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Driving Simulation Study on Speed-change Lanes of the Multi-lane Freeway Interchange

Zhongyin Guo [1] , Haifeng Wan [1]*, Yi Zhao [1], Haocheng Wang [1], Zhenjiang Li [2]

1. Key Laboratory of Road and Traffic Engineering of Ministry of Education, Tongji University, Shanghai, 201804，China

2. Shandong Provincial Communications Planning and Design Institute, Jinan, Shandong, 250031,China

Abstract

Because of the interactions of the multi-lane freeway mainline, upstream, downstream, the diversity of environmental conditions, as well as the complexity of geometric configuration, speed-change lanes of the multi-lane freeway interchange present greatest safety and operational challenges for drivers. Most freeway crashes occur in the vicinity of interchange diverging and merging areas, especially in speed-change lanes. In this paper, the UC-win/Road5 software was used as the technical tool, and a three-dimensional driving scene was built. Multi-lane freeway field data were used for the calibration of model parameters. The geometry configuration of the speed-change lanes as well as the driving behavior characteristics such as speed, acceleration rate, glancing in the diverging and merging areas were studied in this paper. Based on the driving simulation study in the areas, results supply a valuable technical reference for speed-change lane geometry configuration, the length design of speed-change lane, the operational safety evaluation of multi-lane freeway diverging and merging areas, also the operation and management of multi-lane freeways.

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Key Words: freeway; interchange; deceleration lane; acceleration lane; driving simulation

1. Introduction

The multi-lane freeway is a particular type of freeway which adapts to the heavy traffic conditions. Diverging and merging areas in the multi-lane freeway interchange are dynamic segments, where vehicles change lanes frequently to complete merging and diverging operations or use brake and accelerator in a limited spacing. As a result, traffic flow is rather unpredictable and volatile with negative impact on the safety and efficiency of the entire interchange. The design of the ramp-freeway junction is a critical component in the overall safety performance of a controlled access facility. Interchanges present the greatest safety and operational problems for drivers, as most freeway crashes occur in the vicinity of interchanges. Interchanges are inherent points of conflict involving entering and exiting traffic. Both entry and exit operate place increased demands and

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* Corresponding author. Tel.: 021-69585413.
E-mail address: wanhaifeng81@126.com

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workload on drivers associated with navigational decision making, speed changing, and tracking. The combination of these demands results in an increased likelihood of driver error. Speed-change lanes at freeway ramp terminals are critical elements in freeway design, providing the necessary access between the freeway and the adjacent local street network. Freeway speed-change lanes and ramp terminals are designed allow vehicles to depart or enter the freeway safely and efficiently. In the design process of the freeway interchange, speed-change lanes are used to reduce intervention between mainline and ramp vehicles to increase capacity and improve the safety of operation.

According to the current research, accident causes are as following: the geometric characteristics of the freeway，particularly the speed-change lanes; environment and traffic conditions; the features of the vehicle; and, of course, the driver's behavior during the exiting and entering operate. Considering the importance and small body of literature in this area of freeway design, prevailing guidelines for the design of speed-change lanes are well-established, based on longstanding research about the performance characteristics of vehicles and principles of geometric design, but little is known about the behavior of drivers who are making freeway entry or exit maneuvers, for example. Further research is required to gain a deeper comprehension of the relationship between driving performance and speed-change lane features. The geometry configuration of the speed-change lanes as well as the driving behavior characteristic such as lane changing behavior, speed, acceleration rate were studied in this paper.

2. Literature review

Interchange were studied much in history，but few studies take the driving behavior in speed-change lanes into account, and driving behavior characteristic of multi-lane freeway speed-change lane is almost blank. Over the years, many researchers have studied vehicle operating characteristics in an attempt to establish the safest and most efficient design criteria for the improved efficiency of freeway deceleration lanes and exit ramps. However, as noted by Koepke(1993), many of the current design criteria for interchanges (e.g., AASHTO, 2004; SETRA, 1998; TAC, 1999; Ministerio de fomento,2001; MIT, 2006; VSS, 1998) are based on studies that are 50–60years old with geometric requirements that were designed according to kinematic and dynamic equations that neglected driver behavior.

Since the1950s, a number of studies have identified interchanges as the most frequent site of freeway collisions (Conklin, 1959; Oppenlander and Dawson,1970;Twomey et al., 1992). Specifically, the greatest percentage of accidents at interchange are observed in the deceleration lanes as shown by Lundy (1967) and, more recently, by McCartt et al. (2004) and Lord and Bonneson (2005). Notwithstanding the great efforts expended on the improvement of vehicles, their control technologies, road materials and design standards, the safety problems of deceleration lanes have by no means been solved.

Khorashadi (1998) confirmed that compared to traffic, geometric design is not a determining cause of collisions. A recent study of Chen et al. (2009) analyzed the safety performance of deceleration lanes of a freeway in Florida and again confirmed the significant influence of traffic on the safety of freeway divergence areas. Fukutome and Moskowitz (1963) investigated the behavior of drivers approaching deceleration lanes in terms of speed. They found that drivers continue to decelerate on the ramp that follows the deceleration lane, and exiting drivers adopt speeds significantly lower than the speed of through traffic at the beginning of the deceleration lane. Further, this difference in speed is reflected backward and interferes with through traffic on the freeway. Similar results were obtained by Livneh et al. (1988). These authors also found significant differences between their observations and the AASHTO model for the determination of deceleration lane length; specifically, actual deceleration values are lower than the values suggested by AASHTO. Recently, El-Basha et al. (2007) demonstrated that divergence speed is highly dependent on the freeway's mean speed and that the deceleration lengths, the diverging traffic volume and the deceleration rates depend on the freeway's geometry and traffic flow.

Moreover, the authors found that the speed differential between vehicles continuing on the main lane and those diverging is influenced by the deceleration length, the traffic flow upstream and the traffic composition. In any case, it is difficult, if not impossible, to use only site observations to achieve in-depth investigations of human factors. Emerging technologies make it possible to evaluate the interactions between the driver, the vehicle and the road environment through an interdisciplinary approach based on driving simulations. Driving simulators enable one to study the variability of driver performance under different conditions (e.g., geometries and traffic flows) and offer a promising perspective for road safety design and management. Although there are numerous applications that demonstrate the potential of interactive driving simulations for road safety investigations and evaluations, there is few simulation studies in the literature focused on driver behavior in deceleration lanes. Among the studies that do exist, two (Bella et al., 2007; Yan et al., 2008) validate the use of driving simulators for speed and trajectory analyses and encourage the incorporation of these analyses in the design of deceleration lanes. Fitzpatrick and Zimmerman reviewed the acceleration lane lengths in the 2004 Green Book and revealed that the procedure identified to reproduce these values used assumed running speed for the limited-access highway and the ramp along with acceleration rates from 1930s studies. They then used acceleration rate, along with design speeds for the freeway and the ramp curve, to generate potential acceleration lengths. These suggested lengths were longer than the values in the Green Book by as much as 500 ft.

As early as 1960, Fukutome and Moskowitz reviewed traffic behavior relative to the design of entrance ramps. Fukutome and Moskowitz also investigated traffic behavior on exit ramps in California. Michaels and Fazio presented a driver behavior model of merging in a paper. Kondyli and Elefteriadou reported on a study that conducted three focus groups to investigate drivers' intended actions along a freeway-ramp merging segment. The researchers correlated drivers' responses to their individual characteristics, considering both congested and non-congested conditions.

3. The experiment research

3.1 Apparatus

Driving simulations were performed using the UC-win/Road ver.5 driving simulator system at the key laboratory of road and traffic engineering of ministry of education in Tongji University. The full apparatus has been validated extensively. The hardware consists of four networked computers and three hardware interfaces (the steering systems, the pedals and the manual gearshift). The road scenario is projected onto three big screens providing a 135◦ field of view. The resolution of the visual scene is 1024×768 pixels with a refresh rate of 30–60 Hz depending on scene complexity and the traveling conditions of the vehicle. The simulator allows the recording of the intensity of the actions of the driver on the brake, the accelerator pedal and the steering wheel. Additionally, the simulator provides many other parameters that describe traveling conditions, such as the longitudinal position of vehicle's center of gravity, the relative lateral position or displacement of vehicle with respect to the road axis and the local speed and acceleration at 4m intervals.

Figure1. Driving simulator system

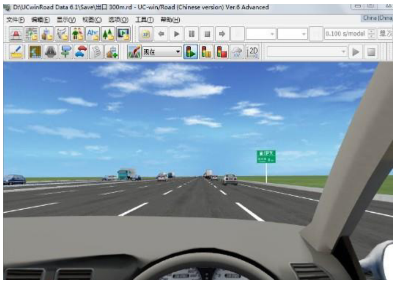

Figure2. Driving simulator interface

3.2 Scenarios

The input parameters of these tests equivalent these variables under considerations. The design speeds for all the selected sites from filed data. For the practical design purpose, these design speeds were simulated respectively with70kmph, 90kmph, 100kmph speeds on the main lanes and ramps accordingly. For the two-lane exits, due to one-lane drop at the freeway diverge areas, the number of through lanes were selected as four.

The determination of exiting and entrancing volumes was based on two resources, the field data and Highway Capacity Manual (HCM2000). Exiting and entrancing volumes were extracted from Shanghai-Nanjing freeway in Su Zhou, and the experiment volumes were about a little higher than the field data. The selection of volume was also determined by presenting the results in a clear, reasonable and practical way for design standards.

Table1. Experiment parameters

Speed-change Lane	Vehicle	Length of Speed-change Lane (m)	Parameters
Deceleration Lane	Car	150/225/300	Vou=100km/h，So=1.5km，Q=1500pcu/h/lane.
	Truck	150/225/300	Vou=90km/h，So=1.5km，Q=1500pcu/h/lane.
Acceleration Lane	Car	300/400/500	Vin=70km/h，So=1.5km，Q=1500pcu/h/lane.
	Truck	300/400/500	Vin=70km/h，So=1.5km，Q=1500pcu/h/lane.

In each scenario, the driver was required to diverge from the freeway at the first exit or entrance. The exit was indicated by vertical signs. The first vertical exit sign was 500 m before the beginning of the taper of the speed-change lane. The driver could see his speed on the speedometer and were free to choose the velocity they preferred.

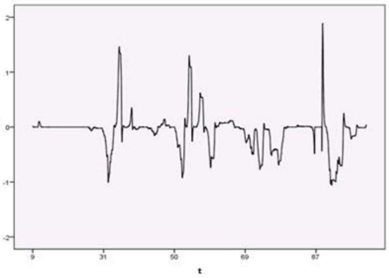

Figure3. Driving simulation data in the exit area

Figure4. UC-win/Road ver.5 driving simulation network

Fig. 3 shows an overhead view of the speed-change lane with a graphical representation of the data profiles collected from the simulations (times, speed and acceleration). We used these data for comparison with design standards and literature findings. Fig.4 shows the UC-win/Road ver.5 driving simulation network for speed-change lanes, and the interface of the driving simulation from different directions.

4. Results and discussion

4.1 Velocity and Acceleration rate

We analyzed the behavior of drivers approaching the speed-change lane, during lane-change operation and along the speed-change lane until the beginning of the exit and entrance ramps. The indicators selected for these analyses included the vehicles' positions or displacements along the road (trajectories) and speeds and deceleration rates as measured by the pressure applied to the accelerator and brake pedals. Data were recorded at different sites along the simulation and are summarized in the following figures, and the data was transformed into three-dimensional figures with the SPSS PASW Statistics software.

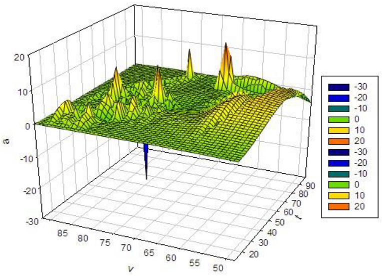

Figure5 Relationship between v-a - t (Exit truck/150m)

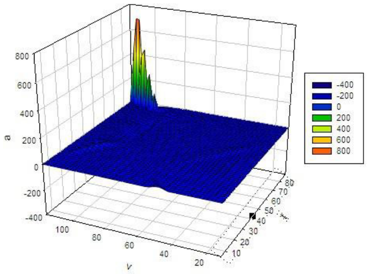

Figure6 Relationship between v-a –t (Exit car/150m)

Fig.5 and Fig.6 show the relationship between velocity、acceleration rate and time in the exit area. It could be induced from the two figures that the acceleration rates of the truck change much more frequently than the car, but the maximum of the car's acceleration rates were larger than the truck's. Analysis the variation of the acceleration in depth it shows that the vehicle acceleration of the start-up phase is generally larger, while the acceleration is relatively stable during operation, as far as the acceleration values concerned, the acceleration value of the car was larger than the acceleration value of the truck, and maximum acceleration value of the car was 0.8m /s2, but the maximum acceleration of the truck was -0.3 m/s2. Analysis the particularity of the acceleration we could know that the main reason why larger acceleration value it's the vehicles interfere with each other caused by the heavy volume.

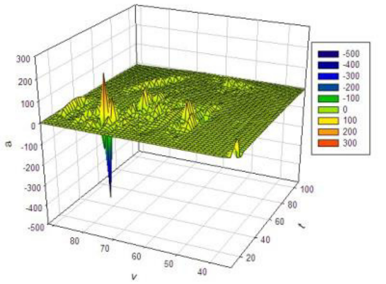

Figure7 Relationship between v-a – t (Exit truck/225m)

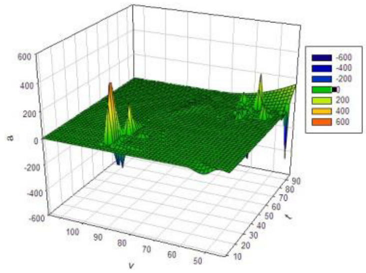

Figure8 Relationship between v-a – t (Exit car/225m)

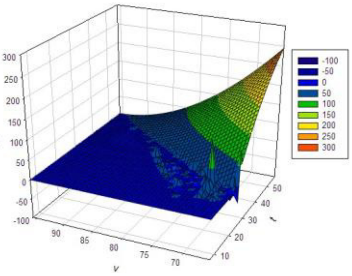

Figure9. Relationship between v-a- t (Exit truck/300m)

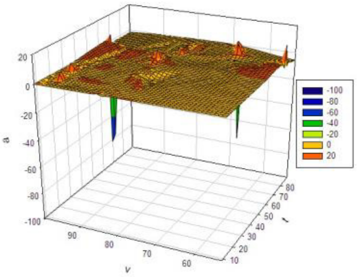

Figure10. Relationship between v-a-t (Exit car/300m)

Fig.7-Fig.10 show that with the length of deceleration lane increased by 75m interval from 150m to 225m, truck deceleration process is still complicated but the trend become much more stabilized, and the maximum acceleration value was-0.3m/s2. But the acceleration will increase when the length of deceleration lane increased to 300m. Analysis the reason we can see that because of the trucks own special performance, the acceleration and deceleration values of vehicle were usually stable at 0.3m/s2, because of the car's excellent acceleration and deceleration performance, the maximum acceleration value will grow when the deceleration lane length up to 300m, at the same time, it is not conducive the vehicle stability diverging, the length of deceleration lane in the conditions should be designed for 250m.

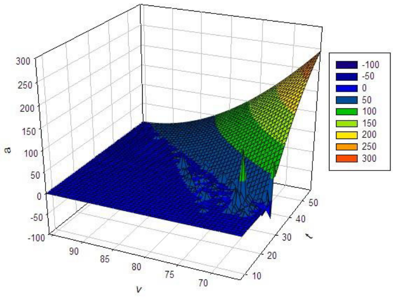

Figure11 Relationship between v-a- t (Entrance truck/300m)

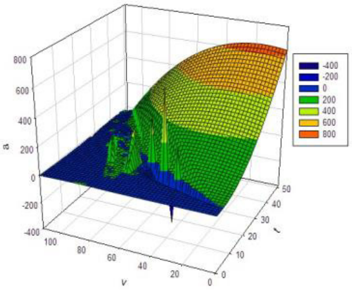

Figure12 Relationship between v-a – t (Entrance car/300m)

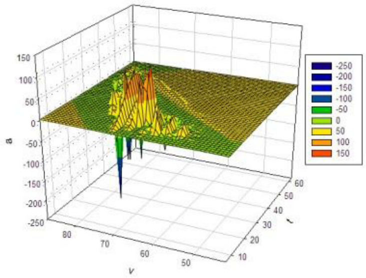

Figure13. Relationship between v-a- t (Entrance truck/400m)

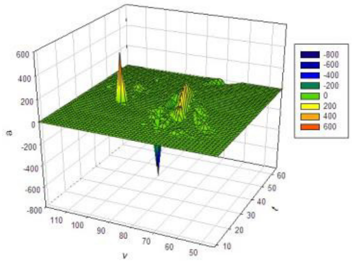

Figure14. Relationship between v-a - t (Entrance car/400m)

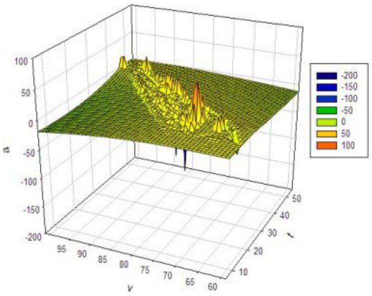

Figure15. Relationship between v-a – t (Entrance truck/500m)

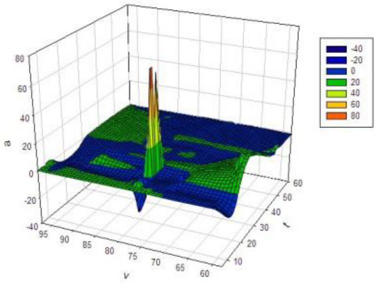

Figure16 Relationship between v-a – t (Entrance car/500m)

Analysis Fig.11-Fig.16 show that when the length of the acceleration lane increase from 300m to 500m at equal interval 100m, the car's acceleration and deceleration processes were extremely complex. It runs relatively stable when the length of the acceleration lane is 400m, but as far as the acceleration values concerned, and the maximum acceleration of the truck was 0.15m/s2, meanwhile, the maximum acceleration of the car was0.20m/s2.When the length of the acceleration lane increase to 500m, the trucks changed speed frequently in the whole process and the maximum acceleration of the cars was up to 0.60m/s2. In summary, the appropriate length of the acceleration lane in the conditions should be 400m.

4.2 Entrance Ramp Glance Activity Analyses

The experiment observed a total of 69 glances by the driver on the three entrance ramps. The time duration of each glance was measured and calculated the corresponding distance traveled and change in speed. Of the 69 glances, 48 of them began prior to the painted nose, as shown in Figure 17 the glance data indicate that the average glance by a merging driver is typically about 3.0to3.5s long, though some glances are very small and others are very lengthy, as drivers occasionally look into their mirrors for extended periods of time with imperceptible breaks. The first glances on a given ramp were frequently longer than subsequent glances, suggesting that later glances were commonly used to confirm the appropriateness of a gap identified previously. Based on the data collected in the driving simulator system, a merging driver travelled 40 to 60m and increased speed by 3 to 5 km/h during an average glance.

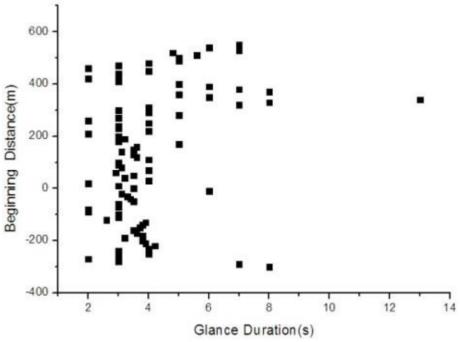

Figure17 Glances in relative position to the painted nose

4.3 Exit Ramp Coasting Analyses

The objective of this analysis was to examine the validity of the assumption in the Green Book methodology that drivers decelerate in gear (i.e., coast) for 3s prior to applying the brake when exiting a freeway. The Green Book states that deceleration is a two-step process: first, the accelerator pedal is released (for a length of time assumed for 3s) and the vehicle slows in gear without the use of brakes, and second, the brakes are applied. Previous research (Fitzpatrick and Zimmerman, 2007) concluded that the graphs were based on data from studies conducted in the 1930s and 1940s, but the underlying methodology was carried through to the current edition of the Green Book (2004).

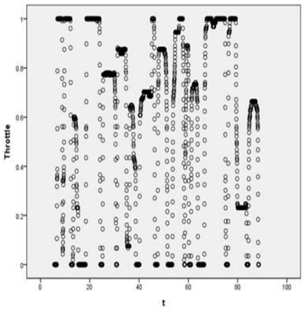

Figure18. Throttle in deceleration lane (Car)

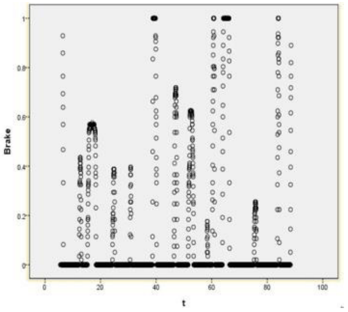

Figure19. Brake in deceleration lane (Car)

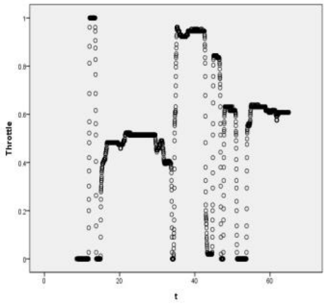

Figure20. Throttle in acceleration lane (Car)

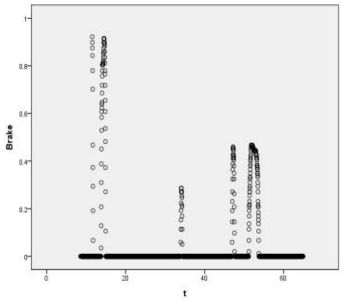

Figure21. Brake in acceleration lane (Car)

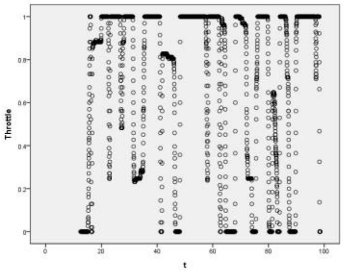

Figure22. Throttle in deceleration lane (Truck)

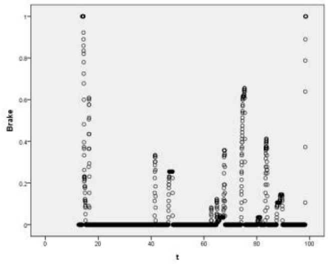

Figure23. Brake in deceleration lane (Truck)

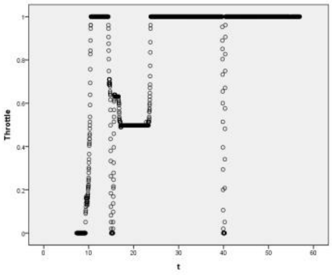

Figure24 Throttle in acceleration lane (Truck)

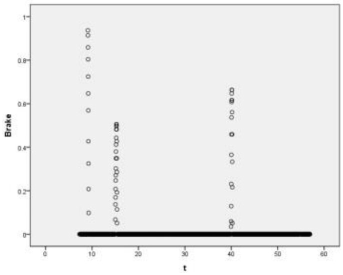

Figure25 Brake in acceleration lane (Truck)

Fig.18- Fig.25 were the experiment results, we can induce from the results that the throttle in speed-change lanes were much more frequently than brake in speed-change lanes, the throttle release time and the brake time were appear in the figures.

Using the reduced and processed data, researchers further examined the details of the data for exit ramp coasting. In the review of coasting data, researchers examined three time values for each subject on each ramp. The elapsed time between the occurrence of peak speed and the deactivation of throttle (i.e., the time spent to remove the foot from the pedal). The elapsed time between the deactivation of throttle and the activation of brake (i.e., the amount of time when neither throttle nor brake was in use).Visual exploration of the data reveals that the times for each ramp follow a lognormal distribution rather than a normal distribution and the differs by ramp.

5 Conclusion

This paper approaches the topic of the speed-change lane and the diverging and merging operate by analyzing drivers' performance in a driving simulator. Specifically, the effects of variation in the length of the speed-change lanes on driving performance have been investigated and statistically verified.

We observed that drivers' performance such as speed、acceleration、glance activity while approaching different length speed-change lanes. Moreover, the actual performance of drivers do not always correspond to the assumptions of many models and technical regulations. In general, this difference occurs because the design of deceleration lanes is traditionally based on kinematic principles that neglect actual human performance.

Several findings underscore this conclusion: First, drivers decelerate or accelerate before the diverging lane or merging lane and maintain reduced speeds for a long section of the road while diverging and merging, and these actions are reflected backward and cause interference with through traffic on the freeway. We could know that the main reason why larger acceleration value it's the vehicles interfere with each other caused by the heavy volume. Third, the length of the deceleration lane in the conditions should be designed for 250m. Forth, the appropriate length of the acceleration lane in the conditions should be 400m.Fifth, the average glance by a merging driver is typically about 3.0to 3.5 s long, though some glances are very small and others are very lengthy.

Although the results of this study are promising, additional simulator studies are planned. Further validation studies that vary traffic flow both in the main lanes and speed-change lanes、vary geometric characteristics should be performed to confirm these findings and strengthen and generalize the results. Furthermore, the field data should be collected under different conditions to modify the driving simulation experiment parameters.

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