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Modeling the Duration of Lane Changes

By

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דו"ח זה משקף את דעות המחברים והמלצותיהם, ואיננו משקף בהכרח את דעותיהם של הטכניון ושל מוסד הטכניון למחקר ופיתוח. מוסד הטכניון למחקר ופיתוח בע"מ אינו אחראי לדיוק הנתונים הכלולים בדו"ח ולמסקנותיו, ואין הדו"ח מהווה הנחיה או המלצה שלו.

תוכן הדו"ח אינו בהכרח משקף את דעותיהם של הגופים הרשמיים והרשויות המוסמכות האחראים לנושא, ואין הדו"ח מהווה תקן, הנחיה או נוהל מחייבים של אותם גופים ורשויות.

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Abstract

Lane changes have a significant impact on the characteristics of traffic flow. Lane changing models are therefore an important component of microscopic traffic simulation tools. Existing lane changing models emphasize the decision-making aspects of the task, but generally neglect the detailed modeling of the lane changing action itself and only model it as an instantaneous event. However, research indicates that lane changing durations are on average in the order of 5 to 6 seconds. The omission of lane-changing duration from microscopic simulation models may have a significant impact on simulated traffic flow characteristics and on simulation outputs. To accomplish a lane-change, a vehicle looks for a gap large enough to switch to its target lane. Once a suitable gap is found the lane-change is initiated. During the lane-change, the driver may have to adjust its speed to the new lane and leader. In this process, following vehicles on the current lane and on the target lane may also have to adjust their acceleration behavior or even decide to change lanes themselves in order to let the vehicle complete the lane change. This research presents models of the duration of lane changes. These models are estimated using detailed vehicle trajectory data that was collected in naturalistic driving using high mounted video cameras. This thesis presents separate models for passenger cars and for heavy vehicles and conducts statistical tests for the similarity between the lane change durations of the two vehicle types.

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This research presents models of the duration of lane changes. These models are estimated using detailed vehicle trajectory data that was collected in naturalistic driving using high mounted video cameras. This thesis presents separate models for passenger cars and for heavy vehicles and conducts statistical tests for the similarity between the lane change durations of the two vehicle types.

List of Symbols

NIS	New Israeli shekel
NA	Not available
HOV	High occupancy vehicle lane
μ	The mean of the distribution
σ	Standard deviation of the distribution
Dx(i)	Lateral change of observation i
d_n	The lane change duration for driver n
β	Corresponding parameters
X_n	Vector of explanatory variables of driver n
ε_n	Error term of associated with observation i of driver n
ΔV_n^{front}	Front vehicle relative speed
$\Delta V_n^{lag,lead}$	Lag – lead relative speed
MLC	Mandatory lane change
ESS_R	Error (unexplained) sums of squared regression residuals for the restricted model
ESS_{UR}	Error (unexplained) sums of squared regression residuals for the unrestricted model
N	Number of observations in the sample
K	Number of parameters in the unrestricted model
Q	Number of restrictions
Cd	Change direction
Hv	Heavy vehicle
Pc	Passenger car
ΔV_n^{ave}	Subject relative speed with respect to the average speed in the section

Chapter 1 Introduction

1.1 Motivation

Traffic congestion is a major problem in urban areas and freeways. It has a significant adverse economic impact through deterioration of mobility, safety and air quality. A recent study (Israel Master Plan, 1999) estimated that the daily travel in major Israel urban areas in 2020 will occur under congested traffic conditions. The average speed predicted for 2020 on the freeway network is 44-48 kph. The annual cost of lost time and excess fuel consumption during congestion is predicted to be approximately 2 billion New Israeli Shekels (NIS).

Development of the road network, particularly within the metropolitan boundaries, has in many cases almost reached the extraction of the road rights. Moreover, in many urban areas, environmental constraints would limit construction of new roads or expansion of existing ones. The budget required for infrastructure investments in Israel until the year 2020 is estimated at 4.25 billion NIS/year. As a result, the importance of better management of the road network to efficiently utilize existing capacity is increasing.

In recent years, a large array of traffic management schemes have been proposed and implemented. Methods and algorithms proposed for traffic management need to be calibrated and tested. In most cases only limited, if any, field tests are feasible because of prohibitively high costs and lack of public acceptance. Furthermore, the usefulness of such field studies is deterred by the inability to fully control the conditions under which they are performed. Hence, tools to perform such evaluations in a laboratory environment are needed.

Microscopic traffic simulation models, which analyse traffic phenomena through explicit and detailed representation of the behavior of individual drivers, have been widely used to that end by both researchers and practitioners. Hence, microscopic traffic simulation is an important tool for traffic analysis and particularly valuable in the context of dynamic traffic management systems.

Lane changes have a significant impact on the characteristics of traffic flow (Sparmann, 1979; Ferrari, 1989). Lane changing models are therefore an important component of microscopic traffic simulation tools. In recent years, following the emergence of traffic simulation models as useful tools for the analysis of transportation systems, interest in the development of more reliable lane changing models has increased (see, for example, Kitamura et al., 2005 and Toledo, 2005, and the references within).

1.2 Problem Description

The lane change task is a process composed of several steps. In order to perform a lane change action, the following steps must be taken by the driver:

1. Decision making:
    a. Incentive – based on knowledge in real time information of the driver such as exiting the freeway by changing lanes to an off ramp in a congested conditions, overtaking and collision avoidance;
    b. Gap acceptance – drivers' decisions to execute the lane change. The driver evaluates the adjacent gap in the lane he is approaching, which is defined by the lead vehicle and the lag vehicles in that lane.
2. Execution:
    a. Duration – is the time lapse between the vehicles' initiation and completion.
3. Impact
    a. On speed and acceleration of the subject vehicle during the lane change action;
    b. On the behavior of neighboring vehicles during the lane change action and immediately after it is completed.

Existing models of lane changing behavior emphasize the decision-making aspects of the task, but generally neglect the detailed modeling of the lane changing action itself and only model it as an instantaneous event. However, this assumption contradicts with research findings in the area of human factors that indicate that lane changing durations are on average in the order of 5 to 6 seconds. The acceleration behavior of the vehicle changing lanes and of other vehicles around it may be affected during the execution of lane changes, but this effect cannot be captured if lane changes are instantaneous. Therefore, the omission of lane-changing duration from microscopic simulation models may have a significant impact on simulated traffic flow characteristics and on simulation outputs. In this research, models of the duration of lane changes are presented. Detailed vehicle trajectory data is used to estimate parameters of these models.

1.3 Thesis Objective

The objective of this research is to improve modeling of driving behavior and in particular to develop detailed models of the duration of lane changes. This research contributes to the state-of-the-art in driving behavior modeling in the following aspects:

- The studies that explored lane change duration focus on the statistics of analysing the lane change duration. In this research the lane change duration driving behavior model has been developed;
- The models presented in the literature usually analyse the data on the basis of variables that are related to drivers' characteristics such as gender, age and character. However, such models are not applicable to microscopic traffic simulators. Our model is oriented towards implementation and uses appropriate variables e.g. traffic conditions such as density and relations with neighboring vehicles such as lag, lead and front vehicles;
- In most studies human observers or obtrusive equipment were used to collect the data. This may have an impact on drivers' behavior. Our model is estimated with a vehicle trajectory dataset that was collected in a freeway section without the drivers' knowledge;
- The models presented in the literature generally only refer to a single type of vehicle, in most cases passenger cars. This research distinguishes between passenger cars and heavy vehicles. This approach is justified by the data.

1.4 Thesis Outline

In Chapter 2, a literature review of the methods used and findings of research conducted to study the duration of lane changes is presented. The data for estimation of the lane change duration is discussed and the definitions for initiation and completion points are suggested in Chapter 3. Estimation results of the duration of lane changes are presented in Chapter 4. Finally, concluding remarks and directions for future research are presented in Chapter 5.

Chapter 2 Literature Review

Most of the lane changing behavior modeling literature focuses on the decision to consider a lane change and the decision to execute the lane change. Researchers that investigate the lane changing action itself often focus on human factors related to the lane-change execution and the safety issues. These studies are mostly conducted either within instrumented vehicles or in driving simulators. However, in most cases the results of these studies are not suitable for microscopic traffic simulation, which do not incorporate factors at the level of detail considered in these models, such as eye movement and vehicle control.

2.1 Lane Change Duration Models

The following summarizes studies that investigated the lane-changing action:
Worrall and Bullen (1970) used aerial photographs to estimate lane change durations. They described a lane change in three parts. First, the head portion is the time and distance required for a vehicle to move from a straight-ahead path to the first intercept of the lane line. The actual lane-change begins when a vehicle first enters on the lane line between the original and destination lane. Secondly, the maneuver has ended once the vehicle has completely crossed that line. Finally, the tail portion of the maneuver is the time and distance required for a vehicle to return to a straight-ahead path in the destination lane after crossing the lane line. They estimated lane change durations in two parts: the time in the initial lane and the time in the target lane. The mean durations were 1.25 and 1.95 seconds, respectively. The respective standard deviations were 0.4 and 0.5 seconds. However, later research (Choavn et al., 1994) suggested that lane change durations were underestimated in this study because of the limitations of the technology that was used.

Finnegan and Green (1990) reviewed previous research conducted in the 1970s and 1980s concerning lane changing behavior. They report that lane changes, including visual search time, took between 4.9 and 7.6 seconds depending on the presence of traffic and the direction of change. They also reported that drivers make, on average, 2.5 head movements when changing lanes, which take 1 to 1.5 seconds each. They concluded that the relevant literature tends to underplay the importance of visual sampling strategies, which vary considerably between individuals and can significantly affect the total lane change time. However, they also point out that the use of obtrusive equipment, such as eye markers and helmets may interfere with drivers' behavior.

Chovan et al. (1994) analyzed lane change vehicle collisions based on 16 reports. The selected cases involved two vehicles. They defined lane change as a deliberate and substantial shift in the lateral position of a vehicle. They conducted a clinical analysis of the data. Their study showed that lane change durations are likely to be between 2 to 16 seconds. But they point out that lane change times may have been underestimated because of resolution and model-prediction limitations. They also concluded that it would be helpful to know if drivers accelerate while changing lanes or if constant longitudinal velocity is maintained.

Tijerina et al. (1997) used observers that accompanied the driver in the vehicle. The observers gave driving instructions and recorded drivers' actions. Each driver drove an instrumented vehicle, in daylight and dry pavement conditions. The study included 39 drivers who drove both on public highways at 55mph and on urban streets at 25 to 35mph. For the urban streets, lane change durations were between 3.5 and 6.5 seconds, with a mean of 5.0 seconds. For highways the duration ranged from 3.5 to 8.5 seconds with a mean of 5.8 seconds. A drawback of this study is the presence of the observer, which may have influenced drivers' behavior, resulting in a lack of natural driving behavior.

Hetrick (1997) also used observers to collect data in the vehicle. In this study, 16 participants drove an instrumented vehicle for 1.5 hours in urban streets and on highways. Eight of the participants were 18 to 25 years old, and eight were 65 to 75 years old. Within each age group, half of the subjects were male and half were female. Lane change duration ranged from 3.4 to 13.6 seconds. Young drivers tended to have short lane change durations, while elderly drivers took longer times to change lanes. The mean lane change duration was 6.0 seconds. As with other studies the presence of an observer and the use of obtrusive equipment may have influenced drivers' behavior. It is important to recognize that this study was conducted on roadways of a mid-size town in traffic conditions that may not represent those in typical city streets or major highways.

Hanowski (2000) used instrumented short-haul trucks to record, among other things, the durations of lane changes in a study designed to evaluate the impact of fatigue. 42 drivers participated in the experiment. The average age in the group was 31 years. Lane change durations ranged from 1.1 to 16.5 seconds. The mean and standard deviation were 4.52 and 1.71 seconds, respectively [results reported in (Olsen et al., 2003)]. The lane change initiation was defined by the time when the wheel crossed the lane line and ended when the vehicle settled in the new lane.

Salvucci et al. (2002) conducted an experiment in which drivers navigated a highway environment in a fixed-base medium-fidelity driving simulator. The highway included two lanes in each direction, standard lane markings, and a barrier off the side of the road. There were no on-rumps or off-ramps and no extraneous scenery. The experiment included 11 participants with at least two years of driving experience. Subjects were asked to report their intention to make a lane change and also the completion of a lane change. Based on these observations, the mean duration of lane changes was estimated at 5.14 seconds with a standard deviation of 0.86 seconds. For overtaking maneuvers, they also found that on average drivers decelerated slightly before starting the lane change, then accelerated to a higher speed, and maintained this speed up until going back to the slow lane. The limited realism of the driving simulator may have biased the results. In addition, obtrusive equipment such as an eye-tracker was used, which may have affected drivers' behavior by making the driving task unnatural.

Lee et al. (2003) conducted an experiment in which 16 commuters that normally drove more than 40km in each direction were observed. Half of the participants commuted on an Interstate highway the other half commuted on a U.S. highway. The interstate route was I-81 in southwestern Virginia, a heavily traveled divided interstate with hills and many heavy vehicles. The highway route included both U.S. 460 and U.S. 11. The two vehicles used in this research were a sedan and a sport utility vehicle. Each participant drove each vehicle for ten days. Participants were aged 20 to 64 with equal gender representation. The vehicles were equipped with a video system which included five channels, sensors and three radar units. Hence, data gathering was automatic, and the presence of an observer was not required in the vehicle. The initiation of the lane changes was defined at a point in time that vehicles began to move laterally. The completion of lane changes was defined by points in time that the centers of the vehicles were in the destination lane. Using these definitions, the mean duration of single lane changes observed in the experiment was 6.28 seconds with a standard deviation of 2.0 seconds. The median lane change duration was 6.0 seconds. They also found that lane changes to the left took longer to complete compared to lane changes to the right, but no significant differences between lane changes taken in the two vehicles. The drawbacks of this study are the small number of individuals in the sample and the obtrusive equipment which may influence the driver's behavior.

The cost associated with the use of driving simulators and equipped vehicles is high. Therefore, in all the studies discussed above only small samples of drivers could be used, which made it difficult to draw statistically significant conclusions on the results. It is therefore not surprising that Chovan et al. (1994) and Lee et al. (2003) both point out the lack of on-road lane changing duration data as an important limitation to studies that use this data in the development and evaluation of driver assistance systems.

2.2 Summary

The following table summarizes the important results from the literature review aforementioned.

Table 2.1 Lane Change Duration as Reported by Various Sources

Source	Range/Std	Mean/Median	Sample size	Limitations /notes
Worrall & Bullen (1970)	2.3 to 4.1 s	Median = 3.2 s	NA	lane change durations were underrated due to aerial photographs
Finnegan & Green (1990)	4.9 to 7.6 s	Median = 6.3 s	5 Articles	Eye markers and helmets may interfere with drivers' behavior
Chovan et al. (1994)	2.0 to 16.0 s	-	16 Reports	Initial range for crash avoidance system
Tijerina et al. (1997)	3.5 to 6.5 s	Mean = 5.0 s (urban streets)	39 drivers	The presence of an observer
Tijerina et al. (1997)	3.5 to 8.5 s	Mean = 5.8 s (highways)		
Hetrick (1997)	3.4 to 13.6	Mean = 6.0 s	16 drivers	The presence of an observer and obtrusive equipment
Hanowski (2000)	1.1 to 16.5 s (std = 1.71)	Mean = 4.52 s	42 drivers	Instrumented trucks
Salvucci et al. (2002)	Std = 0.86 s	Mean = 5.14 s	11 drivers	Small sample and simulated environment

Source	Range/Std	Mean/Median	Sample size	Limitations /notes
Lee et al. (2003)	Std = 2.0 s	Mean = 6.28 s	16 drivers	Small sample and equipped vehicles

The literature shows that the average time to complete a lane change is of the order of 5 to 6 seconds. However, these studies have several important limitations. Most of the studies were conducted in the presence of observers or using driving simulators, which may have affected drivers' behavior. These studies were conducted with small samples of drivers which may not be representative of the population of drivers. Some of the factors that were collected in these studies as potential variables explaining the durations of lane changes, such as eye and head movements, cannot be used in the context of traffic simulation modeling.

The literature mostly presented results using simple summary statistics and not a real modeling effort. This research aims to develop models of the durations of lane changes that address some of these limitations using a large set of trajectory data at a high time resolution. The data was collected by high-mounted video cameras in naturalistic driving conditions and without the use of any obtrusive equipment or even the knowledge of the drivers.

Chapter 3 Data

This research aims to develop models of the durations of lane changes that address some of the limitations presented in the previous chapter by using a large set of detailed trajectory data at a high time resolution (10 or 15 observations per second) that was collected by high-mounted video cameras in naturalistic driving conditions and without the use of any obtrusive equipment or even the knowledge of the drivers.

In this chapter, the data that was obtained from real traffic in order to estimate models of lane changing duration is presented. The data required for estimation of the duration's models of lane changing includes the following information: position, velocity, acceleration, length and width of a subject vehicle, the preceding vehicles and following vehicles in the current lane as well as in adjacent lanes, lane identification, vehicle type and spacing. Data on gap lengths, headways, density of traffic, etc. can be extracted from the above mentioned data by simple mathematical calculations.

3.1 Data Collection Effort

The trajectory dataset used in this research was collected on two different days on a section of the eastbound direction of Interstate-80 in Emeryville California. The data was collected and reduced by the Berkeley Highway Laboratory (NGSIM BHL, 2004 and 2005) using video cameras that were mounted on a 30 story building, Pacific Park Plaza, which is located in 6363 Christie Avenue and is adjacent to the interstate freeway I-80 as shown in Figure 3.1 below.

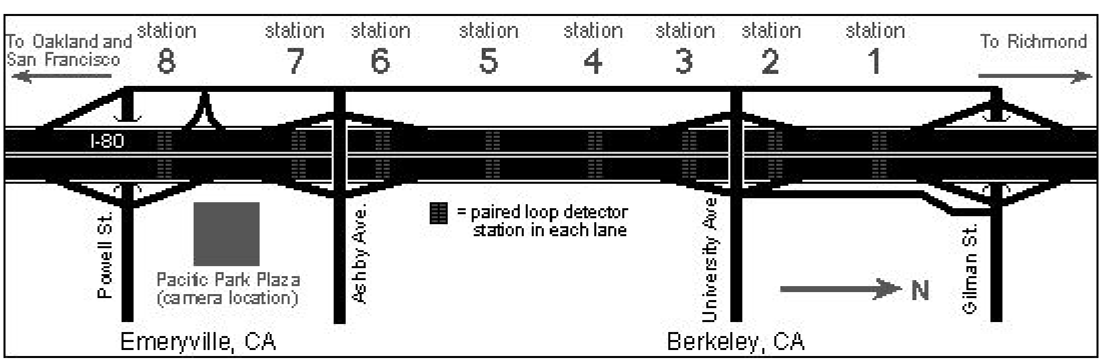

Figure 3.1 Data Site (NGSIM BHL Data Analysis, 2004)

The collection site is shown schematically in Figure 3.2. Distances shown in the figure are in feet. The entire section is approximately 899 meters long and includes six lanes with a weaving section between the on-ramp at Powell Street and the off-ramp at Ashby Avenue in lanes 5 and 6. The left-most lane (lane 1) is a high occupancy vehicle (HOV) lane. The trajectories of all the vehicles that traveled on this section were extracted from the video files. The data includes observations on the physical dimensions of all vehicles and the positions and lanes they travel in at a time resolution of 10 or 15 observations per second depending on the date of collection.

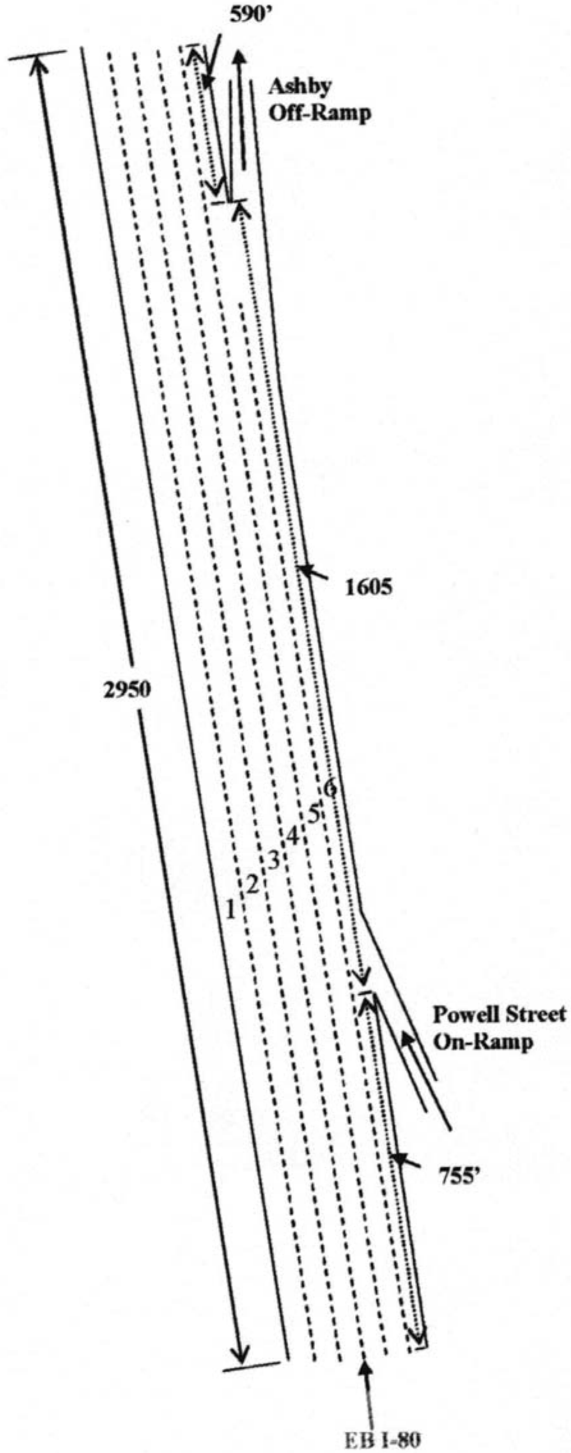

Figure 3.2 Data Collection Site (NGSIM BHL Data Analysis, 2004)

Vehicle trajectory data was transcribed from video data using a customized software application developed for NGSIM. This program automatically detects and tracks most vehicles from video images and transcribes the trajectory data to a database.

The flow process for the vehicle transcription is shown in Figure 3.3. The software detects vehicles in a user-defined detection zone, which is usually set in the camera that is looking straight down from the building, and then tracks vehicles both upstream and downstream from the point of detection. Hence, the vehicle tracking progress was divided into two major parts 1) forward; 2) reverse.

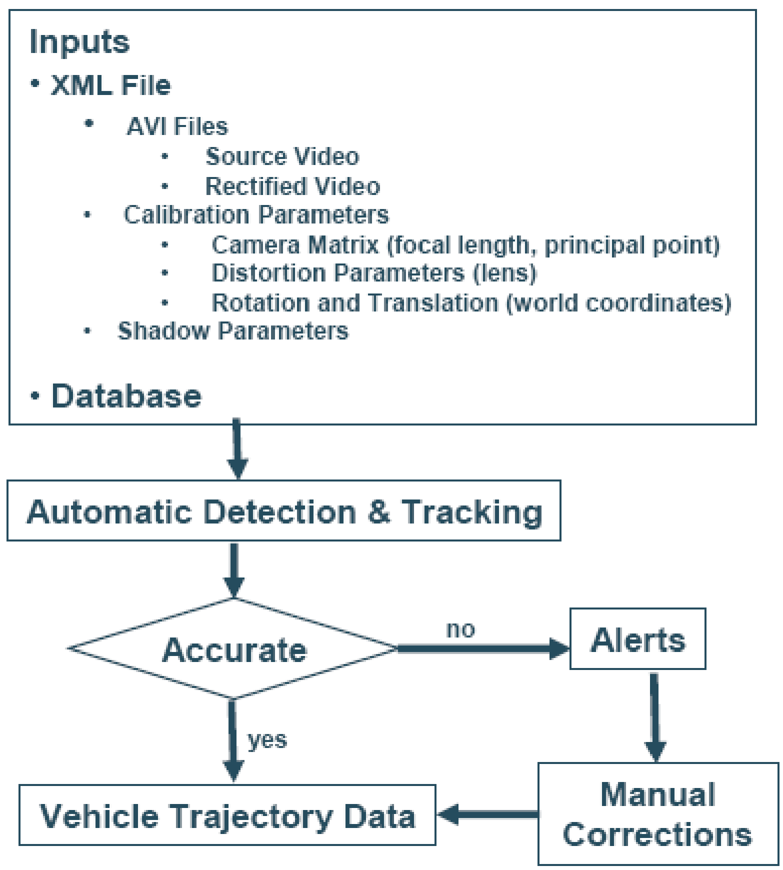

Figure 3.3 Vehicle Detection and Tracking Process (NGSIM BHL Data Analysis, 2005)

The data was collected at three separate time periods, which cover a wide range of traffic conditions:

1. An off-peak period of 30 minutes between 2:35PM and 3:05PM with relatively low traffic densities and high travel speeds was collected on December 3, 2003. This video data was recorded at a resolution of 15 frames per second by using six video cameras. The data contains 4,733 vehicle trajectories and nearly 3 million observations;
2. A 15 minute period between 4:00PM and 4:15PM, which primarily represents transitional traffic conditions during the build-up to congestion, was recorded on April 13 2005. On this date, data was recorded for a shorter section of 503 meters long, up to the Ashby off-ramp. The survey section is shown in Figure 3.4 (distances shown in the figure are in feet). It was recorded at a rate of 10 frames per second by using seven video cameras. The data contains 2,052 vehicle trajectories;
3. An afternoon peak period of 30 minutes between 5:00 PM and 5:30PM, in which congested traffic conditions are observed, was also recorded on April 13 2005. The data contains 3,626 vehicle trajectories.

The weather was clear with no precipitation, good visibility and dry pavement conditions during the data collection periods. Furthermore, there were no incidents or events within the section during these periods.

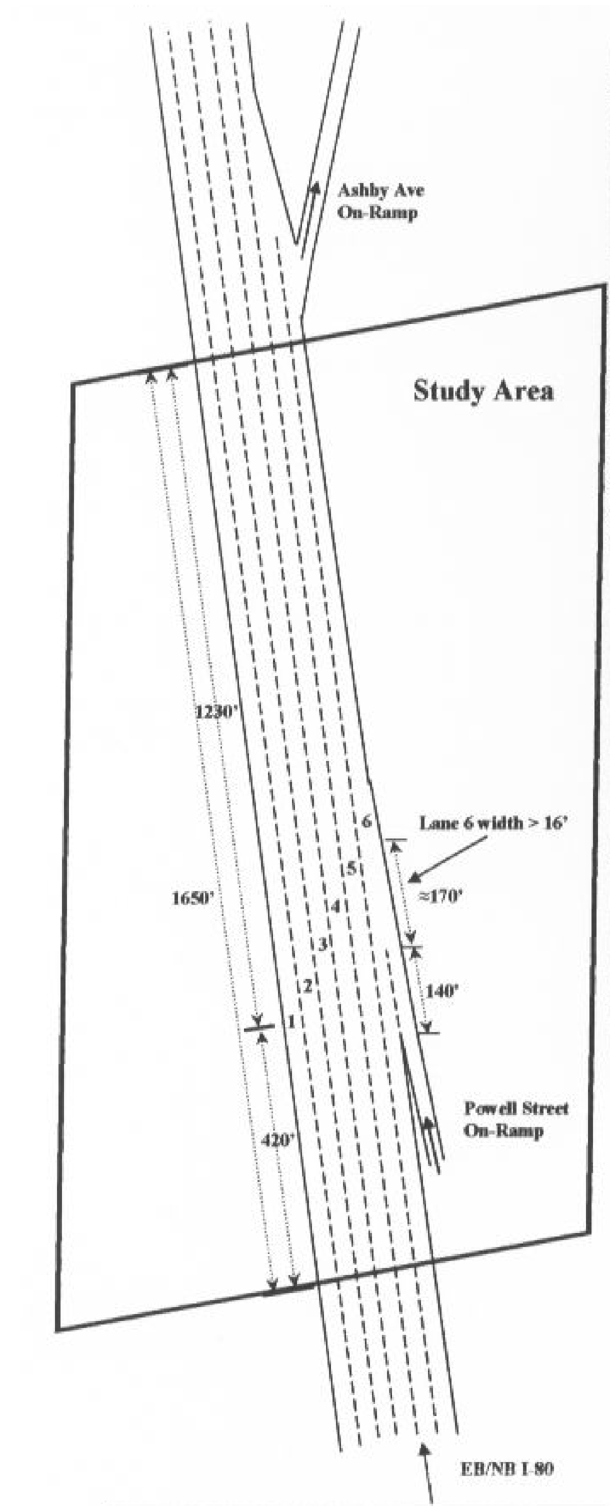

Figure 3.4 Data Collection Site (NGSIM BHL Data Analysis, 2005)

Tables 3.1, 3.2 and 3.3 summarize the average traffic flow characteristics in the three collection periods.

Table 3.1 Average Traffic Flow Characteristics During the Off peak Period

Time period (p.m.)	Number of vehicles	Density (veh/km/lane)	Speed (km/hr)	Flow (vph)	Heavy vehicles (%)
2:35 – 2:40	4,733	16.8	97.1	9,804	4.3
2:40 – 2:45		18.4	93.9	10,344	
2:45 – 2:50		17.7	94.5	10,020	
2:50 – 2:55		17.4	88.2	9,216	
2:55 – 3:00		24.7	65.2	9,648	
3:00 – 3:05		23.2	55.7	7,764	
Average		**19.7**	**80.2**	**9,466**	

Table 3.2 Average Traffic Flow Characteristics During the Transition Period

Time period (p.m.)	Number of vehicles	Density (veh/km/lane)	Speed (km/hr)	Flow (vph)	Heavy vehicles (%)
4:00 – 4:05	2,052	43.7	32.2	8,436	4.7
4:05 – 4:10		46.3	28.7	7,968	
4:10 – 4:15		53.1	25.2	8,028	
Average		**47.3**	**28.7**	**8,144**	

Table 3.3 Average Traffic Flow Characteristics During the Peak Period

Time period (p.m.)	Number of vehicles	Density (veh/km/lane)	Speed (km/hr)	Flow (vph)	Heavy vehicles (%)
5:00 – 5:05	3,626	49.2	27.5	8,124	3.8
5:05 – 5:10		55.6	23.2	7,752	
5:10 – 5:15		66.1	15.1	5,988	
5:15 – 5:20		59.6	21.9	7,836	2.7
5:20 – 5:25		57.3	21.2	7,284	
5:25 – 5:30		63.1	15.9	6,024	
Average		**56.3**	**21.2**	**7,168**	**3.2**

The resulting dataset includes the trajectories of 10,411 vehicles, with a total of about 7 million observations. This data was analyzed to detect all lane changes that took place. In order to be consistent with the way lane changes are handled in traffic simulation models, a lane change is defined as the passing from one lane to the lane immediately next to it. Vehicles that cross two or more lanes in a sequence are considered to make multiple lane changes.

3.2 Data Processing

The raw trajectory data was analyzed to detect all lane changes that took place. After omitting aborted lane changing attempts, a total of 1,617 successful lane changes were identified. Out of these lane changes, 1,233 (76.3%) are to the left, 112 (6.9%) of the lane changing vehicles are classified as heavy vehicles, and the rest are passenger cars.

For each one of these lane changes the initiation and completion points in time were identified. Algorithms to detect these points in the trajectory data and methodologies which identify these points from the line crossing observation for each lane change were developed. Afterwards, candidate points for the initiation were determined by examining observations up to 10 seconds (75 observations) backwards in the trajectory data. Similarly candidate points for the completion were identified up to 10 seconds (75 observations) forward in the trajectory data. The candidate points for the initiation were defined as those in which the change in the lateral position of the trajectory data was continuous for at least 5 observations (i+1: i+5) forwards to initiation i.e. approximately half a second. The difference between left turns to right turns is the sign of the lateral change in meter:

[1]a) $dx(i)>-0.01m$ & $dx(i+1:i+5)\leq-0.01m$ for changing lane to the left

b) $dx(i)<0.01m$ & $dx(i+1:i+5)\geq0.01m$ for changing lane to the right

meaning that the lane change has initiated in observation i+1 and it is not a normal maneuver in the current lane of the subject vehicle. Similarly candidate points for the completion were defined where the change in the lateral position of the trajectory data was continuous for at least 5 observations (i-5:i-1) backwards to completion.

[1] dx(i) is the lateral change of observation i in meter

a) dx(i-5:i-1)<-0.01m & dx(i)≥-0.01m for changing lane to the left

b) dx(i-5:i-1)>0.01m & dx(i)≤0.01m for changing lane to the right

meaning that the lane change has been completed in observation i-1 and it is not a normal maneuver in the current lane of the subject vehicle.

Each candidate initiation point was tested by five criteria to identify the suitable point as showed in Figure 3.5. The difference between left turns to right turns is the sign of the lateral change.

1. Average of 10 observations backwards of the lateral change (before the candidate point).
    - $criteria\ 1 = \frac{\sum_{i-9}^{i} dx(i)}{10} > 0.01m$ for changing lane to the right.
    - $criteria\ 1 = \frac{\sum_{i-9}^{i} dx(i)}{10} < -0.01m$ for changing lane to the left.
2. Average of 20 observations backwards of the lateral change (before the candidate point).
    - $criteria\ 2 = \frac{\sum_{i-19}^{i} dx(i)}{20} > 0.01m$ for changing lane to the right.
    - $criteria\ 2 = \frac{\sum_{i-19}^{i} dx(i)}{20} < -0.01m$ for changing lane to the left.
3. Average of 10 observations forwards of the lateral change (after the candidate point).
    - $criteria\ 3 = \frac{\sum_{i}^{i+9} dx(i)}{10} < 0.01m$ for changing lane to the right.
    - $criteria\ 3 = \frac{\sum_{i}^{i+9} dx(i)}{10} > -0.01m$ for changing lane to the left.
4. Average of 20 observations forwards of the lateral change (after the candidate point).
    - $criteria\ 4 = \frac{\sum_{i}^{i+19} dx(i)}{20} < 0.01m$ for changing lane to the right.

- $criteria\ 4 = \frac{\sum_{i}^{i+19} dx(i)}{20} > -0.01m$ for changing lane to the left.

5. Maximum slope forwards for right turn and minimum slope forwards for left turn of the lateral change of 20 observations (after the candidate point) with the remaining candidates.

- $criteria\ 5 = \max\left[\frac{\sum_{i}^{i+19} dx(i)}{20}\right]_{from\ remaining\ candidates}$ for changing lane to the right.
- $criteria\ 5 = \min\left[\frac{\sum_{i}^{i+19} dx(i)}{20}\right]_{from\ remaining\ candidates}$ for changing lane to the left.

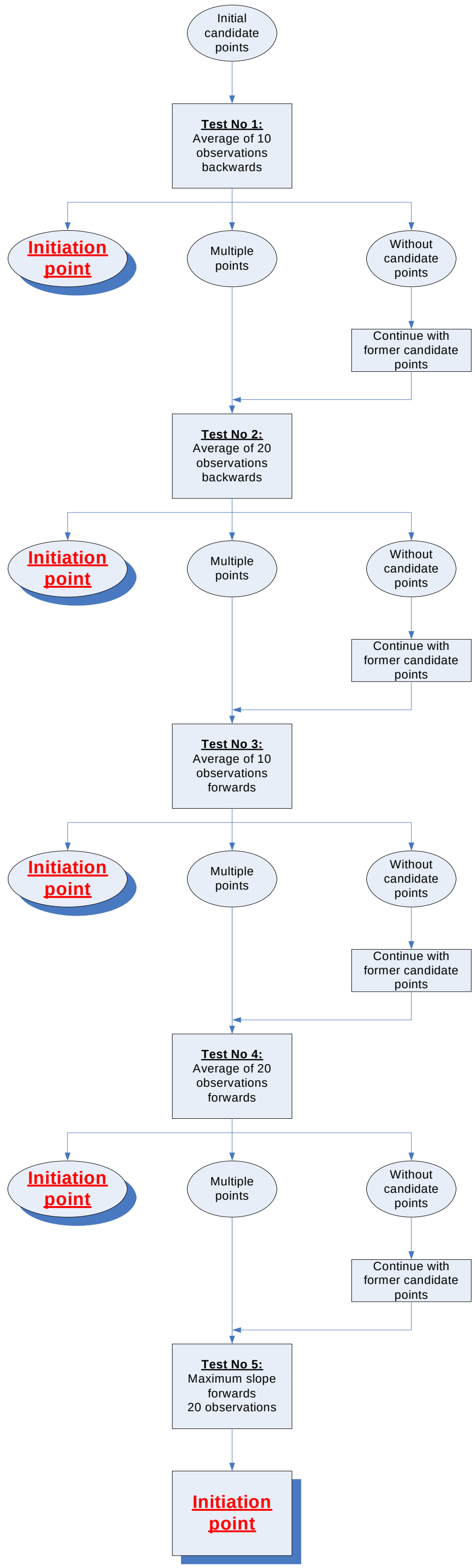

Figure 3.5 Algorithm to Find Lane Change Initiation Point

By running these tests we suitable point for the turnover point which defines the initiation of each lane change. Likewise each completion point was tested by the following five criteria to identify the suitable point as showed in Figure 3.6:

1. Average of 10 observations forwards of the lateral change (after the candidate point).
   - $criteria\ 1 = \frac{\sum_i^{i+9} dx(i)}{10} < 0.01m$ for changing lane to the right.
   - $criteria\ 1 = \frac{\sum_i^{i+9} dx(i)}{10} > -0.01m$ for changing lane to the left.
2. Average of 20 observations forwards of the lateral change (after the candidate point).
   a. $criteria\ 2 = \frac{\sum_i^{i+19} dx(i)}{20} < 0.01m$ for changing lane to the right.
   b. $criteria\ 2 = \frac{\sum_i^{i+19} dx(i)}{20} > -0.01m$ for changing lane to the left.
3. Average of 10 observations backwards of the lateral change (before the candidate point).
   - $criteria\ 3 = \frac{\sum_{i-9}^{i} dx(i)}{10} > 0.01m$ for changing lane to the right.
   - $criteria\ 3 = \frac{\sum_{i-9}^{i} dx(i)}{10} < -0.01m$ for changing lane to the left.
4. Average of 20 observations backwards of the lateral change (before the candidate point).
   - $criteria\ 4 = \frac{\sum_{i-19}^{i} dx(i)}{20} > 0.01m$ for changing lane to the right.
   - $criteria\ 4 = \frac{\sum_{i-19}^{i} dx(i)}{20} < -0.01m$ for changing lane to the left.
5. Maximum slope for right turn backwards and minimum slope backwards of the lateral change of 20 observations (before the candidate point) with the remaining candidates.

- $criteria\ 5 = \max\left[\frac{\sum_{i}^{i-19} dx(i)}{20}\right]_{from\ remaining\ candidates}$ for changing lane to the right.
- $criteria\ 5 = \min\left[\frac{\sum_{i}^{i-19} dx(i)}{20}\right]_{from\ remaining\ candidates}$ for changing lane to the left.

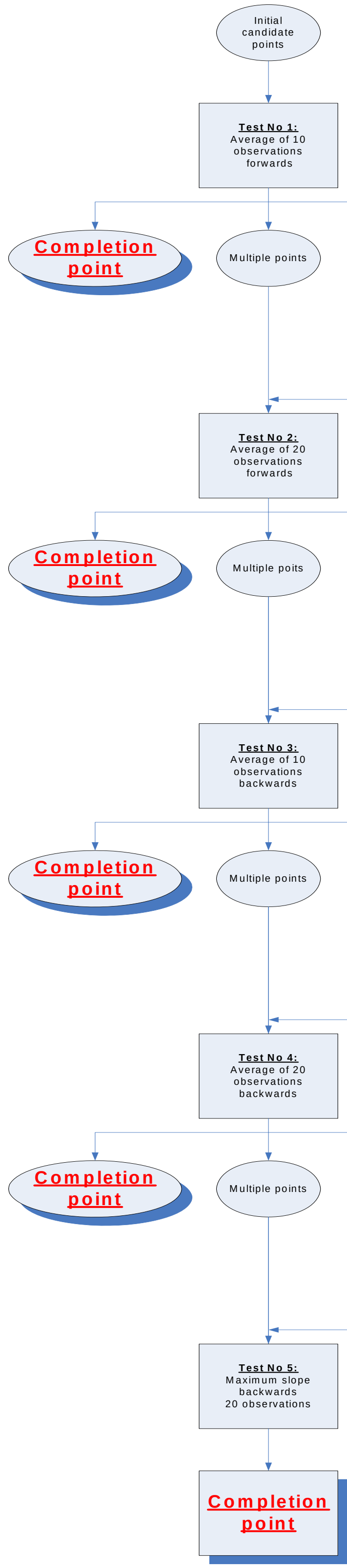

Figure 3.6 Algorithm to Find Lane Change Completion Point

By running these tests the suitable point for the turnover point which defines the completion of each lane change was obtained.

For each one of the lane changes the initiation and completion points in time were identified. The initiation and completion points were defined as the time instances when the lateral movement of the subject vehicle begins and ends, respectively. Figure 3.7 demonstrates these points on the trajectory of one of the vehicles in the dataset. The lane change duration is the time lapse between its initiation and completion. In order to validate the algorithm to detect the initiation and completion points, a Turing test was conducted.

The Turing test was inspired by a party game known as the "Imitation Game", in which a man and a woman go into separate rooms, and guests try to tell them apart by writing a series of questions and reading the type written answers sent back. In this game, both the man and the woman aim to convince the guests that they are the other. Turing proposed a test employing the imitation game as follows: "We now ask the question, 'What will happen when a machine takes the part of A in this game?' Will the interrogator decide wrongly as often when the game is played like this as he does when the game is played between a man and a woman? These questions replace our original, 'Can machines think?'" (Turing 1950) Later he suggested an "equivalent" alternative formulation involving a judge conversing only with a computer and a man.

Another algorithm can be tested in order to detect the initiation and completion points. e.g. Neural network which is sometimes used to refer to a branch of computational science that uses neural networks as models to either simulate or analyze complex phenomena and/or study the principles of operation of neural networks analytically. It addresses problems similar to artificial intelligence (AI) except that AI uses traditional computational algorithms to solve problems whereas neural networks use 'networks of agents' (software or hardware entities linked together) as the computational architecture to solve problems. Well-designed neural networks are trainable systems that can often "learn" to solve complex problems from a set of exemplars and generalize the "acquired knowledge" to solve unforeseen problems, i.e., they are self-adaptive systems.

In regards to the Turing test, the lane change initiation and completion points identified by the algorithm ("computer") for 200 lane changes, were compared against those identified visually ("man") in the trajectory data. The comparison showed a 94.7% matching between the points. The rest (5.3%) are a mistake of approximately $\pm(0.5 \ to \ 1)$ a second which are distributed 46% before and 54% after the identified point of the computer.

The algorithm was then applied to all lane changes in the dataset. In addition, other variables that may be used to explain lane change durations were generated. These variables include traffic characteristics (e.g. lane densities and average speeds), the characteristics and state of the subject vehicles (e.g. vehicle types, speeds, accelerations) and its relations with other vehicles around them (e.g. spacing and relative positions with respect to the vehicles in front and the lead and lag vehicles in the lane subjects are changing to). In all cases, the values of these variables at the time of the lane change initiation were associated with the lane change.

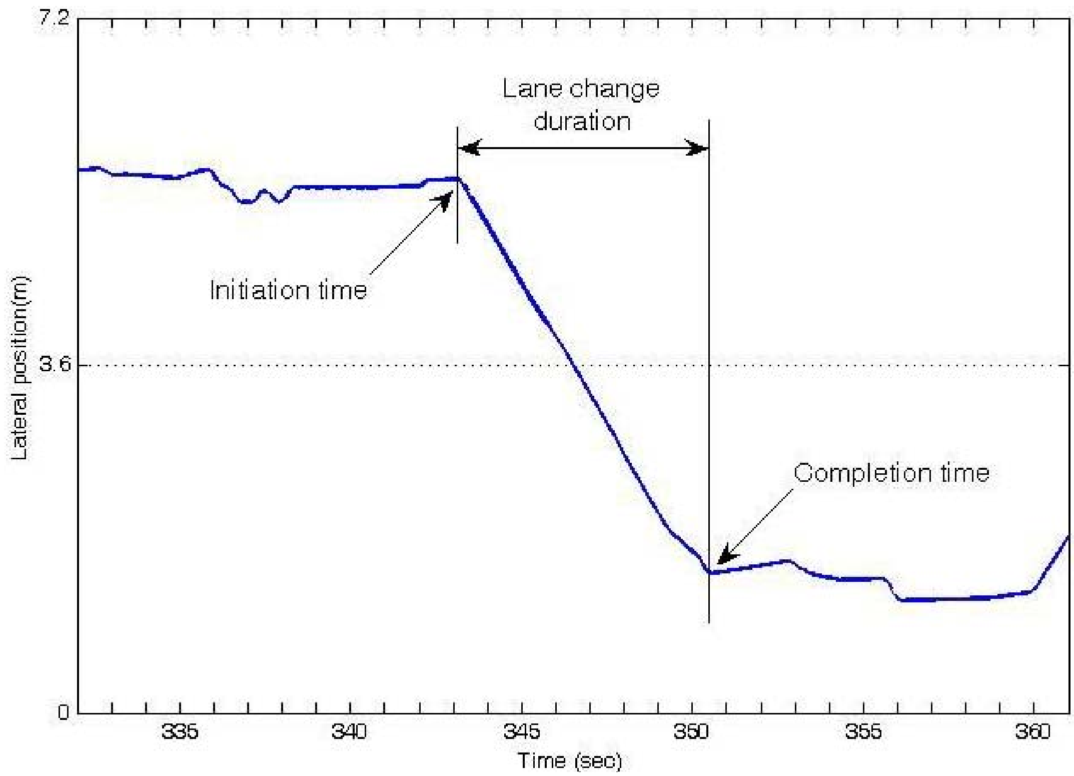

Figure 3.7 Definitions of Lane Change Initiation and Completion Time Points

3.3 Preliminary Analysis and Characteristics

Summary statistics of the lane change durations in the dataset and of other relevant variables are presented in Table 3.4. The subject vehicle, the vehicles around it and the variables that define the relations between them are shown in Figure 3.8. The front vehicle relative speed is calculated as the speed of the front vehicle less the speed of the subject vehicle. The lag – lead relative speed is calculated as the speed of the lag vehicle less the speed of the lead vehicle.

Table 3.4 Summary Statistics of Lane Change Duration and Related Variables

Variable	Mean	Median	Standard deviation	Minimum	Maximum
Lane change duration (sec)					
All	4.6	4.2	2.3	1.0	13.3
To the left	4.6	4.4	2.3	1.0	13.2
To the right	4.4	3.9	2.4	1.0	13.3

Variable	Mean	Median	Standard deviation	Minimum	Maximum
Passenger cars	4.6	4.3	2.3	1.0	13.3
Heavy vehicles	3.8	2.9	2.4	1.1	11.8
Other variables					
Subject speed (m/sec)	16.7	17.6	10.4	0.0	41.5
Front vehicle spacing (m)	30.0	18.4	31.9	0.1	274.6
Front vehicle relative speed (m/sec)	-0.6	-0.4	3.2	-16.7	17.1
Lag – lead spacing (m)	63.6	43.4	59.0	0.4	456.6
Lag – lead relative speed (m/sec)	0.2	-0.1	5.5	-26.1	15.2

As it can be seen in Table 3.4, there are differences between lane change durations executed to the left and those executed to the right. Lane changes to the left are consistently longer than to the right. Therefore, a two-tailed one-sample t-test was conducted on the null hypothesis that the mean lane change durations executed to the left and right are equal. With a t-statistic value of -2.713, the equality of the two means rejected at the 99% confidence level. Moreover, there are differences between lane change durations executed by passenger cars to those of heavy vehicles. The differences seem significant in the means between passengers cars compared to heavy vehicles. Therefore, these variables were tested in detail.

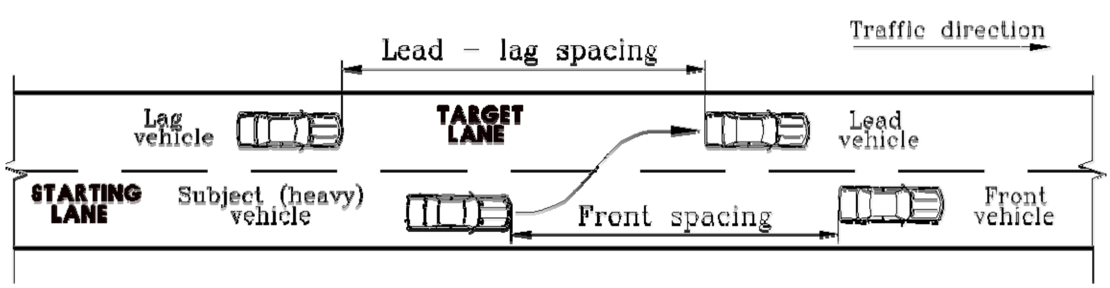

Figure 3.8 Definitions of the Subject Vehicle, Vehicles Around It and the Relations Between Them

The distribution of lane change durations in the sample is shown in Figure 3.9. The fitted line shown in the figure is based on a lognormal distribution that was fitted using maximum likelihood estimation ($\mu = 1.376$, $\sigma = 0.550$). The lognormal distribution guarantees that lane change durations are non-negative.

The models presented in the literature generally only refer to a single type of vehicle, in most cases passenger cars. A-priori it seems reasonable to expect that the lane change durations of heavy vehicles may differ significantly. In order to test that, a two-tailed one-sample t-test was conducted on the null hypothesis that the mean lane change durations of passenger cars and heavy vehicles are equal. With a t-statistic value of -3.55, the equality of the two means can be rejected at the 99% confidence level. Therefore, the presentation of lane change duration models in the next chapter begins with a model for passenger cars only. The observations of lane changes by heavy vehicles are then added and different specifications of their behavior are tested. The behavior of heavy vehicles is first assumed to be identical to that of passenger cars and then models are developed completely separate models for the two vehicle types.

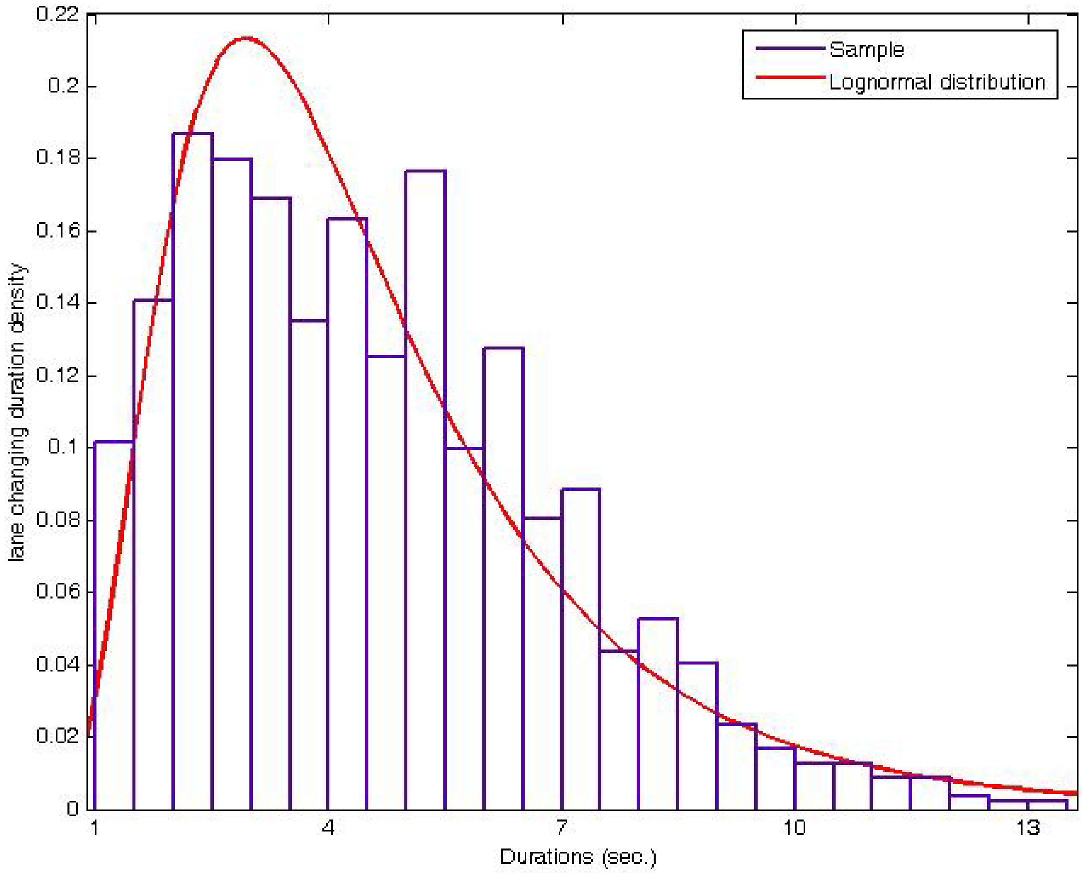

Figure 3.9 Distribution of Lane Changing Duration

3.4 Summary

In this chapter, the data for estimation of the lane change duration driving behavior model was discussed. The raw trajectory data was analyzed to detect all lane changes that took place. After omitting aborted lane changing attempts, a total of 1,617 successful lane changes were identified. 112 (6.9%) of the lane changing vehicles are classified as heavy vehicles, and the rest are passenger cars. 1,233 (76.3%) of the lane changes are to the left: 1,218 (72.6%) by passenger cars and 40 (35.7%) by heavy vehicles. Trajectory data, which consists of observations of the positions of vehicles at discrete points in time, is the basis to infer variables that may explain lane change durations. The characteristics of the collection site and the dataset used for model estimation in this research were summarized. The data represents a wide range of traffic conditions such as: off-peak, transition and peak periods with a total of one hour and fifteen minutes recording.

Definitions for initiation and completion points were suggested. A methodology to identify each one of the lane change initiation and completion points in time was developed and computerized in algorithm. In order to validate the algorithm to detect the initiation and completion points, a Turing test for 200 lane changes was conducted. The comparison showed a 94.7% matching between the points. Therefore the algorithm was then applied to all lane changes in the dataset.

An analysis of the lane change durations dataset was conducted. There are differences between lane change durations executed to the left and those executed to the right. Hence, a two-tailed one-sample t-test was conducted on the null hypothesis that the mean lane change durations executed to the left and right are equal. With a t-statistic value of -2.713, the equality of the two means rejected at the 99% confidence level. Therefore, these variables will be tested in detail in the next chapter. Moreover, there are differences between lane change durations executed by passenger cars to those of heavy vehicles. Hence, a two-tailed one-sample t-test was conducted on the null hypothesis that the mean lane change durations of passenger cars and heavy vehicles are equal. With a t-statistic value of -3.55, the equality of the two means rejected at the 99% confidence level. Therefore, the change direction and the heavy vehicles will be tested in detail in the next chapter.

Chapter 4 Model Specification and Estimation

This chapter presents the estimation results of the lane change duration model using the I-80 in Emeryville, California dataset. Statistical assessment and behavioral interpretation of the model's results are also presented. The models were estimated using a linear regression estimation procedure. The fitted models derived from this dataset are presented in the next section followed by the discussion of estimation results of the various variables.

4.1 General Specification

The lane changing action consists of two steps assumed to have been already decided: the decision to execute a lane chance and to accept the gap. Therefore, only the driver's lane changing actions are observed.

Lane change durations may depend on various factors, such as traffic conditions and the relations of the subject vehicle with other vehicles around it, and especially, the vehicle in front of it and the lead and lag vehicles in the lane it is changing to. Explanatory variables for lane changing can be classified into the following types of considerations:

1. Surrounding conditions – the subject vehicle's surroundings strongly affect its behavior during the lane change action. Most importantly, lane change durations are directly influence by the impact on the speed and acceleration of the subject vehicle and on the behavior of other vehicles during the lane change action and immediately after it is completed;
2. Lane change duration depends on the relative positions and speeds of the subject vehicle with respect to vehicles surrounding it. Other elements of the vehicles surroundings that may affect the behavior include geometry elements;
3. Traffic characteristics – the traffic density and average speed of the observed section influence the duration of lane changing. For example, in congested traffic,

the driver usually has to slow down first and wait for a while or speed up to squeeze in;

4. Urgency of the lane change – this may also be an important explanatory variable. For example, in order to exit a freeway a vehicle may have to perform mandatory lane changes (MLC) to be in the right-most lane. To accomplish this task the lane changes must be completed prior to the exit;
5. Lane change direction – this may also be an important explanatory variable. For example, changing lane to a faster passing traffic generates different durations than to a slower passing traffic.

Lane change durations are by definition non-negative. The fitted line shown in Figure 3.9 is based on a lognormal distribution. In order to ensure that predicted lane change durations are also non-negative we use the following model specification:

$$\ln\left(d_n\right) = \beta X_n + \varepsilon_n \tag{4.1}$$

d_n is the lane change duration for driver *n*. X_n is a vector of explanatory variables. β are the corresponding parameters. ε_n is the error term associated with observation *n*.

The modeling approach to estimate the model consists of three stages:

1. Estimation of a passenger car model;
2. Test suitability for heavy vehicle;
3. Developing heavy vehicle model.

4.2 Passenger Car Model

Estimation results of the passenger car lane change duration model are presented in Table 4.1. All but two of the estimated coefficients are significant at the 95% confidence level, and all are significant at the 90% confidence level.

Table 4.1 Estimation Results of the Passenger Car Lane Changing Duration Model

Variable		Parameter value	t-statistic
	Constant	1.114	19.8
x_{1n}	Traffic density (veh/km/lane)	0.01001	10.5
x_{2n}	Change direction (left=1, right=0)	0.06314	2.04
x_{3n}	$\min\left[0, \Delta V_n^{front}\right]$ (m/sec)	0.02470	3.99
x_{4n}	Front vehicle spacing (m)	0.0009627	1.93
x_{5n}	$\min\left[0, \Delta V_n^{lag,lead}\right]$ (m/sec)	0.01516	2.17
x_{6n}	$\max\left[0, \Delta V_n^{lag,lead}\right]$ (m/sec)	-0.01187	-1.81
x_{7n}	Lag – lead spacing (m)	-0.001064	-3.83
Number of observations = 1518, $R^2 = 0.205$, $adj\ R^2 = 0.201$			
Std error = 0.4834			

In summary, the passenger car lane change durations are given by:

$$\begin{aligned}\ln\left(d_n\right) &= 1.114 + 0.01001\times x_{1n} + 0.06314\times x_{2n} + 0.02470\times x_{3n} \\ &+ 0.0009627\times x_{4n} + 0.01516\times x_{5n} - 0.01187\times x_{6n} \\ &- 0.001064\times x_{7n} + \varepsilon_n \sim N\left(0, 0.4834\right)\end{aligned} \tag{4.2}$$

Figures 4.1, 4.2, 4.3, 4.4, 4.5 and 4.6 demonstrate the effect of the explanatory variables on the lane change durations of passenger cars. When these variables were not varied, the figures were generated with the following assumptions (see Figure 3.8):

- The lane change is to the right;
- Traffic density is 30 veh/km/lane;
- Zero speed differences between the various vehicles;
- Front spacing is 30 meters;

- Total gap size is 60 meters.

The most important variable, both in terms of relative magnitude and statistical significance is traffic density, which captures the impact of traffic conditions. Densities were calculated as a moving average over a period of 1 minute. Figure 4.1 shows that lane change durations increase when traffic density is higher as it becomes more difficult and risky to undertake the lane changing action.

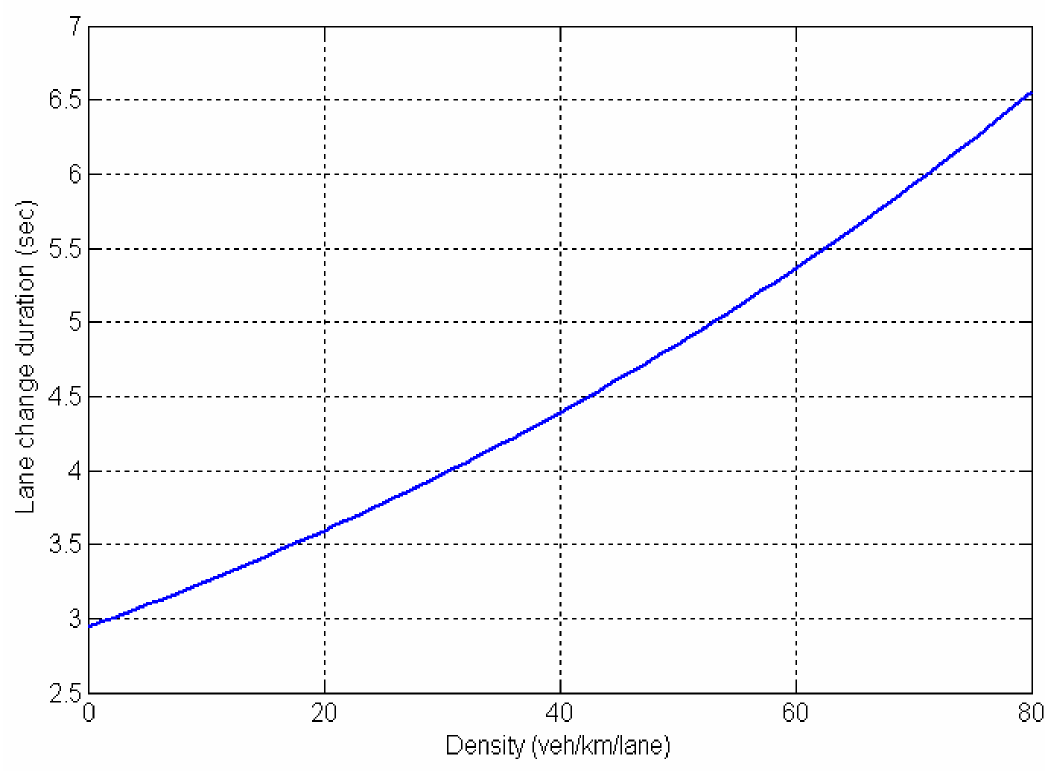

Figure 4.1 Effect of Density on Passenger Car Lane Change Durations

Risk aversion is also an important factor in the relations of the subject vehicle and the vehicle in front. ΔV_n^{front} is the front vehicle relative speed. Figure 4.2 shows the variable $\min\left[0, \Delta V_n^{front}\right]$ which captures the impact of the front vehicle relative speed in the case that the subject is faster, i.e., it is approaching the vehicle in front. In this case the completion of the lane change is more urgent since it is safer to complete the lane change sooner in order to reduce the risk of collision. The estimated parameter of this variable is positive, which indicates shorter lane change durations (the variable itself is always negative). No effect of this variable was identified when the subject is slower (i.e. the front vehicle is moving away from the subject vehicle). When the relative front speed increases the subject need not be concerned with the front vehicle and so can focus on the lane change itself and complete it slower.

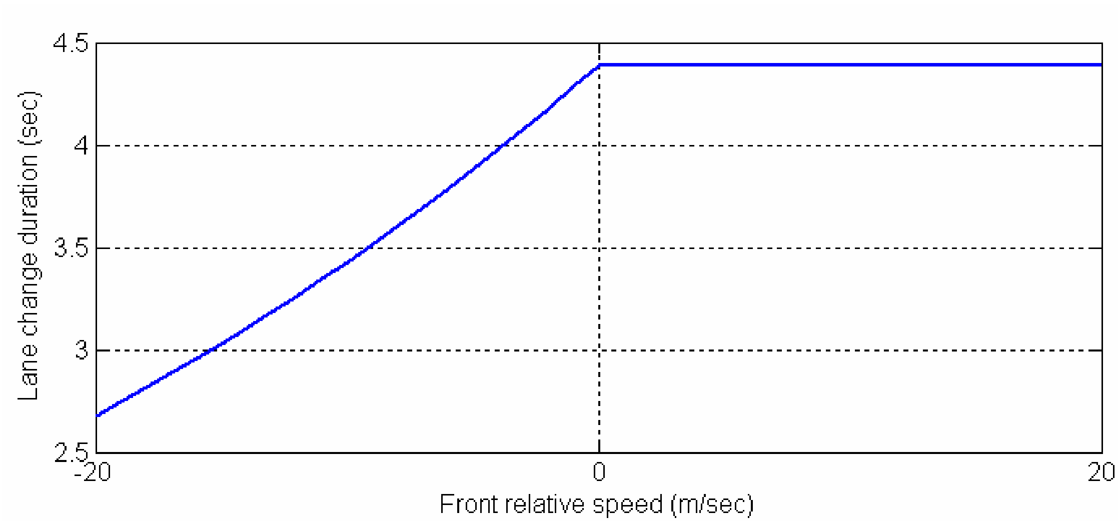

Figure 4.2 Effect of Front Relative Speed on Passenger Car Lane Change Durations

Similarly, lane change durations also decrease when the front vehicle spacing decreases as shown in Figure 4.3. With shorter spacing the collision risk is higher, and so lane change durations are shorter in order to reduce this risk. With large spacing the lane change urgency reduces and so drivers can complete the lane change slowly.

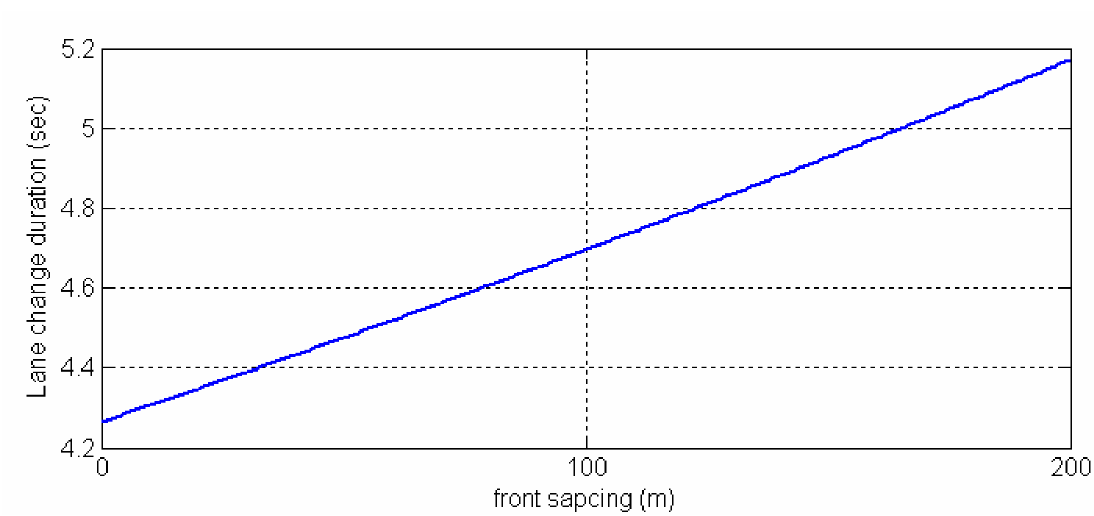

Figure 4.3 Effect of Front Spacing on Passenger Car Lane Change Durations

The other two important vehicles in the lane changing maneuver are the lead and lag vehicles. The model captures their impact through the spacing between them (the size of the gap the subject is changing into) and their relative speed, which indicated whether this gap is increasing or decreasing. There is a "conversation" between the subject vehicle and the lag and lead vehicles, they are transfer information between them following a reaction to each other movement.

$\Delta V_n^{lag,lead}$ is the lag – lead relative speed. Figure 4.4 shows that the lane change duration is longest when the speeds of the lead and the lag vehicles are equal. As with other variables when speeds vary, the risk and urgency associated with the lane change are affected and impact on its duration. When the lag vehicle is faster, i.e., the gap the vehicle is changing into is getting smaller, there may be an urgency on the part of the driver to complete the lane change before the opportunity to do so disappears. The situation in which the lead vehicle is faster, i.e., the gap that the subject is changing into is getting larger, is simpler in terms of the risk associated with the lane change. Therefore, drivers may be able to complete the lane change faster. In order to complete the subject vehicle lane change, the lag vehicle will decelerate. Therefore, drivers may be able to complete the lane change faster.

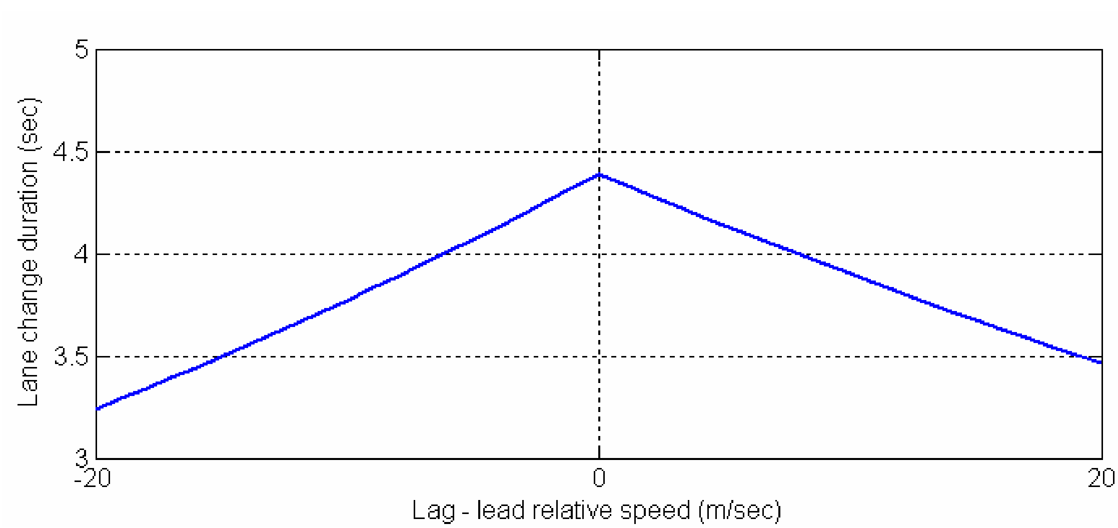

Figure 4.4 Effect of Lag – Lead Relative Speed on Passenger Car Lane Change Durations

Figure 4.5 shows that the lane change duration increases when the size of the gap between the lead and lag vehicles decreases. A smaller gap implies higher risk for lane changing. Consistent with the interpretation of other parameters, drivers may chose to change lanes more cautiously and take longer when the associated risk is higher.

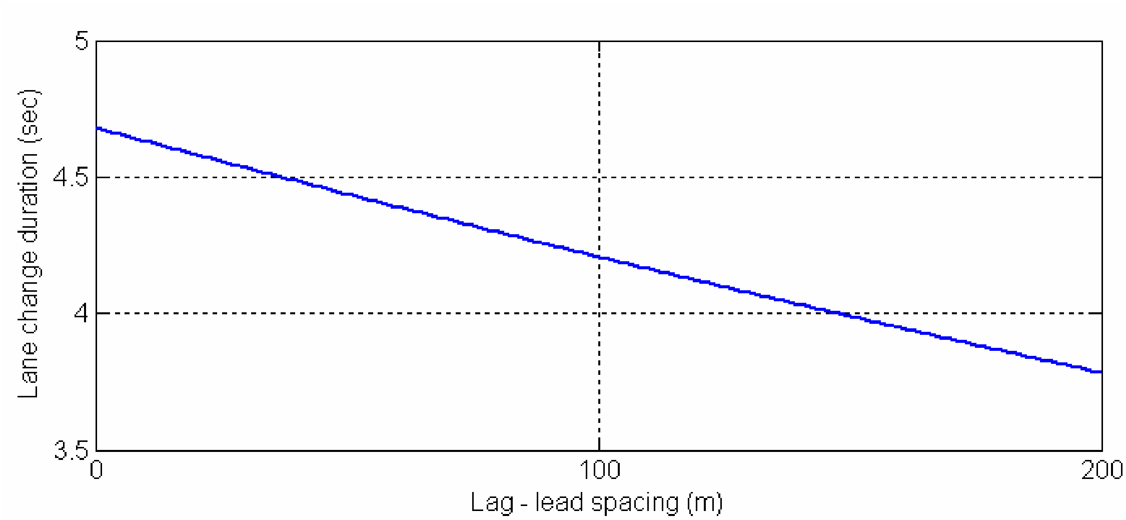

Figure 4.5 Effect of Lag – Lead Spacing on Passenger Car Lane Change Durations

The coefficient of the lane change direction variable is positive, which indicates that drivers take longer to complete changes to the left compared to changes to the right as shown in Figure 4.6. This result is consistent with results reported in Lee et al. (2003) that left lane changes had a larger mean duration (11.1 seconds) than did right lane changes (6.6 seconds). For the mean lane change duration, the difference between the directions is about 0.3 seconds. A possible explanation may be that in the data collection site, as in most cases in right-hand driving, traffic is faster on the left lanes. As a result drivers changing to the left are slower than passing traffic, which makes the lane change riskier. Drivers are then more cautious in changing lanes and so take longer to complete the lane changes. However, in approaching off-ramps and weaving lanes it may be possible that the duration of lane changes to the right will last longer than those to the left because of the queue that is accumulating on the off-ramp.

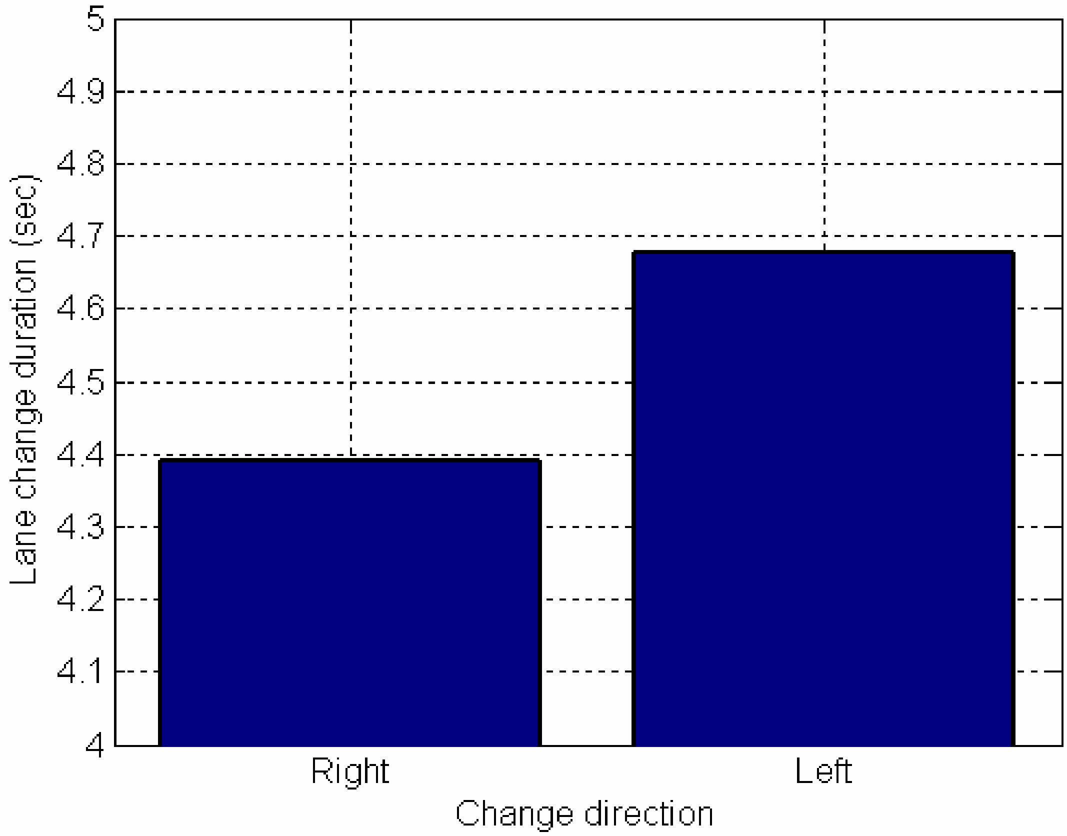

Figure 4.6 Effect of Change Direction on Passenger Car Lane Change Durations

In addition to the t-test that was conducted, the hypothesis that there is a difference between lane change behaviors which executed to the left rather than those executed to the right was tested in more detail. We estimated two models with separation between the change of direction. This model assumes that the lane change durations of the two directions are completely different, and so all explanatory variables of the two directions may differ. It was estimated as two entirely separate models: a model for cars changing lanes to the left and another model for cars changing lanes to the right.

In order to test the difference between these alternative models, F-tests were conducted on the restrictions imposed on the models in which lane change durations who executed to the left and those to the right are similar compared to the change direction models where they are allowed to differ.

The F distribution can be useful for testing a hypothesis in the context of the multiple regression models. There are number of instances in which the F-tests can be useful:

a. Joint tests on several regression coefficients;

b. Tests involving the equality of coefficients of different regressions.

The F-test statistics for these tests are calculated by:

$$F_{q,N-k} = \frac{ESS_R - ESS_{UR}}{ESS_{UR}} \cdot \frac{N-k}{q} \tag{4.3}$$

ESS_R and ESS_{UR} are the errors (unexplained) sums of squared regression residuals for the restricted and the unrestricted models, respectively. N and k are the number of observations in the sample and the number of parameters in the unrestricted model, respectively. q is the number of restrictions made.

Test Involving the Equality of Coefficients of Different Regressions

The passenger car model was tested against the change direction model, which allows all parameters of the model to differ between the change directions.

General Model:

$$Y_{left} = \beta_{0left} + \beta_1 x_{1left} + \beta_2 x_{2left} + \beta_3 x_{3left} + \beta_4 x_{4left} + \beta_5 x_{5left} + \beta_6 x_{6left} + \varepsilon_{left} \tag{4.4}$$

$$\begin{aligned} \ln(d_n) &= 1.17 + 0.02151 \times x_{1n} + 0.01532 \times x_{2n} - 0.01088 \times x_{3n} - 0.00131 \times x_{4n} \\ &\quad + 0.00086 \times x_{5n} + 0.01002 \times x_{6n} + \varepsilon_{left} \sim \left(0, 0.4781)\right) \end{aligned}$$

$$Y_{right} = \alpha_{0right} + \alpha_1 x_{1right} + \alpha_2 x_{2right} + \alpha_3 x_{3right} + \alpha_4 x_{4right} + \alpha_5 x_{5right} + \alpha_6 x_{6right} + \varepsilon_{right} \tag{4.5}$$

$$\begin{aligned} \ln(d_n) &= 1.004 + 0.02061 \times x_{1n} + 0.00717 \times x_{2n} - 0.00909 \times x_{3n} \\ &\quad - 0.00077 \times x_{4n} + 0.00031 \times x_{5n} + 0.01277 \times x_{6n} + \varepsilon_{right} \sim (0, 0.5165) \end{aligned}$$

The null hypothesis, is that – $H_0 : \alpha_0 = \beta_0,\ \alpha_1 = \beta_1, ..., \alpha_6 = \beta_6$.

Since there are 6+6=12 variables in the change direction model and 7 variables in the passenger car model which have been adopted, the result is $q = 12 - 7 = 5$ restrictions. The number of degrees of freedom is the sum of the number of degrees of freedom in each individual regression, that is,

$$(N-k)+(M-k) = N + M - 2k = 1233 + 384 - 12 = 1605.$$

The unrestricted sum of squares calculated as the sum of the error sums of squares of the individual models:

$$ESS_{UR} = ESS_{left} + ESS_{right}$$

The null hypothesis is rejected if $F_{5,1605} > F_{0.90}(5,1605)$.

$$F_{5,1605} = \frac{381.47-(280.29+100.57)}{(280.29+100.57)} \times \frac{1617-12}{5} = 0.514 < 1.84727 \qquad (4.6)$$

Since F is smaller than the critical value at the 10 percent level of significance, the null hypothesis of one model including the change direction dummy as a variable can not be rejected. Hence, it is not possible to split the model into two separate regressions, meaning the data can be pooled.

In summary, the regression statistics for the models and the test statistics and results are shown in Table 4.2. The passenger car model was tested against the change direction model, which allows all parameters of the model to differ between the two directions. For the unrestricted model, ESS_{UR}, N and k are calculated as the respective sums over the two separate models. The test result is that the restricted passenger car model can not be rejected.

The conclusion is therefore that the lane change durations of the two directions can be pooled together, and should not be modeled separately.

Table 4.2 Estimation Results and Statistical F-tests for the Three Models (*cd*)

<table>
<tr><th>Model</th><th>N</th><th>k</th><th>R^2</th><th>ESS</th><th>q</th><th>F</th><th>P-value</th></tr>
<tr><td>Passenger car</td><td>1617</td><td>7</td><td>0.208</td><td>381.47</td><td colspan="2">Against passenger car model</td><td rowspan="3">0.7659</td></tr>
<tr><td rowspan="2">Change direction</td><td>1233</td><td>6 (left)</td><td>0.206</td><td>280.29</td><td rowspan="2">5</td><td rowspan="2">0.514</td></tr>
<tr><td>384</td><td>6 (right)</td><td>0.187</td><td>100.57</td></tr>
</table>

Vehicles which exit from the off-ramp may have to perform MLC in order to be in the right-most lane, otherwise they will miss the off-ramp exit. A-priori hypothesized that the closer the driver is to the off-ramp he will execute the lane changing faster. However, variables related to the nature of the lane change (e.g. MLC that are taken in order to use an off-ramp and drivers that take multiple lane changes in a sequence) and its urgency (e.g. the distance to the exit point) were not statistically significant in the model and therefore omitted. A possible reason for this result is that most of the vehicles making MLC already positioned themselves on the right-most lane or the lane next to it at the upstream end of the section and so, only 48 vehicles were observed making more than one lane change within the section.

4.3 Treatment of Heavy Vehicle

As discussed above, the lane changing behavior of heavy vehicles may differ from that of passenger cars. In this section this hypothesis is tested. Starting with the model presented above for passenger cars, three models were estimated with on increasing level of separation between passenger cars and heavy vehicles:

- **Model 1** – The same model specification that was used for passenger cars was estimated for all observations, including those of heavy vehicles. All parameters are common for the two vehicle types. The assumption in this model is that there is no difference at all between the lane change durations of the two vehicle types;

- **Model 2** – This model extends model 1 by assuming that the regression constant is vehicle type specific. All other parameters in the model are common to the two vehicle types. This model implies that the difference between lane changing durations of passenger cars and heavy vehicles is systematic and constant can be fully captured by a vehicle type dummy variable;
- **Model 3** – This model assumes that the lane change durations of the two vehicle types are completely different, and so all parameters for the two vehicles types may differ. It was estimated as two entirely separate models: a model for passenger cars, and another model for heavy vehicles, with the same specification.

In order to select among these alternative models, F-tests were conducted on the restrictions imposed on the models in which lane change durations of passenger cars and heavy vehicles are similar compared to the more general models where they are allowed to differ. The regression statistics for the three models and the test statistics and results are shown in Table 4.3.

Test 1 – Joint Test on Several Regression Coefficients

The first test is on the null hypothesis that the constants for the two vehicle types are the same. This test is imposed on model 1 compared to model 2.

Model 1:

$$Y_R = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_5 x_5 + \beta_6 x_6 + \beta_7 x_7 + \varepsilon_R \qquad (4.7)$$

$$\ln(d_n) = 1.086 + 0.02052 \times x_{1n} + 0.01340 \times x_{2n} - 0.01053 \times x_{3n} + 0.06146 \times x_{4n}$$
$$0.00634 \times x_{5n} + 0.01056 \times x_{6n} + \varepsilon_n \sim (0,04869)$$

Model 2:

$$Y_{UR} = (\beta_0 + \beta_{hv}) + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_5 x_5 + \beta_6 x_6 + \beta_7 x_7 + \beta_8 x_8 + \varepsilon_{UR} \tag{4.8}$$

$$\ln(d_n) = 1.097 + 0.02282 \times x_{1n} + 0.01298 \times x_{2n} - 0.01026 \times x_{3n} + 0.04723 \times x_{4n}$$
$$- 0.00098 \times x_{5n} + 0.00087 \times x_{6n} - 0.13500 \times x_{7n} + \varepsilon_n \sim (0,04861)$$

The null hypothesis, is that – $H_0 : \beta_{k-q+1} = \cdots = \beta_k = 0 \Rightarrow \quad \beta_{8-1+1} = \cdots = \beta_8$

Since there are 8 variables in model 2 and 7 variables in model 1, then there is $q = 8 - 7 = 1$ restriction. The number of degrees of freedom is $N - k = 1617 - 8 = 1609$.

The null hypothesis will be rejected if $F_{1,1609} > F_{0.95}(1,1609)$.

$$F_{1,1609} = \frac{381.47 - 380.01}{380.01} \times \frac{1617 - 8}{1} \cong 6.18 > 3.8415 \tag{4.9}$$

Since F is greater than the critical value at the 5 percent level of significance, the null hypothesis of the heavy vehicle dummy variable equal to zero is rejected. Hence, the heavy vehicle dummy variable is necessary for the model.

<u>Test 2 – Test Involving the Equality of Coefficients of Different Regressions</u>

Model 2 is tested against the more general model 3, which allows all parameters of the model to differ between passenger cars and heavy vehicles.

Model 3:

$$Y_{pc} = \beta_{0pc} + \beta_1 x_{1pc} + \beta_2 x_{2pc} + \beta_3 x_{3pc} + \beta_4 x_{4pc} + \beta_5 x_{5pc} + \beta_6 x_{6pc} + \beta_7 x_{7pc} + \varepsilon_{pc} \tag{4.10}$$

$$\ln(d_n) = 1.114 + 0.01001 \times x_{1n} + 0.06314 \times x_{2n} + 0.02470 \times x_{3n}$$
$$+ 0.00096 \times x_{4n} + 0.01516 \times x_{5n} - 0.01187 \times x_{6n} - 0.00011 \times x_{7n} + \varepsilon_n \sim (0, 0.4384)$$

$$Y_{hv} = \alpha_{0hv} + \alpha_1 x_{1hv} + \alpha_2 x_{2hv} + \alpha_3 x_{3hv} + \alpha_4 x_{4hv} + \alpha_5 x_{5hv} + \alpha_6 x_{6hv} + \alpha_7 x_{7hv} + \varepsilon_{hv} \tag{4.11}$$

$$\ln(d_n) = 0.586 - 0.02045 \times x_{1n} - 0.00217 \times x_{2n} + 0.00861 \times x_{3n}$$
$$- 0.14400 \times x_{4n} + 0.000009 \times x_{5n} + 0.00020 \times_{6n} + 0.02246 \times x_{7n} + \varepsilon_n \sim (0, 0.5163)$$

The null hypothesis, is that – $H_0 : \alpha_0 = \beta_0, \;\; \alpha_1 = \beta_1, ..., \alpha_7 = \beta_7$.

Since there are 7+7=14 variables in model 3 and 8 variables in model 2 when adopted, then there are $q = 14 - 8 = 6$ restrictions. The number of degrees of freedom is the sum of the number of degrees of freedom in each individual regression, that is, $(N - k) + (M - k) = N + M - 2k = 1518 + 99 - 14 = 1603$.

The unrestricted sum of squares calculated as the sum of the error sums of squares of the individual models: $ESS_{UR} = ESS_{Passenger\ car} + ESS_{Heavy\ vehicle}$

The null hypothesis will be rejected if $F_{6,1603} > F_{0.95}(6,1603)$.

$$F_{6,1603} = \frac{380.01 - (352.78 + 24.26)}{(352.78 + 24.26)} \times \frac{1617 - 14}{6} \cong 2.11 > 2.0986 \qquad (4.12)$$

Since F is greater than the critical value at the 5 percent level of significance, the null hypothesis of one model including heavy vehicle dummy as a variable is rejected. Hence, splitting the model into two separate regressions must be estimated, the data cannot be pooled.

The first test was on the null hypothesis that the restriction that the constants for the two vehicle types are the same, which was imposed on model 1 compared to model 2. This test is justified. The result is that the restricted model can be rejected with a confidence level of more than 98% and the unrestricted model 2 is adopted. Then, model 2 was tested against the more general model 3, which allows all parameters of the model to differ between passenger cars and heavy vehicles. For the unrestricted model, ESS_{UR},

N and k are calculated as the respective sums over the two separate models. The test result is that the restricted model 2 can be rejected at the 95% confidence level.

The conclusion is therefore that the lane change durations of passenger cars and heavy vehicles cannot be pooled together, hence should be modeled separately.

Table 4.3 Estimation Results and Statistical F-tests for the Three Models (*hv*)

Model	N	k	R^2	ESS	q	F	P-value
1	1617	7	0.208	381.47	-	-	-
2	1617	8	0.211	380.01	Against model 1		0.013
					1	6.18	
3	1518	7 (cars)	0.205	352.78	Against model 2		0.049
	99	7 (heavy)	0.232	24.26	6	2.11	

4.4 Heavy Vehicle Model

The test results showed that the heavy vehicle model differs significantly from the passenger car model. Therefore the best model for the heavy vehicles was fitted. Various specifications of models for the lane change durations of heavy vehicles only were tested. The final estimation results are presented in Table 4.4. ΔV_n^{ave} is the subject relative speed with respect to the average speed in the section (i.e. the average speed less the subject speed). All estimated coefficients except the one for the change direction are significant at the 95% confidence level, and all are significant at the 90% confidence level. The mean duration of lane changes for heavy vehicles is shorter compared to passenger cars. This may be because heavy vehicle drivers are usually professional drivers and their field of view forwards is much higher than those of passenger car drivers.

Table 4.4 Estimation Results of the Heavy Vehicle Lane Changing Duration Model

Variable		Parameter value	t-statistic
	Constant	0.790	6.25
x_{1n}	Traffic density (veh/km/lane)	0.02104	5.50
x_{2n}	Change direction (left=1, right=0)	-0.178	-1.76
x_{3n}	$\max\left[0, \Delta V_n^{front}\right]$ (m/sec)	-0.04775	-2.91
x_{4n}	ΔV_n^{ave} (m/sec)	0.02972	2.13
Number of observations = 112, $R^2 = 0.300$, $adj\ R^2 = 0.274$			
Std error = 0.4973			

In summary, the heavy vehicle lane change durations are given by:

$$\begin{aligned} \ln\left(d_n\right) &= 0.79 + 0.02104 \times x_{1n} - 0.178 \times x_{2n} - 0.04775 \times x_{3n} \\ &\quad + 0.02972 \times x_{4n} + \varepsilon_n \sim N\left(0, 0.4973\right) \end{aligned} \tag{4.13}$$

Figures 4.7, 4.8, 4.9 and 4.10 demonstrate the effect of the explanatory variables on the lane change durations of heavy vehicles. The values of the various variables that were used to generate these figures are identical to those used with the passenger car model.

As with the passenger car model, lane change durations increase with traffic density as shown in Figure 4.7. However, the magnitude of the impact on durations here is larger. A possible explanation may be that the size of a heavy vehicle makes it much more difficult and risky to undertake the lane changing action than passenger cars in particular at density conditions.

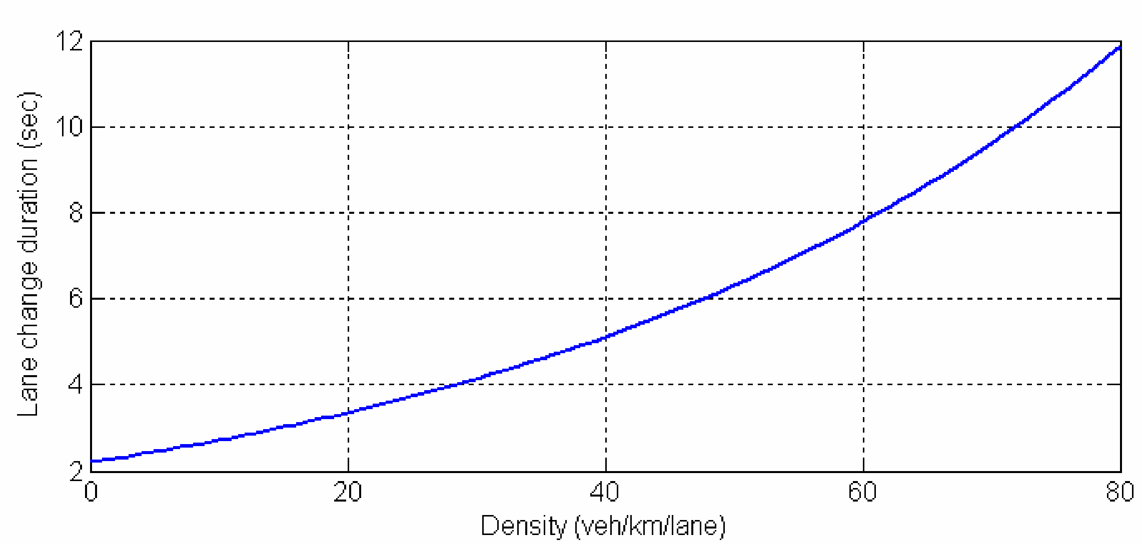

Figure 4.7 Effect of Density on Heavy Vehicle Lane Change Durations

The impact of the front relative speed indicates that drivers may be able to change lanes in a shorter time when the task is easier as shown in Figure 4.8. When the relative front speed increases the subject need not be concerned with the front vehicle and so can focus on the lane change itself and complete it sooner. This is different from what was observed in cars, a possible explanation may be that heavy vehicles needs much more space to maneuver and in order to reduce the risk of collision the driver will execute the lane change faster.

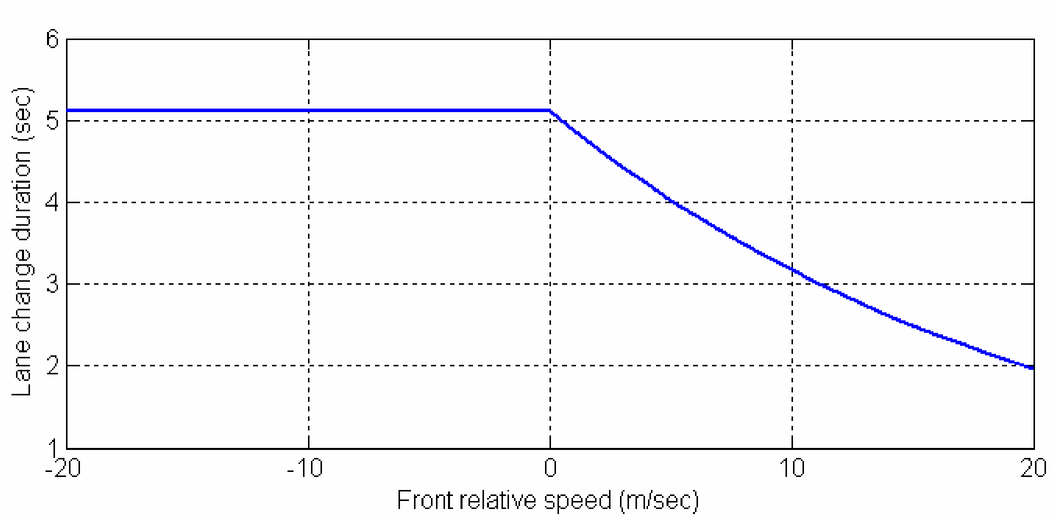

Figure 4.8 Effect of Front Relative Speed on Heavy Vehicle Lane Change Durations

Similar risk aversion behavior can also explain the impact of the difference between the average speed and the subject's speed on the lane change durations as shown in Figure 4.9. As this difference increases (i.e., the subject is slower compared to prevailing traffic speed), lane changes become riskier and so drivers take longer to complete them.

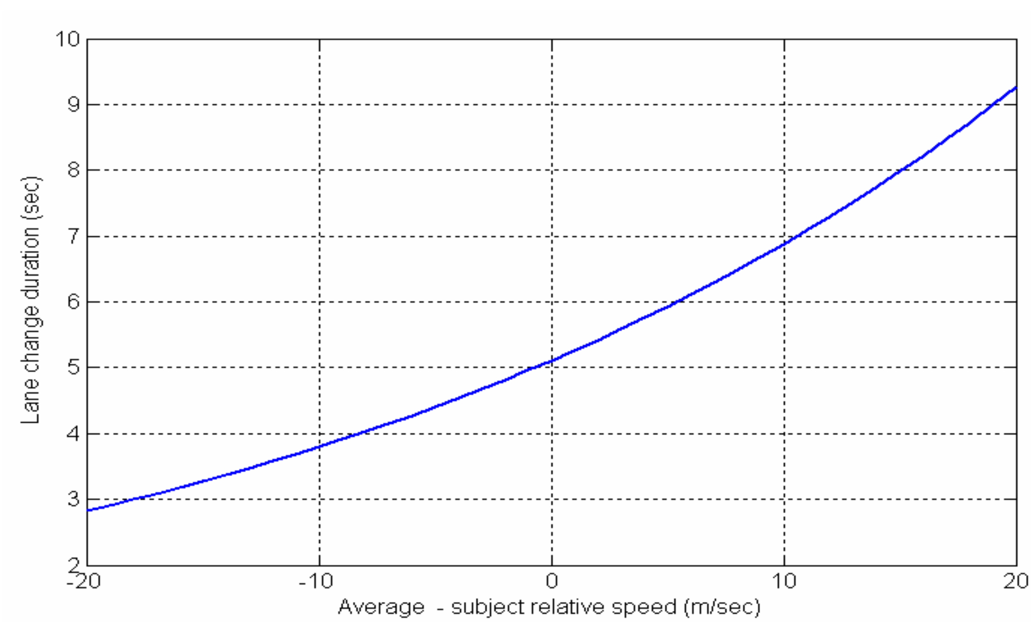

Figure 4.9 Effect of Average – Subject Relative Speed on Heavy Vehicle Lane Change Durations

Unlike passenger cars, heavy vehicles take longer to change lanes to the right compared to the left as shown in Figure 4.10. The reason for this may be that because of the dimensions of the vehicles, heavy vehicle drivers have a very good field of view to their left, but only limited sight on their right.

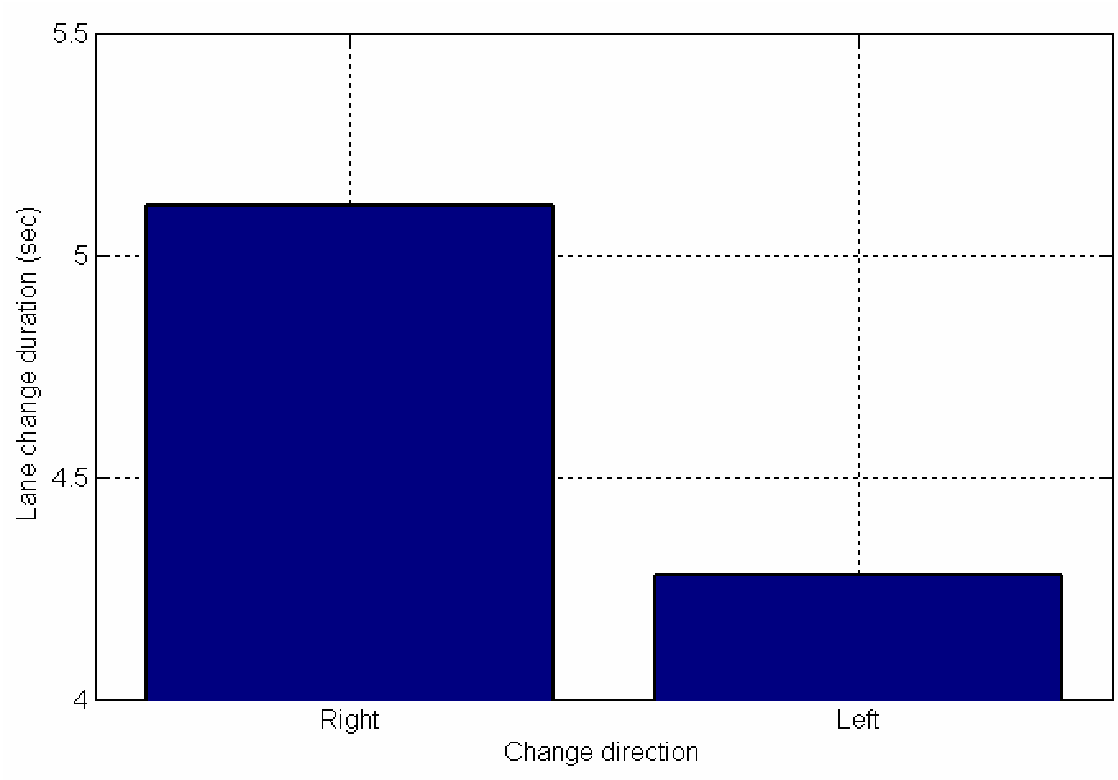

Figure 4.10 Effect of Change Direction on Heavy Vehicle Lane Change Durations

The variables related to the lead and lag vehicles, which were significant in the passenger car model, were not in the heavy vehicle model. A possible explanation may be that the maneuverability of heavy vehicles is lower and so they cannot respond to these vehicles after they initiated the lane change. Furthermore, these vehicles may be more cautious towards the heavy vehicle, and are therefore the ones making changes in their behavior to accommodate the lane change. As with the passenger car model, the lane change urgency was not significant in this model.

4.5 Summary

In this chapter, estimation results of the duration of lane changes were presented. Separate models were presented for passenger cars and for heavy vehicles and statistical tests for the similarity between the lane change durations of the two vehicle types were conducted. In addition, statistical tests were conducted for the similarity between the lane change directions. The results indicate that lane changes are not instantaneous events as most microscopic traffic simulations model them, but may have durations in the range of 1.0 to 13.3 seconds, with a mean of 4.6 seconds.

Lane change durations are affected by traffic conditions captured by the traffic density, by the direction of change and by other vehicles around the subject vehicle. However, lane change durations are not affected by variables related to the nature and urgency of lane change, such as MLC that are taken in order to use an off-ramp.

Our results indicate that the lane change durations for passenger cars and for heavy vehicles differ significantly. The mean duration of lane changes for heavy vehicles is shorter compared to passenger cars. This may be because heavy vehicle drivers are usually professional drivers. However, with both vehicle types, lane change durations are longer when the maneuver is riskier or when the task is complicated by the relations of the subject vehicle with other vehicles.

The variables related to the lead and lag vehicles, which were significant in the passenger car model, were not significant in the heavy vehicle model. A possible explanation may be that the maneuverability of heavy vehicles is lower and so they cannot respond to these vehicles after they have initiated the lane change. Furthermore, these vehicles may be more cautious towards the heavy vehicle, and are therefore the ones making changes in their behavior to accommodate the lane change.

Chapter 5 Conclusions

This chapter summarizes the research reported in this thesis and highlights the major contributions. Finally, directions for future research are suggested.

Lane changes have a significant impact on the characteristics of traffic flow. However, lane changing models used in microscopic traffic simulation models emphasize the decision-making aspects of the task, but generally neglect the detailed modeling of the lane changing action itself and its duration. In the past, data that has been used to estimate lane change durations was mostly collected in small samples using instrumented vehicles or driving simulators, which may introduce biases in drivers' behavior. In this subject research, naturalistic trajectory data has been used at a high time resolution that was collected from high mounted cameras to estimate lane change duration models.

5.1 Research Summary

Lane change duration models were presented separately for passenger cars and heavy vehicles. Lane changes are not instantaneous events as most microscopic traffic simulations model them, but may have durations in the range of 1.0 to 13.3 seconds, with a mean of 4.6 seconds.

For each lane change the initiation and completion points in time were identified. The initiation and completion points were defined as the time instances when the lateral movement of the subject vehicle begins and ends, respectively. The lane change duration is the time lapse between its initiation and completion.

An algorithm to detect these points in trajectory data has been developed. The algorithm is based on five criteria to identify the suitable point five criteria to identify the suitable point for each initiation and completion point. In order to validate the algorithm to detect the initiation and completion points, a Turing test, in which the lane change initiation and completion points identified by the algorithm for 200 lane changes were compared against those identified visually in the trajectory data, was conducted. The comparison showed a 94.7% matching between the points. The algorithm was then applied to all lane changes in the dataset.

Variables that may be used to explain lane change durations were also generated. These variables include traffic characteristics (e.g. lane densities and average speeds), the characteristics and state of the subject vehicles (e.g. vehicle types, speeds, accelerations) and its relations with other vehicles around them (e.g. spacing and relative positions with respect to the vehicles in front and the lead and lag vehicles in the lane subjects are changing to). In all cases, the values of these variables at the time of the lane change initiation were associated with the lane change.

The hypothesis that lane change durations executed to the left may differ significantly from those executed to the right was tested. In order to test that, initially a two-tailed one-sample t-test was conducted on the null hypothesis that the mean lane change durations of the change direction are equal. With t-statistic value of -2.713, the equality of the two means was rejected at the 99% confidence level. Therefore, in the modeling effort, two models were estimated with separation between the change of direction and statistical tests conducted in order to select among them. The test results indicate that the lane change durations executed to the left and right do not differ. The conclusion is therefore that the lane change durations of the two directions can be pooled together as dummy variable, and should not be modeled separately.

Similarly, the hypothesis that lane change durations of heavy vehicles may differ significantly from passenger cars was also tested. In order to test that, initially a two-tailed one-sample t-test was conducted on the null hypothesis that the mean lane change durations of passenger cars and heavy vehicles are equal. With a t-statistic value of -3.55, the equality of the two means was rejected at the 99% confidence level. Therefore, in the modeling effort, three models were estimated with increasing level of separation between passenger cars and heavy vehicles and statistical tests conducted in order to select among them. The test results indicate that the lane change durations for passenger cars and for heavy vehicles differ significantly. However, with both vehicle types, lane change durations are longer when the maneuver is riskier or when the task is complicated by relations of the subject vehicle with other vehicles.

5.2 Contribution

The objective of this research is to improve modeling of driving behavior and in particular to develop detailed models of the duration of the lane changes behavior. Existing models of lane changing behavior generally neglect the detailed modeling of the lane changing action itself and only model it as an instantaneous event. However, this assumption contradicts the research findings that lane changing durations are on average 4.6 seconds. Therefore, the omission of lane-changing duration from microscopic simulation models may have a significant impact on simulated traffic flow characteristics and on simulation outputs. This research contributes to the state-of-the-art in driving behavior modeling in the following aspects:

- The studies that explored lane change duration focus on the statistics analyzing of the lane change duration. In this research we developed lane change duration driving behavior models were developed;
- The models presented in the literature usually analyze the data on the basis of variables that are related to drivers' characteristics such as gender, age and character. However, such models are not applicable to microscopic traffic simulators. The model developed herein is oriented towards implementation of these models and uses appropriate variables e.g. traffic conditions such as density and relations with neighboring vehicles such as lag, lead and front vehicles;
- In most studies human observers or obtrusive equipment were used to collect the data. This may have an impact on drivers' behavior. The model developed herein is estimated with naturalistic vehicle trajectory data that was collected in a freeway section without the drivers' knowledge;
- The models presented in the literature generally only refer to a single type of vehicle, in most cases passenger cars. This research distinguishes between passenger cars and heavy vehicles. This approach is justified by the data;

- A methodology to automatically identify the initiation and completion of lane change duration from naturalistic trajectory data is developed.

5.3 Directions for Future Research

The emergence of microscopic traffic simulation tools in the last few years has brought about increasing interest in driving behavior modeling. However, much more remains to be learned about drivers' behavior. Some of the directions in which further research is needed are presented below:

- Most of the published estimation results lane change durations models are for freeway traffic. Similar models need to be developed for urban streets, in which other factors and considerations such as pedestrians, traffic lights, public-transport and bicycles may affect the behavior. While again, in this research the proposed model structure is used to estimate a model of freeway driving behavior, the model structure is general enough to apply to other environments, including modeling of driving behavior in urban streets;
- Lane change duration models which derived from naturalistic data set are formulated in this research for the first time. The underlying assumptions and specifications of the different explanatory variables of these models need to be further studied, with different datasets, under different traffic conditions;
- Further research is required in order to identify the impact of geometry (e.g. roundabout, different junction configurations, lane width, curvature, grade etc.) other site-specific effects with more datasets, and to study the impact of the lane changing action on traffic flow by incorporating these models in microscopic traffic simulators;
- The lane change task is a process composed of several steps. Modeling the lane change should include several steps: (1) decision making (incentive and gap acceptance), (2) Execution (duration), which is addressed in this thesis and (3) the impact on the speed and acceleration of the subject vehicle and on the behavior of other vehicles during the lane change action and immediately after it is completed;

- Other elements of lane changing that have not been addressed in the literature such as impact should be researched:
    - Effect on speed and acceleration during the lane change action;
    - Effect on the behavior of other vehicles during the lane change action and immediately after it is completed;
- To enhance the ability of the models proposed in this thesis, the models should be implemented in microscopic traffic simulators. The impact on traffic flow characteristics, and the performances of simulators need to be tested.

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מאת

דוד זוהר

תומר טולדו

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הבעות תודה

מחקר זה נעשה בהנחיית דר׳ תומר טולדו בפקולטה להנדסה אזרחית וסביבתית בטכניון – מכון טכנולוגי לישראל.

ברצוני להודות לדר׳ תומר טולדו על ההנחיה וההכוונה המקצועית לאורך המחקר. בזכות הכוונה זו הועשרתי בידע רב.

ברצוני להודות לאמי-מתום על מימון התואר. אחרונות חביבות, אני מודה לאשתי הילה ובתי רותם על עידודן המתמיד ומקור האנרגיה שלי.

תוכן עניינים

רשימת איורים

רשימת טבלאות

תקציר

עומסי תנועה מהווים בעיה גדולה באזורים עירוניים ובכבישים מהירים הינם בעלי השפעה כלכלית שלילית יחד עם ההחמרה של הניידות, הבטיחות ואיכות האוויר במדינית ישראל. העלות השנתית עד שנת 2020 באובדן זמן וצריכת דלק בזמן עומס צפויה להיות 2 מיליון ₪/שנה.

פיתוח רשת הדרכים הארצית ככלל, ובתחומי המטרופולינים בפרט כבר כמעט ומגיע ליכולת של זכויות הדרך המוקצות לכך. יתרה על כך, באזורים עירוניים רבים אילוצים סביבתיים יגבילו את סלילתם של דרכים חדשות או הרחבתן של דרכים קיימות בעתיד. התקציב הנחוץ להשקעה בתשתיות בישראל עד שנת 2020 מוערך בכ- 4.25 מיליון ₪/שנה.

כתוצאה מכך, הצורך בניהול טוב ויעיל יותר של מערכת הדרכים עולה עם עליות הקיבולות בדרכים. בשנים האחרונות מערכים גדולים של ניהול תנועה הוצעו ויושמו. מתודולוגיות ואלגוריתמים שהוצעו לניהול תנועה עוד צריכים לעבור כיול ולהיבחן. ברוב המקרים, אם בכלל, מעט מאד מבחני שדה ישימים עקב עלויות גבוהות וחוסר בהסכמה ציבורית. מלבד זאת, התועלת במבחני שדה אלו יורד, עקב חוסר היכולת בשליטה מלאה של התנאים בהם הם מבוצעים, לכן נחוצים כלים לביצוע הערכות אלו במעבדות.

מודלים של מיקרו-סימולציה תנועתית המנתחים תופעות מוגדרות ומפורטות של התנהגות הנהג, קיבלו שימוש נרחב בשנים האחרונות הן ע״י חוקרים והן ע״י מהנדסים בסקטור הפרטי, לפיכך מיקרו-סימולציה תנועתית הינה כלי חשוב לניתוח התנועה ככלל של ניהול תנועה דינאמי בפרט.

להחלפות נתיב יש השפעה על מאפייני זרימת התנועה, לכן החלפות נתיב הינן מרכיב חשוב בכלים כגון מיקרו-סימולציה תנועתית. בשנים האחרונות עלה הצורך במודלים למיקרו-סימולציה תנועתית ובנוסף התפתח עניין בפיתוח של מודלים אמינים בהקשר של החלפת נתיב. מודלים קיימים של החלפות נתיב שמים דגש מהיבט קבלת ההחלטה של משימת החלפת נתיב, אך בדרך כלל מזניחים את המידול המפורט של פעולת החלפת הנתיב עצמה, וממדלים את הפעולה כמאורע מידי. אולם, מחקרים מראים שזמני החלפת נתיב בממוצע הינם בטווח של 5-6 שניות. ההשמטה של זמן החלפת נתיב ממודלים של מיקרו-סימולציה תנועתית יכולה להשפיע בצורה משמעותית על זרימת התנועה ומאפייניה בסימולציה וכתוצאה מכך בפלטים המתקבלים.

בכדי לבצע החלפת נתיב נהג הרכב ממתין לפער מספיק גדול, על מנת לעבור אל הנתיב אליו הוא חפץ להגיע. ברגע שהפער נמצא מתאים ע״י הנהג התחלת החלפת הנתיב מתבצעת. בזמן החלפת הנתיב הנהג צריך להתאים את מהירותו לנתיב אליו הוא עובר ולמהירויות הרכבים הסובבים אותו. בתהליך זה, רכבים עוקבים מאחורי הנהג המחליף ובנתיב אליו הוא עובר, צריכים להתאים את מהירותם ותאוצותיהם, או אפילו להחליף נתיב בעצמם, על מנת לאפשר לרכב המחליף לסיים את החלפת הנתיב, אך השפעה זו אינה יכולה להיות מרכיב משפיע, כל עוד זמן החלפת נתיב הוא תהליך מיידי.

מטרת המחקר היא לשפר מודלים של התנהגות נסיעה ובמיוחד לפתח מודלים מפורטים של זמן החלפת נתיב. מחקר זה מציג מודלים של זמן החלפת נתיב, המודלים נאמדו באמצעות בסיס נתונים מפורטים ומסלולי נסיעה של רכבים, אשר נאספו בצורה טבעית, על ידי הצבת מצלמות בגובה רב. המחקר מציג מודל נפרד לרכבים פרטיים ולרכב כבד. כמו כן, בוצעו מבחנים סטטיסטיים לדמיון בין זמני החלפת נתיב של שני סוגי הרכב.

במחקר זה התקבל בסיס נתונים של מסלולי נסיעה מפורטים אשר נאספו בשני ימים שונים, בקטע של כביש בין-ארצי (I-80) בקליפורניה באורך 900 מטר ובחתך של 6 נתיבים הכוללים: נתיב תחבורה ציבורית ,נתיב של התמזגות והשתזרות ורמפת כניסה ויציאה מקטע הדרך. בסיס הנתונים כלל מידע על המימדים של כל כלי הרכב, מיקומם ונתיבים בהם נסעו בהתאם ליום בו נאספו, ברזולוציה של 10 תצפיות עד 15 תצפיות בשנייה. הנתונים נאספו בשלושה חלקים נפרדים המכסים טווח רחב של תנאי התעבורה:

1. 30 דקות של תקופת שפל נאספו בין השעות 2:35-3:05 אחה"צ עם צפיפויות נמוכות יחסית ומהירויות נסיעה גבוהות בתאריך 03/12/2003. ביום זה נתונים אלו הוקלטו ברזולוציה של 15 תצפיות בשנייה;
2. 15 דקות של תקופת מעבר לשעת השיא נאספו בין השעות 4:00-4:15 אחה"צ בתאריך 13/04/2005. ביום זה הנתונים הוקלטו ברזולוציה של 10 תצפיות בשנייה בקטע קצר יותר של 503 מטר;
3. 30 דקות של תקופת שיא אחה"צ בין השעות 05:00-05:30 בתאריך 13/04/2005. ביום זה הנתונים הוקלטו ברזולוציה של 10 תצפיות בשנייה.

הנתונים כללו מסלולי נסיעה של 10,411 כלי רכב וכ-7 מיליון תצפיות. נתונים אלו נותחו על מנת לזהות את כל החלפות הנתיב שבוצעו. לאחר השמטת החלפות נתיב לא מוצלחות, זוהו כ-1617 החלפות נתיב מוצלחות. מתוך החלפות נתיב אלו היו כ-1233 החלפות נתיב לצד שמאל המהווים כ-76.3% מסך החלפות הנתיב והשאר לימין. 112 מהרכבים שהחליפו נתיב מוגדרים כרכב כבד המהווים כ-6.9% מסך הרכבים שנצפו והשאר רכבים פרטיים. עבור כל אחת מהחלפות הנתיב, הוגדרה נקודת הזמן של התחלת החלפת נתיב ונקודת הזמן של סיום החלפת נתיב. הגדרנו את נקודות הזמן של התחלה וסיום החלפת נתיב כנקודת זמן בה מתחילה ומסתיימת תנועה רוחבית של כלי הרכב בהתאמה. לפיכך, זמן החלפת נתיב הינו הזמן החולף בין נקודת זמן ההתחלה והסיום.

פותח אלגוריתם המזהה את הנקודות הללו מתוך בסיס הנתונים של מסלולי הנסיעה. האלגוריתם מבוסס על חמישה קריטריונים לזיהוי הנקודה המתאימה, עבור כל נקודת זמן של התחלה וסיום החלפת נתיב. לבחינת האלגוריתם בוצע מבחן Touring על 200 החלפות נתיב שבו נבחנו נקודות הזמן של התחלה וסיום החלפת נתיב שזוהו על ידי האלגוריתם, אל מול אלו שזוהו בצורה ויזואלית. תוצאות ההשוואה הראו 94.7% אחוזי התאמה בין הנקודות, לכן האלגוריתם הוחל על כל החלפות הנתיב שזוהו בבסיס הנתונים.

נאמדו משתנים שיכולים להסביר את זמני החלפת הנתיב. משתנים אלו כוללים: מאפייני תעבורה (לדוגמא, צפיפויות של נתיבים ומהירויות ממוצעות), מאפייני ומיקום הרכב שמחליף נתיב (לדוגמא, סוג הרכב מהירותו ותאוצותיו) והיחסים שלו עם הרכבים הסובבים אותו (לדוגמא, מהירויות יחסיות, מרחקים,ומיקומים יחסיים עם הרכבים שנמצאים לפניו והרכבים המובילים והמשתרכים הנמצאים בנתיב אליו הוא מחליף). בכל המקרים הללו, הערכים של המשתנים חושבו וקושרו לזמן התחלת החלפת נתיב. המשתנה החשוב ביותר במונחים של השפעה יחסית על זמן החלפת נתיב ומובהקות סטטיסטית, הינו הצפיפות. המסקנה הנובעת ממנו היא שזמני החלפת נתיב מתארכים ככל שהצפיפות יותר גבוהה.

זמני החלפת נתיב בהגדרה אינם שליליים. בכדי להבטיח שזמני החלפת נתיב יהיו חיוביים התאמנו התפלגות של lognormal, המאפשרת לקבל זמני החלפת נתיב חיוביים ולנתח אותם עם רגרסיה ליניארית.

צורת המודל הסופית מתוארת כך: $\ln\left(d_n\right)=\beta X_n+\varepsilon_n$.

d_n הינו זמן החלפת נתיב של רכב n, X_n הינו וקטור של משתנים מסבירים, β הינם הפרמטרים המקבילים של הווקטור, ε_n הינו הטעות בתצפית n.

נבחנה ההיפותזה שזמני החלפת נתיב המבוצעים לכיוון שמאל שונים בצורה מובהקת אל מול אלו המבוצעים לצד ימין. בכדי לבדוק השערה זו בוצע t-test, מבחן על השערת האפס, שממוצע זמני החלפת נתיב עבור שני הכיוונים שווים (two-tailed one sample t-test). התוצאה הייתה עם ערך של 2.713-, לפיכך השוויון של שני הממוצעים נדחה ברמת מובהקות של 99%, לכן בפיתוח המודל, נאמד מודל נוסף עם רמת הפרדה עולה בין החלפות נתיב שבוצעו לשמאל, אל מול ימין ובוצעו מבחנים סטטיסטיים (F-tests), על מנת לבחור ביניהם. תוצאות המבחנים הראו, שזמני החלפת נתיב שבוצעו לצד שמאל וימין שונים, משמע ניתן לאמוד אותם יחדיו במשתנה אחד ללא פיצול.

המודלים שהוצגו בסקר הספרות, בדרך כלל התייחסו רק לכלי רכב פרטי, מלכתחילה נראה הגיוני, שזמני החלפת נתיב של רכב כבד שונה בצורה מובהקת מאלו של רכב פרטי, לפיכך נבחנה ההיפותזה שזמני החלפת נתיב המבוצעים על ידי רכב פרטי, יכולים להיות שונים בצורה מובהקת, אל מול אלו המבוצעים על ידי רכב כבד. בכדי לבדוק השערה זו בוצע t-test מבחן על השערת האפס, שממוצע זמני החלפת נתיב עבור שני סוגי הרכב שווים (two-tailed one-sample t-test). התוצאה הייתה עם ערך של 3.55-, לפיכך השוויון של שני הממוצעים נדחה ברמת מובהקות של 99%, לכן בפיתוח המודל נאמדו שלושה מודלים עם רמת הפרדה עולה בין החלפות נתיב שבוצעו על ידי רכב פרטי אל מול רכב כבד ובוצעו מבחנים סטטיסטיים (F-tests) על מנת לבחור ביניהם. תוצאות המבחנים הראו שזמני החלפת נתיב שבוצעו על ידי רכב פרטי שונים בצורה מובהקת, משמע נאמדו שני מודלים עם משתנים מסבירים שונים לכל אחד מכלי הרכב.

בעבר הנתונים ששימשו לאמוד זמני החלפת נתיב נאספו בדרך כלל במדגמים קטנים ובאמצעות רכבים מצוידים במצלמות ,צופים (חוקרים), או סימולטורים שגרמו להתנהגות לא טבעית של הנהגים בזמן החלפת נתיב. במחקר זה השתמשנו בבסיס נתונים טבעיים של מסלולי נסיעה שנאספו על ידי מצלמות בגובה רב, ללא מודעות הנהגים וברזולוציית זמן גבוהה. התוצאות הראו שזמן החלפת נתיב אינה פעולה מידית, כמו שרוב המודלים במיקרו-סימולציה תנועתית אמדו אותה, אלא בטווח של 1.0-13.3 שהיות עם ממוצע של 4.6 שניות. התוצאות שלנו מראות כי שזמני החלפת נתיב שבוצעו לצד שמאל וימין שונים. כמו כן, זמני החלפת נתיב של רכב כבד אל מול רכב פרטי שונים בצורה מובהקת. אולם, בשני סוגי הרכב זמני החלפת נתיב ארוך יותר כאשר התמרון כרוך בסיכון גבוה יותר, או פעולת ההחלפה מורכבת עם היחסים של הרכב המחליף עם הרכבים הסובבים אותו.

יש צורך במחקרים נוספים בכדי לזהות השפעות של גיאומטריה ומאפיינים שונים של דרכים אחרות עם בסיסי נתונים שונים ממקומות אחרים בעולם. כמו כן, יש לחקור את ההשפעה של החלפת נתיב על זרימת התנועה, על ידי הטמעת המודל במיקרו-סימולציה תנועתית.