Analysis on Spatial Lane-Use Change at Freeway Segments with New Additional Lane

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Lane-use rate and maximum flow of median-lane is higher than that of shoulder-lane at freeway segments under free-flow condition because of drivers changing from the shoulder-side lane to the median-side lane at main line of basic freeway segments to attain their desired speed. Unbalanced lane use reduces the stability of traffic flow and makes it more vulnerable for capacity drop. 3-hour continuous observation data is obtained at 4 observation sites at the transition area where vehicles starting to change to a new additional lane implemented at median side at two-lane basic freeway segment. 83 lane-changes are observed at one of the observation sites. Spatial lane-use change and driving behavior within this area is analyzed. A simple and compact lane-use model is built to reproduce the spatial lane-use change. It is proved to be capable of reproducing the temporal and spatial lane-use changes after calibration and validation. Spatial location where lane-use became stable is analyzed at different traffic flow levels.

Key Words : *lane-use, additional lane, freeway segment, observation, simulation, traffic flow level*

1. INTRODUCTION

Congestion happens at bottlenecks such as sag sections and tunnels in Japan(1)(2)(3). One of the biggest reasons is that the unbalanced lane use reduces the stability of traffic flow and makes it more vulnerable for capacity drop. It is widely observed at 3-lane basic freeway segments that traffic flow and lane-use rate of vehicles is bigger at median-lane than that at middle-lane or shoulder-lane when traffic demand becomes relatively high. Generally, congestion happens at the median lane first, then spread to the other lanes with vehicles evading from the congestion and causes total breakdown eventually.

Any theory that explains the change of spatial lane use with traffic demand has not yet been established. This kind of theory can explain the mechanism of unbalanced lane use at high traffic demand condition quantitatively. It is expected that, consequently, some effective measures to prevent unbalanced lane use could be found by applying the mechanism.

This paper aims to construct a simple and compact lane-use model to describe the spatial change of lane-use at basic freeway segments for the further research on both mechanism and influence of the lane-use change. Observation data on the transition area of basic freeway segment with a new additional lane is obtained. Spatial lane-use change at basic freeway segments with new additional lane is analyzed with this data. A theoretical model is built, verified and calibrated to reproduced the spatial lane-use change at basic freeway segments with new additional lane at different traffic demand levels.

The rest of this paper is organized as follows: literature reviews of relevant researches on both driving behaviors under actual traffic condition as well as traffic modeling on these behaviors are presented in Section 2. Introduction and brief analysis on field observation data of actual driving behavior is presented in Section 3. A theoretical model of lane-use behavior is proposed, a simulation model is build and parameters are calibrated in Section 4. Qualitative and quantitative comparison on the results of observation and simulation and further application of the model is estimated in Section 5, follows a discussion and conclusion in Section 6.

2. LITERATURE REVIEW

Lane-use and lane changing of drivers has been widely observed at freeway segments and received increasing scientific attention(1)(2)(3)(4). The main incentive of drivers choosing to change from the shoulder-side lane to the median-side lane at main line of basic freeway segments is to attain their desired speed. Drivers with higher desired speed tend to use the median lane while drivers with lower desired speed traveling on the shoulder lane. For example, at a basic freeway segment with 2 lanes per direction, drivers with higher desired speed than those of its preceding vehicles usually choose to change from shoulder lane to median lane. The lane-use rate of median lane increases with the increase of traffic demand on both 2-lane and 3-lane freeway (See Fig.1) (5).

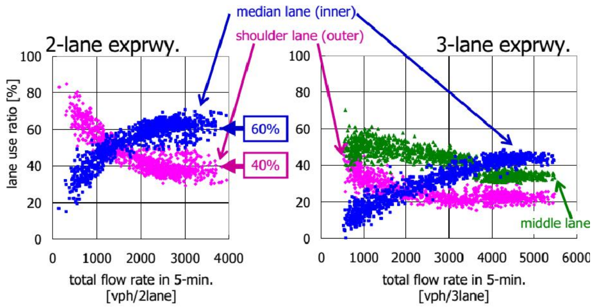


Fig.1 Lane-use rate at basic freeway segments.

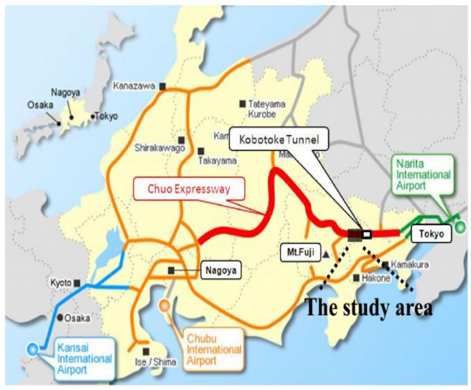
More than 60% of total traffic flow uses the median lane when traffic demand is around 3000 vph/2lanes on two-lane segments. On 3-lane segments, the lane-use rate of shoulder lane and middle lane decreases with the increase of traffic flow, while median lane use increases and exceeds that of other two lanes at 4000 vph/3lanes. The maximum flow of median-lane is also higher than that of shoulder-lane at freeway segments under free-flow condition(6).

When the demand is high enough, small speed disturbance will be easily amplified in median lane and cause the formation of queue. Vehicles will then evade to shoulder-lane to avoid being caught in congestion, which results in rapid capacity drop on other lanes as well(7). After persistent queue forms at all lanes, it takes much longer to dissipate even though the demand drops lower than the capacity. Balancing lane-use is expected to increase the overall capacity and maintain flow stability under heavy traffic demand.

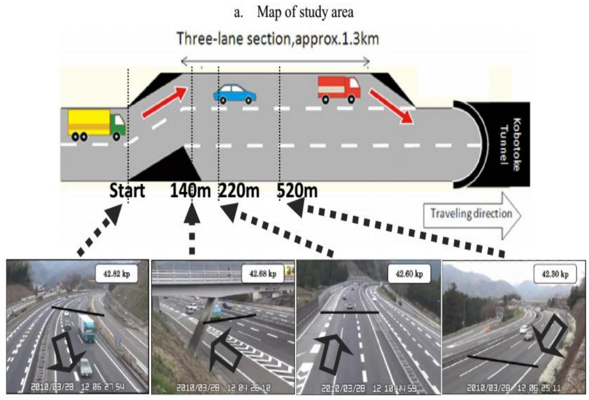
Traffic simulation is generally used to reproduce the stochastic process of traffic conditions with theoretical models. Theoretical models can be proved and modified through verification and calibration in simulation model using field observation data. Microscopic simulator including MITSIM(8), VISSIM(9), Microsimulation of Road Traffic Flow(10) summarize different theoretical driving behavior and traffic flow models. They are tried to be qualified for reproducing dynamic traffic phenomena under various microscopic traffic conditions. However, little works have been done on developing theories for engineering practice such as implementing a new additional lane where the analysis and reproduction of spatial change at segments is expected. Such spatial change could be only reproduced by theoretical models that capture the nature of the phenomenon well.

3. DATA

Field observation data is extracted from videos recorded at the Chuo Expressway in Japan (See Fig.2a). A new lane is added to a 2-lanes/direction basic freeway segment at median side. Videos are taken at 4 locations: the start point of 3-lane segment at 42.82kp, 140m from the start point of 3-lane segment e at 42.68kp, 220m from the start point of the additional lane at 42.6kp and 520m from the start point of 3-lane segment at 42.3kp (See Fig.2b). There is no weaving area, merging area, on-ramp or off-ramp near these segments which would affect the lane-choice by means of route choice.



a. Map of study area



b. Locations of video recording

Fig.2 Place the caption below the drawing.

Field observation data was collected and analyzed for actual lane-use features, including flow rate in every lane and lane-use rate at every detector location, as well as detailed lane change behavior.

(1) Traffic flow and lane-use rate

Flow rate and headway data of vehicles are collected for each lane from a continuous video recording from 12:00 to 15:00 on March. 28, 2010.

Vehicles travel in free flow and no congestion happens during the study time period. Traffic demand gradually increases monotonously from around 2000 veh/h to around 3200veh/h.15-minite aggregated flow rate data is used to eliminate the random oscillation on flow rate. Time headway with which vehicles follows each other is also collected. Flow rate of each lane at each observation site is presented in Fig.3. Lane-use rate is presented in Fig.4.

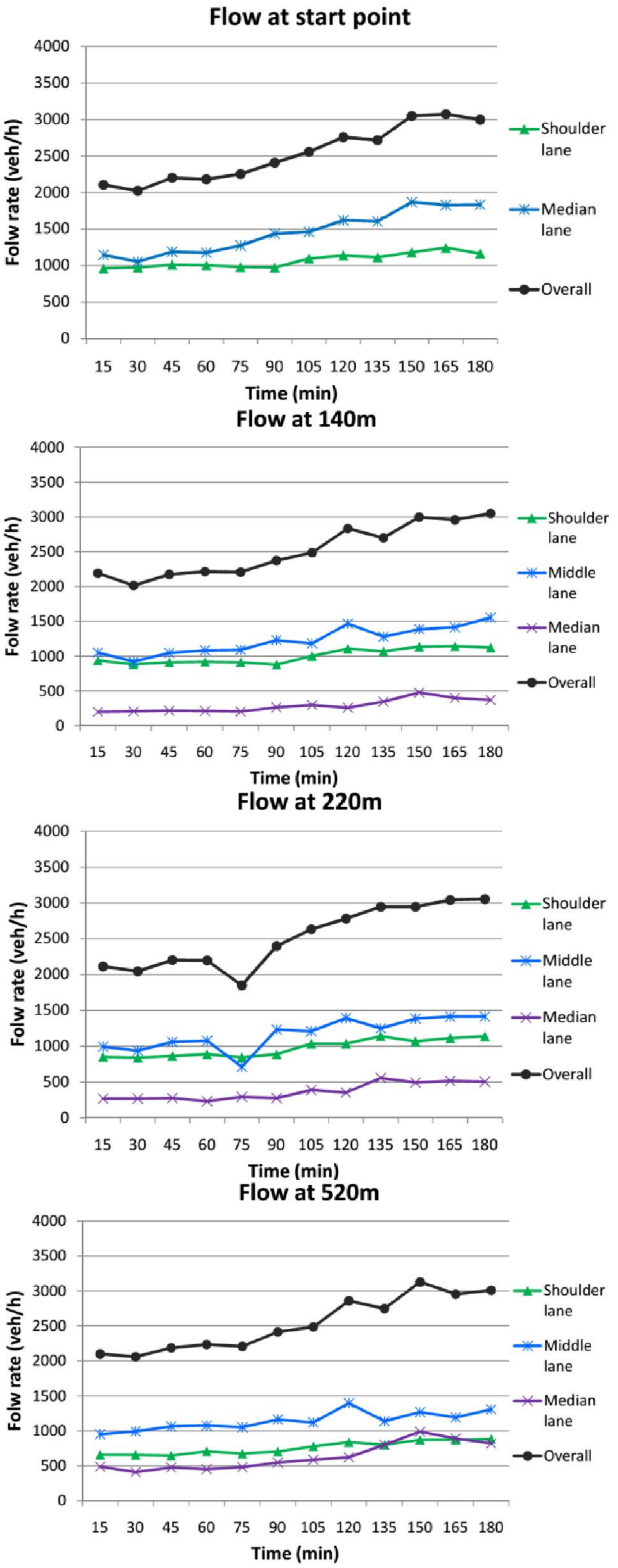


Fig.3 15-min aggregated flow rate at observation sites.

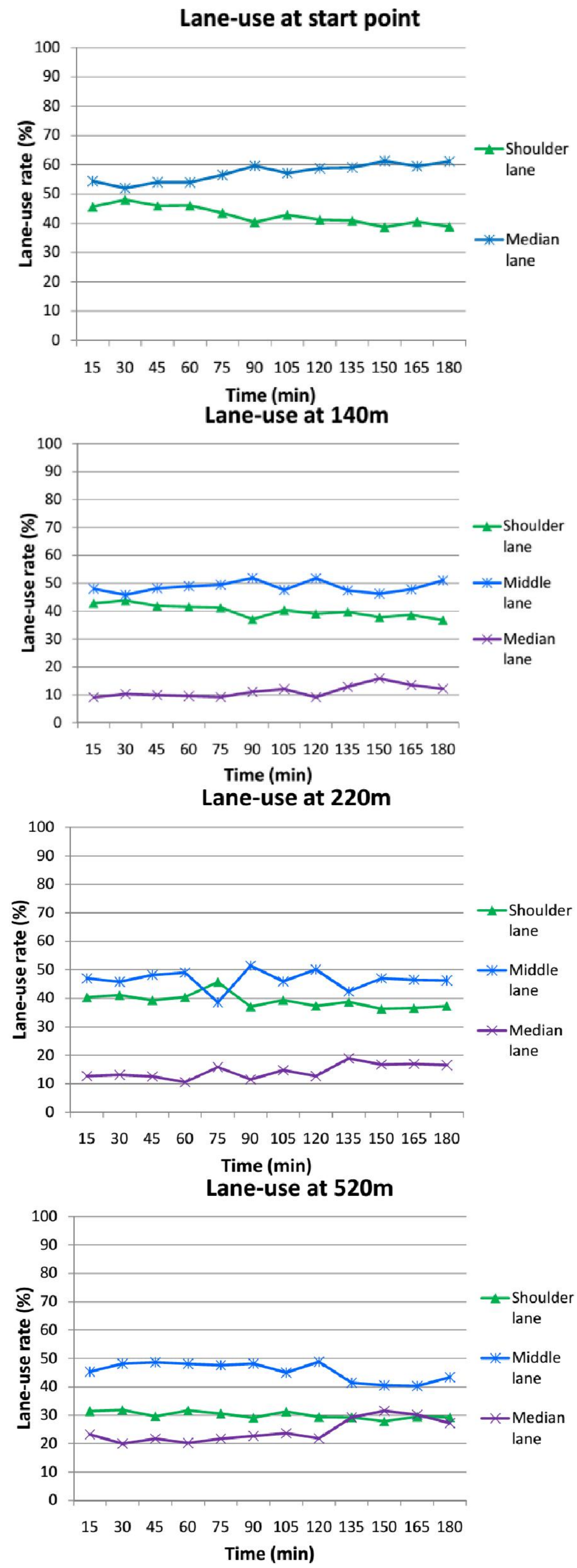


Fig.4 15-min aggregated lane-use rate at observation sites.

Flow rate and lane-use rate of median lane increases with the increase of both traffic demand and distance. The flow rate and lane-use rate of middle lane decreases about 10% at 140m from the start point and changes little with the further increase of distance. On the other hand, the flow rate and lane-use rate on shoulder lane decrease slowly at 140m and 220m but rapidly at 520m.

The increasing use of median lane by vehicles with the increasing distance is majorly resulting from the decrease in the use of shoulder lane. This is because drivers should always use the inner lanes for overtaking the slower vehicles in the shoulder lane by law. Vehicles entering the three-lane section with higher desired speed at middle lane tend to change to median lane to obtain speed increase and try to meet with their desired speed. Vehicles with higher desired speed at shoulder lane also change to middle lane to obtain speed increase and try to meet with their desired speed.

Vehicle speed is collected at the start point of 3-lane segment for the first 15 minutes for every hour to cover all traffic flow levels as well as reduce the load of labor-intensive work. The observed speed samples are found to follow the normal distribution with μ= 84.83 (km/h), $\sigma2$= 12.46 for shoulder lane and μ= 94.71 (km/h), $\sigma2$= 12.03 for median lane.

(2) Lane-changing behavior

Lane-changing behavior is the cause of spatial lane-use change at basic freeway segments beyond the start point of 3-lane segment. Therefore, lane-changing behavior is observed to discover features of lane-changing vehicles and variables affecting lane-changing behavior.

83 lane changes are observed during 13:00 to 14:30 at 42.3kp (220m from the start point) where lane-changing can be most frequently observed. Flow rate increases from around 2100 veh/h to around 2700 veh/h in this 1.5 hours observation , which ensures that lane changes in different flow level are observed. Speed of lane-changing vehicle, its preceding vehicle, leading and following vehicle on the target lane, headway between lane-changing vehicle and preceding vehicle, leading and following lag are collected in observation (See Fig.5).

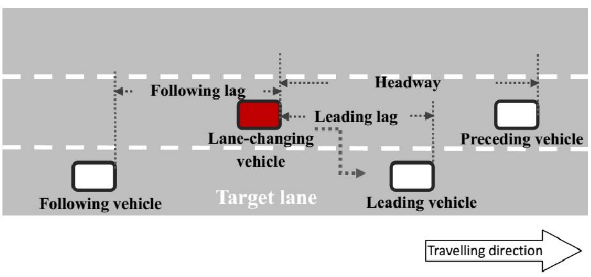


Fig.5 Observation of lane-changing behavior.

Leading lag and following lag are observed for time duration of 5 seconds, which is 111m in spacing under the speed of 80km/h and 125m in spacing under the speed of 90km/h. Vehicles are assumed to consider no leading or following vehicle if lag were longer than 5 seconds. If leading lag and following lag exceeds 5 seconds, they are set as 5 seconds.

T-test shows that the mean speed of vehicles changing from the shoulder lane to the middle lane is significantly lower than the mean speed of vehicles changing from middle lane to median lane (See Fig.6a). The mean speed of preceding vehicles on shoulder lane is also significantly lower than the mean speed of preceding vehicles on middle lane. The mean speed of leading vehicles on middle lane is also significantly lower than the mean speed of leading vehicles on median lane. This shows that generally it was possible for vehicles to obtain speed increase after lane-change. It can also be deduced that the speed of lane-changing vehicles is restrained by its preceding vehicles comparing the 95% confidence interval of the speed of lane-change vehicles and the speed of preceding vehicles.

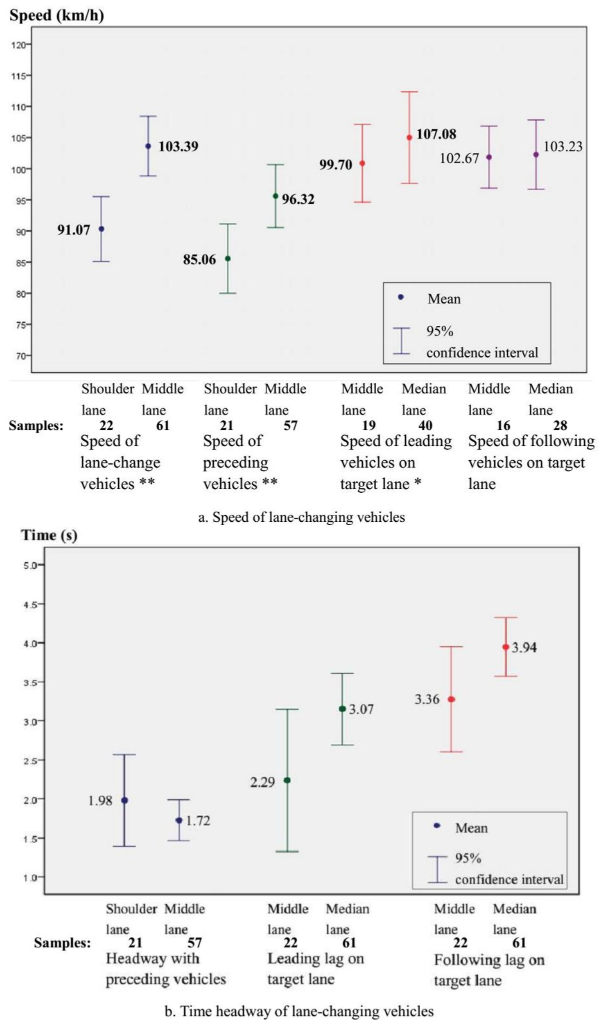


Fig.6 Observation of lane-changing behavior.

The average headway of lane-changing vehicle with its preceding vehicle is around 2 seconds. Average leading lag is around 3 seconds and average following lag was around 4 seconds (See Fig.6b). Average leading lag and following lag is slightly bigger for vehicles changing to median lane than for those changing to middle land. But no significance is shown in t-test. The lag value at the lower bound of the 95% confidence interval are used as initial value for minimum lags in lane-use model.

4. LANE-USE MODEL

The knowledge of observed spatial lane-use change at transition area is not enough for understanding the mechanism of this phenomenon. Theoretical lane-use model in which traffic flow and driving behavior are modeled can provide analytical understanding of the mechanism of lane-use behavior and its changing with growing distance.

A simplified model is proposed to capture the nature of lane-use behavior in this paper. The model is expected to be compact, so that it can be operated efficiently and adapted easily to other traffic simulation platforms.

Lane-use behavior is reproduced by two models: car-following model and lane-changing model. Car-following model is presented in (1) and lane-changing model is presented in (2).

(1) Car-following model

A simplified car-following model is adopted in this model based on the idea of Newell's car-following mode (11). Vehicles are considered accelerating from their current speed to their desired speed as long as the preceding vehicles are far enough away. Key headway is the threshold headway between vehicle and its preceding vehicle under which vehicle no longer traveled freely but had to following the trajectory of its preceding vehicle. The time displacement by which the speed change of vehicles displaced with that of preceding vehicles in Newell's original car-following model is subtracted in this model for simplicity. Acceleration rate is assumed to be constant for every vehicle.

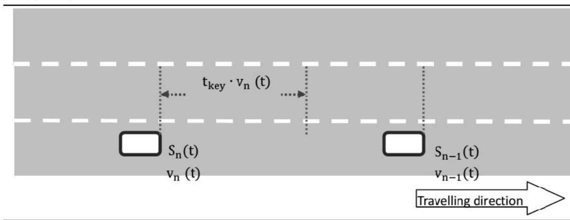
Table 1 Expression of car-following model.

Expression		
States: Travel freely	$S_{n-1}(t) - S_n(t) > t_{key} \cdot v_n(t)$ or $v_n(t) < v_{n-1}(t)$	(1)
Desired speed	$v_n(t) < v_{n\ des}(t)$	(2)
Follow preceding vehicle	$S_{n-1}(t) - S_n(t) \le t_{key} \cdot v_n(t)$ and $v_n(t) \ge v_{n-1}(t)$	(3)
Accelerate when travel freely	$v_n(t+\Delta t) = v_n(t) + a \cdot \Delta t$	(4)
Synchronize with preceding vehicle	$v_n(t+\Delta t) = v_{n-1}(t)$	(5)

Where,

$S_{n-1}(t)$ — Position of n-1*th* (Preceding vehicle) vehicle at time t,
$S_n(t)$—Position of n*th* vehicle at time t,
t_{key} — Key headway,
$v_n(t)$ — Speed of n*th* vehicle at time t,
$v_{n\ des}(t)$ — Desired speed of n*th* vehicle at time t,
Δt — Time step,
$v_n(t+\Delta t)$ — Speed of n*th* vehicle at time $t+\Delta t$,
a — Acceleration rate of vehicle.

Illustration



Explanation of function	
States: Travel freely	(1) The spacing with preceding vehicle is bigger than the product of key headway and current speed of vehicle or the current speed of vehicle is smaller than its preceding vehicle. (2) Current vehicle speed is lower than its desired speed.
Follow leading vehicle	(3) The spacing with preceding vehicle is smaller than the product of key headway current speed of vehicle and the current speed of vehicle is bigger than or equal to its preceding vehicle.
Accelerate when travel freely	(4) Vehicle accelerates constantly at the next time step.
Synchronize with leading vehicle	(5) Vehicle speed change to the speed of preceding vehicle at the next time step.*

Gipps proposed a lane-changing decision model in which drivers decide whether to change lane based on 3 factors: possibility, necessity and desirability(12). The objective of lane-change is to attain the desired speed and in the correct lane to perform turning maneuvers. The logic of this model is widely used in microscopic traffic simulation models(8)(10).

According to Gipps's theory, drivers make the lane-changing decision based on the result of 3 question:

1) Is it possible to change lanes?
2) Is it necessary to change lanes?
3) Is it desirable to change lanes?

In the model proposed in this paper, the first question is presented as "Whether there are enough gaps at target lane so that lane-change can be performed safely ? (See function (8) and (9) in Table2) ". The second question is aimed at turning vehicles which should use the correct lane for its initial route choice. Such condition does not exist in this research for vehicles traveling in the basic freeway segment having no need for route choice and turning. The third question is presented as "Whether a speed restraint is perceived by the driver and whether higher travelling speed can be attained at target lane ? (See function (6) , (7) and (10) in Table2) ". The parameter t_con (Time duration for considering lane-change) is introduced to describe drivers' perceptual process of speed restraint.

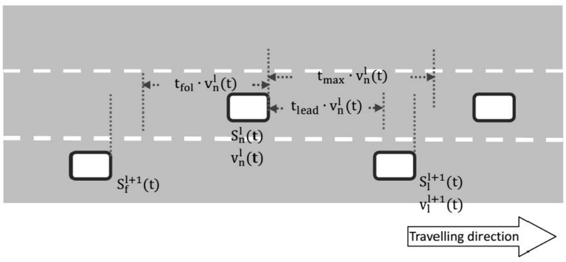
Table 2 Expression of lane-changing model.

Expression		
Lane-change incentive	$v_n^l(t) \le v_n^l(t - t_{con})$	(6)
	$v_n^l(t) < v_{n_{des}}^l(t)$	(7)
Lag choice	$S_n^l(t) - S_f^{l+1}(t) > t_{fol} \cdot v_n^l(t)$	(8)
	$S_l^{l+1}(t) - S_n^l(t) > t_{lead} \cdot v_n^l(t)$	(9)
	$S_l^{l+1}(t) - S_n^l(t) > t_{max} \cdot v_n^l(t)$ or $v_l^{l+1}(t) > v_n^l(t) \cdot c$	(10)
Lane-change	*l*=*l*+1	(11)
	$v_n^l(t + \Delta t) = v_n^l(t) + a \cdot \Delta t$	(12)
Constraints	*l*<2	(13)

Where,

$v_n^l(t)$ —Speed of n*th* vehicle on lane *l* at time t,
t_{con} — Time duration for considering lane-change,
$v_n^l(t - t_{con})$ —Speed of n*th* vehicle on lane *l* at time t_{con} before t,
$v_{n_{des}}^l(t)$ — Desired speed of n*th* vehicle on lane *l* at time t,
$S_n^l(t)$ — Position of n*th* vehicle on lane *l* at time t,
$S_f^{l+1}(t)$ — Position of following vehicle on lane *l+1* (target lane) at time t,
$S_l^{l+1}(t)$ — Position of leading vehicle on lane *l+1* (target lane) at time t,
t_{fol} — Minimum following lag,
t_{lead} —Minimum Leading lag,
t_{max} —Maximum leading lag,
$v_l^{l+1}(t)$ — Speed of leading vehicle on lane *l+1* (target lane) at time t,
c — constant value c>1,
l — Lane number, *l*=0: Shoulder lane; *l*=1: Middle lane; *l*=2: Median lane.

Illustration



Explanation	
Lane-change incentive	(6) The speed of lane-change vehicle is smaller than or equal to the speed it was before the consideration time. (7) The speed of lane-change vehicle is smaller than the desired speed at time t.
Lag choice	(8) The lag between the lane-change vehicle and the following vehicle on the target lane is bigger than the minimum following time lag for lane-change. (9) The lag between the lane-change vehicle and the leading vehicle on the target lane is bigger than the minimum leading time lag for lane-change. (10) The lag between the leading vehicle on the target lane and the lane-change vehicle is bigger than the maximum leading time lag for lane-change. Or the speed of the leading vehicle on the target lane is bigger than c times the lane-change vehicle.
Lane-change	(11) Lane-change vehicle change to the inner lane. (12) Lane-change vehicle accelerate after lane-change at the next time step.
Constraints	(13) Lane-change vehicle is not on the most inner lane (median lane) currently.

(3) Simulation and parameter calibration

A microscopic simulation model is built based on the theoretical models with Python and one of its package for scientific computing called NumPy(13). Vehicles enter the lanes at the start point randomly with time intervals following negative exponential distribution changing for every 30 minutes to reproduce the flow rate increase in observation. The mean flow rate is 2000 veh/h for the first 30 minutes, 2500 veh/h for the second 30 minutes and 3000veh/h for the third 30 minutes. The speed of vehicles follows normal distribution of N(84.83, 12.46) for shoulder lane and N(94.71, 12.03) for median lane, as same as the speed distribution obtained from observation (See 3.(1)). Desired speed is assumed to follow uniform distribution at given boundaries respectively for vehicles on shoulder land and median lane at the start point and remain constant with time and distance. Drivers are assumed to check their traveling state, make decision and perform action at every time step of 1s.

8 parameters affecting the model and their values are listed in Table3. The initial value are set according to observation data and practical experience. Minimum leading, following and maximum lags are assumed as constant value for every vehicles. Initial values of parameters affecting lane-changing behavior are assumed based on observed data shown in 3.2. One dimensional line search is used in searching for the optimal value of parameters. The descent direction along which the lane-use rate difference between observation and simulation at every location is found for every parameter. Lane-use rate difference is calculated for every unit step along the descent direction to obtain optimal value for every parameter.

Table 3 Parameters calibrated.

Parameter	**Remarks**	**Initial value**	**Calibrated value**
a	Acceleration	0.8 m/s^2 *	1.4 m/s^2
v_{des}	Desired speed	Shoulder: U(75, 110) Median: U(85, 110) **	Shoulder: U(75, 110) Median: U(85, 110) **
t_{key}	Key headway	2 s	2 s
t_{con}	Time duration for considering lane-change	3 s	1 s
t_{lead}	Minimum leading lag for lane-changing	1 s	1 s
t_{fol}	Minimum following lag for lane-changing	3 s	3 s
t_{max}	Maximum leading lag for lane-changing	4 s	4s
c	Constant ratio for speed of leading vehicle on target lane	1.05	1.03

*Note: * Minimum acceleration according to the 2004 Green book of AASHTO(14)*
*** Uniform distribution*

5. RESULTS

Traffic state from start point to more than 520m distance is simulated with the proposed model for 90 minutes with randomly input traffic demand increasing from 2000 veh/h to 3000 veh/h after calibration. First 15 minutes is regarded as warm-up time for vehicles entering the whole link. 5-minute aggregated flow rate is calculated for each lane. The traffic flow condition obtained from simulation is presented in Fig.7.

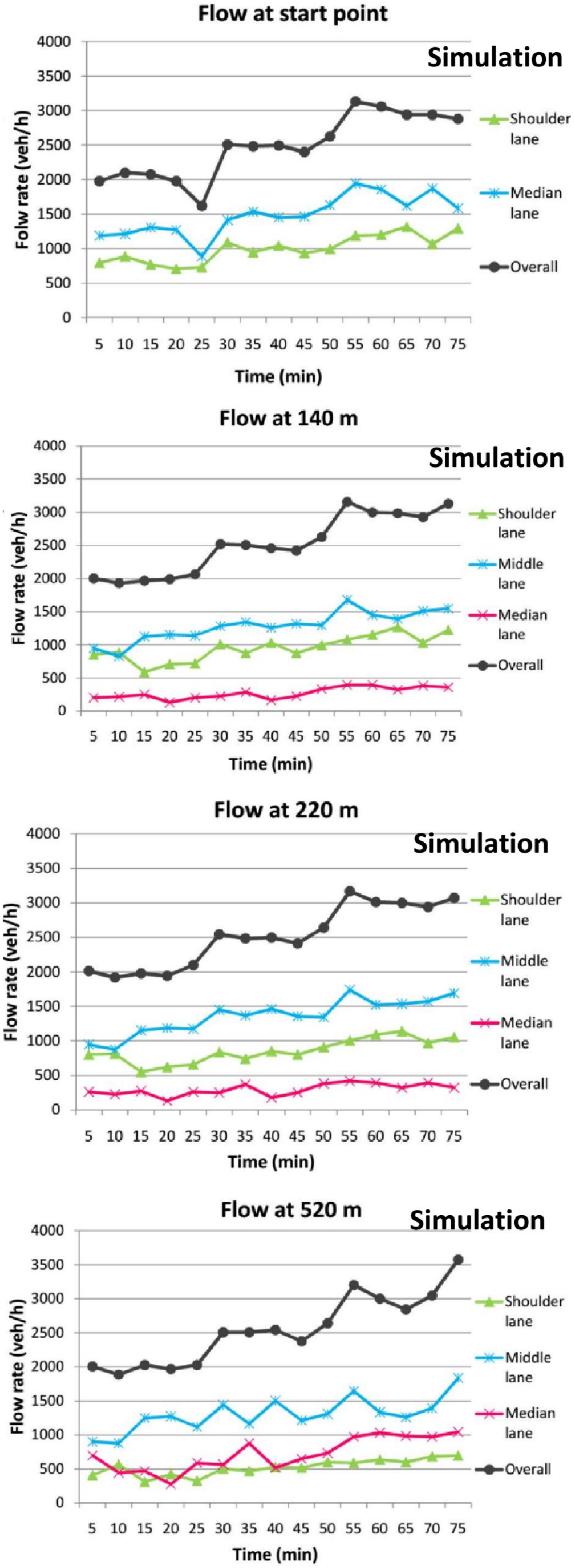


Fig.7 Flow rate in simulation.

Flow rate in simulation shows almost the same dynamic change as well as spatial change with that in field observation. Flow rate of median lane increases with the increase of both traffic demand and distance in simulation as well as in field observation. Median lane flow rates are about 2 times higher at 520m than at 140m in both simulation and observation. Median lane flow rates also exceeds shoulder lane flow rates at 520m both in both simulation and observation.

Middle lane flow rate decreases from the start point of transition area for 3-lane segment to 140m and changed little with the further increase of distance in both simulation and observation. Shoulder lane flow rate decreases rapidly from 220m to 520m in both simulation and observation. Vehicles in the shoulder lane tend to change lane to middle lane and intrigued lane-change towards median lane at the area between 220m and 520m can also be deduced from observation and simulation

Average lane-use rate at each observation location is calculated for three traffic flow level groups: traffic flow rate ranging from 2000veh/h to 2500veh/h; traffic demand ranging from 2500veh/h to 3000veh/h and traffic demand ranging from 3000veh/h to 3200veh/h. Average lane-use rate is calculated for both observation and simulation (See Fig.8).

The tendency of average lane-use change with growing distance on each lane in simulation is the same as that in the observation. Shoulder lane use rate drops faster with growing distance in simulation than in observation. On the other hand, middle lane use rate in simulation is more stable with distance than that in observation.

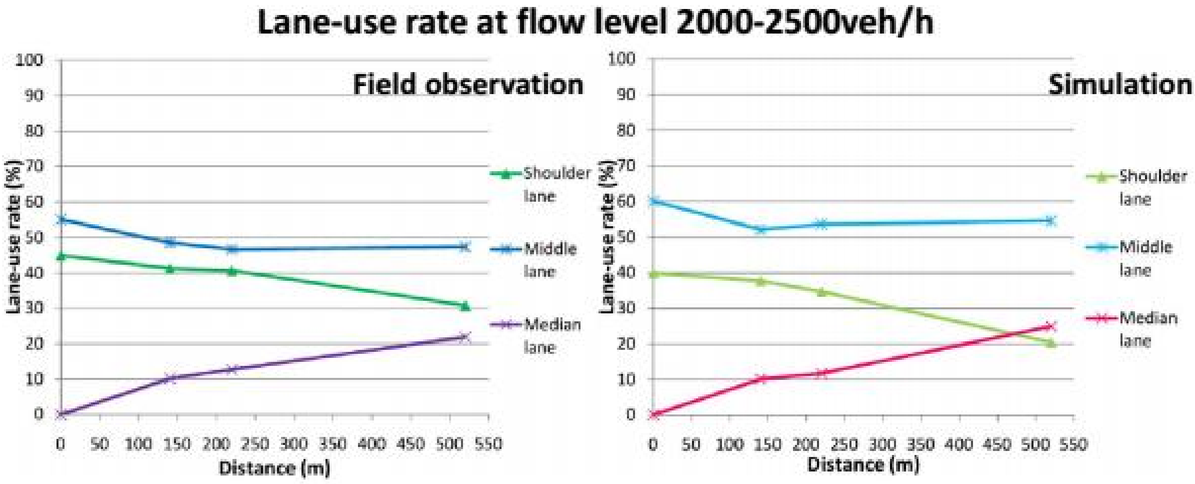
Goodness of fit is tested on lane-use rate in simulation result of a new set of random number with observation data using: Root Mean Square Normalized Error (RMSNE) and Mean Normalized Error (MNE). RMSNE quantifies the total percentage error of the simulation, while MNE indicates the general tendency of underestimation or overestimation happening in simulation.

$$\mathrm{RMSNE} = \sqrt{\frac{1}{N}\sum_{n=1}^{N}\left(\frac{m_n^{sim}-m_n^{obs}}{m_n^{obs}}\right)^2} \quad (14)$$

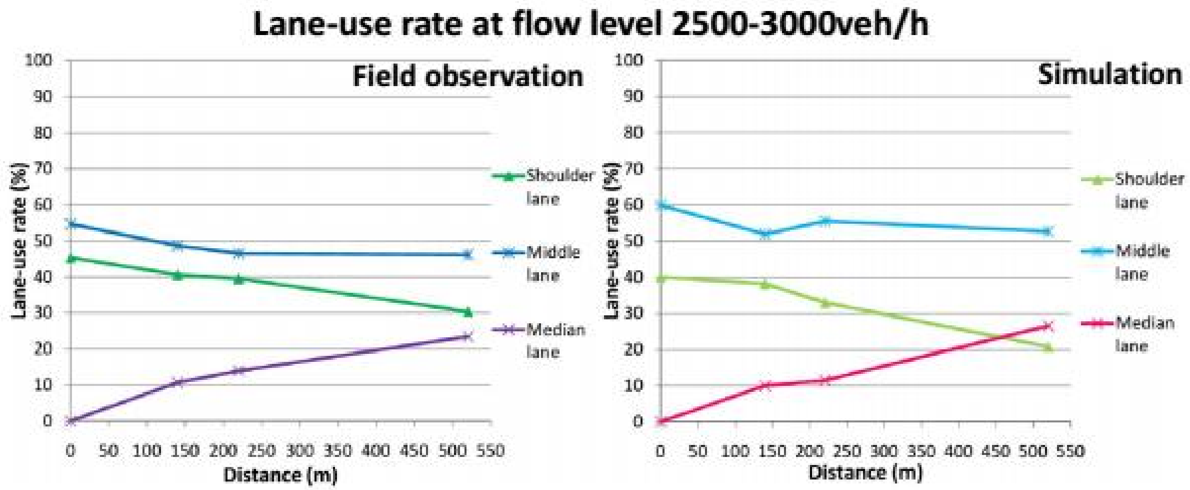
$$\mathrm{MNE} = \frac{1}{N}\sum_{n=1}^{N}\frac{m_n^{sim}-m_n^{obs}}{m_n^{obs}} \quad (15)$$

The RMSNE is 14.09% and MNE is -1.84%. This meant that the simulation results reproduced the actual lane-use change with good validity.

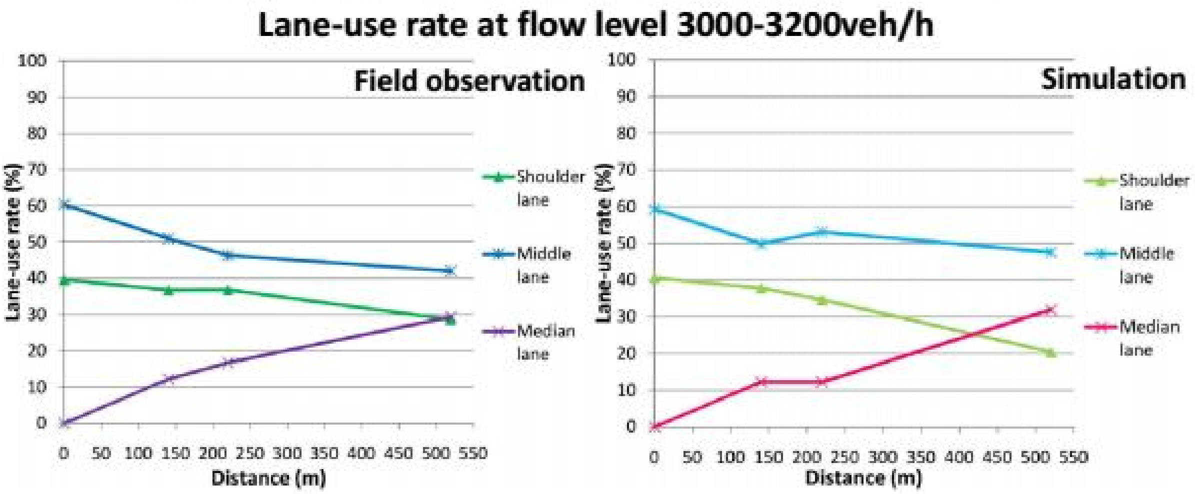
The length of additional lane has a close relationship with the location where lane-use on each lane rate become stable. The average lane-use rate at locations beyond 520 meters can be extrapolated by extending the simulation distance (See Fig.9).



a. Average lane-use rate at the flow level of 2000~2500 veh/h in simulation

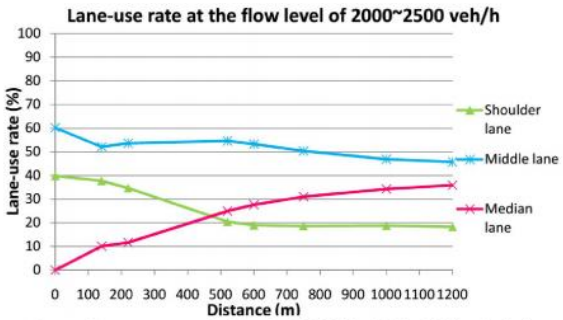


b. Average lane-use rate at the flow level of 2500~3000 veh/h in simulation

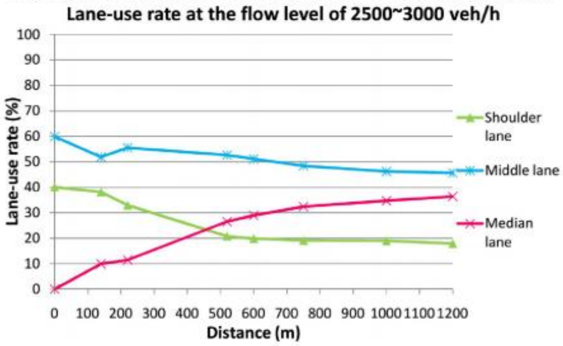


c. Average lane-use rate at the flow level of 3000~3200 veh/h in simulation

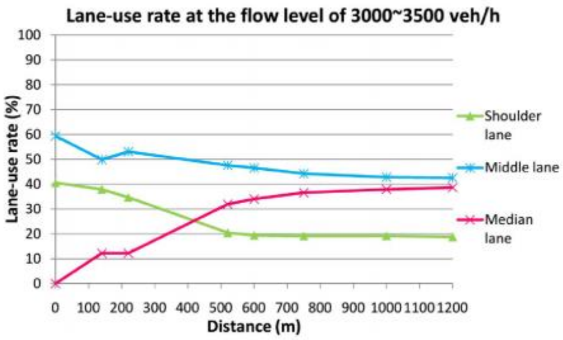
Fig.8 Average lane-use rate for groups of traffic demand.



a. Average lane-use rate at the flow level of 2000~2500 veh/h in simulation



b. Average lane-use rate at the flow level of 2500~3000 veh/h in simulation



c. Average lane-use rate at the flow level of 3000~3500 veh/h in simulation

Fig.9 Average lane-use rate for groups of traffic demand in simulation..

Shoulder lane use rate drops to 20% at 600m and almost stable after 600m for every traffic demand group. Lane-use rate on middle lane and median lane become stable at around 1000m. These phenomena are more obvious when traffic demand exceeded 3000veh/h, where the lane-use rate on middle lane and median lane change no more after 1000m. The same tendency can also be observed at the flow level of 2000-2500 veh/h and 2500-3000 veh/h.

The stable flow rate values derived from this simulation results at around 1000m such as around 45%, 36%, 19% for middle, median and shoulder lane use rates respectively at the flow level of 2000-2500 veh/h shown good consistency with the empirically knowledge of lane-use rate demonstrated in FIGURE 1. The simulation results such as around 43%, 38%, 19% for middle, median, and shoulder lane use rates respectively at the flow level of 2500-3000 veh/h, and around 41%, 39%, 20% at the flow level of 3000-3200 veh/h also shown good consistency with the lane-use rates demonstrated in Fig.1.

6. DISCUSSION AND CONCLUSIONS

The lane-use at basic freeway segment with an additional lane changes temporally as well as spatially. On the other hand, conventional microscopic simulation models emphasize on the dynamic features rather than the spatial features of traffic performance.

In this paper, the transition area of 2-lane basic freeway segment with a new additional lane where vehicles disperse to the new additional lane is focused and observation with empirical analysis is conducted. A model to describe spatial change of lane-use is proposed theoretically based on the empirical findings. It is proved to be capable of reproducing the temporal and spatial lane-use changes after the parameter calibration. The lane-use rates become equilibrium state at around 1000m from the start point of 3-lane segment in the simulation results.

Only free-flow condition at the overall flow rate of 2000-3200veh/h is studied in this research. The developed simulation model could also estimate the extrapolated cases at lighter or heavier traffic flow rate to obtain the extreme value of the lane use rates. Sensitivity analysis of each parameter will be conducted in further study to show the precise mechanism of any observed phenomena. Basic model establishment for describing lane-use rate at basic segments, the model enhancement to be applicable for merging section, diverging section, weaving section, uphill section, and so forth would also be the future works.

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