European Transport \ Trasporti Europei (2014) Issue 56, Paper n° 6, ISSN 1825-3997

Lane Flow Distribution ofaLong Continuous Highway

Chongzi Xiao, Chunfu Shao†, Meng Meng, Pinxi Wang, Bobin Wang

MOE Key Laboratory for Urban Transportation Complex Systems Theory and Technology,Beijing Jiaotong University, Beijing100044, China

Abstract

The promotion of short sea shipping (SSS) aims at providing a more sustainable mode of freight The datasfrom 13 detectors located on the West Side Highwaywith two lanes in each directionare used, and the smooth curves of the difference between the volume ratio of the median lane and the shoulder lane is applied to analyze the influenced lane flow distribution (LFD) in this paper. It is found that LFD can be deeply influenced by highway geometric characteristics, and Long Straight Segment of highway can lead to a high ultilization of the median lane.It also finds that high on-ramp volume can increase the ultilization of the shoulder lane downstream and make high speed vehicles upstream in the shoulder lane choose to slow down to pass the merging area instead of changing lane to pass.The field data used in the paper also reveals that vehicles sometimes prefer to use a specific lane at night and lead to an empty lane adjacent, which is caused by speed perturbation and dark night and can last for hours or even all night.In addition, data of daytime and nighttime arecompared, and finds that there is no difference of LFD of two or three lanes highway.

Keywords: lane flow distribution;geometric characteristics; on-ramp volume; nighttime

1. Introduction

Lane flow distribution (LFD) (sometimes named as traffic split, lane distribution, traffic distribution or lane ultilization) is a result of lane choice behavior of drivers, and varies widely in multilane highway, and dependslargely on traffic regulations, traffic composition, speed and volume, the number and location of access points, the origin-destination patterns of drivers, the development environment, and local driver habitsas mentioned in *Highway Capacity Manual*(2010).

†Corresponding author.Tel:+86 105168 2236;fax:+86 105168 2236
E-mail address:bjtu_cfshao@163.com

Different lanes in the same direction were identified as having identical characteristics in many previous studies. Kinematic-wave (K-W) model (Lighthill and Whitham, 1955a;Lighthill and Whitham, 1955b;Richards, 1956) is a traffic flow model like this. Although some basic traffic features can be reproduced by the model, some evidences still showed that lane-specific features should be attributed to capacity drop phenomenon (Daganzo, 2002a, 2002b;Patire and Cassidy, 2011). On this basis, Daganzo (2002a, 2002b) proposed a new traffic behavior theory which assumes two types of divers, namely 'rabbits' and 'slugs', where 'rabbits' prefer to the median lane and 'slugs' prefer to the shoulder lane according to their desired speed. Daganzo's behavior theory is a result of lane choice behavior, which can be validated by LFD data. Despite the reasonable descriptionof Daganzo's theory for dynamic traffic flow, some observations were reported inconsistent with the prediction of the theory(Banks and Amin, 2003;Chung and Cassidy, 2004).

Abovementioned models indicate that driving behaviorsof vehicles in different lanes are practical significance of explaining some traffic phenomenon, and LFD may be a key solution for some complicated dynamic traffic flow phenomenons. Otherwise, LFD can also used to solve some practical problems.Golias and Tsamboulas (1995) proposed and calibrated the LFD models based on collected data of Greece, and a tool for traffic management was developed to scheme pavement maintenance based on the LFD models. Smith et al.(2002) found a consistent lane flow distribution pattern and a methodology based on the pattern was used to estimate missing detector data, which achieved a low error.

There are numerous notable studies on LFD over the last decades, such as the influence of trucks, on-ramp, and culture/regulation difference. There are few investigators put their attention for LFD of trucks. One of the earliest researches had been done by Hollis and Evans (1976) and Turner (1983). Fwa and Li (1995) presented a project to study on the LFD characteristics of truck traffic, and a statistical regression model was established. In their study, the effects of four factors which influence LFD of trucks were presented, namely the functional class of the road, the number of traffic lanes, the total directional traffic volume, and the volume of truck traffic. Recently, Hong and Oguchi(2008) took the influence of trucks into consideration in their work, and Lee and Park (2010) noticed that LFDwas much affected by truck volume. Duret et al.(2012) analyzed LFD with/without driving ban for trucks (DBTs), and found that DBTs had an distinct effect on LFD. Yousif et al.(2012) used individual vehicle's raw data to develop a LFD model for trucks.

For the influence of on-ramp segment, previous articles seem to go to conflicting results. Knoop et al.(2010) found that an on-ramp can can change LFD, namely reducing the use of outside (right) lane, while Amin and Banks (2005) claimed that on-ramp volume was not a major influence on LFD, which is contrary to their expectations. Despite their efforts on this subject, there is still not a clear answer to the influence of on-ramp volume on LFD.

Drivers' behavior is much affected by the culture differences among countries(Özkan et ak,, 2006). Wu (2006) studied two and three lane highway in one direction, and found that LFD was significant difference between Germany and North America. Where the average capacity of highways in North America was higher than that in Germany, this was ascribed to the difference in LFD.

But more than for these, a number of other researches were done and some characteristics of LFD were found. Based on the field data of five extended freeway segments in San Diego, Amin and Banks (2005)noticed that the volume of the midian lane was always greater than that of other lanes under congested and high-volume uncongested condition.Besides, Banks(2006)analyzed the effect of LFD on freeway bottleneck capacity. Xiao and Jia (2005) used microsimulation method to study LFD and found some non-linear LFD trends, which is inconsistent with the statement of Duret et al. 2012) and the field data of Moriyama et al. (2011).Patire and Cassidy(2011) noticed that the shoulder lane with relatively low volume can acts as a 'release valve'for the high vehicular accumulations. Some researchers (Lee and Park, 2010;Knoop et al., 2010;Lee and Park, 2012) expressed LFD as a function of density instead of volume to overcome the drawback that one traffic volume always corresponds to two traffic states. This method is questionable, however, for the indirectly measured density (Yousif et al., 2012).

Previous work of LFD is exciting and worthy of attention for its theory and practical applications. Despite some observed LFD features, many general features are still unrevealed.It is remarkble that most of the studies focused on someisolateddetectors, but the studies of a long continuous higway is rare. It is found that LFD can be significantly different from site to site on highway.

This paper is organized as follows: the following section is about study sites and field data, where the description of the analytical method is included. In Section 3, the effects of geometric characteristics on LFD are analyzed, which follows a brief description of the effect of on-ramp volume on LFD. In Section 5, an abnormal phenomenon occuring at night is discovered, and data from daytime and nighttime are compared. Finally, conclusions and comments are provided in Section 6.

2. Experiment highway and method

2.1. Sites and data

Distinguishable from most previous studies, a long continuous highway with two lanes in each direction is used. The highway, namely the West Side Highway, connects Woodland and Sacramento, where 13 detectors are located on the south side. All the data aredownloaded from UC Berkeley PeMS website. 100% observed data which does not contain any estimated flow or occupancy datais used. Taking 5 minutes as the counting interval, flow and occupancy are directly measured, while speed is an estimated parameter. In the study area, congested data is notfound, and the total volume is under 250 veh/5min, namely 1500 veh/h/ln. It is remarkable that the highway can be divided into three classes according to its geometric characteristics: (1) Long Straight Segment, like the segment between the detector station VDS 318698 and 317373, and the segment between detector stations VDS 317284 and 317199, where both of them have a length more than 3 km and the highway nonlinear factors are close or equal to 1; (2) Frequent Turning Segment, namely the segment between detector station VDS 317389 and 317474, or its extended part from detector station VDS 317474 to its northwest area, where highway nonlinear fator is obviously bigger than 1, and curves largely exist; (3) Transition Segment with unconspicuous curve between two Long Straight Segments, like the segment between detector stations VDS 317373 and 317284, and the segment between detector station VDS 317199 and 317843.

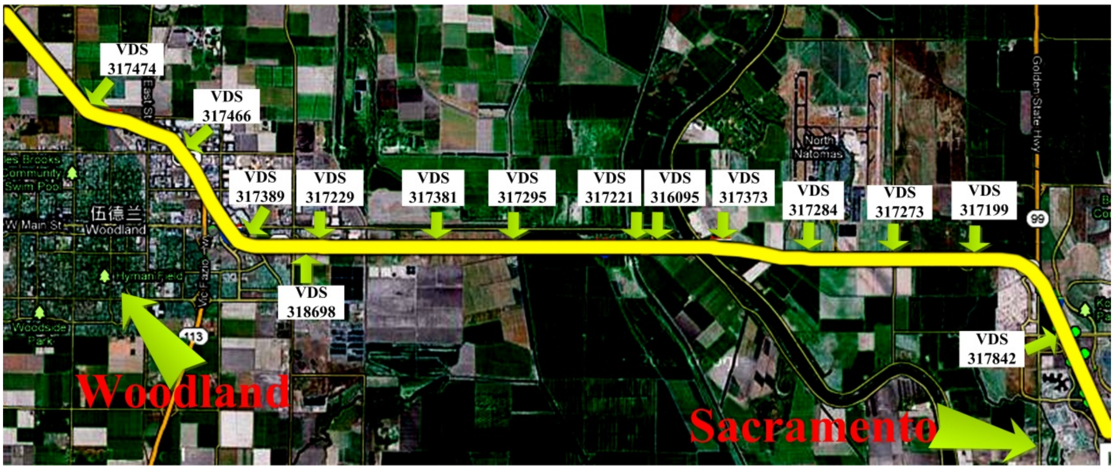

Fig. 1. Sites of the detectors located on the West Side Highway between Woodland and Sacramento[1]

One goal of the study is to reveal some general features of LFD, and to analyze the effects of geometric characteristics,on-ramp volume, and nighttime on LFD. Because the study sites are located on the same highway and the data can be collected synchronously, it is evidence enough that traffic regulations, traffic composition, the development environment, and local driver habitsof these sites are about the same. For these, it is easy to trick people coming to an inference that significant difference of LFD of all these sites will not occur. Field data shown in Fig. 2, however, are inconsistent with the assumption for LFD can remarkably change from site to site. One reason for this may be the influence of on-ramp volume, but a remarkable difference of some sites far from on-ramp or off-ramp still appear, as the field data from detector stations VDS 317295 and 317199. Another reason needed to be comfirmed may be the difference of the geometric characteristics of the highway from site to site, which will be analyzed in the following section.

[1] The map is from UC Berkeley PeMS website, and the data of the 14 detectors used in the paper ranges from 3/8/2012 0:00 to 3/11/2012 24:00, for all sites were 100% observed during this period.

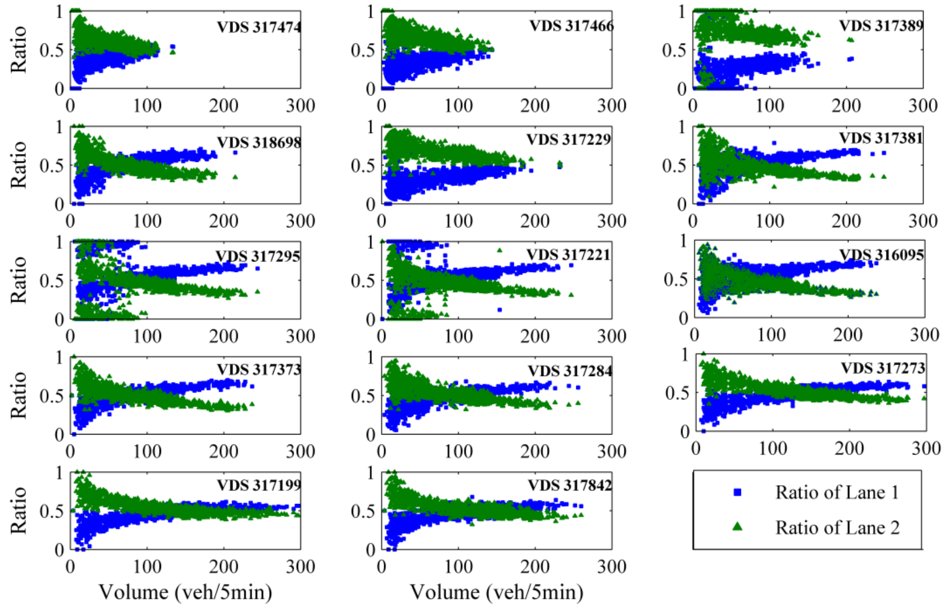

Fig. 2. LFD of West Side Highway from site to site (Lane 1 referes to the median lane and Lane 2 is the outside lane for the two lanes road)

2.2. Method

Although the difference of LFD is largefrom site to site, it is still necessary to find a quantitative analysis method to give a comprehensive and accurate description of the difference. Most of the previous works faulted to establish method to compare the difference of LFD from one site to another. Duret et al.(2012) used crossing points (ponits where the volume ratios of different lanes cross) to analyze the change of LFD under different condition. However, the crossing point can only reflect local change of LFD. Herein, the difference value of the ratios of Lane 1 and Lane 2, namely the value of the volume percentage of Lane 1 minus that of Lane 2, is used to analyze LFD. For two lanes highways, curves of LFD are centered exactly on the line where the percentage of volume for each lane is 0.5. LFD can be expressed as below:

$$\begin{cases} p_1 = f(q) \\ p_2 = 1 - f(q) \end{cases} \tag{1}$$

where q is the total volume of the highway; p_1, namely $f(q)$, is the volume ratio of Lane 1; p_2 is that of Lane 2. It is easy to find that Δp, the difference of p_1 and p_2, can be expressed as:

$$\Delta p = p_1 - p_2 = 2f(q) - 1 \tag{2}$$

From Eqs. (1) and (2), it can be confirmed that the characteristic of LFD can be reflected byΔp. Using Δp has an advantage of comparing data of different sites for it is a single line function. Fig. 3 provides a framework of data processing. The raw data of $\Delta p$is always too scattering to analyze, so it is necessary to choose the mean value of Δp to analyze/compare the chacteristic of LFD from site to site. However, the mean value of Δp is still a little scattering as shown in Fig. 3(c). In this paper, FFT (Fast Fourier Transform)filter smoothing method is used to smooth the scattering data. After the smoothing processing, scattering points can be replaced by a curve with same properties as shown in Fig. 3(c).

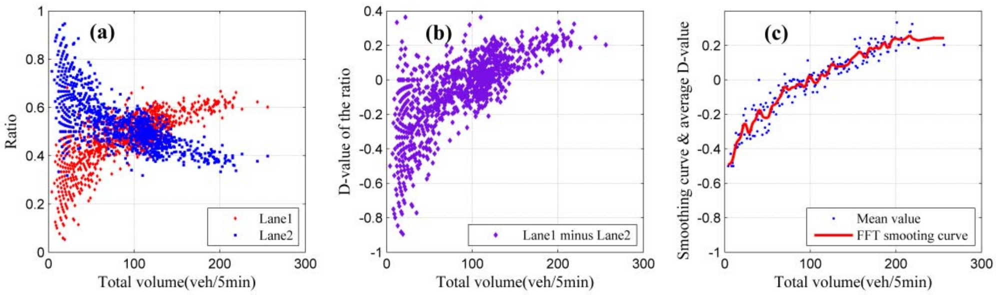

Fig. 3. FFT filter smooth curve of LFD: (a) is the diagram of LFD of the detector station VDS 317284; (b) is the diagram of the difference of Lane 1 and Lane 2; (c) is the diagram of the mean value of the data in Fig. 3(b), which contains a smooth curve as a result of FFT filter method.

3. Effects of geometric characteristics

3.1 Long straight segment

Contrary to our expectations, LFD changes remarkably from site to site according to data shown in Fig. 2. As abovementioned, the highway studied in this paper can be divided into three classes, namely Long Straight Segment, Frequent Turning Segment, and Transition Segment. For Long Straight Segment, there are several located detector stations (VDS 317698, 317229, 317381, 317295, 317221, 316095, 317273, and 317199). Although detector station VDS 317229 is located on the Long Straight Segment, LFD of this site shows a different feature (see Figs. 2 and 5), and this may be caused by on-ramp volume which will be discussed in Scetion 4.It is notable thatΔp becomes bigger and bigger with respect to the increasing total traffic volume. However, this phenomenon does not occur at other sites.Herein, this phenomenon is named as *scissors phenomenon* for its scissors liked shape.

Observation 1: scissors phenomenon
Definition:Δpincreasesremarkablywith respect to q while $\Delta p>0$ for Long Straight Segments.

LFD of Long Straight Segments is clearly different from that of others. The difference of volume ratio in the median and shoulder lane increases and most of the vehicles choose to use the median lane. From Fig. 4, it is clear that LFD of different sites are almost the same while total volume is over 80 veh/5min. Although the *scissors phenomenon* is abnormal, it can be interpreted. For Long Straight Segment, drivers have a good view of highway condition and can drive more easier for no turning movements needed. Trucks and slow vehicles usually choose the shoulder lane, and fast vehicles prefer to the median lane. Estimated speed from PeMS website reveals that the speed differences of the two lanes of Long Straight Segments are not obvious, and speed of the median lane is usually a little bigger than that of the shoulder lane, which also applys to that of most sites of Frequent Turning Segment or Transition Segment. That is to say, fast vehicles also largely exist in the shoulder lane. For Long Straight Segments, divers in the fast lane, namely the median lane, need only to maintain the fast speed. However, fast divers in the slow lane, namely the shoulder lane, need to turn to the median lane to avoid slow vehicles or trucks sometimes. And after that, there is no need for the fast vehicles to move back to the shoulder lane. In this case, a large number of fast vehicles in the shoulder lane turn to the median lane, and almost no fast vehicles prefer to turn back to the shoulder lane.This leads to a result of *scissor phenomenon*.In fact, this kind of phenomenon is also observed at other sites loccated on different Long Straight Segments, like detector stations VDS 403524 and 1009210.

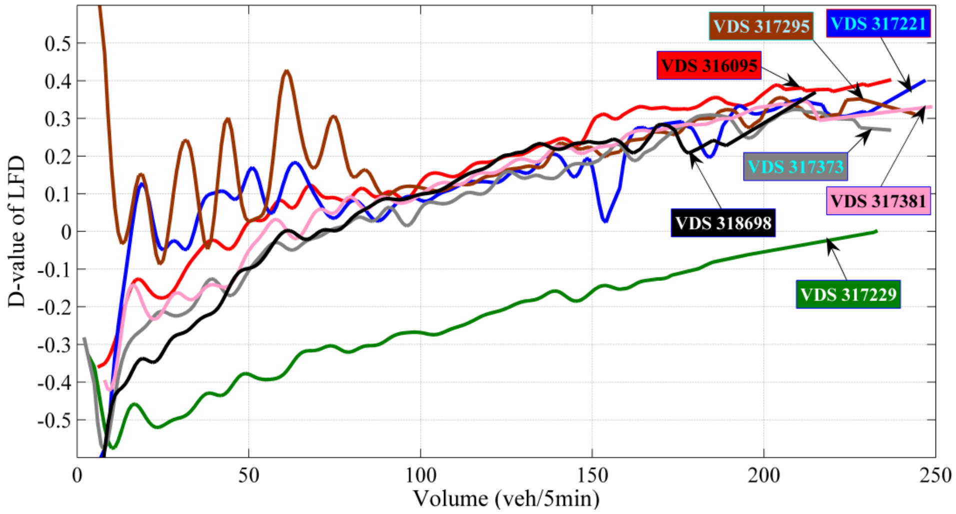

Fig. 4.Δp of Long Straight Segment

3.2 Frequent turning Segment&Transition Segment

For Frequent Turning Segment (detector stations VDS317474, 317466, and 317389), linear trends of LFD are found, and Δpcomes to zero with the increasing total volume. As shown in Fig. 5,$\Delta p$of each site are more like parallel lines while total volume is over 30 veh/5min. When total volume is 150veh/5min, a jump of the line of Δp of detector station VDS 317389is observed, this is because the LFD data with total volume over 150 veh/5min is scarce, which forced the smooth curve to behave abnormal, as shown in Fig. 4 and Fig. 2 (VDS 317389).Although lines of Δpshow different properties, similarity of LFD of these sites is distinct, namely the parallel lines characteristic. This kind of phenomenon is named as *translational transform phenomenon* for LFD of a specific site can be determined by a parallel moving of LFD lines of other sites.

Observation 2: translational transform phenomenon
Definition:Δptrends to zero with respect to increasing total volume, and lines of $\Delta p$are parallel of different sites for Frequent Turning Segment.

According to Fig. 5, it is evident enough that linear trends can be used to describe LFD of these sites.Suppose that the slope ofΔp of all these sites are same. After removing some unduly scattering datas (this is a necessary step which will be analyzed in Scetion 5) and the fitting process, the formulas of LFD of these sites are obtained as belowaccording to Eq.(2):

$$\begin{cases} \text{VDS 317474}: \Delta p = p_1 - p_2 = 0.0032q - 0.358 & \Delta R^2 \approx 0 \\ \text{VDS 317466}: \Delta p = p_1 - p_2 = 0.0032q - 0.481 & \Delta R^2 = 0 \\ \text{VDS 317389}: \Delta p = p_1 - p_2 = 0.0032q - 0.696 & \Delta R^2 \approx 0 \end{cases} \tag{3}$$

where q is the total volume of a two lane highway, veh/5min; ΔR^2 is the difference between the best linear multiple correlation coefficient and the multiple correlation coefficient of Eq. (3).

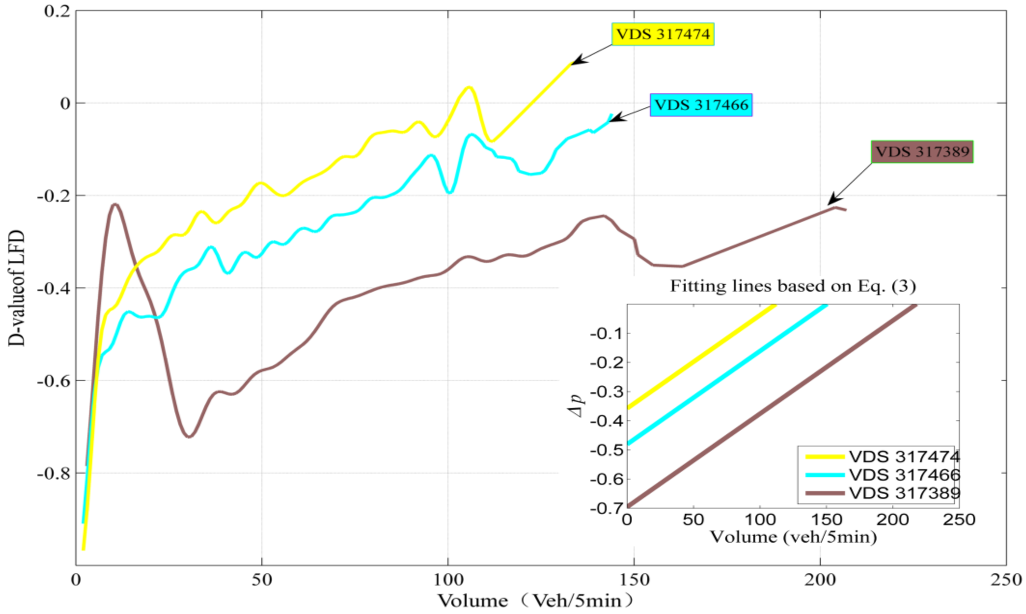

Fig. 5.Δ*p* of Frequent Turning Segment

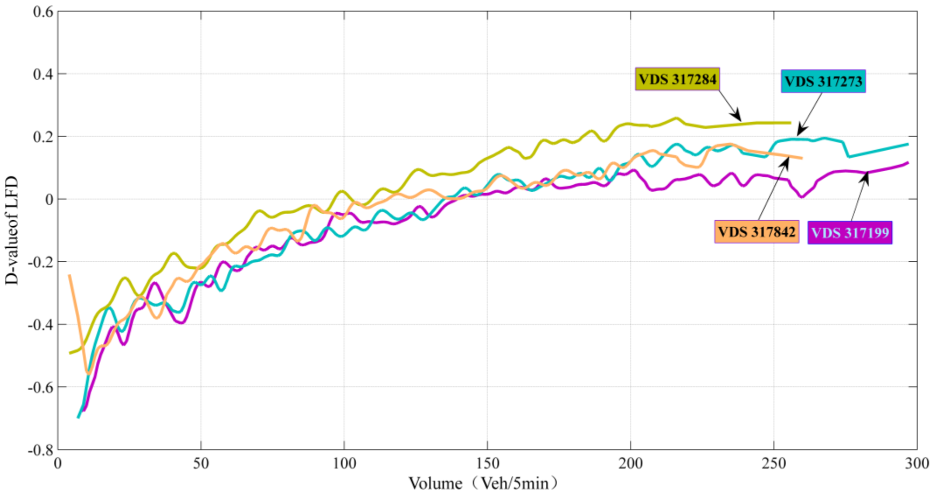

Fig. 6.Δ*p* of Transition Segments

For detector stations VDS 317284, 317273, 317 199, and 317842, another state of LFD is found (as shown in Fig. 6). Although detector stations VDS 317284, 317273, and 317199 are located on the Long Straight Segment, they are all near to Transition Segment, and field data shows an resultof transitionstatus, which is apparently different from that in Section 3.1. For these sites, Δ*p*becomes smaller and smaller from west location to east location, and finaly tends to 0. The most reasonable cause forthis should be attributed totheTransitionSegment between detector station VDS 317199 and 317842. The radian of the segment is very big, which can make more vehicles choose the lane with smaller curve radius, namely the shoulder lane. This kind of change is obvious in near area than that of far area, like detector stations VDS 317119 and 317842, where detector station VDS 317199 is closer to the transition area, (see Figs. 1 and 6).

4. Effects of on-ramp volume

It can be clearly claimed that there have effects of on-ramp volume on LFD, but it is still an uncertain question that how deeply the on-ramp volume affects LFD. One reasonable hypothesis is that on-ramp volume can decreases the ultilization of outside lane upstream, which has been comfirmed by experimental data(Amin and Banks, 2005). Most previous work focused on analyzing upstream area of on-ramp sections(Knoop et al., 2010;Amin and Banks, 2005). However, the research about downstream area is lacking.

Detector stations VDS 318698, 317229, and 317381 are all located on the long straight segment, while LFD of detector station VDS 317229 is totally different from that of both stattions VDS 318698 and 317381 (see Figs. 2 and 4). The main reason for this is the influnce of on-ramp volume, for other characteristics of these sites are almost the same. From Tab. 1, it can be derived that the volume of the on-ramp between the two stations is 10484 veh, which accounts for 11.7% of the total volume of detector staion VDS 317229.The two sites (stations VDS 318698 and 317229) are so close, about 0.32 km, and LFD state are so different, so it can be concluded that a relative high on-ramp volume can totally change the LFD state of downstream area nearby, namely increasing the use of outside lane. However, this kind of influence can not extend to sites far away from the on-ramp site. More accurately, the influence range is below 2.7 km (the distance between the on-ramp site and detector station VDS 317381) or far smaller than this, because LFD state of detector station VDS 317381 is totally normal (see Fig. 4).

For detector station VDS 318698, although on-ramp volume largely exists downstream, LFD seems not to be influenced (see Fig. 4), which is inconsistent with our expectation. However, estimated speed data from PeMS website can be used to explain this. From Fig. 8, it is clear that average speed of the shoulder lane of detector station VDS 318698 is far smaller than the median lane, but the differences of speedof othe sites between the two lanes are not significant.In most cases, LFD is directly related to lane choice behavior, and LFD always changes with large portion of vehicles changing from a specific lane to others.But for detector station VDS 318698, LFD is normal (see Fig. 4), this suggests that most vehicles in the shoulder lane do not choose to change to the median lane when they are passing the merging area. In fact, vehicles prefer to slow down to wait for passing the merging area, and Fig. 8 is a result of this. It is notable that the result is based on uncongested and high speed condition, while speed is far smaller than drivers' desired ones, and things may change. Herein, this kind of phenomenon was named as *slowing to pass*.

Observation 3: slowing to pass
Definition: vehicles in shoulder lanewith high speed in the upstream area of an on-ramp site prefer to slow down than change their lane to pass the merging area under uncongested condition.

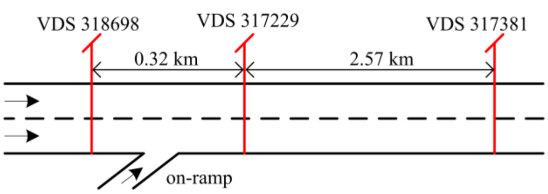

Fig. 7. Schematic diagram of on-ramp sections

Tab. 1. Total volume the detector stations

Detector station	318698	317229
Volume (veh)	79162	89646

Notes: data acquisition time began on 3/8/2012 0:00 and continued to 3/11/2012 24:00.

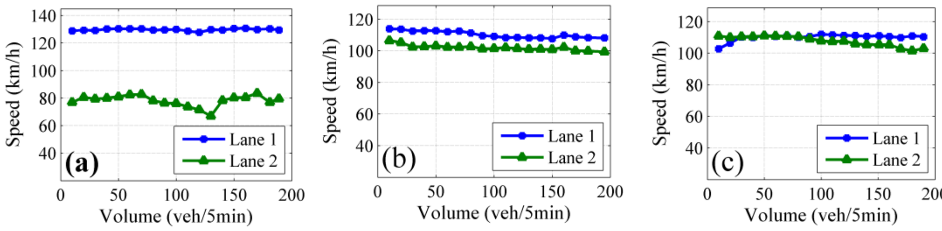

Fig. 8. Volume-speed diagram of each detector station:(a) is the diagram of detector station VDS 318698; (b) is the diagram ofdetector station VDS 317229; (c) is the diagram of detector station VDS 317381.

5. Effects of nighttime

5.1 A new phenomenon

Sometimes, the ratio of volume of a specific lane can go extremly high (usually equals to 1) while total volume is below 80 veh/5min, see Fig. 2 (detector stationsVDS 317389, VDS 317295, and VDS 317221), and this is the main reason that makes $\Delta p$of different sites located onLong Straight Segment be different from others under low volume condition, as shown in Fig. 4. Figs. 9, 10, and 11can provide a detail look at this phonomenon (data in the red boxes). From Table 1, it is shocked to find that the phenomenon always occurs at night, and can last for hours or all night. Sometimes, almost all vehicles changed their lane form Lane 1 to Lane 2 or from Lane 2 to Lane 1 at specific times, as shown in Figs. 10 and 11, and it is hard to say which lane do vehicles prefer to choose at night.When this phenomenon occurs, it seems like that all vehicles follows the vehicle in the same lane ahead.In this paper, the phenonmenon is named as *following at night*.

Observation 4: following at night
Definition: almost all vehicles choose to drive on a specific lane at night, which leads to an empty/unused lane adjacent.

The phenomenon can be explained by speed changing. From the Fig.9, it is clearly to find that the sudden change in LFD is always accompanied by a speed change, usually with a suddenly speed increasing or decreasing. Herein, speed is not directly observed for these stations, so estimated speed is used instead. Suppose that the average vehicle length is a constant, sothe constant value g can be used to convert occupancy to density, then the estimated speed can finally be calculated on the basis of fundamental speed, volume, density formulation(Wang and Nihan, 2000).Because the average vehicle length is an unknown parameter, $v{\cdot}g$ is used to repalce the speed.

$$v = \frac{q}{g \cdot o} \tag{4}$$

For normal condition, speed of lane 1 is always bigger than that of lane 2. However, a leap increase/decrease of the average speed of lane 1/lane 2 occurs for point A in Fig. 9, point B and C in Fig. 10, and point E in Fig. 11. After the leap increase/decrease, speed of lane 1 becomes smaller than that of lane 2, where the phenomenon of *following at night* occurs.It should notice that station VDS 317221 and 317295 are located on Long Straight Segment, while station VDS 317389 is located on Frequent Turning Segment.From Figs. 9, and 10, it seems that speed of lane 1 are more stable than that of lane 2 which change around the relatively stable speed of lane1, while the situation is opposite of station VDS 317389 located on Frequent Turning Segment. On this basis, it can go to a conclusion that traffic is more stable for lane 1 of Long Straight Segment and more stable for lane 2 of Frequent Turning Segment for two lane highway while total volume is below 80 veh/30 s at night.

The phenomenon of *following at night* is interesting, but the lack of more detailed data makes it difficult to explain. However, field data in the paper confirms that dark night is the fundamental condition, and speed perturbation acts as a trigger factor. Once a speed perturbation triggers the phenomenon, it can lasts for hours or even total night. When the speed perturbation is big enough, LFD can be totally reversed, like point C in Fig. 10 and point F in Fig. 11. This tell us that traffic perturbation can cause a specific traffic status which can propagate in timeeven under uncongested traffic condition (actually refers to the traffic while total volume is below 80 veh/5 min).

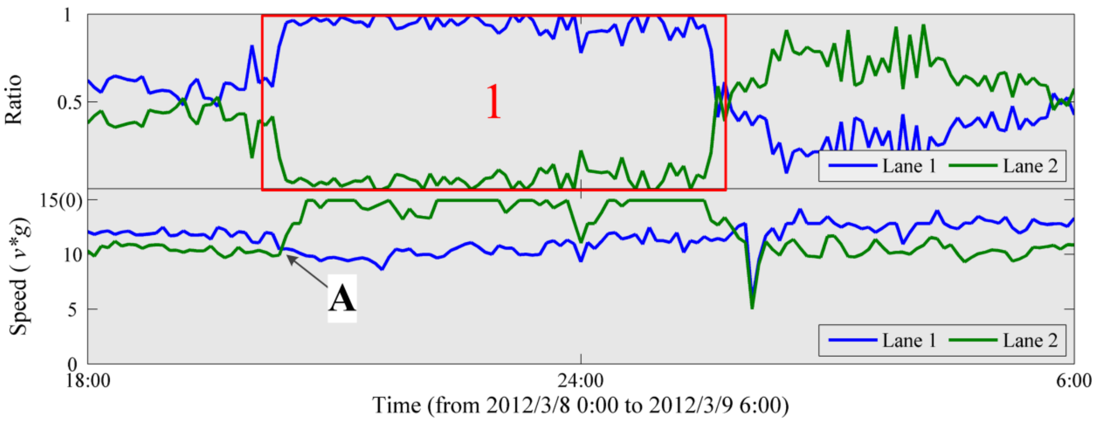

Fig. 9. LFD of the detector station VDS 317221

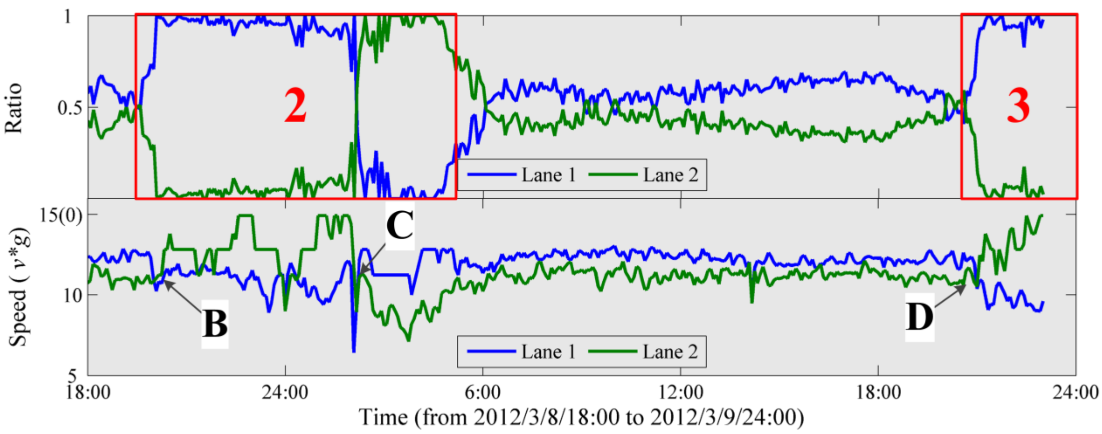

Fig. 10. LFD of the detector station VDS 317295

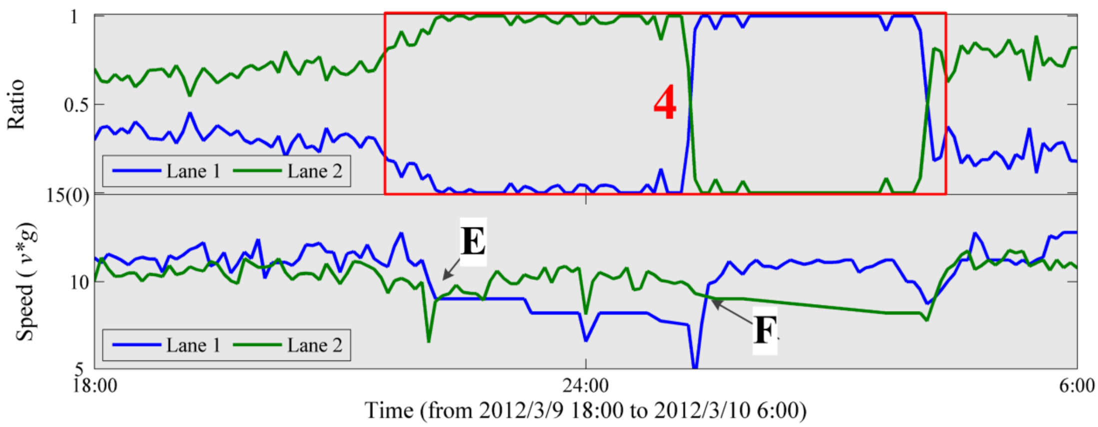

Fig. 11. LFD of the detector station VDS 317389

Tab.2. Sunrise and sunset in Sacramento[2]

Data	Civil Twilight		Sunrise	Sunset
	Starts	Ends		
8 Mar 2012	6:00	18:33	6:27	18:07
9 Mar 2012	5:59	18:34	6:25	18:08
10 Mar 2012	5:57	18:35	6:24	18:09
11 Mar 2012	6:56	19:36	7:22	19:10

Notes: hours shift because clocks change forward 1 hour (Daylight Saving Time started on Sunday, 11 March 2012, 02:00)

5.2 Comparision LFD data of daytime and nighttime

Back to 1990s, Okura and Somasundaraswaran (1996) studied the effect of light on LFD of a highway in Japan, and found that the ratio of volume in the shoulder lane and the middle lane decreased, while the ratio of volume in the median lane increased in nighttime. They attributed this kind of change to speed and heavy vehicles. However, the traffic regulation of Japan is different from that of U.S., for vehicles moves on the right in U.S. in this paper, the effect of daytime and nighttime on LFD was studied based on three highway sites. Two lanes, three lanes, and four lanes highway were choosed in the paper, and the data of five consecutive days wasseperated as daytime dataset and nighttime dataset for each site.

For two lane highway (see Fig. 12(b)), it can be found that the difference between daytime and nighttime is not significant. Difference only exists while total traffic volume is below 40 veh/5min or beyond 100 veh/5min, and the main reason for this may be the data lacking for high volume of nighttime and low volume in daytime, because only few datas like this were observed in the five days. This is also applied to the three lanes highway (see Fig. 12 (c)), and the difference may be caused by data lacking in daytimewhile total volume is below 100 veh/5min. Howeveer, the difference of LFD between daytime and nighttime is significant for the four lanes highway (see Fig. 12 (a)). The volume ratio of Lane 1 (namely the median lane) in nighttime is significant smaller than that in daytime while total volume is over 200 veh/5min, and more vehicles choose to

[2] The data is from www.timeanddate.com.

use Lane 2 and Lane 4 in nighttime.This finding is totally contrary tothe conclusion of Okura andSomasundaraswaran(1996).It is notable that the detector station VDS 810117 is located near an on-ramp site, and this may be a reason that makes the differences.Moreover, drivers have more options while driving on a four lanes highway than that of two or three lanes highway, and this leads to a more complicated and inconstant result.

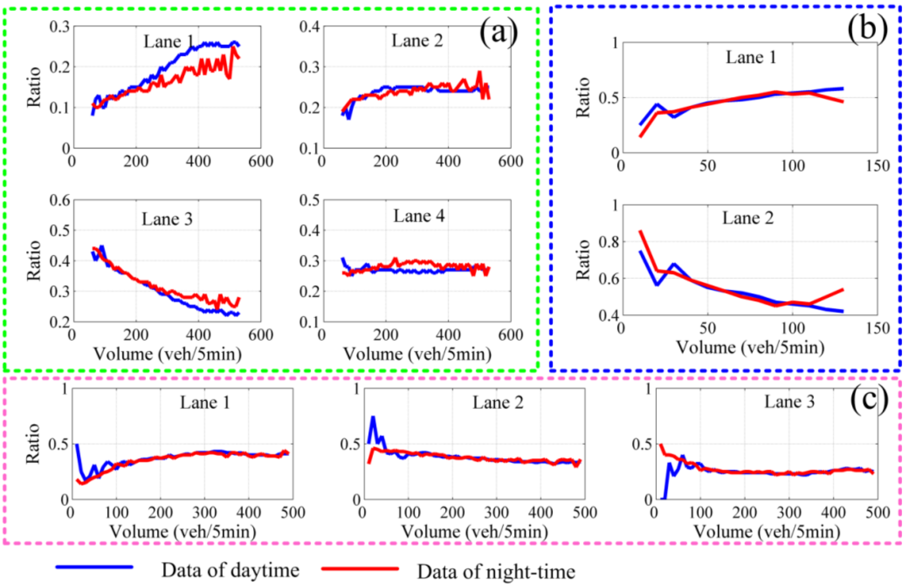

Fig. 12. LFD contrast between daytime and nighttime.((a): data is from a four lanes highway site, namely the detector station VDS 810117, 11 consecutive days, 30 seconds counting interval; (b): data is from a two lanes highway site, namely the detector station VDS 317295,5 consecutive days, 30 seconds counting interval; (c): data is from a three lanes highway site, namely the detector station VDS 316803, 5 consecutive days, 30 seconds counting interval).

6. Conclusion

LFD has its own theoretical and pratical applications, and related researches are worthy of attention. Although many scholars focused on it and have made some progresses, the research achievements are not sufficient and there are still huge gaps in our understanding of LFD. In this paper, a two lane highway segment with a total length more than23 km was analyzed as a whole. Some major findings are listed below:

1) LFD is deeply influenced by geometrical characteristics. For long straight segment, vehicles prefer to choose median lane (lane 1) andΔp becomes bigger and bigger with respect to total volume. For frequent turning segment, volume of shouder lane (lane 2) is always bigger than median lane under uncongested condition, and Δpfinally comes to zero with the increasing total volume. Although LFD of frequent turning segment can change from site to site, the slopes of $\Delta p$of different site are equal.
2) On-ramp volume can increase the ultilization of shoulder lane downstream distinctly, but it has very little impact on LFD upstream under uncongested condition. The analysis of Section 4 indicates that vehicles in the shoulder lane always choose to slow down to pass the on-ramp merging area instead of changing to the median lane, which is quite a shocker.

3) Sometimes, almost all vehicles choose to drive on a specific lane at night, while the lane adjacent is always unused. This long time lasted phenomenon can make LFD diagram be different from others, as shown in Figure 4. It is suggested that field data from night should be removed while compares/analyzes LFD of different sites, for these abnormal data can lead to an extremly high/low value of Δp.
4) A mass of data in Sectin 5 shows that LFD in daytime and nighttime are almost the same for two/three lanes highway. However, the difference is observed for a four lanes highway site. It reveals that the willingness of drivers to drive on the median lane is insufficient at night.

Anyway, LFD is such a changeful thing that little change of related factors can totally reconstruct it. In the process of analyzing LFD, it is extremely important to describe the external environment of the selected sites.

Acknowledgements

This work is supported by the National Basic Research Program of China (Grant No. 2012CB725403) and the Fundamental Research Funds for the Central Universities (Grant No. 2013YJS047).

References

[1] Manual, H. C. (2010). "Highway capacity manual." Washington, DC.

[2] Lighthill, M., and Whitham, G. (1955a). "On kinematic waves. I. Flood movement in long rivers." *Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences*, 229(1178), 281-316.

[3] Lighthill, M. J., and Whitham, G. B. (1955b). "On kinematic waves. II. A theory of traffic flow on long crowded roads." *Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences*, 229(1178), 317-345.

[4] Richards, P. I. (1956). "Shock waves on the highway." *Operations research*, 4(1), 42-51.

[5] Daganzo, C. F. (2002a). "A behavioral theory of multi-lane traffic flow. Part I: Long homogeneous freeway sections." *Transportation Research Part B: Methodological*, 36(2), 131-158.

[6] Daganzo, C. F. (2002b). "A behavioral theory of multi-lane traffic flow. Part II: Merges and the onset of congestion." *Transportation Research Part B: Methodological*, 36(2), 159-169.

[7] Patire, A. D., and Cassidy, M. J. (2011). "Lane changing patterns of bane and benefit: Observations of an uphill expressway." *Transportation Research Part B: Methodological*, 45(4), 656-666.

[8] Banks, J. H., and Amin, M. R. (2003). "Test of behavioral theory of multilane traffic flow: Queue and queue discharge flows." *Transportation Research Record: Journal of the Transportation Research Board*, 1852(-1), 159-166.

[9] Chung, K., and Cassidy, M. J. (2004). "Test of theory of driver behavior on homogeneous freeways." *Transportation Research Record: Journal of the Transportation Research Board*, 1883(-1), 14-20.

[10] Golias, J., and Tsamboulas, D. (1995). "Macrolevel Estimation of Highway Lane Usage." *Journal of Transportation Engineering*, 121(1), 40-49.

[11] Smith, B. L., and Conklin, J. H. (2002). "Use of local lane distribution patterns to estimate missing data values from traffic monitoring systems." *Transportation Research Record: Journal of the Transportation Research Board*, 1811(-1), 50-56.

[12] Hurley, J. (1997). "Utilization of Auxiliary Through Lanes at Signalized Intersections with

Downstream Lane Reductions." *Transportation Research Record: Journal of the Transportation Research Board*, 1572(-1), 167-173.

[13] Hurley, J. W. (1998). "Utilization of double left-turn lanes with downstream lane reductions." *Journal of Transportation Engineering*, 124(3), 235-239.

[14] Tarawneh, M. (2000). "Utilization of Auxiliary Through Lanes at Intersections of Four-Lane, Two-Way Roadways." *Transportation Research Record: Journal of the Transportation Research Board*, 1737(-1), 26-33.

[15] Lee, J.J., Rouphail, N. M., and Hummer, J. E. "Models for lane utilization prediction for lane drop intersections." National Research Council, 47-56.

[16] Moriyama, Y., Mitsuhashi, M., Hirai, S., and Oguchi, T. (2011). "The Effect on Lane Utilization and Traffic Capacity of Adding an Auxiliary Lane." *Procedia - Social and Behavioral Sciences*, 16(0), 37-47.

[17] Hollis, E., and Evans, R. (1976). "Motorway traffic patterns." Transport and Road Research Laboratory (TRRL), UK.

[18] Turner, D. (1983). "Traffic characteristics of a rural motorway." *Traffic Engineering and Control*, 24(5), 248-251.

[19] Fwa, T., and Li, S. (1995). "Estimation of Lane Distribution of Truck Traffic for Pavement Design." *Journal of Transportation Engineering*, 121(3), 241-248.

[20] Hong, S., and Oguchi, T. "Lane use and speed-flow relationship on basic segments of multilane motorways in Japan." *Proc., Transportation Research Board 87th Annual Meeting*.

[21] Lee, J., and Park, B. B. "Lane flow distributions on basic segments of freeways under different traffic conditions." *Proc., Transportation Research Board 89th Annual Meeting*.

[22] Duret, A., Ahn, S., and Buisson, C. (2012). "Lane flow distribution on a three-lane freeway: General features and the effects of traffic controls." *Transportation Research Part C: Emerging Technologies*, 24(0), 157-167.

[23] Yousif, S., Al-Obaedi, J., and Henson, R. (2012). "Drivers' Lane Utilization for UK Motorways." *Journal of Transportation Engineering*, 0(ja), null.

[24] Carlson, R. C., Papamichail, I., Papageorgiou, M., and Messmer, A. (2010). "Optimal mainstream traffic flow control of large-scale motorway networks." *Transportation Research Part C: Emerging Technologies*, 18(2), 193-212.

[25] Carlson, R. C., Papamichail, I., Papageorgiou, M., and Messmer, A. (2010). "Optimal motorway traffic flow control involving variable speed limits and ramp metering." *Transportation Science*, 44(2), 238-253.

[26] Knoop, V. L., Duret, A., Buisson, C., and van Arem, B. "Lane distribution of traffic near merging zones influence of variable speed limits." *Proc., Intelligent Transportation Systems (ITSC), 2010 13th International IEEE Conference on*, 485-490.

[27] Amin, M. R., and Banks, J. H. (2005). "Variation in freeway lane use patterns with volume, time of day, and location." *Transportation Research Record: Journal of the Transportation Research Board*, 1934(-1), 132-139.

[28] Özkan, T., Lajunen, T., Chliaoutakis, J. E., Parker, D., and Summala, H. (2006). "Cross-cultural differences in driving behaviours: A comparison of six countries." *Transportation Research Part F: Traffic Psychology and Behaviour*, 9(3), 227-242.

[29] Wu, N. (2006). "Equilibrium of Lane Flow Distribution on Motorways." *Transportation Research Record: Journal of the Transportation Research Board*, 1965(-1), 48-59.

[30] Banks, J. H. (2006). "Part 1: Traffic flow theory and characteristics: Effect of time gaps and lane flow distributions on freeway bottleneck capacity." *Transportation Research Record: Journal of the Transportation Research Board*, 1965(-1), 3-11.

[31] Wang, X. Y., and Liu, J. S. "Research of the lane utilization with microsimulation." *Proc., Machine Learning and Cybernetics, 2005. Proceedings of 2005 International Conference on*, 2681-2687 Vol. 2685.

[32] Lee, J., and Park, B. (2012). "Determining Lane Use Distributions Using Basic Freeway Segment Density Measures." *Journal of Transportation Engineering*, 138(2), 210-217.

[33] Wang, Y., and Nihan, N. L. (2000). "Freeway traffic speed estimation with single-loop outputs." *Transportation Research Record: Journal of the Transportation Research Board*, 1727(1), 120-126.

[34] Okura, I., and Somasundaraswaran, K. (1996). "Analysis of traffic distribution in three lane uni-directional freeway." *Journal of Infrastructure planning and Management*(13), 885-892.

Table Captions

Figure Captions