greater than the impact of the loss of lanes to ATL, even though free running deteriorates when the number of general purpose lanes is reduced. The variability in travel speed over a day is reduced in both "all six lanes" and "ATL + four lanes" cases. In particular, the speed decrease that occurs during rush hour is dramatically alleviated by the introduction of ATL

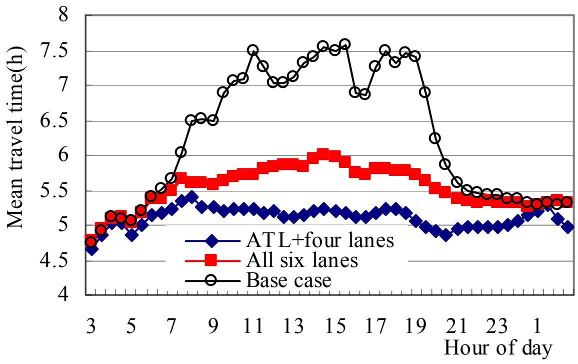


Figure 3: Change in travel time on New Tomei Meishin Exp. down direction (Ebina South JCT → Kobe JCT)

(2) Change of total travel time

Table 1 lists total travel time for the three cases described above. Compared with "base case", "all six lanes" case saves 138,000 vehicle hours of travel time per day, with trucks accounting for 40% of this total. Moreover, the saving in travel time on expressways other than New Tomei-Meishin Expressway contributes most to the savings. The introduction of ATL saves 357,000 vehicle hours per day compared with "base case", with passenger vehicles making up the majority. "ATL + four lanes" case results in improved travel time savings both on the expressway and ordinary road network.

Table 1: Change in total travel time (upper: all vehicles, lower: only for truck)

	Total networks		Expressways		New Tomei Meishin	
Base case	7,549 1,824	(-)	1,755 794	(-)	448 300	(-)
All 6lanes	7,411 1,765	(-138) (-59)	1,647 755	(-108) (-39)	453 315	(+5) (+15)
ATL＋4lanes	7,192 1,735	(-357) (-89)	1,527 713	(-228) (-81)	465 330	(+17) (+30)

Unit: 1000 vehicle • hour/Day, ( ): the difference between "Base case" and the other cases

5. Travel time variability during incident

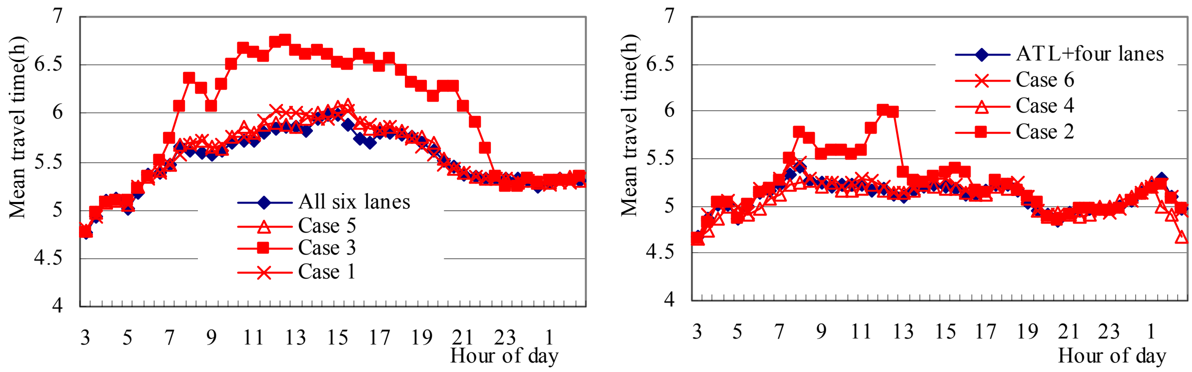
Various traffic restrictions are applied because of accidents or road repair work every day. Moreover, both the Tomei and New Tomei expressways pass through the area at risk from the anticipated Tokai earthquake that could strike in the near future. Indeed, the Tomei Expressway was damaged by an earthquake in Shizuoka in 2009 and was closed to traffic for five days. The damaged segment is located between the Sagara-Makinohara IC and Kikugawa IC. In this paper, we assume that traffic restrictions are applied to general-purpose lanes and then analyze the impact of the incident in different cases. The incident is assumed to occur in the down direction of Tomei Expressway (damaged segment described above) or New Tomei-Meishin Expressway between the Kanaya IC and Mori-Kakegawa IC which is a point close to the earthquake-damaged section mentioned above. This is one of the sections with the heaviest traffic. The traffic restriction is assumed to stay in place all day. Six cases of different incident location are evaluated.

Table 2: Cases evaluated during incident

Case	Incident location	Lane number of expressway(one way)	Restriction lane number	Scenario for New Tomei Meishin Expressway
1	New Tomei	3	1	Two general-purpose lanes
2	New Tomei	3	1	ATL + general-purpose lane
3	New Tomei	3	2	General-purpose lane
4	New Tomei	3	2	ATL
5	Tomei	2	2	Three general-purpose lanes
6	Tomei	2	2	ATL + two general-purpose lanes

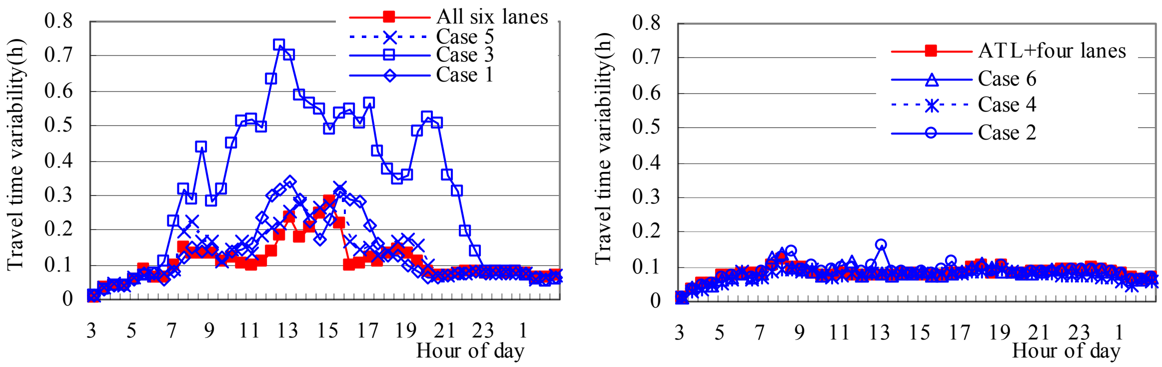
In order to examine the impact of incident, mean travel time and travel time variability on New Tomei-Meishin Expressway under incident and normal situation are expressed in Figure 4 and 5.

In Figure 4, we find that the mean travel time during incident is generally more than the normal case, and in Figure 5, the travel time variability also becomes more intense for the influence of incident. According to the comparison result, travel time variability performance of cases with ATL is apparently better than that of cases using general-purpose lanes no matter what the incident is. Case 2 (one lane of New Tomei-Meishin Expressway restricted) suffers more impact of incident compared with other ATL cases, the same as Case 3 (two lane of New Tomei-Meishin Expressway restricted). The reason may lies in that cases with only one general-purpose lane remained are more apt suffering from traffic congestion. We also find that incident of Tomei Expressway only has a little impact on travel time variability of general-purpose lane case, and for ATL case, New Tomei-Meishin Expressway as an alternative route to Tomei Expressway suffers no impact from the incident of Tomei Expressway.



(a) (b)

Figure 4: Mean travel time of New Tomei-Meishin Expressway (a) all general-purpose lanes; (b) one lane is ATL, others are general-purpose lanes.



(a) (b)

Figure 5: Travel time variability of New Tomei-Meishin Expressway (a) all general-purpose lanes; (b) one lane

is ATL, others are general-purpose lanes.

We also compare Case 2(worst situation of ATL in incident) with the corresponding Case 1 in figure 6. The incident has more impact on "ATL + four lanes" case than on "all six lanes" case because there are fewer general-purpose lanes after the introduction of ATL. With the increased traffic demand, traffic congestion occurs during the period 7:00-13:00. However, the mean travel times are only slightly different during this period of congestion. Hence, even if an incident causes one lane of New Tomei-Meishin Expressway to be closed, "ATL + four lanes" case can be said to maintain the functional capacity for traffic as "all six lanes" case.

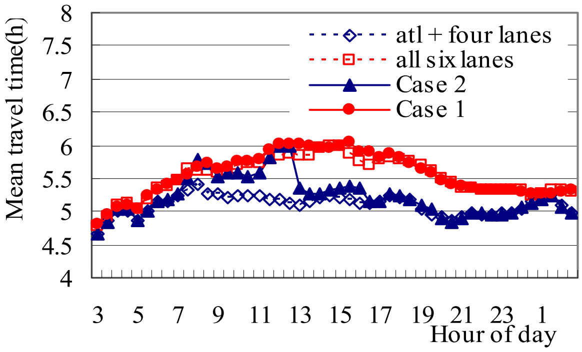


Figure 6: Mean travel time of New Tomei-Meishin Exp. under normal and incident situation (case 1 and 2)

6. Conclusion

In order to obtain an overall evaluation of the effects of introducing an automated truck lane (ATL) on New Tomei-Meishin Expressway, a basic analysis of ATL performance in a large-scale road network has been carried out. According to simulation results, the introduction of ATL can result in travel time change on New Tomei-Meishin Expressway, with total travel time decreasing dramatically. It is shown that ATL can have a desirable effect on traffic both on the expressway network and the ordinary road network. ATL performance on travel time is better than that of general-purpose lane cases. Even in the case of an incident that leads to traffic restrictions, the same functional capacity remains available during periods of congestion as when there is no ATL.

One major assumption made in this paper is that all expressway interchanges are equipped with a dedicated ramp for ATL. In order to move forward and develop a more accurate analysis, future effort will be needed to determine logistics center capacity and suitable ramp position according to various ATL operation modes.

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