The Effect of Surrounding Traffic Characteristics on Lane Changing Behavior

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Effect of Surrounding Traffic Characteristics on Lane Changing Behavior

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Abstract

Lane changing maneuvers could have a substantial influence on traffic flow characteristics as a result of their interfering effect on surrounding vehicles. The interference effect of lane changing is more pronounced when heavy vehicles change lanes compared to when passenger cars undertake the same maneuver. This is due to the physical effects that the heavy vehicles impose on surrounding traffic. This paper investigates and compares the traffic flow characteristics which influence the lane changing behavior of heavy vehicle and passenger car drivers on freeways under heavy traffic conditions. A trajectory dataset comprising 28 heavy vehicle and 28 passenger car lane changing maneuvers is analyzed in this study. The results suggest a substantial difference exists between the traffic characteristics influencing the lane changing behavior of heavy vehicle and passenger car drivers. Heavy vehicles' speed changes little during a lane changing maneuver. Heavy vehicle drivers mainly move into the slower lanes to prevent obstructing the fast moving vehicles which approach from the rear. However, passenger car drivers increase their speed according to the speeds of the lead and lag vehicles in the target lane. They more commonly move into the faster lanes to gain speed advantages.

CE Database subject headings: Trucks; Automobiles; Traffic analysis; Traffic congestion.

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Introduction

Design and assessment of traffic management policies is very difficult in real transportation networks due to the cost and risks of field trails. Therefore, microscopic traffic simulations are used to evaluate new traffic management policies and assess their effects. Due to the extensive application of microscopic traffic simulations in traffic and transportation studies, it is essential to improve their accuracy in modeling the driving behavior. Lane changing models are one of the essential components of any microscopic traffic simulation. Therefore, developing a more accurate lane changing model is important in simulating drivers' behavior.

Lane changing maneuvers have a substantial influence on traffic flow characteristics due to the interfering effect that they have on surrounding vehicles (Daganzo et al. 1999; Mauch and Cassidy 2002; Sasoh and Ohara 2002; Chen et al. 2004; Al-Kaisy et al. 2005). Speed and traffic flow oscillations are often observed due to the effects of lane changing maneuvers on traffic flows. In heavy traffic conditions, the oscillation is mainly the reason of lane changing rather than car following. Lane changing generates shockwave in both lanes. The resulting capacity drop may even be sufficient to cause flow breakdown under heavy traffic conditions (Daganzo et al. 1999; Mauch and Cassidy 2002; Sasoh and Ohara 2002; Jin 2005).

The interference effect of lane changing is more important during the lane changing maneuver of heavy vehicles. Despite their smaller proportion of vehicular traffic, heavy vehicles are known for their important impacts on traffic flow (Al-Kaisy et al. 2002). Heavy vehicles may impose some physical and psychological effects on surrounding traffic due to their physical (e.g. length and weight) and operational (e.g. acceleration, deceleration and maneuverability) characteristics (Uddin and Ardekani 2002; Al-Kaisy and Hall 2003; Al-Kaisy and Jung 2005). The number of heavy vehicles has increased considerably in recent decades and that trend is likely to continue (Bureau of Transportation Statistics 2002). In Australia, the national capital city road freight task will increase by 50% between 2006 and 2020 (Wright 2006).

Despite the increasing number of heavy vehicles on freeways, previous lane changing studies are mainly associated with passenger cars and the lane changing maneuver of heavy vehicles has received little attention (Gipps 1986; McDonald et al. 1997; Brackstone et al. 1998; Wu et al. 2000; Toledo et al. 2003; Hidas 2005;

Schlenoff et al. 2006; Webster et al. 2007). The current lane changing behavior models mainly deal with a general lane changing model for heavy vehicles and passenger cars rather than considering a specific lane changing model for heavy vehicles. In these models, the parameters of the general lane changing model are calibrated for heavy vehicles and passenger cars separately. Meanwhile, a general lane changing model (with exclusive parameters) is applied for heavy vehicles and passenger cars in microscopic traffic simulations. However, heavy vehicle and passenger car drivers may have different patterns in lane changing behavior. The heavy vehicle and passenger car lane changing models may have distinction in their structure and variables rather than only the parameters.

This paper examines the nature of surrounding traffic characteristics at the time of lane changing maneuver on freeways. The aim of the analysis is to identify differences in those surrounding traffic conditions at the time of lane changing maneuvers by heavy vehicles and passenger cars. The analysis focuses on heavy traffic conditions (level of service E) and makes use of trajectory data for 28 heavy vehicle and 28 passenger car lane changing maneuvers.

This paper is structured as follows. The following section presents the trajectory dataset used in this study. It is followed by an examination and comparison of the surrounding traffic characteristics around the time of lane changing maneuvers by heavy vehicles and passenger cars. The final section summarizes the findings and conclusions of the paper and identifies directions for further model development.

Trajectory dataset

The trajectory dataset which is used in this study was prepared by Cambridge Systematics incorporated for the Federal Highway Administration (FHWA) as a part of Next Generation SIMulation (NGSIM) project. In December 2005, NGSIM provided the video images of two sections of two highways in California: Hollywood Freeway (US-101) and Berkeley Highway (I-80). Subsequently, a comprehensive vehicle trajectory dataset was developed through processing the video images.

The section considered on US-101 is 640 meters long and comprises five main lanes and one auxiliary lane. There is one on-ramp and one off-ramp exit in this section and there is no lane restriction for heavy vehicles. The data for US-101 was collected from 7:50 to 8:35 AM with a video capture rate of 10 frames per second (FHWA 2005). The section considered on I-80 is 503 meters long and it comprises five main lanes and one auxiliary lane. There is one on-ramp in this section and an exit off-ramp is located downstream of the section. There are no lane restrictions for the heavy vehicles in this section of freeway. The data for I-80 were collected from 4:00 to 4:15 PM and 5:00 to 5:30 PM using a video capture rate of 10 frames per second (FHWA 2005). Weather was clear for both sites with good visibility and dry pavement conditions. The dataset has classified the vehicles as automobiles, heavy vehicles and motorcycles. The details of the traffic composition, along with the traffic flow parameters for each section are presented in Table 1.

The proportion of heavy vehicles is around 3% of total vehicles in the available dataset (Table 1). However, the proportion of heavy vehicles varies in different freeways depending on the location within the highway network, proximity to city centers, and the availability of alternative routes in a specific transportation corridor. Typically, the proportion of heavy vehicles ranges from as low as 2% to as high as 25% of total traffic during the daytime (Al-Kaisy et al. 2002). In Australia, the proportion of heavy vehicles could increase to 30% of total vehicles in the morning peak and 20% in the afternoon peak in some freeways (Conway 2005). The high proportion of heavy vehicles in some urban freeways enhances the importance of analyzing the lane changing behavior of heavy vehicles in further detail.

To better understand the heavy vehicle drivers' lane changing behavior, all heavy vehicles longer than 10 meters are analyzed in this study. As it was mentioned earlier, the length and size of heavy vehicles and the existence of some limitations in their maneuverability may impose physical and psychological effects on surrounding traffic. Therefore, larger heavy vehicles may have greater influence on surrounding vehicles. Over the time period when the data was captured, there were a total of 28 lane changing maneuvers by heavy vehicles (over 10 meters in length). Therefore, 28 passenger car lane changing maneuvers were selected for comparison. To ensure a valid comparison, the surrounding traffic characteristics of the selected passenger car lane changing maneuvers were close to the surrounding traffic characteristics of the available heavy vehicle lane changing maneuvers. For instance, the selected passenger cars executed the lane changing maneuver approximately at the same time that the heavy vehicles changed lanes. Furthermore, in selected passenger car lane changes, the initial lane and the destination lane were similar to the initial and destination lanes in available heavy vehicle lane changing maneuvers. Consequently, the heavy vehicle and passenger car lane changing maneuvers were compatible.

Lane changing maneuvers

Lane changing behavior can be characterized as a sequence of three stages: the motivation to change lanes, the selection of a lane to change into (the target lane), and the execution of the lane change. The first two stages of the lane changing maneuver constitute the lane changing decision and the final stage is associated with the execution of the lane changing maneuver. This study focuses on examining the surrounding traffic characteristics at each stage of the heavy vehicle and passenger car drivers' lane changing behavior.

The trajectory dataset provides information on the traffic characteristics of the subject vehicles (that is the one about to change lanes) and the surrounding vehicles in both adjacent lanes. Fig. 1 shows the vehicles for which information would be typically available during a lane changing maneuver for a case where the target lane is on the right of the subject vehicle. In this figure, G_{0L} and G_{0R} are the gaps which exist exactly next to the subject vehicle in either the left or the right adjacent lane. G_{1L}, G_{1R}, G_{2L} and G_{2R} are the gaps which exist in front of or behind the immediate adjacent vehicles in either the left or the right lane.

The trajectory dataset includes the physical characteristics of each vehicle such as its length and width. It is also possible to determine all relevant positions, space gaps, speeds and accelerations, at discrete time points throughout the analysis period. The traffic flow characteristics investigated in this study include the speeds of the subject vehicle and surrounding vehicles (Fig. 1) along with the space gaps and the relative speeds of surrounding vehicles with respect to the subject vehicle.

To investigate the influencing traffic flow characteristics which may affect the lane changing behavior of heavy vehicle and passenger car drivers, the lane changing maneuvers are analyzed over a period from several seconds prior to the start of the lane changing maneuver until several seconds after it is completed. The start and the end of the lane changing maneuver are the times that the lateral movements of the subject vehicle are initiated and completed respectively, based on changes in the lateral movements of the subject vehicle. Analyzing the traffic flow characteristics around the time that a heavy vehicle performs lane changing maneuver is complicated. This is due to the number of lane changing maneuvers in the traffic surrounding the heavy vehicles. However, the driving behavior of surrounding traffic was found to be more stable from around 8 seconds before heavy vehicles start changing lanes. Therefore, the lane changing maneuvers were analyzed from 8 seconds before the start of the lane changing until the end of the lane changing maneuver. For consistency, all the figures in the following subsections are based on the values of the explanatory variables from 8 seconds before the start of the lane changing until the end of the lane changing maneuver. The following figures were provided based on the aggregated trajectory data at each 0.5 second time interval for all studied heavy vehicle and passenger car lane changing maneuvers. Therefore, several observations are available for each lane changing maneuver. In the following figures, each observation is shown by either a dot or a cross for heavy vehicles and passenger cars respectively.

Motivation to change lanes

Lane changing maneuvers are typically classified as either Mandatory Lane Changes (MLC) or Discretionary Lane Changes (DLC). MLC happens when drivers have to leave the current lane for instance when merging onto the freeway from an on-ramp or taking an exit off-ramp (Yang and Koutsopoulos 1996). DLC are executed when the drivers are not satisfied with the driving situation in the current lane and wish to gain a speed advantage. Therefore, based on the common classification of lane changing maneuvers, entry via an on-ramp or exit via an off-ramp or the traffic characteristics in the current lane could be considered as motivations to change lanes. Entry via an on-ramp or exit via an off-ramp depends on drivers' route choice and drivers need to perform the lane changing maneuver in order to follow their desired route. Alternatively, the traffic characteristics in the current lane may motivate some drivers to perform a DLC. In this section, the traffic characteristics which may motivate heavy vehicle and passenger car drivers to perform a DLC are investigated.

Speeds of surrounding vehicles in the current lane

The traffic characteristics of the surrounding vehicles in the current lane may have an influence on the drivers' lane changing behavior. The speeds of the front and rear vehicles in the current lane could motivate drivers to change lanes. Fig. 2 shows the relationship between the subject vehicle speed and the front vehicle speed in the current lane for heavy vehicles and passenger cars.

Fig. 2 highlights that the subject vehicle speed is smaller than the front vehicle speed in heavy vehicle lane changing maneuvers while the reverse is the case for passenger car lane changing maneuvers. The results of the data analysis show that in about two third of the heavy vehicle and in more than one third of the passenger car lane changing maneuvers, the front vehicle speed is greater than the subject vehicle speed. The greater values of the subject vehicle speed compared to the front vehicle speed may encourage passenger car drivers to perform a lane changing maneuver. In other words, gaining speed advantage may motivate the passenger car drivers to change lanes. The relationship between the subject vehicle speed and the rear vehicle speed in heavy vehicle and passenger car lane changing maneuvers are shown in Fig. 3.

In heavy vehicle lane changing maneuvers, the rear vehicle speed is generally greater that the subject vehicle speed or it is less than the subject vehicle speed by not more than 1 m/s (90% of the heavy vehicle lane changes). This is shown by the dashed line in Fig. 3. However, in passenger car lane changing maneuvers the rear vehicle speed is mainly smaller than the subject vehicle speed or it is greater than the subject vehicle speed by not more than 1 m/s (around 85% of passenger car lane changing maneuvers). The greater values of the rear vehicle speed than the subject vehicle speed implies that the heavy vehicles may change lanes in order to prevent obstructing the fast moving vehicles which approach from the rear. Therefore, providing an opportunity for the faster moving vehicles to maintain their speeds in their current lane may motivate the heavy vehicle drivers to change lanes.

The space gaps of surrounding vehicles in the current lane and target lane

The space gaps between the subject vehicle and the front and rear vehicles in the current lane may motivate drivers to change lanes. In this section, the front and the rear space gaps are compared to the lead and the lag space gaps in the target lane, respectively.

The relationship between the front space gaps and the target lead space gaps during the heavy vehicle and passenger car lane changing maneuvers are shown in Fig. 4. During the heavy vehicle lane changes, the front space gap is considerably greater than the front space gap in passenger cars’ lane changing maneuver. The large space gaps between the subject vehicle and the front vehicle may be due the limitations in maneuverability of heavy vehicles. In 81% of the heavy vehicle lane changing maneuvers, the front space gap is greater than the target lead space gap during the lane changing maneuver. That is not the case for passenger car lane changing maneuvers. In some heavy vehicle lane changing maneuvers, the lag vehicle drivers in the target lane increase their speeds from a few seconds before the start of the lane changing to pass the slow moving heavy vehicle in an adjacent lane (possibly because the subject vehicle drivers turn their indicators on). This was confirmed by a detailed examination of the heavy vehicle lane changing maneuvers. Therefore, the lag vehicles a few seconds before the start of the lane changing would be the target lead vehicles during the lane changing maneuver. This may explain the small values of the target lead space gaps in heavy vehicle lane changes. However, in around half of the passenger car lane changing maneuvers, the target lead space gap is greater than the front space gap. This implies that the size of the target lead space gap is an inconsiderable factor in motivating the passenger car drivers to perform lane changing maneuver.

The relationship between the rear space gaps and the target lag space gaps during the heavy vehicle and passenger car lane changing maneuvers is shown in Fig. 5. In 68% of heavy vehicle lane changing maneuvers and in 44% of passenger car lane changes, the rear space gap is greater than the target lag space gap. In some heavy vehicle lane changing maneuvers, the target lag vehicle drivers increase their speeds from a few seconds before the start of the lane changing to pass the slow moving heavy vehicle. In other words, the target lag vehicle drivers try to prevent being obstructed by the slow moving heavy vehicles in front of them. This may explain the small sizes of the target lag space gaps in heavy vehicles’ lane changing maneuver. Furthermore, the large rear space gaps in heavy vehicle lane changing maneuvers may be due to the safety concerns of the rear vehicle drivers when following large heavy vehicles. This could also be partially due to the limited visibility of drivers in the vehicles which are immediately behind the heavy vehicles.

Selection of the target lane

In MLC, drivers have to select a specific lane as the target lane according to their desired route/destination choice. However, in DLC drivers are able to select either the left or the right adjacent lane as their target lane. In order to investigate the traffic flow characteristics which may influence the selection of the target lane in DLC, the traffic characteristics in both adjacent lanes are analyzed in this section. In this study, the non-target lane is referred to as the 'alternative' lane. The alternative lane is either the left or the right adjacent lane depending on the lane which was selected as the target lane.

The speeds of surrounding vehicles in the current lane, the target lane and the alternative lane

In this section, the front and the rear vehicle speeds in the current lane are compared to the lead and the lag vehicle speeds in the target lane and the alternative lane. The relationship between the front vehicle speed and the target lead vehicle speed in both heavy vehicle and passenger car lane changing maneuvers are shown Fig. 6. In heavy vehicle lane changing, the target lead vehicle speed is generally greater than the front vehicle speed (65% of heavy vehicle lane changes). This effect is more pronounced in passenger car lane changing maneuvers where in 83% of the cases the target lead vehicle speed is greater than the front vehicle speed. These results suggest that the lead vehicle speed may be an influencing factor in selection of the target lane for heavy vehicle and passenger car drivers.

The relationship between the rear vehicle speed and the target lag vehicle speed in heavy vehicle and passenger car lane changing maneuvers are presented in Fig. 7. The figure shows that the rear vehicle speed is mainly greater than the target lag vehicle speed during the heavy vehicles' lane changing maneuver (66% of heavy vehicle lane changes). This implies that the lower speed of the lag vehicle in the target lane may be an influencing factor in selection of the target lane in heavy vehicle lane changing maneuvers. In contrast, in 46% of passenger car lane changing maneuvers, the rear vehicle speed is greater than the target lag vehicle speed.

The relationships between the front vehicle speed and the lead vehicle speed in the alternative lane, and the rear vehicle speed and the lag vehicle speed in the alternative lane, are presented in Fig. 8 and Fig. 9 respectively for both heavy vehicle and passenger car lane changing maneuvers. The lead and the lag vehicle speeds in the alternative lane are mainly greater than the front and the rear vehicle speeds in the current lane during the lane changing maneuver of heavy vehicles. In around 60% of the heavy vehicle lane changing maneuvers, the lead and lag vehicle speeds in the alternative lane are greater than the front and rear vehicle speeds in the current lane respectively. The greater value of the lead vehicle speed in the alternative lane compared to the front vehicle speed in the current lane may motivate the heavy vehicle drivers to change lanes. However, the lag vehicle speed in the alternative lane is generally greater than the rear vehicle speed.

Heavy vehicles have limited maneuverability and acceleration/deceleration characteristics compared to passenger cars. Consequently, moving into the alternative lane and adjusting their speeds according to the speed of the lag vehicle in the alternative lane may be difficult for heavy vehicle drivers. As a result, the alternative lane is not selected as the target lane in heavy vehicle lane changing maneuvers. In around 70% of available DLC of heavy vehicles, the subject vehicles moved into the slower lane.

In about 70% of passenger car lane changing maneuvers, the front and rear vehicle speeds are greater than the lead and lag vehicle speeds in the alternative lane respectively. This shows that the speed of the surrounding traffic in the alternative lane is less than the speed of the surrounding traffic in the current lane. The greater value of the speed in the current lane than the alternative lane implies that gaining speed advantage may be an influencing factor in selection of the target lane in passenger car lane changing maneuvers. In more than 90% of the available DLC of passenger cars used in this study, the subject vehicle moved into the faster lane.

The speed differences in the current lane, the target lane and the alternative lane

The speed difference between the front and the rear vehicles in the current lane and the lead and the lag vehicles in both adjacent lanes may have an influence on selection of the target lane. The speed difference of the surrounding vehicles in the current lane and the target lane are shown in Fig. 10.

In both heavy vehicle and passenger car lane changing maneuvers, the speed difference between the lead and the lag vehicles in the target lane is positive. Furthermore, in 80% of heavy vehicle lane changing maneuvers, the speed difference in the target lane is positive. The positive speed difference between the lead and the lag vehicles in the target lane may provide the opportunity for heavy vehicle drivers to move into the target lane more easily and safely. In 64% of heavy vehicle lane changing maneuvers and in about 75% of passenger car lane changing maneuvers, the speed difference between the lead and the lag vehicles in the target lane is greater than the speed difference between the front and rear vehicles in the current lane. Previous examination of the data in Fig. 7 suggested there was no approvable difference between the rear vehicle speed and the target lag vehicle speed in passenger car lane changing maneuvers. The greater speed difference in the target lane than the current lane is due to greater values of the target lead vehicle speed than the front vehicle speed. Therefore, the fast lead vehicle is an important factor in selection of the target lane in passenger car lane changing maneuvers.

Fig. 11 shows the speed difference of the surrounding vehicles in the current lane and the alternative lane. In both heavy vehicle and passenger car lane changing maneuvers, the speed difference between the lead and the lag vehicles in the alternative lane is generally positive (60% for heavy vehicles and 58% for passenger cars). Despite the positive speed difference in the alternative lane, this lane is not selected as the target lane in either heavy vehicle or passenger car lane changing maneuvers. The reason may be similar to that discussed in the previous section. In heavy vehicle lane changing maneuvers, the lead and lag vehicle speeds in the alternative lane are greater than the front and rear vehicle speeds in the current lane respectively. Therefore, it is difficult for heavy vehicle drivers to adjust their speed according to the speed of the lead and lag vehicles in the alternative lane. This is in contrast to the passenger car lane changing maneuvers in which the lead and the lag vehicle speeds in the alternative lane are mainly smaller than the front and the rear vehicle speeds in the current lane correspondingly. Therefore, the alternative lane is an inappropriate choice for passenger car drivers who look for gaining speed advantages when changing lanes.

To enhance the comparison, summary statistics on traffic flow characteristics of the surrounding vehicles during the heavy vehicle and passenger car lane changing decision are summarized in Table 2. This table clarifies the influencing traffic characteristics of the surrounding vehicles on lane changing motivation and target lane selection of heavy vehicle and passenger car drivers. The figures shown in this table reinforce the earlier analysis:

- The front vehicle speed is smaller than the subject vehicle speed in passenger car lane changing maneuvers. Thus, gaining speed advantages may motivate the passenger car drivers to change lanes.
- The rear vehicle speed is greater than the subject vehicle speed in heavy vehicle lane changing maneuvers. Therefore, heavy vehicle drivers may change lanes to prevent obstructing the fast moving vehicles behind them.
- In heavy vehicle lane changes, the front space gap is considerably larger than the front space gap in passenger car lane changing maneuvers. This may be due to lower maneuverability of the heavy

vehicles compared to passenger cars and their smaller speed compared to the speed of surrounding vehicles in the current lane.

- The target lead speed is greater than the subject vehicle speed in both heavy vehicle and passenger car lane changing maneuvers.
- The speeds of the lead and lag vehicles in the alternative lane are greater than the heavy vehicle speed. Therefore, it is difficult for the heavy vehicle drivers to adjust their speed according to the speeds of the lead and lag vehicles in the alternative lane.
- In passenger car lane changing, the speeds of the lead and lag vehicles in the alternative lane are smaller than the speed of the vehicle changing lanes. Since, passenger car drivers mainly seek for speed advantages, the alternative lane is an inappropriate lane for them as the target lane.

Lane changing execution

As mentioned earlier, lane changing execution is the last stage of a lane changing maneuver. In this section, the traffic characteristics of the surrounding vehicles are analyzed and compared to each other from 8 seconds before the start of lane changing until the end of the lane changing maneuver. The following figures are based on the aggregated traffic characteristics from all lane changing maneuvers.

Speed profile of subject vehicle and surrounding vehicles during the lane changing maneuver

The changes in the speeds of the subject vehicle and the surrounding vehicles in the current lane are shown in Fig. 12 for heavy vehicles and passenger cars. In this figure, time is represented by the X-axis and the speeds of the subject vehicle and the surrounding vehicles are represented by the Y-axis. The position of the Y-axis represents the point in time when the subject vehicle started to move into the target lane, based on changes in the lateral movements of the subject vehicle.

Fig. 12 shows that the front vehicle speed is greater than the subject vehicle speed in heavy vehicle lane changing maneuvers. In addition, the rear vehicle speed is greater than the subject vehicle speed from a few seconds before the start of lane changing. In passenger car lane changes, the front and rear vehicle speeds are smaller than the subject vehicle speed from a few seconds before the start of the lane changing maneuver

(Fig. 12). The lower value of the front vehicle speed and therefore the desire to gain speed advantages may motivate the passenger car drivers to change lanes. This is similar to the obtained results from analyzing the motivations to change lanes in which the relationship between the speeds of the surrounding vehicles in the current lane was analyzed.

Fig. 13 presents the changes in the speeds of the subject vehicle and the surrounding vehicles in the target lane from a few seconds before the start until the end of the lane changing. In heavy vehicle and passenger car lane changing maneuvers, the lead and the lag vehicle speeds in the target lane are greater than the subject vehicle speed before the start of the lane changing maneuver. In heavy vehicle lane changes, the lag vehicle drivers in the target lane increase their speeds from a few seconds before the start of the lane changing to pass the slow moving heavy vehicle. This may be interpreted as the result of competition between the lane changing heavy vehicle and the target lag vehicles. The target lag vehicle drivers try to pass the heavy vehicle in the adjacent lane and prevent being obstructed by a slow moving heavy vehicle in front of them. However, they reduce their speeds after the start of the lane changing maneuver to provide the opportunity for heavy vehicle to move into the target lane.

A similar trend is observed in passenger car lane changing maneuvers. The lag vehicle drivers in the target lane exhibit a considerable increase in their speeds from a few seconds before the start of the lane changing to pass the lane changing vehicle. As mentioned earlier, passenger car drivers mainly move into the faster lane during the lane changing maneuver. At the start of the lane changing, the passenger car speed is smaller than the speed of the lead and lag vehicles in the target lane and the driver tries to adopt a speed according to the speed of the surrounding vehicles in the target lane. Therefore, there might be a competition between the lane changing vehicle and the target lag vehicles. The target lag vehicle drivers try to pass the lane changing vehicle which has lower speed. However, they stop increasing their speeds a few seconds after the start of the lane changing maneuver to help the lane changing vehicle adjust the speed accordingly.

The results presented in Fig. 12 and Fig. 13 suggest that there are different profiles in the speeds of heavy vehicles and passenger cars during the lane changing maneuver. In heavy vehicle lane changing, the subject vehicle speed varies little over the execution of lane changing maneuver. That is, the heavy vehicle drivers maintain their vehicles' speed almost constant during the lane changing maneuver. They do not perform rapid acceleration or deceleration to adjunct their speeds according to the speed of the surrounding vehicles in the target lane. This implies that heavy vehicle drivers move into the gaps which are alongside the heavy vehicle while performing the lane changing maneuver (G_0 in Fig. 1). They do not accelerate/decelerate to move into the gaps which are in front of or behind the heavy vehicle in heavy traffic conditions (G_1 or G_2 in Fig. 1). Therefore, vehicles traveling upstream of the heavy vehicles in the target lane may be forced to reduce their speed to adjust their speed according to the lane changing heavy vehicle. This may cause speed oscillations in the target lane or may result in flow breakdown in heavy traffic conditions.

In passenger car lane changing maneuvers, the drivers mainly increase their speeds to move into the faster target lane. They adopt their speeds according to the speeds of the lead and lag vehicles in the target lane. Therefore considerable changes can be observed in passenger cars' speed profile during the lane changing maneuver. In addition, passenger car drivers may move into the gaps which are in front of or behind the immediate adjacent vehicle in the target lane (G_1 or G_2 in Fig. 1). Therefore, they may accelerate or decelerate to become closer to the gaps of sufficient size before the start of the lane changing maneuver.

Space gap profiles in the current lane and the target lane during the lane changing maneuver

Fig. 14 shows the changes in the size of the space gaps in the current lane from a few seconds before the start of the lane changing until the end of the lane changing maneuver. Time is represented by the X-axis and the space gaps between the subject vehicle and the surrounding vehicles are represented by the Y-axis. The position of the Y-axis represents the point in time when the subject vehicle started to move into the target lane, based on changes in the lateral movements of the subject vehicle. There is a large space gap between the subject vehicle and the front vehicle in heavy vehicle lane changing maneuvers. This large front space gap may result from the limitations in maneuverability of the subject heavy vehicles. In addition, the size of the rear space gap in heavy vehicle lane changing maneuvers is greater than the corresponding value in passenger car lane changes. As noted earlier, this may be due to the safety concerns of the rear vehicle drivers when following a heavy vehicle.

The changes in the size of the space gaps in the target lane during the lane changing maneuver are shown in Fig. 15. In heavy vehicle lane changing, the target lead space gap increases from a few seconds before the start of the lane changing until around three seconds after the start of the lane changing maneuver. However, it remains almost constant from three seconds after the start of the lane changing until the lane changing is completed. This result is in accordance with Fig. 13 in which the lead vehicle drivers in the target lane increase their speeds to pass the slow moving heavy vehicle in the adjacent lane. Subsequently, the target lead vehicle drivers are forced to adjust their speeds according to the speed of the preceding vehicle. In passenger car lane changing, the target lead space gap increases from a few seconds before the start of the lane changing until a few seconds after the end of the lane changing maneuver. The results of these two figures (Fig. 14 and Fig. 15) confirm the obtained results from analyzing the motivations to change lanes in which the relationship between the space gaps of the surrounding vehicles in the current lane and the target lane were analyzed.

In heavy vehicle lane changing, the target lag space gap decreases slightly before the start of the lane changing and then remains almost constant once the lane changing maneuver commences. In passenger car lane changing, the target lag space gap remains essentially constant throughout the lane changing maneuver. It should be noted that the target lag space gap is greater in passenger car lane changes compared to the corresponding value in heavy vehicle lane changing. This implies that in heavy vehicle lane changing maneuvers, the lag vehicle drivers in the target lane increase their speeds from a few seconds prior to the start of the lane changing. They increase their speeds (possibly because the heavy vehicle drivers turn their indicators on) and reduce their space gaps to pass the slow moving heavy vehicle. However, a couple of seconds after the start of the lane changing maneuver, the target lag vehicle drivers' do not consider passing the heavy vehicle and instead provide the opportunity for the heavy vehicle driver to move into the target lane. This implies the existence of a competition between the lane changing heavy vehicle and the target lag vehicles. The target lag vehicle drivers attempt to pass the heavy vehicle in the adjacent lane. They try to prevent being obstructed by a slow moving heavy vehicle in front of them. However, they reduce their speeds after the start of the lane changing maneuver and make it possible for heavy vehicle to move into the target lane.

Results from analyzing the lane changing execution of heavy vehicle and passenger car drivers are summarized below:

- The heavy vehicles' speed has little variation during a lane changing maneuver. Heavy vehicle drivers keep an almost constant speed during the lane changing execution.

- The passenger cars' speed has considerable changes during the lane changing execution. Passenger car drivers mainly increase their speed according to the speeds of the lead and lag vehicles in the target lane.

Summary and conclusions

Lane changing behavior can be characterized as a sequence of three stages: the motivation to change lanes, the selection of a lane to change into as the target lane and the execution of the lane change. The first two stages of the lane changing maneuver constitute the lane changing decision and the final stage is associated with the execution of the lane changing maneuver. This study investigated and compared the variables influencing the three stages of the lane changing behavior of heavy vehicle and passenger car drivers. The explanatory variables were investigated using detailed vehicle trajectory data captured for 28 heavy vehicle and 28 passenger car lane changing maneuvers under heavy traffic conditions.

It was found that speeds of the front and rear vehicles in the current lane have a substantial impact on the motivation to change lanes. In heavy vehicle lane changing maneuvers, the rear vehicle speed is mainly greater than the subject vehicle speed. Therefore, preventing obstruction of the fast moving vehicles which approach from the rear may motivate the heavy vehicle drivers to change lanes. In passenger car lane changes, the front vehicle speed is considerably smaller than the subject vehicle speed. Therefore, gaining speed advantages may motivate the passenger car drivers to change lanes.

The heavy vehicle drivers mostly move into the slower lane and the passenger car drivers mainly move into the faster lane during the lane changing maneuver. The lead and the lag vehicle speeds in the target lane are greater than the subject vehicle speed in both heavy vehicle and passenger car lane changing maneuvers. In heavy vehicle lane changing, the subject vehicle speed changes little during the lane changing maneuver. The heavy vehicle drivers do not adjust their speeds according to the speed of the surrounding traffic in the target lane. On the other hand, passenger car drivers typically increase their speeds to move into the faster target lane. They adjust their speeds according to the speeds of the lead and lag vehicles in the target lane. Therefore considerable changes are observed in the speed of passenger cars during the lane changing maneuver.

There is a large space gap between the subject vehicle and the front vehicle in heavy vehicle lane changing maneuvers which may result from the limitations in maneuverability of the subject heavy vehicles. In heavy vehicle lane changing maneuvers, the target lead space gap increases from a few seconds before the start of the lane changing until a couple of seconds after the start of the lane changing maneuver. It then remains almost constant from a couple of seconds after the start until the end of the lane changing. This may be due to the fact that the target lead vehicle drivers are forced to adjust their space gaps according to the position and speed of the preceding vehicles. In passenger car lane changes, the target lead space gap increases few seconds before the start of the lane changing until a few seconds after the end of the lane changing maneuver. In heavy vehicle lane changes, the target lag space gap decreases slightly before the start of the lane changing and then remains almost constant after the start of the lane changing maneuver. This implies that in heavy vehicle lane changing, the lag vehicle drivers in the target lane increase their speeds from a few seconds prior to the start of the lane changing. Those drivers then increase their speeds (possibly because the subject heavy vehicle drivers turn their blinkers on) and reduce their space gaps to pass the slow moving heavy vehicle. However, the target lag vehicle drivers do not pursue the option of passing the heavy vehicles and instead provide the opportunity for the heavy vehicle drivers to move into the target lane. In passenger car lane changes, the target lag space gap remains relatively constant during the lane changing maneuver.

The surrounding traffic characteristics during the heavy vehicle and passenger car lane changing maneuvers are summarized in Table 3. This table presents the differences between traffic characteristics of the surrounding vehicles during the lane changing decision of heavy vehicle and passenger car drivers as well as the difference in the lane changing execution of these two vehicle types.

This study has highlighted the considerable differences in the lane changing decision as well as the lane changing execution of heavy vehicle and passenger car drivers. The results from this research revealed the existence of differences in the structure of heavy vehicle and passenger car lane changing behavior. Consequently, heavy vehicle and passenger car lane changing models should have distinction in their structure and variables rather than simply the parameters.

The proportion of heavy vehicles was around 3% of total vehicles in the available dataset. However, the proportion of heavy vehicles varies in different freeways from as low as 2% to as high as 25% of total traffic during the daytime. Therefore, developing an exclusive lane changing behavior model for heavy vehicle drivers is an important priority for model development. An exclusive heavy vehicle lane changing model could enhance the accuracy of microscopic traffic simulations when estimating heavy vehicle drivers' lane changing behavior. Developing an exclusive lane changing behavior model for heavy vehicle drivers based on these influencing traffic flow characteristics is a promising future direction for this research.

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Fig. 1: Subject vehicle and the surrounding vehicles in lane changing behavior analysis.

Fig. 2: The speeds of the subject vehicle and front vehicle in the current lane.

Fig. 3: The speeds of the subject vehicle and rear vehicle in the current lane.

Fig. 4: The space gaps of the surrounding vehicles in the current lane.

Fig. 5: The space gaps of the surrounding vehicles in the target lane.

Fig. 6: The speeds of the front vehicle and the lead vehicle in the target lane.

Fig. 7: The speeds of the rear vehicle and the lag vehicle in the target lane.

Fig. 8: The speeds of the front vehicle and the lead vehicle in the alternative lane.

Fig. 9: The speeds of the rear vehicle and the lag vehicle in the alternative lane.

Fig. 10: The speed difference of the surrounding vehicles in the current lane and the target lane.

Fig. 11: The speed difference of the surrounding vehicles in the current lane and the alternative lane.

Fig. 12: The speed profiles in the current lane in heavy vehicle and passenger car lane changing maneuvers.

Fig. 13: The speed profiles in the target lane in heavy vehicle and passenger car lane changing maneuvers.

Fig. 14: The space gap profiles in the current lane in heavy vehicle and passenger car lane changing maneuvers.

Fig. 15: The space gap profiles in the target lane in heavy vehicle and passenger car lane changing maneuvers.

Table 1: The traffic flow characteristics in each freeway section.

Site Name	Automobile		Heavy Vehicle		Motorcycle		Flow (veh/hr)	Speed (km/hr)	Density (veh/km)	Level Of Service (LOS)
	Number	(%)	Number	(%)	Number	(%)				
US-101	5919	97.0	137	2.2	45	0.7	8077	35.0	231	E
I-80	5408	95.2	215	3.8	55	1.0	7493	23.8	315	E
Total	11327	96.2	352	3.0	100	0.8	7785	29.4	273	E

Table 2: Summary statistics on surrounding traffic characteristics in a lane changing decision.

Lane Changing Decision	Variable	Heavy Vehicles		Passenger Cars	
		Mean	Standard Deviation	Mean	Standard Deviation
Motivation to Change Lanes	Subject vehicle speed (m/sec)	7.2	0.8	9.0	2.2
	Front vehicle speed (m/sec)	8.0	3.8	8.2	3.3
	Rear vehicle speed (m/sec)	7.9	3.4	8.4	3.2
	Front space gap (m)	27.0	12.9	8.7	3.6
	Rear space gap (m)	11.5	5.7	14.9	8.3
Selection of the Target Lane	Target Lead vehicle speed (m/sec)	9.2	4.3	10.5	3.3
	Target lag vehicle speed (m/sec)	7.2	3.6	8.9	3.1
	Lead vehicle speed in alternative lane (m/sec)	8.5	4.3	7.2	2.6
	Lag vehicle speed in alternative lane (m/sec)	8.1	4.1	5.9	4.3
	Target lead space gap (m)	9.4	16.2	7.0	11.0
	Target lag space gap (m)	6.9	7.5	15.5	7.2

Table 3: The surrounding traffic characteristics associated with heavy vehicle and passenger car lane changes.

Surrounding Traffic Characteristics	Heavy Vehicles	Passenger Cars
Motivation to Change lanes		
Front vehicle speed		Smaller than subject vehicle speed
Rear vehicle speed	Greater than subject vehicle speed	
Front Space Gap	Large value	
Selection of the target lane		
Target lead vehicle speed		Greater than front vehicle speed in the current lane
Target lag vehicle speed	Smaller than rear vehicle speed in the current lane	
Execution of the lane changing		
Subject vehicle Speed	Inconsiderable changes	Considerable increase