

Evaluation of Freeway Merging Assistance System Using Driving Simulator

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Abstract

Covering from traffic safety education to cutting-edge Connected and Automated Vehicles (C/AV) technologies, the use of a driving simulator enables to seamlessly capture the behaviours of individual drivers, which is predictably challenging when attempted through legacy simulation models (e.g., VISSIM, AIMSUN, Synchro, etc.). This paper utilizes virtual realities to assess the impacts Freeway Merging Assistance (FMA) application. The Freeway Merging Assistance (FMA) provides drivers with forecasted situational awareness along with advisory speed range on the merging area. Specifically, the application provides an advisory speed range to any driver merging to the mainline through an in-vehicle display device. The advisory speed range is determined by analyzing the speed and position information of the mainline vehicles approaching the merge segment. The impacts of FMA applications were successfully evaluated by precisely capturing the diverse driving behaviours of human drivers. A total of 13 subject drivers were recruited and the final group of 10 participants was selected for inclusion in the experiments after initial screening tests for all subject participant to detect any potential problems (e.g., simulation sickness). The research team designed a questionnaire for the subjects based on a Likert Scale and then conducted experiments with the human subjects. With the projected situational awareness provided by the FMA application, 70% of subject drivers responded that the FMA application enabled drivers on the on-ramp to make safe and smooth merges to the mainline.

KEYWORDS:

Connected vehicles, driving simulator, ITS, Freeway management, Human factor

Introduction

The Driving Simulator (DS) has gained great attention in recent years as a powerful tool to support highway safety and operational assessments from the perspective of drivers. More recently, DS has been applied for analyzing drivers' reactions in response to Intelligent Transportation Systems (ITS) technologies, including a wide range of Transportation Systems Management and Operations (TSM&O) strategies (e.g., variable speed limit, queue warning for smart work zone, etc.) and connected and automated vehicles (C/AV). By providing drivers with risk-free virtual reality, driving simulators offer a high-fidelity evaluation environment, thus enabling to assess the impact of such ITS technologies prior to conducting field testing and pilot deployment studies.

DS enables test drivers to encounter potentially dangerous or 'unsafe' driving conditions without being physically at risk. DS can be used to capture the drivers' reactions to these conditions and record unpredictable or safety-critical reactions and behavior that may be inappropriate to practice on the road, such as collision avoidance or risky driving. In addition, DS makes it possible to study hazard anticipation and perception by exposing drivers to an uncommon or an extreme driving task, which would present an ethically challenging endeavor on any actual highway facility.

DS offers an ability to manipulate and adjust as needed the behavior of virtual traffic, weather conditions, and the road layout. This ability can be customized to a specific experiment or study objective. Given the purpose-driven scenarios, it is certainly possible to record the reactions of test drivers responding to a large number of 'driving challenges' and study their ability or willingness to make different types of driving maneuvers. Thus, DS can measure drivers' performance accurately and efficiently. With an actual vehicle, it is far more cumbersome to obtain complete, synchronized, and accurate measurement of comparable data. In an uncontrolled environment, it is a fundamental challenge to obtain an accurate recording of driving behaviors that correspond to specific driving conditions.

DS offers the opportunity for gathering drivers' instantaneous feedback, which is challenging to achieve in real vehicles. For instance, in case of a Dynamic Speed Limit (DSL) application for a 'smart work zone' implementation, the compliance of drivers in response to the speed limit dynamically changing based on prevailing traffic congestion conditions would be critical for the performance of the DSL. Collecting instantaneous drivers' reactions may be useful for predicting drivers' potential behavior for future traffic congestion mitigation strategies, especially those involving travelers' compliances. Similar types of studies could be conducted to evaluate driver reaction to adaptive signal control, different layouts of dynamic signalization and traveler information messaging, distractions along the roadway, connected vehicle applications, etc.

Exploiting DS, this paper presents a human-in-the loop experiment to examine the effectiveness of a Freeway Merge Assistance(FMA) System as one of emerging Connected Vehicles applications. This paper is organized in the following sequence. In literature review, relevant research efforts that deal with DS for the evaluation of ITS applications are reviewed. In the next section, the details of FMA system, including its implementation algorithm and methodologies required to realize it into the DS environment. The evaluations of the FMA system are addressed in the section of experiment followed evaluation results in the following section. Findings and conclusions are discussed in the section of concluding remarks.

Review of Literature

This section briefly reviews the state-of-the practices of DS-involved activities to perform the evaluations of ITS applications from the perspective of drivers.

Jamson et al. (1) and Jamson and Smith (2) examined driver's behavioral changes at different traffic patterns in an automated vehicle condition. The authors designed experiments for both light and heavy traffic conditions handling 500 and 1,500 vehicles per hour per lane (vphpl) of traffic volumes, respectively. A total of 48 subject drivers participated in the experiments by operating an automated simulator vehicle. Overall, given the automated vehicle condition, it was observed that the participants performed fewer changing maneuvers during automated driving than during manual driving, even while their travel time was increased. Particularly in the light traffic condition, the safety distance between the leading and the following vehicles was reduced, thereby resulting in potential roadway capacity

improvement. On the other hand, no significant improvement in the safe distance reduction was observed in the heavy traffic condition.

Punzo and Ciuffo (3) incorporated a microscopic traffic simulator, AIMSUN(4), into a driving simulators platform, SCANeR(5), to achieve a high-fidelity simulation modeling framework. SCANeR employs the Virtual Environment for Road Safety (VERA) (6) as a primary driving simulator engine. SCANeR enables realistic driving maneuvers (e.g., car-following, lane changing, and route decision) of background traffics in VERA by synchronizing AIMSUN in real-time to enable realistic behaviors of background traffic. It is necessary to note that background traffics indicate ambient vehicles that are controlled by a driving simulator. Using the integrated modeling framework, the authors examined the reality of a driving simulator environment for a 4-mile long two-lane rural highway segment. To this end, the authors conducted a before-and-after study for multiple participants by examining their responses to a questionnaire about the improvement of simulation realism. It was discovered that the AIMSUN-incorporated driving simulator provided a high-mature reality with respect to the behavior of back ground traffics.

Winter et al. (7) conducted a meta-analysis for the driving workload (i.e., effort to manipulate a vehicle) and situational awareness of drivers, given adaptive cruise control (ACC) and highly automated driving (HAD) technologies. Including data from adaptive cruise control, automated, and manual driving tasks, the authors captured drivers' reactions in response to the following scenario combinations: 1) manual vs. ACC; 2) manual vs. HAD; and 3) ACC vs. HAD, in terms of driving tasks and drivers' state. The major findings showed that driving workloads for manual driving, ACC, and HAD were 43.5%, 38.6%, and 22.7%, respectively. It is necessary to note that 0% and 100% workloads indicate the minimum and the maximum efforts based on the NASA task load index (TLX) scale (8).

Siebert et al. (9) investigated the relationship between time headway and driver's situational awareness driving states, such as the risk, effort, comfort, maneuvering difficulty (e.g., accelerating/decelerating, steering wheel manipulating), performance at different speeds when an Adaptive Cruise Control (ACC) function is activated. A total of 32 subject drivers participated in the experiments and reported their feelings after conducting a 1 minute-long driving session to follow the leading vehicle. The major findings showed that in cases of short headway (e.g., 0.6 seconds), the subject drivers felt higher risks when they drove at lower speeds (e.g., 30 mph) rather than higher speeds (e.g., 60mph and 90 mph). The experiments also discovered that the low speed with short headway condition increased the level of discomfort than drivers experienced in the case of high speed with short headways.

Guoy et al. (10) examined how drivers reacted to the platoon of automated vehicles in the vicinity of the subject vehicle. A total of 32 subject drivers participated in the experiments. The experiment's results showed that drivers maintain shorter time headways to the leading vehicle while driving next to the platoon. The headways of the designed platoon were 0.3 and 1.4 seconds, respectively, to measure the participants' response to the change of headway. Interestingly, it was discovered that the variation of headway in the platoon of automated vehicles had no significant impact on drivers.

For driving simulator studies, Islam et al (11) studied driver's responses in the presence of a Red Signal Countdown Timer (RSCT) and developed a Linear Mixed Effect (LME) model to predict the effect of the timer on the headway of the first vehicle waiting on a red signal. Traffic Signal Countdown Timer (TSCT) is to assist drivers in decision-making at signalized intersections with real-time signal duration information. The model predicted 0.72-second headway reduction for the first queued vehicle resulting from the presence of RSCT, while the observed difference in mean headway was 0.82-second. The result indicates a reduction in start-up lost time at signalized intersections.

Similar to Punzo and Ciuffo (3), Sun et al. (12) designed an integrated platform incorporating VISSIM 5.40 (13), a microscopic traffic simulator, and VIRTOOLS (12), a driving simulator. Exploiting the integrated platform, the authors collected driving behaviors from a total of 27 participants who drove a simulated vehicle with background traffic manipulated by VISSIM. The authors conducted surveys to investigate the reality of the entire driving simulation platform by asking the participants to drive an actual car under real-world circumstance. Despite several reported discrepancies in terms of the simulation reality compared to the real world, the comparison experiment results showed that the VISSIM-integrated platform provides the subject drivers with improved reality.

Jeihani and Ardeshiri (14) evaluated the effectiveness of dynamic message signs (DMS) by utilizing a driving simulator namely UC-Win/Road(15). To this end, the authors developed a large-scale 3-dimensional virtual test bed covering a 12-mile X 12-mile urban-rural area with multiple freeways and arterials. With over 100 subject drivers participating in the experiment, the wide variety of driver behaviors, such as route choice, speed selection, and lane changing, were recorded and analyzed to examine the

impact of DMS as a congestion mitigation approach. The research results showed that 1) drivers would not reduce their speeds to read the DMS message and 2) DMS made significant impacts of drivers' route choice behaviors.

In summary, with ever-increasing attention towards driving simulator as a viable tool enabling to precisely capture human drivers' behavior in response to the wide variety of ITS and TSM&O applications, numerous state-of-the-art efforts have been proposed and performed, as briefed in this chapter. Covering from traditional traffic operation strategies to cutting-edge Connected/Automated Vehicles applications, the driving simulator has played a critical role for the evaluations of such strategies and applications since the early 2000s. However, it was discovered that the fidelity of ambient traffics' driving behaviors (e.g., longitudinal movement, lane changing maneuvers) in the driving simulator often appears unsuitable for the precise evaluations of several ITS and TSM&O applications that heavily rely on the interactions between ambient traffics and the subject driver. To overcome this issue, efforts to incorporate an external microscopic traffic simulator (e.g., VISSIM, AIMSUN) into the driving simulator have been conducted as reviewed in this section. By replacing rudimentary driving behavior logics of ambient traffics in the driving simulator with high-fidelity car-following and lane changing models embedded in microscopic traffic simulators, analysts were able to improve the realism of the driving simulator.

Methodology

Freeway Merge Assistance

The FMA application provides a moving vehicle on the ramp with a range of speed enabling the driver to enter the mainline in a safe manner. Once a vehicle equipped with the FMA application passes over a triggering point (e.g., 600-foot from the merging point), the algorithm calculates the arrival time of the ramp vehicle at the merging point, denoted by t_0 . Using the instantaneous information of vehicles on the mainline (e.g., speed, position, acceleration/deceleration rate), the algorithm estimates the arrival time of an individual vehicle, i , on the mainline at the merging point, denoted by t_i ($i=1,2, \dots, n$) as graphically illustrated in Figure 1.

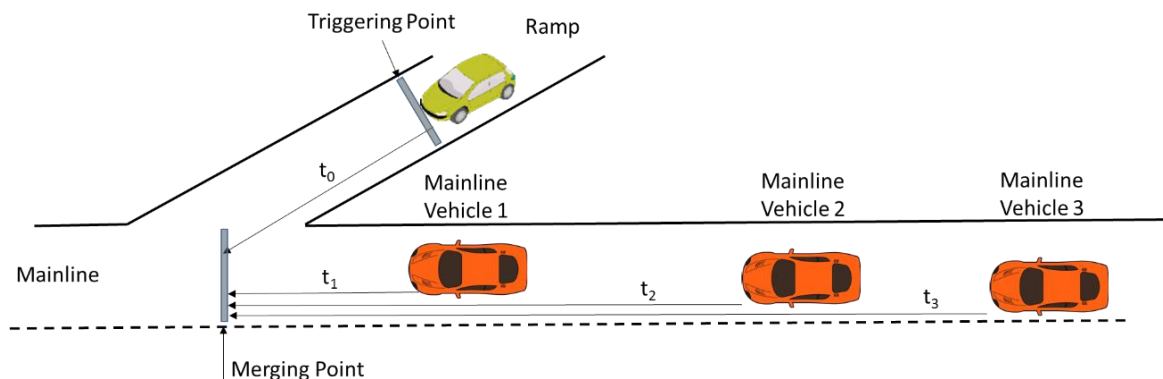


Figure 1 Arrival Time Estimation

Figure 2 presents time-space diagrams conceptually depicting the trajectories of vehicles around the merging point. The basic idea of the assistance algorithm is to detect a condition satisfying: $t_0 = t_i$, which indicates a collision of two approaching vehicles at the merging point; one from the ramp and the other one from the mainline. Once a collision condition is anticipated, as shown in the middle of Figure 2, the algorithm recalculates the approaching speed of the ramp vehicle by adjusting its arrival speed to avoid the collision based on the arrival time t_i , as shown in the right of Figure 2.

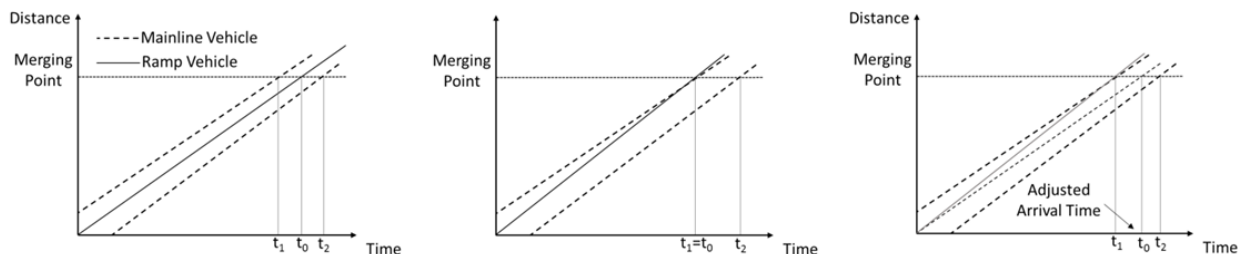


Figure 2 Collision Detection Approach

The actual advisory speed range is determined by taking into consideration a safety headway, denoted by h , into the estimation of the arrival times of mainline vehicles as shown in Figure 3(a). From the estimated arrival time of the ramp vehicle, t_0 , the algorithm examines the arrival times of the mainline vehicles (i.e., t_1, t_2, t_3) that are within the lower and upper boundaries of the ramp vehicle's arrival time, denoted by t_0-h and t_0+h , respectively, as shown in Figure 3(b). In case the arrival time of a mainline vehicle is within the arrival time boundary of the ramp vehicle as shown in Figure 3(c), the algorithm attempts to adjust the arrival time by providing a speed advisory to the driver of the ramp vehicle, which is conceptually depicted in Figure 3(d). Thus, the range of advisory speeds given to the ramp vehicle driver is determined by finding the safe arrival time of the ramp vehicle in order to avoid any conflicts with the mainline vehicles within the safety headway boundary.

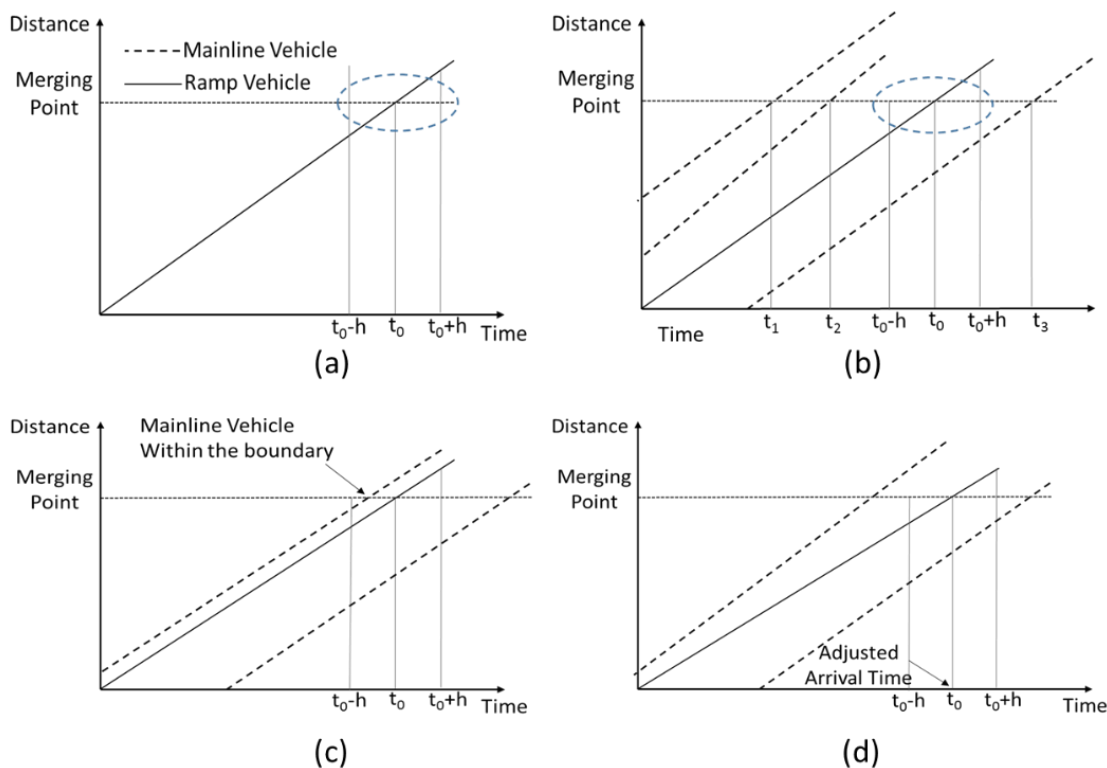


Figure 3 Advisory speed range determination

Depending on the arrivals of the mainline vehicles at the merging point, the advisory speed is grouped into 5 cases as illustrated in Figure 4. Case 1 in Figure 4(a) indicates that no vehicles on the mainline exist within the reasonably wide range from the merging point; thus, there is no need for adjusting the arrival time of the ramp vehicle. Cases 2 and 3 both deal with occasions when a mainline vehicle is

anticipated to be within either the upper (i.e., t_0+h) or the lower (i.e., t_0-h) safety boundary, as shown in Figure 4(b) and (c), respectively. However, in both cases, the arrival time of the ramp vehicle was adjusted to avoid the conflict, thereby resulting in a safe merge condition within the corresponding advisory speed range. Similarly, Case 4, which is depicted in Figure 4(d), shows that two mainline vehicles' potential conflicts within the safety boundary have been removed by adjusting the arrival time of the ramp vehicle. However, Figure 4(e) is the case where an attempt to adjust the arrival time of the ramp vehicle is considered as failed; therefore, no available advisory speed range enabling a safe merge exists. In this particular case, the algorithm produces a warning message to assist the driver to stop before entering the mainline.

The FMA application graphically displays the speed range through a Head-up Display (HUD) unit. Figure 4 illustrates the actual messages provided by the FMA application to assist the ramp vehicle driver as the vehicle enters the mainline in a safe manner, depending on the particular cases. Since the example seen in case #1 yields a free entering condition, the upper and lower speed boundaries are tied to the speed limits of the mainline (e.g., 65 MPH) and the ramp (e.g., 35 MPH) as depicted in Figure 4(a). Figure 4(b) and (c) show the speed range displayed to assist the ramp vehicle driver; this information allows the driver to adjust the arrival time and thus avoid an anticipated conflict caused by a mainline vehicle in the upper boundary (e.g., case #2 in Figure 4(b)) and the lower boundary (e.g., case #3 in Figure 4(c)). Similarly, in case #2, mainline vehicles are anticipated to be located within the upper- and lower boundaries, so the FMA application estimates whether the ramp vehicle is able to avoid conflict by adjusting its arrival time. If the arrival time adjustment enables the drivers to avoid conflicts within the speed boundary, the safe speed range is displayed as shown in Figure 4(d); otherwise, it displays a warning message for the ramp vehicle driver to prepare for a stop, as depicted in Figure 4(e).

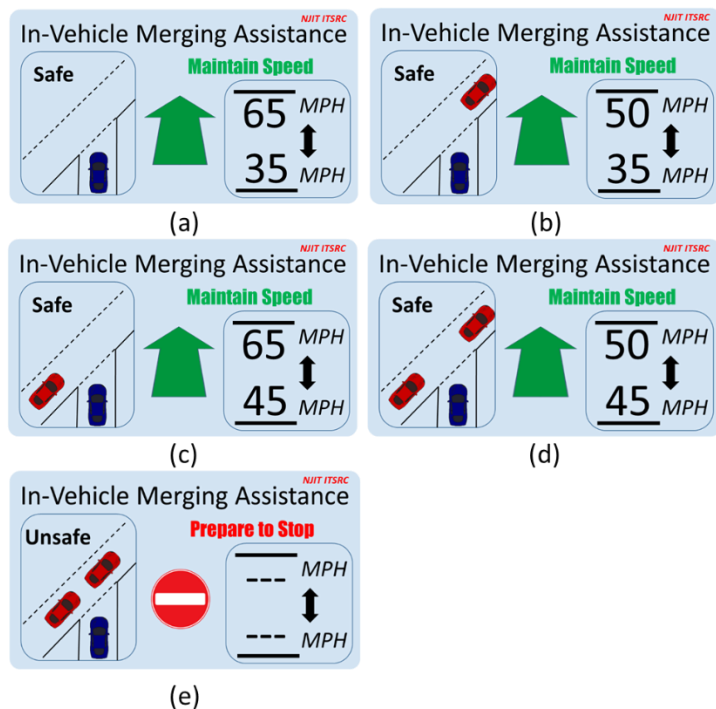


Figure 4 HUD images for the advisory information

Experiments

Figure 5 shows the bird's eye view of a virtual test site for the evaluation of the FMA application. The on-ramp of the test site merges with a two-lane freeway with 65 MPH of speed limit through an approximately 200-foot acceleration lane. Connected from a local road separated by a bridge crossing over the freeway

mainline, the ramp has a 1500-foot long down-hill segment with approximately 2% grade prior to merging. Combined with the 200-foot acceleration lane, the down-hill ramp is likely to cause unsafe merging maneuvers from drivers due to 1) insufficient acceleration lane length; and 2) difficulty to visually observe approaching vehicles from the mainline to the merging area.

Traffic volume on the mainline is randomly selected by the driving simulator within the range of between 1200 and 1800 vehicles per hour per lane including approximately 5% truck traffics. A total of 5 scenarios dealing with different traffic volume conditions on the mainline are presented to individual subject drivers. For each scenario, a subject driver manipulates the ego vehicle until he/she completes merging maneuvers with and without the FMA application.



Figure 5 FMA simulation test site

The effectiveness of the FSA application is examined by analyzing both quantitative and qualitative measures captured from each subject driver. With respect to the qualitative analysis for the usefulness of the FMA application, a total set of 5 questions is provisioned to the subject drivers who completed the experiment. Table 1 shows the questions for the evaluation of the FMA application. The first question set is presented to drivers to examine how they feel about the FMA application with respect to its usefulness as a driving assistance tool to improve safety, driver comfort, and mobility. The second and third question sets are 1) to analyze the acceptance of drivers for the advisory information provided and 2) to capture the actual reactions of drivers in response to the information, respectively. The fourth question group attempt to determine the most useful case that improved the safety of the drivers when they used the FMA application.

Results

The FMA application appears effective in improving the safety and mobility of driving conditions when performing freeway merges. 70% of subject drivers responded that the FMA application enabled drivers on the on-ramp to make safe and smooth merges to the mainline. Despite the proven effectiveness for the safety and mobility measures, 30% of subject drivers reported that the FMA application caused a distraction that adversely affected their merging maneuvers, while 40% of subject drivers did not feel any confusion.

Table 1 Summary of the participant responses for the FMA questionnaire

* 1 : Disagree Completely □ 5: Agree Completely (Percent)	1	2	3	4	5
A system to improve safety (e.g., avoid dangerous condition)	0	0	30	30	40
A system to improve mobility (e.g., delay/stop reduction)	0	0	30	30	40
A source of confusion or distraction	0	40	30	20	10
A useful driving assistance tool	0	30	10	20	40
Increasing mental (and visual) effort	0	20	20	40	20
Increasing driver comfort	30	30	10	30	0
Making the driver less vigilant	20	0	20	60	0
Making the driver less stressed	0	30	10	60	0
Unreliable in its operations	50	30	10	10	0
The information presented on the in-vehicle device was helpful	0	20	10	30	40

Through conducting post-experiment interviews with the responders, it was discovered that the main reason for the distraction were the changes of safe speed ranges seen before entering the mainline. It is noted that the speed range provided by the FMA application is updated every 3-seconds to properly capture the dynamic changes of traffic conditions on the mainline. Nevertheless, 60% of subject drivers agreed that the FMA application is a useful tool. It appears that the FMA application increases drivers' mental focus efforts when they conducted merging maneuvers, a fact which was reported by 60% of the subject drivers. It is very likely that the group of subject drivers who both responded "neutral" and agreed in response to the questionnaire that the FMA is a source of distraction experienced extra mental efforts. As a result, only 30% of subject drivers felt comfort with the FMA application.

Despite the additional mental efforts that the subject drivers experienced, the FMA application appears to help drivers reduce stress by relieving their vigilance when they attempt to merge onto the mainline. In cases without the FMA application, it was observed that 60% of subject drivers stated that they felt uncomfortable when approaching the mainline to conduct merging maneuvers due to their uncertainty at the merging point. Responding that the uncertainty is mainly caused by a lack of sufficient situational awareness for the merging, the subject drivers stated that they often become nervous, thereby resulting in somewhat more dangerous maneuvers when merging. However, with the FMA application providing the subject drivers with the projected situational awareness at the merging point, they were able to perform proper maneuvers, thus enabling them to evade potential dangerous conditions in advance, which made them feel the need to be less vigilant.

It is discovered that the high reliability for the advisory information leads elevating the compliance rate of the subject drivers. 70% of subject drivers followed the provided information more than 4 times out of 5, resulting in 80% of compliance rate. 30% of subject drivers also followed the provided information 3 times out of 5 (i.e., 60% compliance rate). Following the advisory information, the primary driving maneuver (i.e., 80%) that the subject drivers performed appeared to be accelerating. It is necessary to repeat that the advisory speed information depends on prevailing traffic condition in and around the merging segment. Depending on mainline traffic condition, FMA application tends to adjust the arrival time of the ramp vehicle to avoid forecasted conflicts. When the subject drivers enter the ramp, they maintain the speed limit of the ramp (i.e., 35 mph). Thus, the speed of the subject vehicle at which the FMA application conducts advisory speed estimation is low enough (e.g., 35 mph). Given such a low speed, it is easy for the FMA application to shorten the arrival time of the ramp vehicle by increasing its approaching speed to evade a forecasted conflict, rather than either reducing the speed or stopping the ramp vehicle. As a consequence, accelerating became the primary maneuver that the subject drivers performed when they followed the advisory speed information. Overall, 90% of the subject drivers agreed that the FMA application enables drivers to feel safe when they conduct freeway merging, particularly in case the leading vehicle on the merging point is projected.

The research team also captured individual drivers' driving maneuvers with and without the FMA application as shown in Figure 7. Captured from the ramp area, the changes of the average acceleration rates demonstrate that the FMA application helped the subject drivers prevent excessive acceleration/deceleration maneuvers. That is, the subject drivers assisted by the FMA application achieved up to +/- 0.5 m/sec² of acceleration change, which would result in smooth longitudinal movements,

compared to the cases without the FMA application that produced up to 1.5 m/sec^2 acceleration. With the projected situational awareness provided by the FMA application, the subject drivers with the application were able to conduct proactive driving maneuvers that reduced excessive speed changes prior to entering the merging area (i.e., 210 feet or 70 meters from the merging point). Without the situational awareness, however, the subject drivers were unable to perform any proactive maneuvers until they arrived at the merging area and conducted visual observations on the traffic conditions. Depending on the visual observation results, the actions of the subject drivers were necessary to perform evasive maneuverings within approximately 200-foot ahead from the merging point, which would result in unsmooth longitudinal movements as shown in Figure 7 (Left). Unlike an acceleration profile, no significant difference is observed from the time-space diagram as demonstrated in Figure 7 (Right), indicating no mobility impacts were improved by the FMA application.

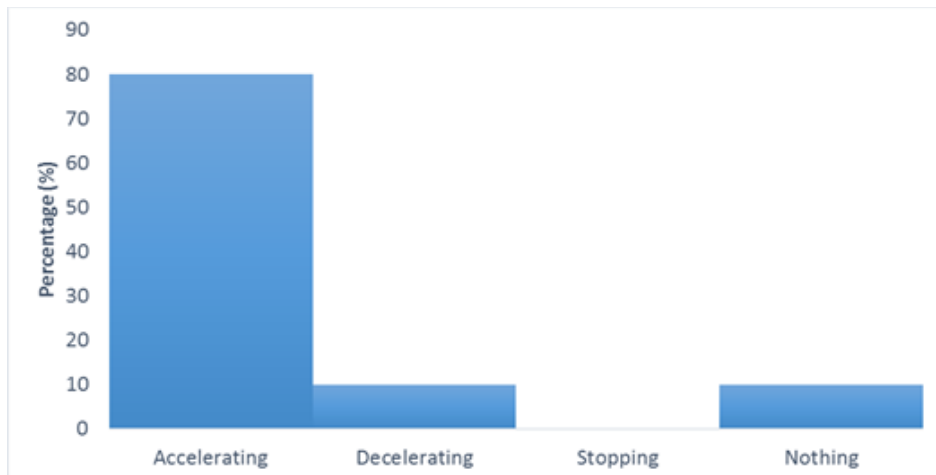


Figure 6 Primary driving maneuver given the advisory speed range by FMA

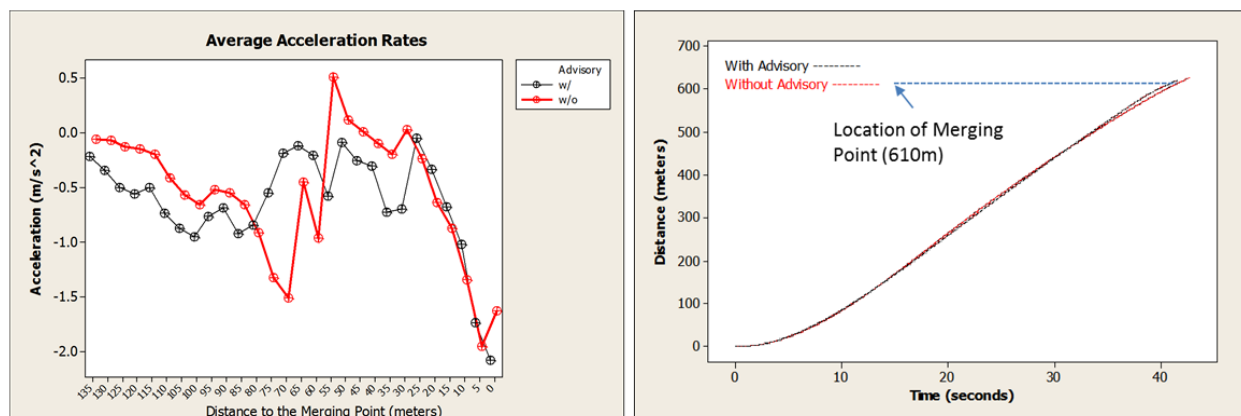


Figure 7 Acceleration profile (Left) and time-space diagram (Right) w/ and w/o FMA

Concluding Remarks

Using driving simulator, this paper assessed the effectiveness of Freeway Merging Assistance (FMA) system as one of CV applications from the perspective of human drivers. FMA assists drivers to conduct safe and smooth merging maneuvers by providing the projected situational awareness on the traffic conditions in and around the merging segment. The FMA system required advanced modeling capabilities, such as vehicular information message dissemination, approaching vehicle detection, HUD simulation, and arrival time estimation, which are beyond the off-the-shelf functions defaulted by the driving simulator. The

NJIT driving simulator provided operators with high flexibility enabling to customize the driving simulator to be retrofitted to any given scenario. The research team successfully performed the customizations to achieve high-fidelity experiment test for the FMA system. Based on Likert Scale (16), this research conducted experiments with the human subjects to assess the effectiveness of FMA by precisely capturing the diverse driving behaviors of the subject drivers. 10 final human subject participated in the experiments after the team screened all subject applicants to detect any potential problems (e.g., simulation sickness).

The experiment results showed that 70% of subject drivers complied the guidance information provided from the FMA application to make safe and smooth merges to the mainline, thereby resulting in 60% of subject drivers who agreed that the FMA application is a useful tool for drivers. It appeared that the FMA application increases drivers' mental focus efforts when they conducted merging maneuvers, a fact which was reported by 60% of the subject drivers. Despite the additional mental efforts, the FMA application appears to help drivers reduce stress by relieving their vigilance when they attempt to merge onto the mainline. Individual drivers' driving maneuvers with and without the FMA application were also captured. The changes of the average acceleration rates demonstrate that the FMA application helped the subject drivers prevent excessive acceleration/deceleration maneuvers. With the projected situational awareness provided by the FMA application, the subject drivers with the application were able to conduct proactive driving maneuvers that reduced excessive speed changes prior to entering the merging area. Without the situational awareness, however, the subject drivers were unable to perform any proactive maneuverings until they arrived at the merging area and conducted visual observations on the traffic conditions

This research also discovered that the virtual reality provided by a driving simulator can be a useful tool and will aid in a variety of ITS and CV applications in the future. The methodology presented in this paper is highly suitable for evaluation of active traffic management and Connected Vehicle applications. Specifically, driver behaviors (reactions) are one of the crucial components enabling a precise evaluation of Active Traffic Management strategies and Connected Vehicle applications. Thus, using driving simulator to investigate how drivers would react to these or other future (and possibly more advanced) ATM and CV applications prior to making a decision about their deployment will provide a cost-effective and worry-free approach to conduct such investigations.

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