Empirical Analysis of the Speed Synchronization of Merging Vehicle from the Entrance Ramp

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ABSTRACT

Exploring the lane change preparation, termed as synchronization, with a new integrated view may trigger the understanding of the complex lane change behavior and help microscopic traffic flow modeling. This paper reports a fundamental work from various aspects to study the speed synchronization behavior of the merging vehicle by tracking their trajectories on the merge-related lanes. By classifying the merging vehicles into “Original Gap” type and “Overtaking” type, the existence of the speed synchronization during the lane change preparation stage is proved by comparing the speed difference between the merging vehicle and PL (putative leader) /PF(putative follower) at different locations. After this, a synchronization rule of the merging vehicles is constructed. The merging vehicles tend to maintain a speed which is 5~7 m/s higher than the speed of PL to overtake unsatisfied current gap on the adjacent main lane. When they meet an acceptable gap, they would take a two-step strategy to merge into main lane. Then, the effect of the speed difference between merge vehicles and PL/PF on the gap selection are concluded, which is that higher speed difference leads to gap rejection. Finally, the absolute speed difference between merging vehicle and PL/PF are modeled using multi-regression method. The number of rejected gaps by merging vehicles, the merging vehicles' speed synchronization direction (acceleration or deceleration), the speed difference between PL and PF, the time headways, the distance from merging vehicles’ current location to the end of the auxiliary lane and the vehicle type of PL of merging vehicles are found to have significant effects on the speed difference tolerance.

Key Words: Merging Vehicles, Speed Synchronization, Merge Duration, Overtaking, Gap Selection

1. INTRODUCTION

The ability of existing microscopic simulation models to interpret lane-changing behavior according to individual observations has recently been interrogated *(1, 2)*. These lane change models emphasized on driver's decision-making process, which contains the decision to consider a lane change, choice of a target lane, and gap acceptance steps, and generally neglecting the detailed modeling of the lane change action itself and modeling it only as an instantaneous event*(3)*. Toledo's research pointed out that lane-changing durations are on average in the range of 5 to 6 seconds, so the existing microscopic model which omits the lane change duration component would lead to considerable amount of errors in the simulation outputs *(4)*.

The lane change duration are commonly defined as the process of lane change execution, whose typical feature is marked as the starting of lateral movement of lane change vehicle *(5, 6)*. Recently, some researchers started to pay attention to the importance of the lane change preparation process before the lane change execution, which is termed as synchronization. This tactical synchronization stage, in which the drivers synchronize their vehicles' speed or acceleration to accord with the vehicles on the target lane, is important to achieve successful merge action *(7)*. However, there are few studies investigating this behavior and that how the lane-change vehicles technically manipulate the synchronization tactics are still unknown *(5, 7, 8)*. To help us understand the whole lane change process, in this paper, we extend the definition of lane change duration further to include both the lane change preparation and execution stage to analyze the synchronization behavior of merging vehicles.

We target on the merging vehicles which have clear motivation to conduct lane change actions once they arrive at the starting point of auxiliary lane. Such vehicles' lane change preparation stages could be easily identified for conclusive investigation. In addition, some empirical analysis found, in certain circumstances, the merge vehicle is overtaken by or overtakes the vehicles on the adjacent main lane *(2)*. If certain synchronization rule exists, we intend to clarify the changing of vehicle's speeds during the overtaking or being-overtaken process and their decision-making behaviors among the multiple gaps formed by the sequential flowing vehicles on the target lane. To figure out these puzzles and exploit the lane change tactics, the synchronization characteristics of merging vehicles at a freeway with on-ramp section are studied in this paper.

This paper is followed with the literature review of the lane change models and characteristics of merging vehicles. The third section is the description of the data and definitions used in this paper. The fourth section explores the important features of the speed synchronization of the merging vehicles. The models to describe the speed difference between merging vehicle and PL/PF at the merge point are built in section Five and the summaries of the conclusion are listed in section Six.

2. LITERATURE REVIEW

2.1 Models of Lane Change

A lane-change model is usually composed of three basic categories: a decision model, a condition model, and a maneuver model *(8, 9)*. The decision actions are initialized in terms of the route plans, the current lane type, and the driving conditions on the current and nearby lanes. The condition model interprets the acceptable conditions for distinct types of lane changes, while the maneuver model illustrates the vehicle's speed and the dwelling of the lane change.

Based on the driver's decision-making process, the microscopic lane changes are commonly classified as three types: Mandatory Lane Change, Discretionary Lane Change and Anticipatory Lane Change (or Preemptive Lane change) *(10-13)*. The Anticipatory Lane Change is recently introduced as one peculiar type of lane change, in which the driver makes lane change in order to avoid potential traffic congestion downstream *(9, 14, 15)*. The research in this paper emphasizes on merging vehicles, whose lane change type belongs to the mandatory lane change.

Based on the lane change condition and the execution duration, the microscopic lane changes are often set as three aspects：Free lane change，Forced Lane Change and Cooperative Lane Change *(12, 16, 17).* What needs to be pointed out is an extra category lane change introduced by Schakel et al. (2012), namely the Synchronized Lane Change (SLC). In their paper, it described that, in the SLC condition, a potential lane change driver intends to synchronize his/her vehicle's speed with the vehicles on the target lane, which is practiced by following a vehicle on that lane *(7)*. However, there is no analysis based on field data to support such conclusion. By exploring the trajectories of the merging vehicles, we propose that the speed synchronization behavior exists in all of the lane change preparing stage. The synchronization behavior of merging vehicles will be analyzed in this paper no matter which type of lane change it belongs to.

Different theoretical frameworks have been developed to model the lane change process. Gipps first developed a structure to describe the decision tree of the lane change on multilane urban networks *(8).* The most important factors of the decision of lane change are whether it is physically possible and safe to change lanes, the utilities of current lane and target lane, and the urgency of changing lane. In 2007, Kesting et al. presents a generic approach whose utility function is based on the ability to improve the driver's acceleration to decide lance change or not *(18).* Choudhury proposed a complete decision model for drivers under three different lane change phases: normal state, courtesy merging state and forced merging state *(19).* Under the decision process, the drivers do not only consider the adjacent lane as the target lane, but also all the available lanes on the road. A combined integration model based on car following and lane change was proposed by Schakel et al *(7).* The incentives for lane change in Schakel's model include following a route, gaining speed and keeping right, and the classification of lane changes depends on the level of lane change desire.

Although these frameworks of lane change models seem rather comprehensive, one big shortcoming of these models has been criticized *(8).*Most models do not contain the lane change preparation process toward a selected gap, which may lead to incorrect predictions of speeds and merge locations.

2.2Analysis of Merge Vehicle

From trajectories of the merging vehicle *(2,10,17)*, some vehicles merge in the first gap they meet on the adjacent main lane, and the others overtake or are overtaken by vehicles on the adjacent main lane before successfully lane change and occasionally even fully stop to find the second or third feasible gap. The latter kind of merging vehicle needs to spend considerable part of time in merge preparation and, extend the lane change duration. What reasons result in the different merge behavior of these vehicles? Some researchers have conducted the analysis of vehicle trajectories in merge section to investigate the drive behavior of merge vehicle *(2, 10, 20)*, the interaction between vehicles in lane change duration *(16, 22, 23)* and relaxation phenomenon after the lane change *(21, 24, 25)*.

Wang et al. analyzed the merging behavior on the motorway merge section and built a model for the acceleration of merge vehicles which are being affected of the target gap and other vehicle on the auxiliary lane *(17)*. They concluded that that the more alert the drivers are, the higher the percentages of successfully merging into their first choice of gaps are. However, in Wang's report, they didn't discuss the drive status of the merging vehicles after their failure merge which target on the first choice merge gap.

Daamen (2010) used a 35 min data set of vehicle maneuvers on a merge section of freeway to conduct some empirical analysis of merge behavior *(2).* They found different merge location distributions for congested and free-flow condition, and slightly smaller gaps are accepted at the end of the auxiliary lane compared to the beginning part of the auxiliary lane. They also proved the existence of the relaxation after the merge execution. They argued that every merging vehicle is able to find a suitable gap without being overtaken by multiple vehicles on the main road and without full stop at the end of the auxiliary road.

Yeo (2009) built a freeway flow algorithm with the NGSIM data *(20).* In their conclusion, the merge vehicle, prior to lane changing, follows the leader vehicles on the current lane or on the target lane (depending on which one is closer). During and after the lane change execution, the merge vehicle follows the new leader. The entire car following models for every step is base on the safety constraints to avoid collisions during the simulation. The validation test of the algorithm showed that it could accurately track the propagation of congestion.

The above-mentioned research has provided an explanatory image to understand the lane change behavior of merging vehicle. However, the research is rather fragmented since most of them only focus on the short term and meanwhile successful lane change execution, neglecting the failure trials in merging process. A comprehensive characteristic and logic merge behavior in the whole lane change duration (including preparation, attempts and final triumphant merge) is highly demanded. The analysis and modeling of the speed synchronization characteristics of merging vehicle on the whole merge-related lanes in this paper would complement the lack of the previous research.

3. DATA SET AND DEFINITIONS

3.1 NGSIM Data General Description

The present study carefully analyzes vehicles trajectories on a five lane freeway section with an on-ramp from Ventura Boulevard and an off-ramp to Cahuenga Boulevard on U.S. Highway 101 (Hollywood Freeway), Log Angeles, California, USA (see figure 1*a*). The road section is covered by eight cameras collecting the vehicle trajectories in every 10th second from 7:50 to 8:35 a.m. on June 15, 2005. The speed of the vehicles on the main lane is fluctuant from 32.18 to 49.88 km/h during 45 minutes, while the speed of the merging vehicles at the location where they just get on the auxiliary lane is around 50.01km/h.

In our research, we focus on the travel behavior of the vehicles coming from the Ventura Boulevard on-ramp which intend to merge into the main lane. These merging vehicles must merge into lane five near the auxiliary lane, and their merge motivation is strong and persistent. The total length of the auxiliary lane is 212.25 m. The NGSIM database distinguishes the on-ramp, auxiliary lane and main lane clearly, so in the data process we can easily identify when the merging vehicle get on the auxiliary lane and when it merges into the main lane.

In the 45-minute data, we collected a total of 399 merging vehicles. Except one vehicle which is motorcycle and whose length is less than 2.0 m, the other 398 vehicles are automobiles and set as valid sample set in this research. Among the 398 merging vehicles whose lengths range from 2.5 m to 7.8 m, only 51 vehicles' length are above 5 m and none is truck, so we do not distinguish the difference of merge vehicles among Cars, SUVs and Pickups in terms of their lengths.

3.2 Definitions and Sample Data

Based on the existing researches which are summarized in 2.1, the definition of synchronization of merging vehicle is the process during which merging vehicles try to decrease the speed difference between their PL/PF and itself. The reason why we focus on the speed synchronization stems from the motivation that drivers always attempt to keep the same speed with preceding vehicles to reproduce synchronized flow speed near on-ramps. This was presented in Kerner's three-phase traffic flow theory (26).

It is reasonable and understandable to assume that once the vehicles coming from the on-ramp get to the auxiliary lane they will immediately start to seek for the opportunity to merge into the left neighbor main lane. In figure 1*b*, we sketched the merge area, where the merging vehicle (M) interacts with its putative leader (PL) and putative follower (PF) on the nearside main lane. A PL or PF exists if the leading or the lag gap is less than 5 seconds, and the merging vehicle examines the original gap, the previous gap in front the PL and the following gap behind PF *(17)*.

Three definitions regulating the gaps are used in this paper:

Original gap: It is the gap between PL and PF which is faced by M when it arrives at the auxiliary lane.

Current gap: It is the gap between PL and PF in which a merging vehicle is involved at current time. This gap is time dependent in the merging process.

Accepted gap: It is the gap between PL and PF that a merging vehicle final merges in.

The interval spent for the merging vehicle from the time it right arrives at lane 6 to the time it successfully merges into lane 5 is defined as the whole lane change duration in this paper. With ten times updating of every vehicle's location and speed within one second, we sketched out the trajectories of the 398 merging vehicles (red line) and the vehicles on the adjacent main lane (lane 5, blue line) in the figure 2. The merging vehicles getting onto lane 5 at the merge location is rendered with the red circle.

In figure 2*a*, the vehicle (ID 310) merges from auxiliary lane (lane 6) to the right most main lane (lane 5) by taking the original gap. In figure 2*b*, merging vehicle (ID 21135) overtakes the PL (ID 21134) and takes the gap in front of the original gap to merge into lane 5. In figure 2*c*, the merging vehicle (ID 10723) overtakes seven vehicles in front of it on lane 5 before the successful merge. Its "current gap" changed seven times in the lane change duration. In figure 2*d*, the merging vehicle (ID 12237) chooses the first following gap of its original gap as the accepted gap.

Does the synchronization behavior exist during such diverse merge process? How do the merging vehicles synchronize their speeds with changeable PL and PF? Answering these questions is the task of this paper.

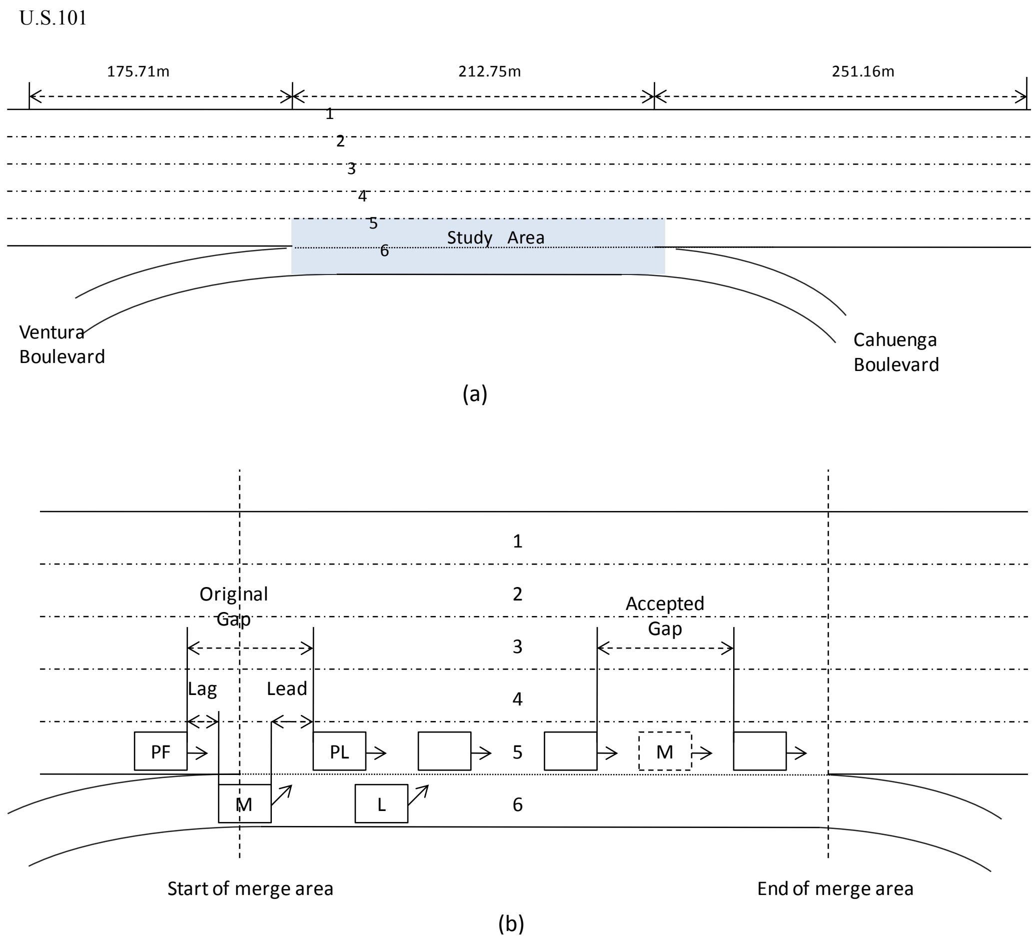


Figure 1 Data collection site (a) and the related vehicles (b)

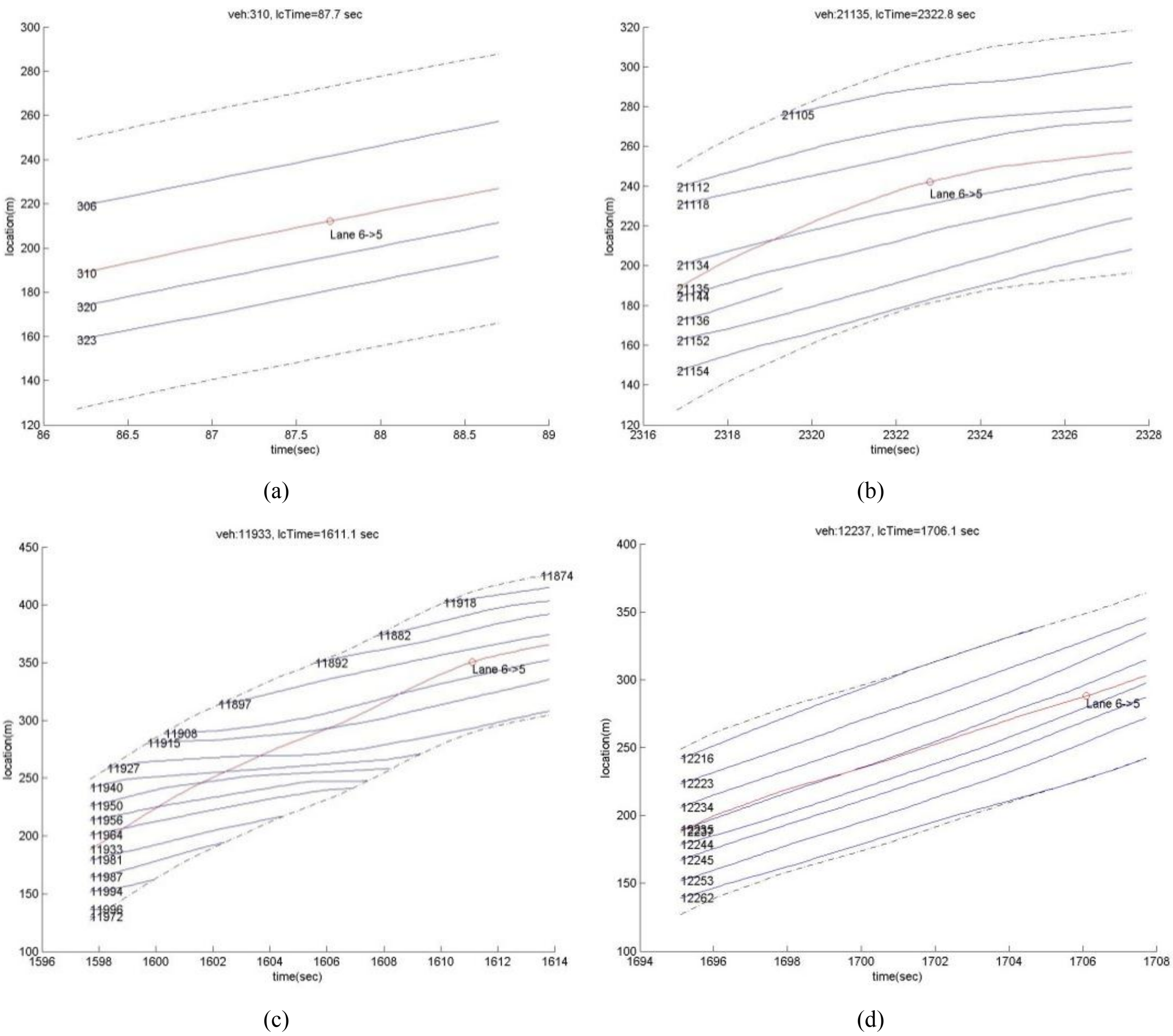


Figure 2 The trajectories of the sampling merging vehicles
ID 310(a) ID 21135(b) ID11933(c) ID12237(d)

4. SYNCHRONIZATION OF MERGING VEHICLES

4.1 Characteristics of the Merging Vehicles at Merge Point

At the beginning, we explore the target gap selection for merging vehicles. With the calculation of the lane change process of 398 vehicles and the gaps they accept, we divided their merging behaviors into four types and their proportions are: Original Gap (59.05%), Overtaking (39.45%), Being Overtaken (1.01%) and Combined (0.50%). The "Original Gap" type means the merging vehicle merges in its original gap. "Overtaking"/"Being Overtaken"/"Combined" type presents that the merging vehicle overtakes/is overtaken by/do both actions the vehicle (or vehicles) on the adjacent main lane to eventually merge in main lane. From the empirical statistic results, we found that the majority merge vehicles overtake their PL of their current gap to purse acceptable gap when they could not merge in the original gap. They rarely consider the following gap of original gap according to the proportion of the "Being Overtaken" type and "Combined" type which are as low as 1.01%

and 0.50%, respectively. What needs to mention is that the above conclusion is based on 70.72% of merging vehicles whose speed is higher than their PL and PF of original gap. Thus in the following parts of this paper we focus on the "original gap" and "overtaking" type and the other two types are omitted due to the small percentages.

Figure 3 shows the histogram-type percentage distribution of the merge location (*a* and *b*), and merge-in space gaps (*c* and *d*) and merge speed (*e* and *f*) for the "Overtaking" and "Original Gap" types.

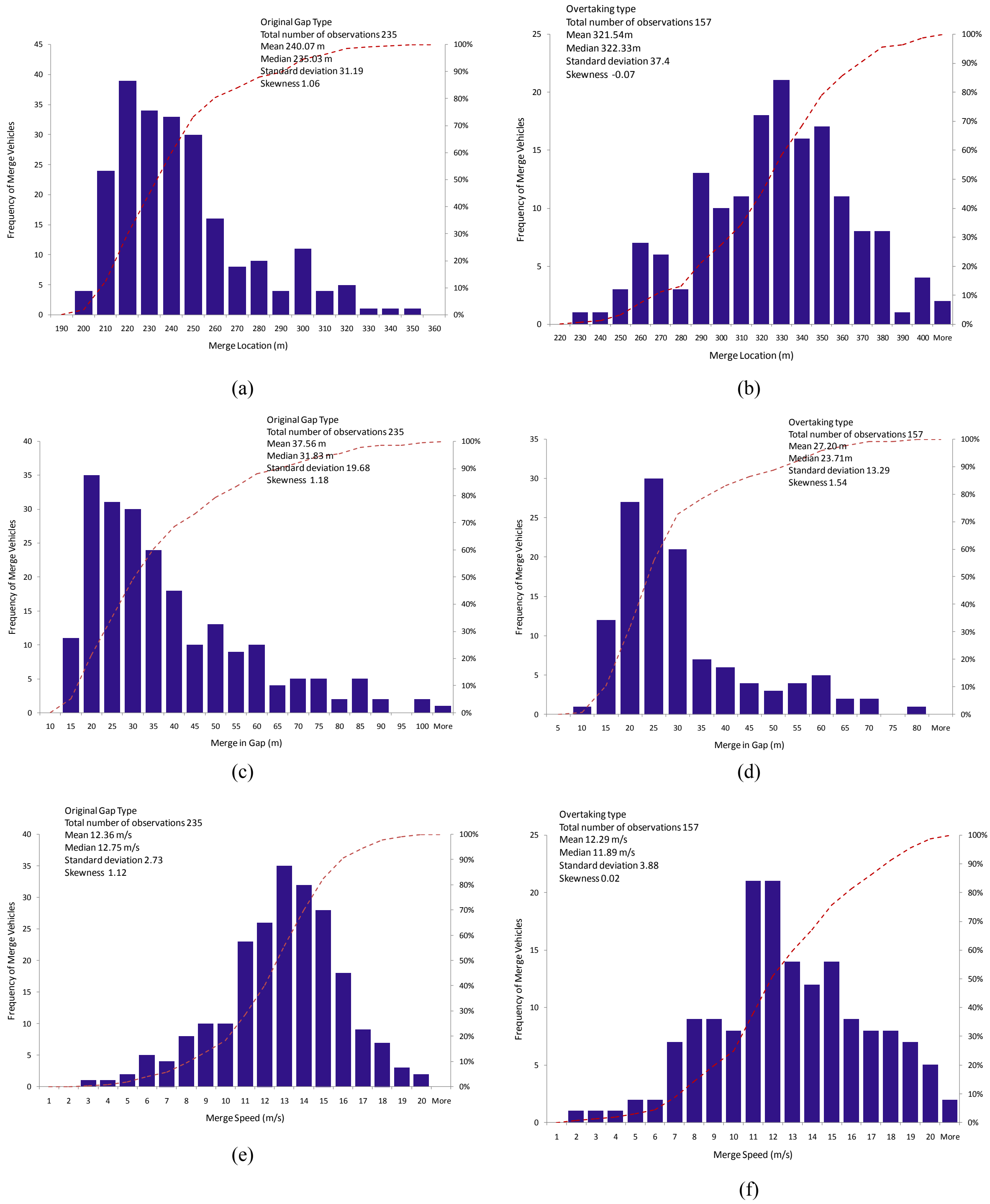


Figure 3 Characteristics of merging vehicles at merge point

Merge location (a and b) Space headway of accepted gap (c and d) Merge speed (e and f)

Referring to the auxiliary lane starting from at x= 176.17 m to x = 388.92m, 80 percent of the "Original Gap" type vehicles merge before x=260m, while 90 percent of the "Overtaking" type vehicles merge after x=260m. If the PL and PF for the accepted gap of merging vehicles exist, these gaps are counted in the calculation of merge-in gaps. The results showed the "Overtaking" vehicles accept smaller gap with smaller standard deviation compared to the "Original Gap" vehicles, and the smallest accepted gap is 8.61m. These differences between the merge location and accepted gap can be explained as follows: since the "Overtaking" vehicles need to purse the gaps in front of current PL, they need to drive longer on the auxiliary lane. However, the further they approach to the end of the auxiliary lane, the higher pressure they feel for merge, which then results in the acceptance of the smaller merge gap.

It is interesting that the average merge speeds of these two-type vehicles are both around 12.30 m/s, but the Kolmogorov-Smirnov test results show that the two merge speed histograms (3*a* and 3*b*) can not stem from one sample. The higher standard deviation of the merge in speed of "Overtaking" vehicles compared to that of the "Original Gap" indicates that the merge condition of "Overtaking" vehicles are more complex then "Original Gap" vehicles. In the following subsection, the dynamics changes of merging vehicles' speed in the merge duration will be detailed explored.

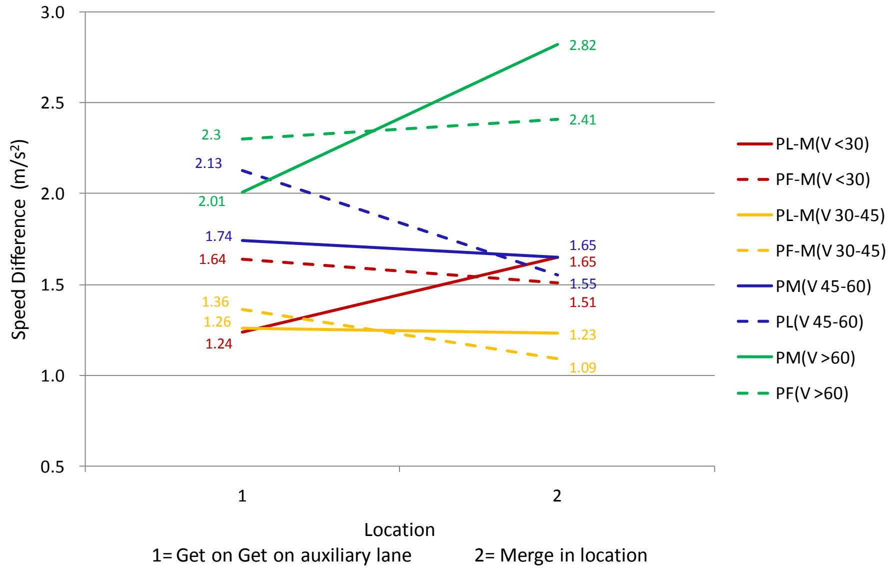
4.2 Speed Synchronization

To investigate the existence of the synchronization in lane change duration, we compare the absolute speed difference between the merging vehicle and its current PL and PF at different locations. The locations where the merging vehicles get on the auxiliary lane (x= 176.17) and where they merge in the main lane are selected as sample locations. Comparison results for different merging vehicle types are showed in Figure 4. To consider the effect of the traffic flow speed on the driver's driving behavior, the speed of merging vehicles at the merge point is used as mark to regulate the merging vehicles into four groups (below 30km/h, at 30~45km/h, at 45~60km/h, above 60 km/h). Based on the calculation, 97.7 percent of the "Overtaking" vehicles' speed is higher than the PL and PF's of the original gap while for the "Original Gap" vehicles the proportion drops to 59.45 percent.

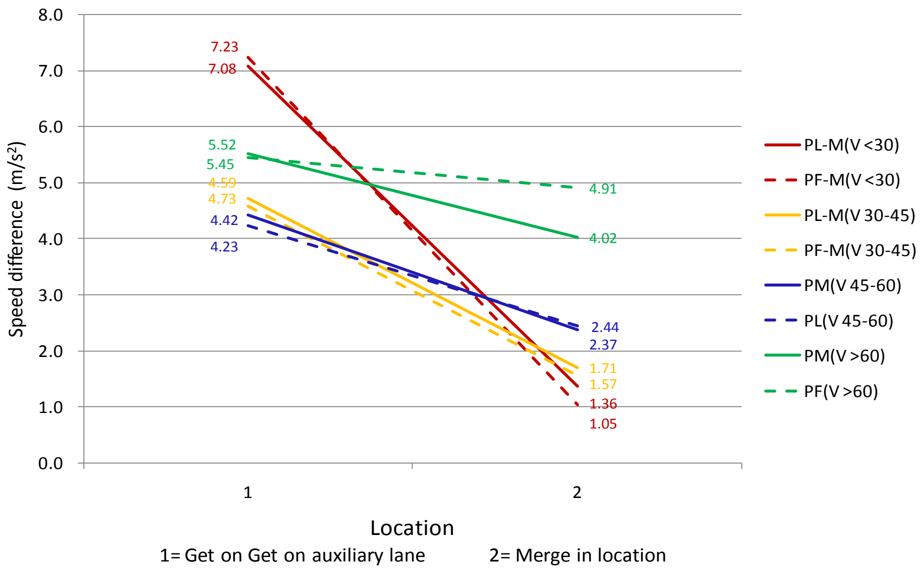
Figure 4*b* illustrates that most "Overtaking" vehicles have big speed difference from PL and PF of the original gap, and they obviously decrease their speed in the merge duration to reduce the speed difference from the PL and PL of the accepted gap, especially from the PL. Meanwhile, the merging vehicles with slow speed hold smaller speed difference with the PL and PF of the accepted gap. The vehicles having the highest speed (speed above 60 km/h) could tolerate the biggest speed difference with their PL and PF (4.02 and 4.91 m/s) when they merge in main lane, while for the slowest vehicles these tolerance values drop to 1.36 and 1.05 m/s.

As it showed in Figure 4*a*, the "Original Gap" vehicles have much smaller speed difference from PL/PF of the accepted gap compared to the "Overtaking" vehicles when these two types of vehicles just get on the auxiliary lane. And the "Original Gap" vehicles do keep the smaller speed difference until they reach the merge point.

Based on the analysis above, we conclude that small speed difference between the merging vehicle and PL/PF are required for successful merge action. The preferred absolute speed difference between the merging vehicle and PL or PF is below 3.0 m/s, except these vehicles whose speed is higher than 60km/h. Merging vehicles with high speed difference from the vehicles on the target lane need to apply speed synchronization.



(a) "Original Gap" vehicles



(b) "Overtaking" vehicles

Figure 4 Speed difference between merging vehicles and PL/PF at different locations

4.3 Speed Synchronization during the Lane Change Process

With the evidence of the existence of synchronization in merge duration, we further investigate that how the merging vehicles conduct speed synchronization along with the changing PL and PF, focusing on the merge vehicles which overtake several vehicles on the adjacent lane. To understand it, two random merging vehicles for "Original Gap" type and the "Overtaking" type, respectively, are chosen. Their speed, acceleration and speed difference from their PL and PF of current gap in the whole merge duration are plotted in Figure 5. The horizontal axis presents the span of time (in second) when the merging vehicle is driving on the auxiliary lane and the x = 0.0 point presents the spot time of the successful merge of the vehicle.

Figure 5*a* and 5*c* shows the “Original Gap” vehicles gradually adjust their speed (ID36 increases speed and ID118 decreases speed) to reduce their speed difference from PL and PF in the merge duration in two steps. First, they primarily synchronize their speed with the speed of PL and PF of current gap to keep the difference within 2m/s seconds, and then they maintain their speed and regulate their relative distance to PL and PF. Second, they further synchronize their speed with the speed of the PL and merge in the target gap in two seconds.

In Figure 5*b* and 5*d*, the “Overtaking” vehicles apply the same two-step strategy for speed synchronization as the “Original Gap” vehicles after they reach the final accepted gap. They merge in the accepted gap within 3 seconds after further synchronizing their speed with PL and PF. Agreeing with the previous aggregated results, the “Overtaking” vehicles have larger speed difference from their PL/PF in the whole merge duration and drive for longer time on the auxiliary lane to seek acceptable gap. For example, the vehicle ID 93 has higher speed, so it stands higher tolerance of speed difference between itself and PL/ PF at the merge point.

To prove the assumption above, every trajectory of the 157 “Overtaking” vehicles is divided to two parts from the point where it is parallel with the PF of its accepted gap (Parallel point). Figure 5*e* plots the average speed differences between the merging vehicles and their PL/PF in 5 seconds span right before the parallel point and right before the merge point, respectively. The green lines illustrate that the “Overtaking” vehicles averagely hold around 6m/s speed difference from PL and PF before they are parallel with the PF of their accepted gap, support our above conclusion (here, the “Original Gap” vehicles do not have parallel point). The red and blue lines present the dwelling for merging vehicles conducting the further speed synchronization is around 2 seconds before the merge execution.

The courtesy yielding of the PFs of ID 118 and ID 227 is found in figure 4*c* and 4*d* illustrated by the red dashed line. These PFs conduct courtesy yielding (deceleration) after the merging vehicles get into the second step synchronization. For the vehicles ID36 and ID96, the PLs accelerate to create bigger gap for merge action, which also occurs right after the merge vehicles initialize the second step synchronization. So, when the merging vehicles start the second step synchronization stage, the interaction between the merging vehicle and the PL and PF becomes more intense and the possible courtesy yielding (PL or PF involved) begins.

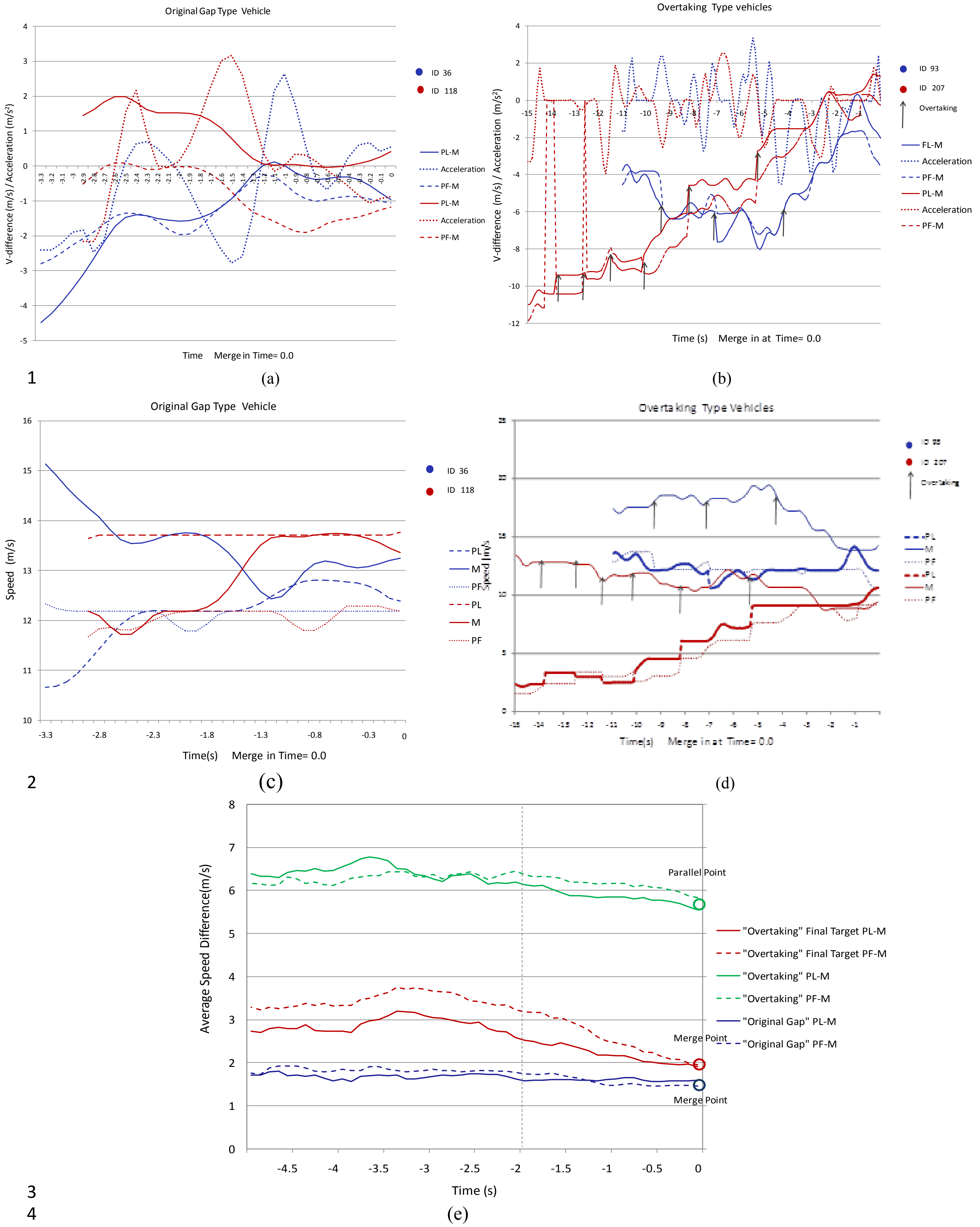


Figure 5 Speed synchronization of sample vehicles

"Original Gap" vehicles(a) (c) "Overtaking" vehicles (b)(d) Average speed difference (e)

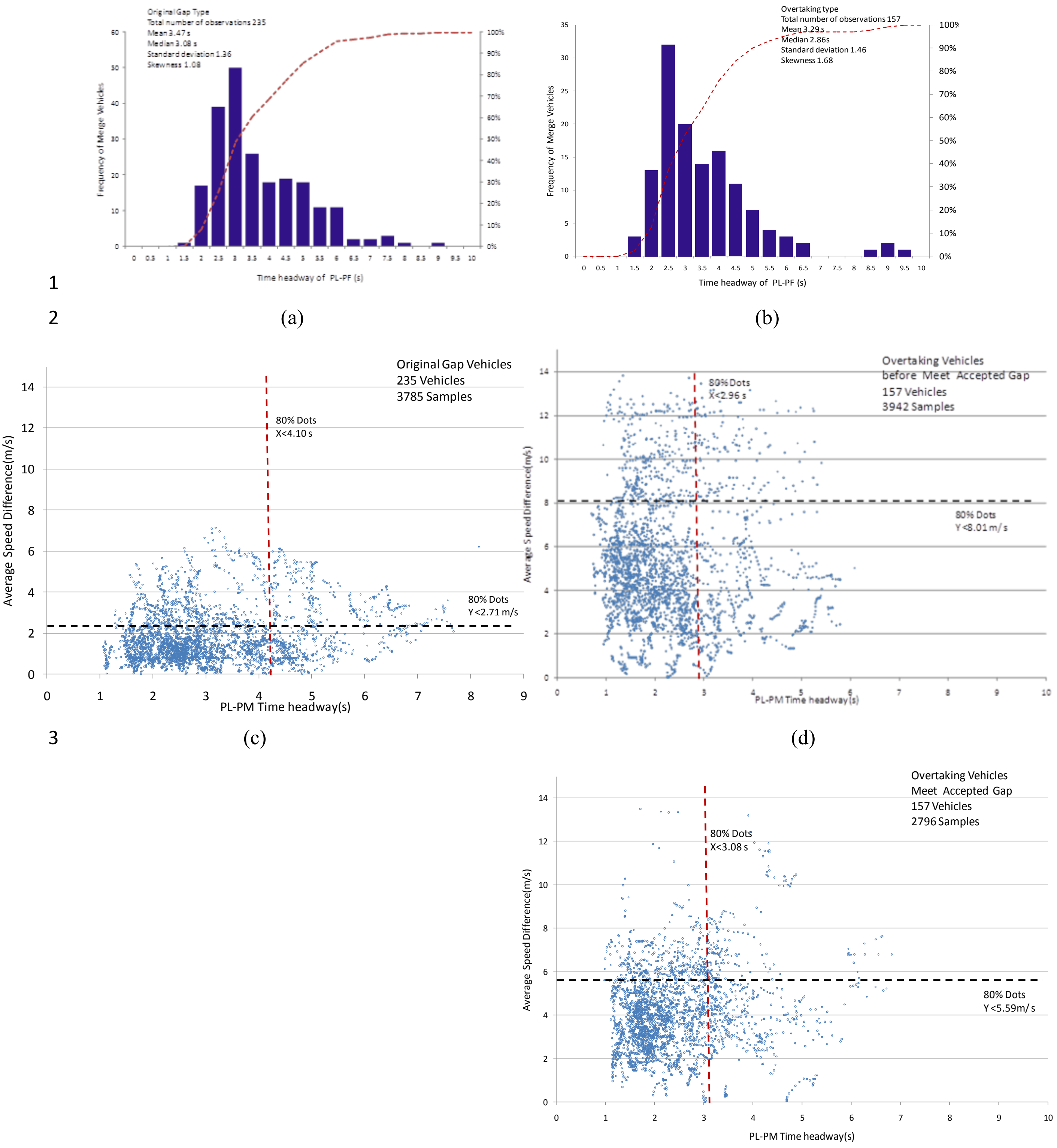
4.4 Speed Difference and Gap Selection

Whether the speed difference affects the target gap selection or not is investigated in this section. Figure 6*a* and 6*b* show the time headway histograms of the accepted gaps for the "Original Gap" and "Overtaking" merging vehicles at the merge point. A Kolmogorov-Smirnov test showed there is no significant difference between them (with 95 percents confidence). The sample merging vehicles could accept the gaps with headway as small as 1.51s, which is the sum of two critical gaps (from PL to merging vehicles and from merging vehicle to PF). This result is consistent with the conclusions based on the observations in the Netherlands which is the smallest time headway of accepted gaps is smaller than the critical gap in the lane change gap acceptance theory *(2)*.

The gap between the PL and PF was argued as the most important factor for the merging vehicles to choose a gap or not. Does the speed difference of the merging vehicle from the PL and PF play a role in the gap selection process? To address this question, the relationship between the time headway of PL to PF and the absolute average speed difference of merging vehicle with respect to PL/PF are plotted in Figure 6. The data are collected in two seconds interval starting from a spot time when the merging vehicles begin to involve in a new pair of PL and PF with the updating of every 0.1s. Here, three conditions, the "Original Gap" vehicles' accepted gaps (6*c*), the "Overtaking" vehicles' rejected gaps (6*d*) and accepted gaps (6*e*), are considered, respectively.

Figure 6*c* illustrates that, besides the large time headway between PL and PF, relatively low speed difference between merge vehicles and their PL/PF would lead the merging vehicles to targeting the original gaps as the accepted gaps. Figure 6*d* presents the scenario that the "Overtaking" vehicles reject current gaps as their accepted gap as higher speed difference between merge vehicles and their PF/PL, and the lower time headways between PL and PF exist. However, the "Overtaking" vehicles do not only pursue bigger gaps between PL and PF during the merging duration, as the time headways between PL and PF of their accepted gaps (showed in figure 6*e*) have no obvious increment compared with the headways in figure 6*d*. While smaller speed difference between merge vehicles and PF/PL occurs when these "overtaking" merge vehicles reach their accepted gaps in figure 6*e*.

Even though the gap selection is determined by various factors, with the analysis above, it could be deducted that speed synchronization helps the merging vehicles successfully merge in tight gap.



(a) (b)

(c) (d)

(e)

Figure 6 Time headway and gap selection

Time headway distribution (a) and accepted gap (b) of "Original" vehicle

Time headway distribution (c), rejected gap (d) and accepted gap (e) of "Overtaking" vehicle

5. MODELING OF THE SPEED DIFFENENCE AT THE MERGE POINT

The speed of the merging vehicles in the merge duration may rely on various factors, such as the driver's drive behavior and judgment ability, traffic conditions and the relations of the merging vehicles with other vehicles nearby. The models for the absolute speed difference between merging vehicles and PL/PF at the merging point are developed here to find the key effective factors of speed difference tolerance of merging vehicles at merge point and to provide some practical information for traffic flow microscopic simulation. As the speed and the speed difference of merging vehicles are highly relate to the speed of the PL and PF after synchronization, it is not meaningful to model these indexes. The absolute speed difference model is to test the tolerance of the merging vehicles to speed difference between themselves and PL/PF.

In these models, the average speed in two seconds span before the merge location is defined as the speed of the merging vehicles at the merge location. The speeds of the PL/PF and the time headway between them are also defined as the average values in two seconds in our models. Adapting of 2 seconds average speeds to represent 21 spot speeds here has two reasons. First, it agrees with our previous analysis results that the merging vehicles maintain a further synchronized speed for around 2 seconds before they merge in adjacent main lane. Second, it may prevent some distinct errors brought by the application of instantaneously deviated speed.

A multi-liner regression model is built here with following specifications:

$$\mathrm{SD_n} = \beta X_n + \epsilon_n \quad (1)$$

Where

$\mathrm{SD_n} = \mathrm{SD_n^{PL-M}}$ or $\mathrm{SD_n^{PF-M}}$. $\mathrm{SD_n^{PL-M}}$ refers to absolute speed difference between merging vehicle n and its PL. $\mathrm{SD_n^{PF-M}}$ stands for absolute speed difference between merging vehicle n and its PF

X_n = vector of explanatory variables,

β = corresponding parameters, and

ϵ_n= error term associated with observation n.

The considering explanatory variables in these models contain three types: the characteristics of the merging vehicle (the number of gaps the merging vehicle rejected before getting into its accepted gap, distance between the current location of merge vehicles and the end point of the auxiliary lane, the speed synchronization direction - acceleration or deceleration when the merge vehicle is involved in the gap), the characteristics of the vehicles surrounding the merging vehicle (speeds, type, lengths and corresponding time headways of merging vehicle' PL/PF/the leader on auxiliary lane) and the relationship between the merging vehicle and the vehicles surrounding it (time headways between merging vehicle and it's PL/PF/the leader on auxiliary lane). As the research area is a weaving section, which contains an on ramp and an off ramp, the vehicles surrounding the merging vehicle are classified to three types by their origin and destination: going-through vehicle (the vehicle which passes through along the main lane without involving any merging/leaving process), merging/merged vehicle and leaving vehicle.

After correlation tests between variables, the estimation results of the speed difference models are presented in Table 1.

Table 1 Estimation Results of the Speed Difference Models

Variable	SD^{PL-M} model		SD^{PF-M} model	
	Parameter Value	t-Statistic	Parameter Value	t-Statistic
Constant	2.486	3.892	1.515	3.759
Number of rejected gaps	0.316	4.886	0.364	6.030
Speed change direction (acceleration =1,Deceleration = 0)	-.432	-2.485	-0.163	-1.802
Time headway PL-M (m/s)	0.456	3.071		
Distance to the end of Auxiliary lane (m)	-0.003	-2.648	-0.002	-2.305
Speed difference PL-PF (m/s)	0.419	3.955	0.227	3.019
Time headway PL-PF (m/s)			0.201	3.441
PL- merged vehicle	-0.638	-2.648	-0.507	-1.837
R	0.679		0.590	
R^2	0.461		0.348	

*Number of observations 333 samples

As showed in Table1, the significance and positive parameter of Number of Rejected Gaps variable in both models indicates that the more number of gaps rejected by merging vehicles before they get in to the merge position, the larger speed difference between the merging vehicles and their PL/PF. The larger number of rejected gap makes the drivers lose patient and represents the difficulty for merging-in action.

The negative parameters of the Speed Change Direction variable in these two models refer to that through acceleration the merging vehicles synchronize their speed with PL and PF and eventually yield a smaller speed difference at merge point. In this condition, the main lane probably is at pleased service level and it is comparably easy for the merge vehicle driver to well predict the speeds of the PL and PF and precisely conduct synchronization.

Bigger time headways between the merging vehicle and its PL (inSD^{PL-M} model) and between the PL and the PF (inSD^{PF-M} model) could increase speed difference tolerance of the merging vehicle. This is reasonable since the bigger gap among vehicles allows merging vehicles to practice merge execution with higher freedom for speed management.

The positive value of the speed difference between PL and PF in both models illustrates that when the PL holds higher speed than the PF, it brings wider speed choice for merging vehicle.

The negative parameter of the distance to the end point of the auxiliary lane variable shows that the pressure felt by the driver when approaching the ending point of the auxiliary lane forces the merging vehicle to take more risk to execute merge action with higher speed difference with its PF and PL. This phenomenon is proved by actions of the "Overtaking" merging vehicles. The higher speed of the PL or the leader vehicle of the merging vehicle leads to the speed difference between the merge vehicle and PL decreasing.

The only significant vehicle type factor in these two models is the PL-merged vehicle in the weaving section, which have a negative parameter. It means when the PL of the merging vehicle which also merged from the on ramp to the main lane in this weaving section will decrease the speed difference between the merging vehicle and its PL/PF. The possible explanation is that the identical character of merging vehicle and its PL lessen the speed difference between the merging vehicle and its PL/PF when the merging vehicle is involved into this accepted gap. However, the complex condition in weaving section need to be further explored in the future.

6. CONCLUSION AND OUTLOOK

As the merging vehicles lane change preparation could be easily detected, the speed synchronization behavior of the merging vehicles is implicitly explored in this research with the NGSIM data at the US101. In this data set, we have tracked down the trajectories of 399 merging vehicles after they get on the auxiliary lane and before successfully merge into the main lane. Following results are obtained based on data analysis:

Based on the statistic results, there are seldom merge vehicles which are overtaken by the vehicles on the adjacent main lane as 70.72% of merging vehicles' speeds is higher than their PL and PF of original gap. The merging vehicles are divided into two types: the "Original gap" vehicles and the "Overtaking" vehicles. The "Overtaking" vehicles overtake vehicles on the adjacent main lane, drive for longer time on the auxiliary lane and take smaller lane change gap compared to the "Original" vehicles.

With the comparison of the speed difference of the merging vehicle from their PL and PF separately at two locations (the place where the merging vehicles just get on the auxiliary and the place where merge action is finished), it is found that the merging vehicles adjust their speed difference from the PL and PF, and the existence of the speed synchronization of the merge vehicles is proved. The "Overtaking" vehicles hold larger speed difference from PL and PF when they just get on the auxiliary lane and obviously reduce the speed difference during the merging preparation. The higher speeds of merging vehicles result in higher the speed difference it can tolerate at the merge location.

Based on four randomly selected trajectories of these merging vehicles, the speed synchronization rules of the merging vehicle are portrayed as: when the current gap is not the target one, the merging vehicles adjust its speed intending to maintain a 5~7 m/s higher speed to current PL and then overtake it. When the current gap is an acceptable one, the merging vehicle adopts a two-step tactics to accomplish merge action: first, they regulate their speeds to keep within around 2 m/s difference from their PL and PF adjusting their positions in the gap; second, they further arrange their speeds to approach to the speed of the PL/PF and then merge in the target gaps in 2~3 seconds. The courtesy yielding behavior of the PL or PF is observed after the second synchronization step of the merging vehicles.

The effect of the speed difference on gap selection is also carried out in this study. By plotting the relationship between the speed difference and time headway for the accepted and rejected gaps, respectively, it is found that when merging vehicles have a larger speed difference with PL and PF, they reject such gaps.

Finally, the absolute speed difference multi-regression models between merging vehicle and PL/PF at the merge point are constructed. Based on the estimation results, the number of rejected gaps by merging vehicles, the speed synchronization direction, speed difference between PL and PF, the time headways, the distance to the ending of the auxiliary lane and the vehicle type of PL of merging vehicles are all found to have significant impacts on speed difference tolerance of merging vehicles at merge location.

The paper presents an empirical investigation of the speed difference, speed synchronization and gaps of the merging vehicles with their PL and PF. Understanding of the merging behavior would help us to accurately model the complicated microscopic driving behavior. Further study is to analyze the interactions between the vehicles during the synchronization with the help of multiple data sources, and fuse the synchronization with the car following model to built dynamics lane change model.

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