October 2019

Impact of the Number of Lane-Changing Times on Throughput by Fundamental Diagram Based on NGSIM Data

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Impact of the Number of Lane-Changing Times on Throughput by Fundamental Diagram

Based on NGSIM Data

by

Gangyan Zhang

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Civil Engineering
Department of Civil and Environmental Engineering
College of Engineering
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Date of Approval:
October 17, 2019

Keywords: freeway, frequency, speed, congestion, trajectory

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Acknowledgments

I want to express my gratitude to all those who helped me during the writing of this thesis. I acknowledge the help of Dr. Li, who offered me suggestions in academic studies. In the preparation of the thesis, he spent much time reading through drafts and providing me with advice. Without his patient, insightful, and expert guidance, the completion of this thesis would not be possible. I am also deeply indebted to my committee members Dr. Lin and Dr. Lu for their direct and indirect help. I am also pleased to acknowledge all in the CUTR lab for their invaluable assistance throughout the preparation of the original manuscript. They graciously made considerable comments and sound suggestions on the outline of this thesis.
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Abstract

In the present report, the characteristics of the fundamental diagram (FD) are exploited to delve into the effect of the number of times of lane changes on traffic throughput. The NGSIM data are classified and screened by splitting the regions of US-101 and I-80; the relevant traffic variables (e.g., traffic flow, density and speed) are calculated. Appropriate statistical approaches are employed to verify the correlation of the impact of lane changes on different traffic variables. Lane changes could affect traffic throughput in light congestion instead of in heavy congestion. The causes of the effects of lane changes on throughput are delved into.
Chapter 1: Introduction

Lane change behavior is common during the driving process. Existing studies have reported that lane changes cause traffic disturbances and affect the capacity of traffic. The rationality of driver lane-changing behavior will also affect the safety of traffic. Furthermore, aggressive driving behavior will increase lane-change frequency compared with routine driving behavior. This study aims to delve into the effect of lane changing on traffic speed.

Traffic congestion is a continual problem around the world. Much of the existing literature on lane-changing problems discusses how it can lead to traffic jams or oscillation. However, there are few studies on the effect of lane changes on traffic in a congestion state. This thesis delves into the data for two freeways, US-101 and I-80, collected using NGSIM (next generation simulation). The Fundamental Diagram (FD) acts as the primary method to develop a relationship between lane changes and traffic throughput. Traffic flow indicates the overall number of vehicles passing a certain point in a certain period.

Traffic density refers to the number of vehicles occupying a given length of highway in a traffic lane. The FD is capable of describing these traffic variables as visible traffic conditions. Accordingly, given the features of NGSIM microdata, the details of the traffic state can be well preserved. Based on Edie’s generalized definition, the FD can be drawn. Such general definition can balance these traffic properties and can accurately count lane-change frequency, as NGSIM data are at 10Hz intervals.
The rest of this thesis is organized as follows: Chapter 2 reviews existing work on the FD and the effect of lane-change behavior; Chapter 3 processes NGSIM data for the FD; Chapter 4 develops the relationship of combining the FD with lane-change frequency; Chapter 5 employs statistical methods to process the data and discusses findings; and Chapter 6 draws conclusions.
Chapter 2: Literature review

Much earlier research on lane-change behavior identified that traffic jams can occur with an increase in the number of transfers. Olsen et al. (2002) acquired practical data and concluded that drivers change lanes frequently on an interstate highway. This behavior may result from higher traffic density. The authors also reported that different vehicle types lead to significant behavioral differences. In addition, sedan drivers travel more time in the right lane and more frequently change lanes to reach a higher speed, whereas SUV drivers drive more in the left lane. The right path was in low traffic flow in early rush time, and drivers attempted to avoid speed disturbances. Ahn and Cassidy (2007) reported that oscillations were formed in both a driver’s existing lane and neighboring lane, and that drivers exhibit more lane-change behavior on a multi-lane freeway than in single-lane traffic when changing their path to adjacent roads. Likewise, Patire and Cassidy (2011) concluded that lane changing is the key to lead oscillation; they found that drivers changed to low flow lanes to escape upcoming speed disturbances.

It is notable that if every driver changes to a low flow lane, the traffic flow of their present lane may change to a low flow rate. During this period, issues related to lane-change behavior are considerable. In this study, lane changes are measured using reasonable methods and combined with traffic flow and speed to explore their specific effect on traffic conditions.

Laval and Daganzo (2006) introduced a four-parameter multilane hybrid model; they explained that lane-change behavior has a limitation on acceleration. The difference in spatial distribution and speed induced by lane-change is significant. According to microscopic vehicle trajectory data, Wang and Coifman (2008) also found that lane-change behavior perturbs vehicles'
ability to follow the maneuver and making maneuvers on the spacing-speed relationship. Several researchers also reported that lane-change behavior is critical to traffic streams. Sala and Soriguera (2018) found that lane-change action reached its peak during congestion, and maximum lane-change times concentrated around shock waves. A clear relationship of lane-change probability to traffic flow is that lane-change probability decreases with a rise in traffic flow.

This relationship can be interpreted as when the traffic condition is in a free-flow state, most drivers can reach their desired speed. In this study, lane-changing is considered in traffic flow. Though it is different from lane-change probability, it may still affect traffic throughput. The reason for this finding is that if drivers try to escape a congested road as soon as possible, they may change to a low flow lane while meeting the lane-change conditions, and lane changes will increase.

Tang et al. (2008) built a dynamic lane-change model and drew qualitative conclusions. The model suggests that lane-change behavior can stop small disturbances from moving backward. They also found that when traffic is unstable, lane changes can cause worse traffic conditions; nevertheless, the effect of lane changes had a slight effect on traffic density and flow when traffic was stable. Aggressive driving behavior was also simulated in different models to make lane-change action more realistic.

The above studies reveal that lane-change behavior has a negative effect on the traffic stream. The ideal situation is to set up two control groups, one for lane-change action and one for no lane-change behavior, to achieve comparative quantitative analysis. However, this situation is difficult to meet, and different driver behaviors cannot be controlled. In this study, NGSIM data were employed to achieve in-depth analysis. The study aimed to find a specific impact between number of lane changes and traffic variables by calculating existing practical data and combining it with the FD.
Chapter 3: Dataset

3.1 NGSIM Data

NGSIM data is a microscopic dataset collected from practice. It can effectively record the details of a vehicle’s trajectory and speed. The precise location of each vehicle on a 0.5–1-kilometer section of roadway is recorded per 1/10th of a second. Except for the precise dataset, a core of open behavioral algorithms was developed to support traffic simulation of microscopic modeling. In this study, NGSIM data were adopted as raw data to analyze the number of lane changes and essential traffic variables. The NGSIM dataset consists of vehicle ID, lane number, positions with local X and local Y, and frame ID. The selected study area is I-80 in Emeryville, California, and US-101 in Los Angeles. To ensure the accuracy of traffic variables, the dataset of these two places was practical raw data supported by NGSIM. The data of these two places are only available as practical data. Six datasets were selected for further analysis, and each dataset was 15 minutes in length at different time points. Though the time interval was 15 minutes, some datasets were continuous.

3.2 US-101 Dataset

Fig. 3.1 suggests the specific study area of the US-101 freeway. The whole length of the study area is 2100 feet. Details of trajectories were collected between 7:50 a.m. and 8:35 a.m. on June 15, 2005. Given that the NGSIM data was converted from video data, some data were missed. In this study, each dataset was set at 700-sec intervals. The first dataset, from 7:50 a.m. to 8:05 a.m., contains 1993 vehicles, and the next dataset, from 8:05 a.m. to 8:20 a.m., contains 1533
vehicles; the last dataset contains 1298 vehicles. For the next calculation, the time of these datasets was processed, as it would affect the accuracy of the calculation of the FD.

Fig. 3.2 shows the trajectories of US-101 over three periods. For some voids on the trajectories map, the length of time used in the calculation was selected. Following the trajectories in the figure, the length of the selected time is a total of 600 sec for the first two periods and 520 sec for the last period. Other related variables (e.g., distance, spent time, lane number) can be quickly obtained from the original dataset.
3.3 I-80 Dataset

Fig. 3.3 presents the study area of I-80. The dataset for I-80 was collected from 4:00 p.m. to 4:15 p.m. and 5:00 p.m. to 5:30 p.m. Each dataset from NGSIM was a 15-min interval, but not a continuous time interval. The missing data in I-80 were less than the US-101 data, and time intervals were set to 750 sec. The length of the selected study area is 1650 feet. In total, 1725 vehicles were observed in the first period, 1416 in the second, and 2658 in the third. The length of the time selected for I-80 was different from that of US-101. Fig. 3.4 suggests the trajectory of I-80 for three periods; 500 sec was for the first two periods and 460 sec was for the last.
The subjects of this study were extracted as automobiles based on the original data, excluding motorcycles and trucks. Each piece of data was captured at 0.1-sec intervals. For recognizing the lane number of the dataset, lane 6 was the ramp for both US-101 and I-80. This study primarily aimed to explore lane-change behavior on the main road. However, the lane-change to the ramp includes some effect of driving routes, so this lane was not considered in the next calculation. In the next section, processing data for traffic flow, density and speed are discussed. In addition, lane-change frequency associated with this study was calculated.

Figure 3.3 Study area of I-80.

Source: Public Domain “Federal Highway Administration Research and Technology”
Figure 3.4 Trajectory map of I-80 Lane 1
Chapter 4: Methodology

4.1 Method for Fundamental Diagram

In this section, specific methods are presented to combine the FD with the number of lane changes. The FD is defined as the relationship between traffic flow and traffic density in steady traffic; or it is considered the general term for the relationship between vehicle mileage and running time. In this study, Edie’s generalized definition will act as a feasible method to calculate three critical elements of traffic.

Edie’s generalized definition defines a time-space region to calculate traffic flow, density, and speed (Edie, 1963).

\[
q(A) = \frac{\sum_{n \in N(A)} d_n(A)}{|A|},
\]

\[
k(A) = \frac{\sum_{n \in N(A)} t_n(A)}{|A|},
\]

\[
v(A) = \frac{\sum_{n \in N(A)} d_n(A)}{\sum_{n \in N(A)} t_n(A)},
\]

where \(A\) denotes a time-space region; \(q(A)\), \(k(A)\) and \(v(A)\) are three variables—traffic flow, density, and speed—in time-space region \(A\), respectively; \(N(A)\) is a whole number of vehicles in region \(A\); \(d_n(A)\) and \(t_n(A)\) are the driving distances of vehicles and time spent in region \(A\), respectively; \(|A|\) is the area of the selected region \(A\).

Fig. 4.1 is a schematic diagram of what the time-space region represents in the trajectory map as well as related variables in the map. The black square area is the time-space region \(A\). The horizontal length is the time intervals selected, and vertical length is the length of the whole study.
area. The area in the diagram represents the distance of the square by the time interval, which will be the time-space region A.

![Figure 4.1 Calculation schematic diagram](image)

The aggregation intervals of different times and distances were tested. The length of time and mileage intervals for aggregation display the clean static relationship. However, it cannot reflect the specific traffic condition clearly for real-time control. Appropriate time and distance intervals should be met. Short time intervals can reduce time delay, and sufficient length includes sufficient data points of traffic variables as well as the macroscopic traffic parameters maintained by \( q(A) = k(A)v(A) \) (Lu, Varaiya, & Horowitz, 2009). Thus, the time aggregation interval is taken as 10 sec. The distance aggregation interval is 2100 feet for US-101 and 1650 feet for I-80 because this study requires the number of lane changes for the whole section of the road.
The mentioned contents refer to the primitive method to plot the FD figure, capable of showing the traffic status and characteristics of US-101 and I-80. Given that the number of lane changes should be combined with the FD figure, each time point was adopted as the reference object. Each aspect of the FD figure represents the traffic condition currently. According to this requirement, the number of lane changes was also collected as vehicles changed their lanes in $t_n(A)$, where $t_n(A)$ denotes the time interval.

### 4.2 Method for Lane-Change Times

The following methods were used to calculate the number of lane changes $m$. Because the selected time interval was 10 sec, the lane-change frequency was tallied in the past 10 sec for all vehicles in the whole section of the study area. According to the NGSIM data format, each piece of relevant information was collected at 10 Hz. The first step was to select all data in the first 10 sec. Next, the lane ID was checked for the vehicle. For the identical vehicle ID, if the lane ID is changed, it was counted. By repeating the above steps, the sum of the number of lane changes could be achieved in 10 sec.

The necessary FD variables and the number of lane changes were calculated. Their commonality was that they have identical corresponding time intervals. According to this point, each point in the FD figure represents the lane-change frequency in the whole section of the study area within the time interval of this point. When combined, a special relationship between them can be found. In the following section, findings and conclusions are discussed.
Chapter 5: Discussion

In this section, the specific findings and the relationship between speed and the number of lane changes is discussed. Different periods of the FD figure for US-101 and I-80 are introduced. The number of lane changes also are shown at different periods. Subsequently, the relationship between the speed of vehicles and lane-change frequency is analyzed.

5.1 Fundamental Diagram for US-101

The first-period fundamental diagram of US-101 is given in Fig. 5.1. The maximum traffic flow at this period is 1600 veh/hr/lane, and the density is 38 veh/km/lane. Fig. 5.2 gives the FD for the next period. The traffic condition begins to vary to congestion. Traffic flow decreases from the maximum traffic flow, while density rises. A clear linear relationship can be recognized.

Figure 5.1 Fundamental Diagram of US-101 (7:50 a.m.–8:05 a.m.)
Fig. 5.3 presents the last period FD. The continuity of the second period can be seen. They have similar traffic conditions, and the change in traffic flow and density is not apparent. Comparison of the three diagrams suggests that the maximum traffic flow is in the first one, and all positions are concentrated in the same place. In this period, traffic conditions are stable, so vehicles can pass at maximum speed. In the second diagram, these points are more evenly distributed. The traffic condition in this period starts to enter the congestion state, so the traffic capacity of vehicles decreases. Traffic flow also starts to fall, and traffic density starts to increase. The third is the continuation of the traffic state in the second diagram. In the third, the traffic density ranges from 30 to 60 veh/km/lane, and the maximum traffic flow is nearly 1600 veh/hr/lane. For US-101, the early peak starts at 8:05 a.m., and the traffic gradually becomes congested. Next, the relationship with the number of lane changes is discussed.

![Figure 5.2 Fundamental Diagram of US-101 (8:05 a.m.–8:20 a.m.)](image)
Figure 5.3 Fundamental Diagram of US-101 (8:20 a.m.–8:35 a.m.)

Figure 5.4 Lane-change times of US-101 (7:50 a.m.–8:05 a.m.)
Figure 5.5 Lane-change times of US-101 (8:05 a.m.–8:20 a.m.)

Figure 5.6 Lane-change times of US-101 (8:20 a.m.–8:35 a.m.)
Fig. 5.4–5.6 show the specific lane-change frequency at each time point. In the all-time intervals, the maximum number of lane-changes does not exceed 15. For each vehicle, the lane-change behavior time varies in line with the actual condition. Another reason may be that the ramp is not counted in the calculation. In the limited 10 sec, there will be no excessive vehicles to perform lane changes. During early rush hour, lane-change frequency is more evenly distributed, and each vehicle will change lanes according to different driver’s habits. The traffic throughput is also at a high level for the uncongested state. As mentioned, traffic begins to be congested from 8:05 a.m. to 8:35 a.m., and lane-change frequency of vehicles declines noticeably. From 8:05 a.m. to 8:20 a.m., the number of lane changes most of the time is less than 10. Even in the initial period, no vehicles change lanes. The reason for this may be the effect of traffic congestion; conditions for lane changes are limited. Subsequently, the distribution of lane-change times does not change significantly. The average number of lane changes in these two periods is similar. Traffic status remains in the congested state, which is limited by the inability to conduct more lane-change behavior. Though the maximum speed has been achieved from a macro perspective, drivers may attempt to achieve a faster speed by changing lanes. The specific numerical analysis is discussed below.

Fig. 5.7 shows how to combine lane-change frequency with FD. In this study, the lane-change frequency was divided into two different intervals, 0–5 times, and > 5 times, noted by different colors. The higher lane-change frequency is at the maximum traffic flow rate. However, for the congested state, high lane-change frequency decreases significantly, and the distribution of low lane-change frequency is more uniform. Traffic conditions limit the number of lane changes. Whether the lane-change frequency can also have a negative effect on speed is noteworthy.
5.2 Statistical Analysis for US-101

All US-101 data for the three periods was integrated for processing. The feasible method to find out whether there is a significant correlation between two variables is to perform a one-factor ANOVA test. For the existing data statistics, Table 5.1 describes the relevant variables. To further confirm the relationship between speed and frequency, the variance was analyzed. A homogeneity test of variance was required before the ANOVA test.

Lane-change times concentrated on intervals 4–6 times, and during these intervals, the mean speed was nearly 37.9 km/h higher than the mean speed of the whole section. It is suggested that a larger number of lane changes displays a positive relationship on speed.

Figure 5.7 Combined lane-change times of US-101
Table 5.1 Description of Variables (Speed and Frequency of US-101)

<table>
<thead>
<tr>
<th>Speed (km/h)</th>
<th>Times</th>
<th>N</th>
<th>Mean Speed</th>
<th>Std. Deviation</th>
<th>Std. Error</th>
<th>95% Confidence Interval for Mean</th>
<th>Minimu m</th>
<th>Maximu m</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Lower Bound</td>
<td></td>
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<tr>
<td>.00</td>
<td>2</td>
<td>2</td>
<td>25.90</td>
<td>1.76</td>
<td>1.25</td>
<td>9.91</td>
<td>41.79</td>
<td>24.64</td>
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<tr>
<td>1.00</td>
<td>9</td>
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<td>18.06</td>
<td>35.05</td>
<td>17.47</td>
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<td>32.48</td>
<td>15.27</td>
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<td>35.83</td>
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<td>45.45</td>
<td>25.71</td>
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<td>40.14</td>
<td>7.48</td>
<td>2.25</td>
<td>35.11</td>
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<td>42.12</td>
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<td>36.77</td>
<td>47.47</td>
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<td>42.43</td>
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<td>2</td>
<td>45.61</td>
<td>7.67</td>
<td>4.43</td>
<td>26.54</td>
<td>64.68</td>
<td>37.79</td>
</tr>
<tr>
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<td>175</td>
<td>1</td>
<td>35.95</td>
<td>10.38</td>
<td>0.78</td>
<td>34.40</td>
<td>37.50</td>
<td>15.27</td>
</tr>
</tbody>
</table>

Satisfying the homogeneity of variance is a prerequisite for analyzing variance. In this way, the variables counted in such a state can comply with the distribution. If the population variances in each experimental group are homogeneous and the overall average of the multiple samples ascertained by the test are significantly different, the difference between the population averages of multiple samples can be attributed to the differences in various experimental treatments. If the variances of the populations are uneven, the results of the significant difference in the population averages of the multiple samples obtained may be partially attributed to the differences in the overall variance within each experimental group. The analysis of variance cannot be conducted. The homogeneity test of variance for two variables is presented in Table 5.2.
Table 5.2 Test of Homogeneity of Variances (Speed and Frequency of US-101)

<table>
<thead>
<tr>
<th>Speed</th>
<th>Levene Statistic</th>
<th>df1</th>
<th>df2</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Based on Mean</td>
<td>1.806</td>
<td>12</td>
<td>162</td>
<td>.051</td>
</tr>
<tr>
<td>Based on Median</td>
<td>1.175</td>
<td>12</td>
<td>162</td>
<td>.305</td>
</tr>
<tr>
<td>Based on Median and with adjusted df</td>
<td>1.175</td>
<td>12</td>
<td>135.552</td>
<td>.307</td>
</tr>
<tr>
<td>Based on trimmed mean</td>
<td>1.834</td>
<td>12</td>
<td>162</td>
<td>.047</td>
</tr>
</tbody>
</table>

Table 5.2 suggests that the significance is 0.051 and greater than 0.05, and the distribution of the speed and the number of lane changes is homogeneous, so the analysis of variance can be used.

Table 5.3 ANOVA Test Statistics for US-101

<table>
<thead>
<tr>
<th>Speed</th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Between Groups</td>
<td>4686.626</td>
<td>12</td>
<td>390.552</td>
<td>4.492</td>
<td>.000</td>
</tr>
<tr>
<td>Within Groups</td>
<td>14085.087</td>
<td>162</td>
<td>86.945</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>18771.712</td>
<td>174</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5.3 gives the results of the ANOVA test for US-101. The significance is about 0, and it is suggested that frequency noticeably affects traffic speed. The coefficient of determination of these two variables is about 0.231. In Table 5.4, the correlation between these variables is 0.446. In accordance with the theory of statistics, lane changes are positively correlated with speed, whereas its correlation is not strong. To address this phenomenon, the data of I-80 was for in-depth analysis.
Table 5.4 Pearson Test Statistics for US-101

<table>
<thead>
<tr>
<th></th>
<th>Speed</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed</td>
<td>Pearson Correlation</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Sig. (2-tailed)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>N</td>
<td>175</td>
</tr>
<tr>
<td>Frequency</td>
<td>Pearson Correlation</td>
<td>0.446*</td>
</tr>
<tr>
<td></td>
<td>Sig. (2-tailed)</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>N</td>
<td>175</td>
</tr>
</tbody>
</table>

*Correlation is significant at the 0.01 level (2-tailed).

5.3 Fundamental Diagram for I-80

To further verify the conclusions drawn from the analysis of US-101 data, the I-80 condition is discussed in the next section. According to the particularity of NGSIM data, the three pieces of data for I-80 were not overall continuous data. Continuous data appear only from the beginning of 5:00 p.m. to the 5:30 p.m. The fundamental diagram of the first period is given in Fig. 5.8. It is suggested that from 4 p.m. to 4:15 p.m., traffic conditions were similar to the first period of US-101. These points are concentrated, and the variation in traffic density is not apparent. Fig. 5.9 and 5.10 present diagrams of two continuous periods. The number of vehicles grows gradually, and the traffic condition is congested, whereas traffic remains relatively stable. Though it also has a linear relationship like US-101, the variation in traffic density is not as much as US-101. The traffic density is about 40–60 veh/km/lane, and the traffic flow is near the maximum flow rate of about 1400 veh/hr/lane. The calculation results reveal that the speeds at the maximum flow rates of the two periods are consistent. This condition is different from the data of US-101. The traffic throughput at this time remains almost unchanged.
Figure 5.8 Fundamental Diagram of I-80 (4:00 p.m.–4:15 p.m.)

Figure 5.9 Fundamental Diagram of I-80 (5:00 p.m.–5:15 p.m.)
Figure 5.10 Fundamental Diagram of I-80 (5:15 p.m.–5:30 p.m.)

Figure 5.11 Lane-change times of I-80 (4:00 p.m.–4:15 p.m.)
Figure 5.12 Lane-change times of I-80 (5:00 p.m.–5:15 p.m.)

Figure 5.13 Lane-change times of I-80 (5:30 p.m.–5:30 p.m.)
In the next part, the change of lane changes in these three periods is discussed. Fig. 5.11–5.13 show the specific lane-change times during the three periods. In each period, lane changes do not exceed 10, and it remains almost unchanged. The total number of lane changes in the first period is 281, the second period is 252, and the third is 230. The change in the number of lane changes in these three periods is not noticeable, and the traffic conditions of these three periods are similar. It is suggested that during this period, the traffic condition is being shifting to the congested state. This condition is different from US-101 since the condition of US-101 varies to congestion, and traffic density increases obviously.

Fig. 5.14 presents the result of FD combined with lane-change times. This FD covers the last two periods, from 5:00 p.m. to 5:30 p.m. After combining these periods, it is obvious that these points remain concentrated, and high lane-change times are not dominant. During the maximum flow period, every driver can still pass through the section at the desired speed. Thus, the traffic

![Figure 5.14 Combined lane-change times of I-80](image)
condition remains stable currently. Nevertheless, traffic conditions do not change to congestion if lane changes have the same effect on speed, which is discussed in the next section.

5.4 Statistical Analysis for I-80

Table 5.5 describes two variables, speed and lane-change frequency for I-80. These data are the integration of the content of the last two periods because their time is continuous. Most lane changes were concentrated three times and the mean speed under different lane-change times is similar. The mean speed for the whole section was about 23.51 km/h, and the maximum lane-change times’ mean speed was 22.62 km/h. The in-depth analysis of the ANOVA test is discussed.

Table 5.5 Description of Variables (Speed and Frequency of I-80)

<table>
<thead>
<tr>
<th>Times</th>
<th>N</th>
<th>Mean Speed</th>
<th>Std. Deviation</th>
<th>Std. Error</th>
<th>95% Confidence Interval for Mean</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Lower Bound</td>
<td>Upper Bound</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.00</td>
<td>2</td>
<td>18.45</td>
<td>0.69</td>
<td>0.49</td>
<td>12.22</td>
<td>24.67</td>
<td>17.96</td>
</tr>
<tr>
<td>2.00</td>
<td>14</td>
<td>22.14</td>
<td>3.41</td>
<td>0.91</td>
<td>20.17</td>
<td>24.11</td>
<td>16.26</td>
</tr>
<tr>
<td>3.00</td>
<td>25</td>
<td>22.62</td>
<td>4.36</td>
<td>0.87</td>
<td>20.82</td>
<td>24.42</td>
<td>12.14</td>
</tr>
<tr>
<td>4.00</td>
<td>15</td>
<td>24.15</td>
<td>4.35</td>
<td>1.12</td>
<td>21.74</td>
<td>26.56</td>
<td>16.41</td>
</tr>
<tr>
<td>5.00</td>
<td>10</td>
<td>24.58</td>
<td>3.65</td>
<td>1.15</td>
<td>21.97</td>
<td>27.20</td>
<td>18.21</td>
</tr>
<tr>
<td>6.00</td>
<td>12</td>
<td>24.23</td>
<td>4.52</td>
<td>1.30</td>
<td>21.36</td>
<td>27.11</td>
<td>14.13</td>
</tr>
<tr>
<td>7.00</td>
<td>2</td>
<td>24.26</td>
<td>6.08</td>
<td>4.30</td>
<td>-30.42</td>
<td>78.94</td>
<td>19.96</td>
</tr>
<tr>
<td>8.00</td>
<td>5</td>
<td>25.71</td>
<td>2.56</td>
<td>1.14</td>
<td>22.53</td>
<td>28.90</td>
<td>22.34</td>
</tr>
<tr>
<td>9.00</td>
<td>7</td>
<td>23.86</td>
<td>2.64</td>
<td>1.00</td>
<td>21.41</td>
<td>26.31</td>
<td>19.69</td>
</tr>
<tr>
<td>12.00</td>
<td>4</td>
<td>26.96</td>
<td>1.85</td>
<td>0.92</td>
<td>24.00</td>
<td>29.92</td>
<td>25.01</td>
</tr>
<tr>
<td>15.00</td>
<td>2</td>
<td>20.48</td>
<td>1.87</td>
<td>1.32</td>
<td>3.63</td>
<td>37.33</td>
<td>19.16</td>
</tr>
<tr>
<td>Total</td>
<td>98</td>
<td>23.51</td>
<td>4.00</td>
<td>0.40</td>
<td>22.71</td>
<td>24.31</td>
<td>12.14</td>
</tr>
</tbody>
</table>
Test of homogeneity of variances still require consideration, and Table 5.6 lists the relevant results. The significance in Table 5.6 is 0.258, greater than 0.05. It accepts the null hypothesis, and the variance tests can be performed.

Table 5.6 Test of Homogeneity of Variances (Speed and Frequency of I-80)

<table>
<thead>
<tr>
<th>Test of Homogeneity of Variances</th>
<th>Levene Statistic</th>
<th>df1</th>
<th>df2</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed (km/h)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Based on Mean</td>
<td>1.274</td>
<td>10</td>
<td>87</td>
<td>.258</td>
</tr>
<tr>
<td>Based on Median</td>
<td>.918</td>
<td>10</td>
<td>87</td>
<td>.521</td>
</tr>
<tr>
<td>Based on Median and with adjusted df</td>
<td>.918</td>
<td>10</td>
<td>71.447</td>
<td>.522</td>
</tr>
<tr>
<td>Based on trimmed mean</td>
<td>1.236</td>
<td>10</td>
<td>87</td>
<td>.280</td>
</tr>
</tbody>
</table>

Table 5.7 shows the results of the ANOVA test, and the significance is 0.200 greater than 0.05. Accordingly, it is considered as accepting the null hypothesis and lane-change times do not affect speed.

Table 5.7 ANOVA Test Statistics for I-80

<table>
<thead>
<tr>
<th>ANOVA</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed (km/h)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sum of Squares</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Between Groups</td>
<td>213.555</td>
<td>10</td>
<td>21.356</td>
<td>1.387</td>
</tr>
<tr>
<td>Within Groups</td>
<td>1339.112</td>
<td>87</td>
<td>15.392</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>1552.668</td>
<td>97</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

According to the two groups, for US-101, lane changes have a positive effect on speed but for I-80, they do not affect speed. The traffic condition of US-101 is in the congested state, whereas I-80 remains at the transition to the congestion. This difference may lead to different results. Some existing studies indicate that drivers sometimes might escape early peak hours by changing lanes.
Chapter 6: Conclusions

In this study, lane-change frequency was combined with the FD figure to determine its effect on traffic throughput. According to the characteristics of NGSIM data, Edie’s generalized definition is taken to generate the FD figure. This method is capable of effectively preserving the details and changes in traffic conditions. The combination of the number of lane changes and the FD figure is that since there is a specific relationship between the time intervals between them, they are drawn together by this standard variable.

The results of the US-101 analysis reveal that lane changes can effectively increase the speed of vehicles and traffic throughput when a traffic is in a light congested state. It can be considered that congestion starts from the beginning of a specific lane, and the surrounding lanes may not be congested; thus, a driver will immediately switch to the surrounding lanes to get a faster speed. The analysis of I-80 suggests that when the traffic state is in the transition of becoming congested, the speed of the vehicle is not overly affected by traffic conditions. Also, the effect of lane changes on traffic throughput is not noticeable.

In subsequent research, whether the generation of lane change behavior will immediately affect the traffic state is a noteworthy problem. It is also worth adding multiple variables with lane-changes to explore the effect on the FD. Considerable raw data are also required, and the method to measure the fundamental diagram can also adopt several different models to compare the differences.
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