UNDERSTANDING THE DIFFERENCES IN LANE CHANGE MANEUVERS OF CARS AND HEAVY VEHICLES ON FREEWAYS

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Introduction

Lane change is fundamental to understand driver behavior and is an integral component of microscopic traffic simulation (Treiber & Kesting, 2013). It is considered to be a sequence of three stages. The first two of the stages, motivation for the lane change and selection of a target lane, are a part of *lane changing decision* and the last stage is the *lane change execution* (Moridpour et al., 2010). The lane changing vehicle (LCV) and surrounding vehicles are illustrated in Figure 1.

Many researchers have developed lane-changing models in the past. Rahman et al. (2013) reviewed the existing lane-changing models and categorized the models into rule-based, discrete-choice-based, artificial intelligence and incentive-based models. The rule based models, such as Gipp's model and *CORridor SIMulation* (CORSIM), predicts lane-changing decisions based on safety distance, presence of heavy vehicles, permanent obstructions, speed advantage, avoiding specific lanes (e.g. transit lanes), turning at downstream intersections, lead vehicle speed threshold, the number of lanes to change, spacing between lead and trailing vehicles in the target lane, speed conditions in the current and target lanes, etc. (Rahman et al., 2013)

Ahmed (1999) and Toledo et al. (2003) proposed discrete choice models for lane change that considered the available gaps in the target lane when they were higher than some minimum values called critical gaps. Similarly, the incentive-based models predicted lane-changing decision based on the criterion of incentive (choice utility of a given lane, route choice, gaining speed, keeping right) and safety (risk associated with lane changing) (Kesting et al., 2007).

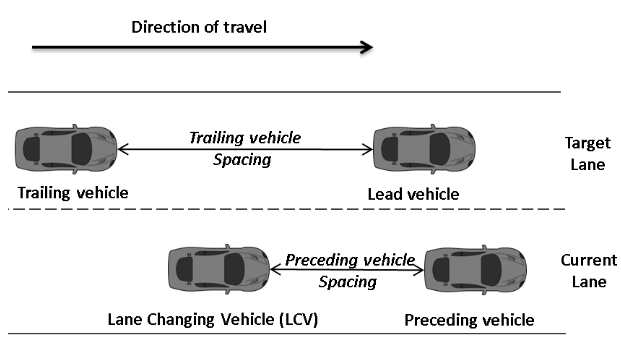


Figure 1. Lane changing vehicle and surrounding traffic

Wiedemann & Reiter (1992) developed a lane-changing model based on driver's own wishes about driving and their perceptions. Wiedemann & Reiter (1992) validated their model by comparing the observed and predicted lane occupancies. They reported a good model fit and suggested that the model could be calibrated for heavy vehicles.

Rahman et al. (2013) noted that the existing models only considered the lead and trailing vehicles in the target lane, but not the traffic characteristics around these vehicles. Also, the models did not consider the driver's planning and estimation of future conditions for lane changes and the lane-changing execution process which takes several seconds. Moreover, the influence of lead and trailing vehicle types on target lane has not been considered in a lane change execution.

To address the limitations of the existing models, recent studies have investigated detailed lane-changing behavior using vehicle trajectory data. Moridpour et al., (2010) studied the lane-changing behavior of cars and heavy vehicles under the influence of surrounding vehicles on freeways. The start and end of lane-changing execution were defined based on the change in the lateral movements (Δx) of LCV. However, the study did not explain how much change in Δx was considered as a part of the lane-changing maneuver. This is important due to the fact that Δx continuously changes over time. They found that heavy vehicles kept higher spacing from the preceding vehicle in the current lane than cars due to the limited maneuverability of heavy vehicles. The preceding vehicle speed in the target lane was an influencing factor for changing lanes for both cars and heavy vehicles.

Some studies focused on the lane change duration (LCD). Aghabayk et al. (2012) found that the LCD was longer for longer vehicles on freeways. However, the method used to estimate the LCD was not discussed in the study. Toledo & Zohar (2007) also investigated the LCD of cars and heavy vehicles on a freeways. They considered the start and end of lane changes are the time frames when the lateral movements of front center of the vehicle initiated in one lane and completed in the target lane, respectively. The LCD was modeled separately for each vehicle type. The model results showed that both cars and heavy vehicles took longer time to change lanes in higher traffic density than lower traffic density. The result also showed that the LCD of cars was longer when they move to left compared to moving to right. However, the LCD of heavy vehicles was longer when they moved to right compared to moving to left because of their poor field view of right side. Overall, the LCD was found to be shorter for heavy vehicles than cars.

This paper addresses the limitations in the definition of the LCD and examines the effects of various factors such as vehicle types in the target lane on the LCD. Therefore, the objectives of this paper are to estimate the LCD of cars and heavy vehicles using an objective manner and develop a statistical model to predict the LCD based on the maneuvers of LCV and surrounding vehicles during the lane change.

This paper is structured as follows. The second section describes the vehicle trajectory data set used in this study is provided. The third section explains the methods to estimate the LCD and its relationships with various explanatory variables. The fourth section develops the model which predicts the LCD and discusses the results. The final section summarizes the findings and suggests future work.

Data

This study analyzed the data collected from a 640-meter (2100-ft.) segment of the southbound US-101 freeway in Los Angeles, California, U.S.A. on June 15, 2005. Eight synchronized video cameras mounted at the top of an adjacent 36-story building recorded the traffic. The freeway consisted of five lanes in the mainline along with an auxiliary lane between the on-ramp at Ventura Boulevard and off-ramp at Cahuenga Boulevard as shown in Figure 2. These data were collected as a part of the Next Generation Simulation (NGSIM) project. NGSIM was an initiative taken by the U.S. Federal Highway

Administration (FHWA) to develop the enhanced behavioral algorithms for the current microscopic simulation modelling.

Vehicle trajectories were extracted for the 30-min. transition period (7:50 – 8:20 am) and the 15-min. congested conditions (8:20 - 8:35 am) at the resolution of 0.1 seconds. The trajectory data include the lane numbers of vehicle position, speeds, accelerations, IDs of the lead and following vehicles, spacing and time headways. The lane number in the data changes whenever the front center of the vehicle crosses the lane marking. To analyze the behaviour of only LVCs, the trajectories of the vehicles which lane numbers changed were extracted. The vehicles in the data are classified into cars, motorcycles and heavy vehicles (trucks and buses) using FHWA classification system. Due to some noise in the location data in the NGSIM data set, the symmetric exponential moving average was applied to smooth the data (Thiemann et al., 2008).

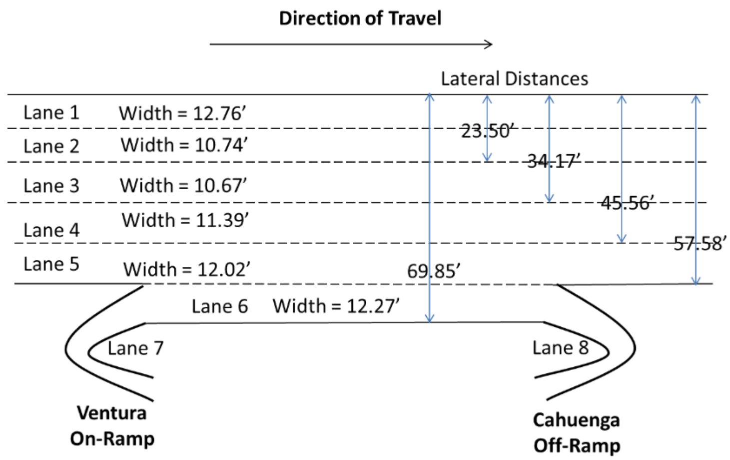
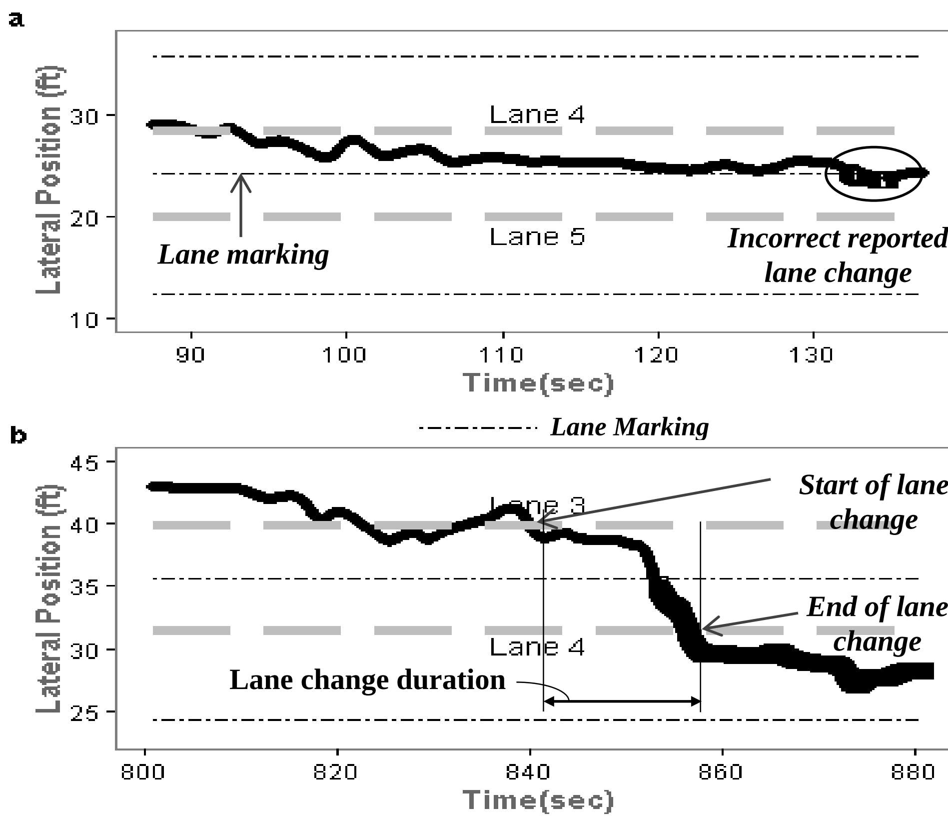


Figure 2. Schematic diagram of US-101

In this study, only discretionary lane changes were analyzed using the vehicle trajectories. In discretionary lane changes, drivers are not forced to change lanes and they voluntarily change lanes unlike mandatory lane changes. To investigate only discretionary lane change maneuver, the vehicles entering from the on-ramp and exiting to the off-ramp were excluded and only the vehicles which changed lanes within the mainline freeway were selected. The lateral position of each vehicle's front center point was plotted over time as shown in Figure 3.

It was observed in many of the reported lane changes that the vehicle's front center temporarily touched the lane marking between the lanes while the lateral position was generally within the same lane as shown in Figure 3(a). Clearly, these lane changes are not actual lane changes. Thus, the trajectories for these reported lane changes were excluded from the analysis.

As a result, a total of 428 LCVs were identified. Among these vehicles, 354 cars and 6 heavy vehicles changed lanes only once (i.e., single lane changes) and 68 cars changed lanes twice (i.e., two lane changes) during the observed time period. It was observed that two lane changes typically occurred when 1) vehicles overtook slow-moving lead vehicles using the left or right lane and return to the original lane; and 2) vehicles consecutively changed to the outer lane or inner lane. In the latter case, the start and end of each lane change could not be determined because vehicles continue moving laterally during the lane change maneuver. In this case, it's hard to determine when the lane change completes. Also in the latter case, vehicles potentially changed the lanes to follow a certain route, which is not considered as discretionary lane changes. Thus, single lane changes and only the former case of two lane changes were analyzed in this study. In case of two lane changes, only the first lane change was analyzed.



(a) Reported lane change without actual lane change, (b) Start and end of lane change maneuver

Figure 3. Determination of start and end of lane change and lane change duration

Methods

Estimation of Lane Change Duration (LCD)

To determine the LCD and accepted gaps, the start and end points of each lane change maneuver were determined based on the lateral position of the front center of each vehicle. Instead of subjectively determining the start and end of lane change, the times when the vehicle initiated and completed the lane change execution based on the vehicle's width were determined in this study.

The half width of each LCV was plotted around the lane marking of the current and target lanes as shown in Figure 3. The dashed lines in lane 3 and lane 4 indicate the lateral positions of LCV's front center when the front left and front right of the vehicle touch the lane marking, respectively. For the lane changes from inner to outer lanes (e.g., lane 3 to 4), the last time frame when the vehicle's front center touched the dashed line was considered as the start of lane change execution as the vehicle entered the target lane in the next time frame. Similarly, the first time frame when the front center of the vehicle touched the dashed line was considered the end of lane change as the vehicle entered the lane completely. In the same manner, the start and end of lane change to outer lanes were determined. Finally, the LCD was estimated as the time elapsed between the start and end of lane change.

Lane change duration model

Lane change duration might depend on several factors such as vehicle types, speeds and spacing of surrounding traffic. Therefore, a multinomial linear regression model was fitted with the following specification:

$$\ln(LCD) = \beta(X) + \varepsilon$$

where LCD = lane change duration (sec), X = independent variables, β = the coefficients of independent variables and ε = the error term. The log form of model was used to ensure that LCD is always a positive value.

Results

The preliminary analysis of lane changes shows that most cars moved to faster lanes and heavy vehicles moved to slower lanes. Only 9% of cars changed from faster to slower lanes. No heavy-vehicle changed from slower to faster lanes.

Lane change duration estimate

Figure **4** shows the distributions of LCD for cars when the lead vehicle is a car or a heavy-vehicle in the current lane and the direction of lane change was left or right. The mean durations of lane change for different are shown in

Table **1**.

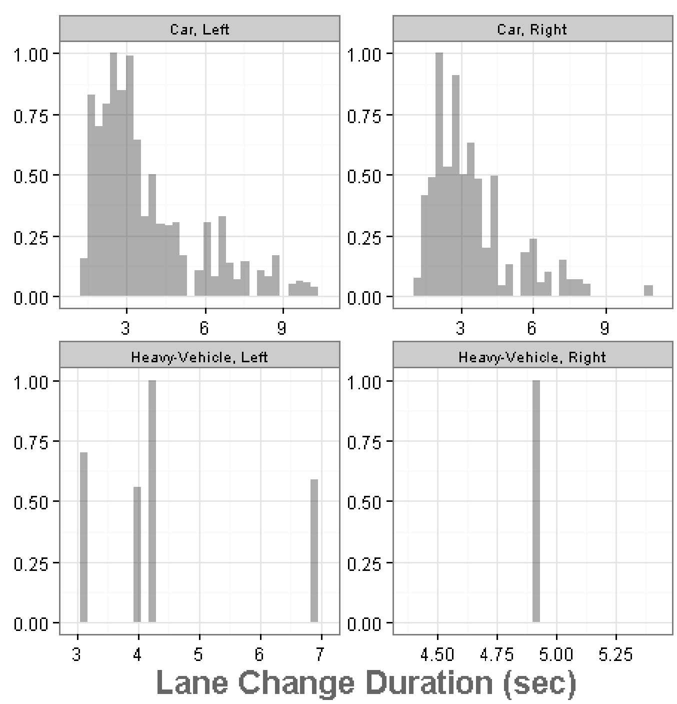


Figure 4. Distributions of lane change durations for cars

Table 1. Descriptive statistics of lane change duration of cars and heavy vehicles

Lane changing vehicle type	Lane change direction	Lead vehicle type in target lane	Trailing vehicle type in target lane	Lane change duration (seconds)			
				Mean	Std.	Min.	Max.
Car	Left	Car	Car	3.76	2.00	1.20	10.10
			Heavy-veh	2.92	1.20	1.50	6.50
		Heavy-veh	Car	3.81	0.60	3.10	4.30
			Heavy-veh	3.83	1.83	2.00	6.90
		Motorcycle	Car	4.47	1.88	2.00	5.90
	Right	Car	Car	3.53	1.86	1.20	11.30
			Heavy-veh	2.90	1.33	1.70	6.60
Heavy-veh	Right	Car	Car	15.08	6.20	4.60	21.80

The results show that the mean LCD was generally similar between lane changes to the left and right for cars. Also, the LCD was shorter when cars change lanes between the lead car and the trailing heavy vehicle compared to the lead car and the trailing car. This is potentially because the trailing heavy vehicles keep longer spacing from lead cars and this creates larger available gaps for executing the lane change.

On the other hand, the mean LCD was longer when cars change lanes behind the lead heavy vehicle in the left lane, regardless of type of the trailing vehicle. This is potentially because the speeds of the lead heavy vehicles are lower than the lane-change cars and car drivers want to maintain longer spacing to the lead heavy vehicles. For a similar reason, the mean LCD was longer when cars changes lanes behind the lead motorcycles.

It was found that the mean LCD for heavy-vehicles was more than 4 times longer than the LCD for cars. This is mainly because heavy-vehicles move at slower speeds and have poor maneuverability characteristics compared to cars.

Lane change duration model

A multiple linear regression model was developed to identify the isolated effects of the factors on LCD. The independent variables include the positive relative speed (speed difference) and spacing between the LCV and the preceding vehicle in the current lane, positive relative speed and spacing between the trailing vehicle and the lead vehicle in the target lane, the types of LCV, lead and trailing vehicles, speeds of the lead and trailing vehicles, and the direction of lane change (right/left). All these data were collected at one time frame, 1.5 seconds before the start of lane change based on the assumption that it takes 1.5 seconds for drivers to make decision to change lanes. The results of the regression model are shown in Table 2. All of the variables are significant at a 95% confidence level except the trailing vehicle spacing which is significant at a 90% confidence level.

The results show that the LCD decreases as the preceding vehicle relative speed increases. A positive relative speed represents faster LCV than the preceding vehicle in the current lane. The effect of the relative speed on the LCD is negative because the LCVs tend to change the lanes quickly at higher speeds to avoid the collision with the preceding vehicle. On the other hand, the LCD is longer at higher spacing from the preceding vehicle as the risk of collision during lane change is lower.

Table 2. Estimated parameters of lane change duration model

Variable	Coefficient	p-value
Intercept	1.450	<0.001
Preceding vehicle relative speed (ft/s) (Lane change vehicle speed – Preceding vehicle speed)	-0.022	0.013
Preceding vehicle spacing (ft)	0.002	0.004
Trailing vehicle spacing (ft)	-0.001	0.050
Lead vehicle speed (ft/s)	-0.006	0.029
Lane changing Vehicle type (1 = Heavy-vehicle, 0 = Car)	1.220	<0.001
Number of observations = 350 R^2 = 0.20		

The trailing vehicle spacing represents the spacing between the preceding vehicle and the trailing vehicle in the target lane that is available to a LCV. The effect of the trailing vehicle spacing on the LCD is negative because the risk of collision increases with shorter spacing and drivers take longer time to change lanes to avoid collisions.

The speed of the lead vehicle in the target lane was also found to be a significant factor influencing the LCD. The negative effect indicates that in the presence of the slow-moving lead vehicles in the target lane, it takes longer time to change lanes. This is because drivers need to reduce speed to create a sufficient gap with the lead vehicle and safely enter the target lane.

A positive coefficient for lane-changing heavy vehicles indicates that the LCD is longer for heavy vehicles than cars. This is because heavy vehicles require larger spacing in the target lane than cars and heavy vehicles' speed and acceleration are also lower than cars.

However, the goodness-of-fit of the model was not high as indicated by a small R-squared value (= 0.20). This indicates that there are other unobserved factors that influence the LCD. The potential factors are driver characteristics (e.g., driving experience, aggressiveness) and vehicle dynamics (e.g., vehicle performance, weight).

Conclusions and Recommendations

This study analyzes the differences in the lane change duration (LCD) between cars and heavy vehicles as a LCV. The study also analyzes the differences in LCD among lane changes for different types of lead and trailing vehicles (cars and heavy vehicles) in the target lane. This study developed an objective method of determining the lane change duration using the vehicle trajectory data from the US-101 freeway in California, U.S.A.

The relationship between the LCD and explanatory variables was modeled by using a multinomial linear regression model. The result shows that the LCD decreases when the positive speed difference between the LCV and the lead vehicle in the current lane increases. However, the LCD increases as the spacing between them increases. The result also shows,that drivers take less time to change lanes when the spacing between the trailing vehicle and the lead vehicle in the target lane is longer. On the contrary, the LCD is longer if the lead vehicle speed is lower and LCV is a heavy vehicle.

These differences in the lane changing maneuvers between cars and heavy vehicles are mainly due to different requirements of safety distances, acceptable headways in congested/uncongested traffic conditions and degrees of cooperation between vehicles during lane changes.

However, there are some limitations in this study. First, lane change durations for mandatory lane changes were not analyzed. Also, the lane change duration models could not be developed for cars and heavy vehicles separately due to low number of heavy vehicles in the data. In future studies, it is recommended that mandatory lane changes are also analyzed using vehicle trajectory data. It is also recommended that the lane change model in the microscopic traffic simulation for heterogeneous traffic is calibrated based on the observed lane change behaviour.

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