ITS RESOURCE CENTER

NJIT
New Jersey Institute of Technology

Activity 2:
ITS Technology Evaluation and Pilot Deployment

Examining the Applicability of a Driving Simulator for the Evaluation of ITS and TSM&O Strategies

Final Report

Prepared for
State of New Jersey
Department of Transportation

March 2017

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Examining the Applicability of a Driving Simulator for the Evaluation of ITS and TSM&O Strategies

FINAL REPORT

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This report has been prepared as part of the CY 2015-2016 work program for the ITS Resource Center at the New Jersey Institute of Technology.

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Executive Summary

Driving simulators have emerged as powerful tools to incorporate the impacts of human factors into the evaluation process across a wide spectrum of transportation technologies and policies. From traffic safety education to cutting-edge Connected and Automated Vehicles (C/AV) technologies, driving simulators better capture the behavior of individual drivers compared to legacy simulation models such as VISSIM, AIMSUN, and SimTraffic. In recent years, driving simulators have been used to evaluate state-of-the-art Intelligent Transportation System (ITS) and Transportation Systems Management and Operations (TSM&O) applications, such as variable speed limits, queue warning, and automated vehicles, in which human factors: compliance, route decision, and lane selection, play a critical role in the performance assessment.

The ITS Resource Center at NJIT, in technical partnership with NJDOT, has operated an open cockpit driving simulator since November 2016. The NJIT driving simulator is equipped with several advanced features to perform evaluations of ITS and TSM&O applications. With the open cockpit configuration designed to mimic an actual driving environment, the highlighted features of the NJIT driving simulator include: 1) a programming interface to integrate a microscopic traffic simulator; 2) three-dimensional modeling tools for rendering virtual reality; and 3) high-fidelity vehicle dynamics models.

In addition, the NJIT driving simulator provides a user-friendly scenario management tool to address a wide variety of simulation environments. The simulation environments are defined by the following parameters: 1) traffic signal and signage location, shape, caption, color, and dimensions; 2) various traffic signal control logics and sensing devices; 3) ambient traffic volumes; 4) various vehicle types: passenger car, bus, truck, tractor-trailer, etc.; 5) weather conditions; 6) lighting condition; and 7) real-time interactions with background traffic.

To examine the applicability of the NJIT driving simulator for the evaluation of ITS and TSM&O applications, the project team constructed virtual realities to assess the impacts of In-Vehicle Signal Assistance (ISA) using Signal Phase and Timing (SPaT) data; and Freeway Merging Assistance (FMA). Using SPaT messages, ISA assists drivers to perform safe and smooth crossings at the next intersection. FMA provides on-ramp drivers with forecasted situational awareness along with an advisory speed range in the freeway merge area. Both applications utilize a Head-Up display unit replicated in the simulator to convey the information.

Thirteen subject drivers were recruited and ten participants were selected for the experiments after a preliminary screening testing to detect any potential problems such as simulation sickness. The project team designed a questionnaire based on a Likert Scale, and conducted experiments involving the human subjects. The impacts of both the ISA and FMA applications were successfully evaluated by accurately capturing the diverse driving behaviors of the subject drivers.

While the NJIT driving simulator has proven to be suitable for ITS and TSM&O evaluations, modeling virtual reality in a timely manner remains a challenge. The primary reasons for the challenge are: 1) the significant time and effort required to prepare and run the multiple scenarios needed for the data set; 2) 3-D and other simulation modeling skills and experience is required in developing simulation scenarios; and 3) the large number of human subject drivers is required in order to perform a meaningful statistical analysis.

It is anticipated that the ITS Resource Center team will be able to overcome all of the above challenges as more work is done and more experience is gained working with the Driving Simulator.

1. Introduction

Driving Simulators (DS) have gained great attention in recent years as powerful tools to support highway safety and operational assessments from the perspective of drivers. DS have been used to analyze driver reactions in response to Intelligent Transportation Systems (ITS) technologies, including a wide range of Transportation Systems Management and Operations (TSM&O) strategies: variable speed limit, queue warning for smart work zone, and Connected and Automated Vehicles (C/AV). By providing drivers with risk-free virtual reality, driving simulators offer high-fidelity evaluation environments to assess the impact of ITS technologies prior to conducing field testing and pilot deployment studies.

DS enable test drivers to encounter potentially dangerous or ‘unsafe’ driving conditions without being physically at risk. DS capture driver 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 and risky driving. In addition, DS make it possible to study hazard anticipation and perception by exposing drivers to uncommon or extreme driving tasks, that would present an ethically challenging endeavor on any actual highway facility.

DS offer the ability to manipulate and adjust the behavior of virtual traffic, weather conditions, and road layout. This ability can be customized to a specific experiment or study objective. Given the purpose-driven scenarios, driver reactions can be recorded in response to a large number of ‘driving challenges’ to 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 driver behavior that corresponds to specific driving conditions.

DS offer the opportunity to gather instantaneous feedback, which is also a challenge to achieve in real vehicles. For instance, in the case of a Dynamic Speed Limit (DSL) application for a ‘smart work zone’ implementation, the compliance of drivers to the variable speed limit dynamically changing based on prevailing traffic congestion conditions would be critical for the performance of the DSL. Collecting instantaneous driver reactions may be useful for predicting driver behavior for future traffic congestion mitigation strategies, especially those involving driver compliance. 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, and connected vehicle applications.

In technical partnership with the New Jersey Department of Transportation (NJDOT) through the New Jersey Intelligent Transportation Systems Resource Center (ITSRC), NJIT procured a high-fidelity driving simulator, to enable the project teams to evaluate a wide spectrum of cutting-edge ITS and TSM&O applications. The primary purpose of this project is to conduct pilot tests to determine the applicability of DS to evaluate ITS and TSM&O applications. To this end, this project team selected two emerging ITS applications: 1) In-Vehicle Signal Assistance (ISA) using Signal Phase and Timing (SPaT) data and 2) Freeway Merging Assistance (FMA). ISA provides drivers with real-time traffic signal status of the next intersection as the driver approaches. Utilizing SPaT data disseminated from the intersection signal controller, the ISA application displays the current signal status through an animated heads-up display (HUD) unit. FMA manages the entry of ramp vehicles into a freeway merge segment. By predicting the arrivals of mainline vehicles onto the merge segment, the FMA application provides drivers on the ramp with advisory speed ranges to achieve smooth and safe merging through a head-up display unit. With recent advancements in sensing and communications technologies, both applications have been highlighted as ready-to-implement TSMO applications and various evaluation efforts for both applications have been performed. However, the majority of these evaluations have focused on assessing system-wide performances: travel time savings and delay reduction, and not taking into account human factors such as driver compliance, reaction time, and how the drivers feel. Using the DS environment, the impacts of human factors can be captured to more fully assess the effectiveness of both ISA and FMA applications.

With the selected ITS applications, this project team established the following objectives to accomplish:

- To review the state-of-the-practice for driving simulator utilization and evaluation of both ISA and FMA applications;
- To build a high-fidelity simulation environment for both the ISA and FMA applications;
- To conduct a human-in-the loop experiment to examine the effectiveness of the selected ITS applications;
- To summarize the findings from the experiments;
- To identify gaps and challenges that are discovered during the ITS application evaluation and to discuss the next steps in future research.

This report is organized in the following sequence. In Chapter 2, relevant research efforts that deal with DS for the evaluation of ITS applications are reviewed. In Chapter 3, the investigation covers the state-of-the-practice of DS for ITS, followed by an overview of the DS system that is operated by NJIT. Chapter 4 presents the details of ISA and FMA applications, including the algorithms that were developed to realize the application in the DS environment. In Chapter 5, the evaluation of both applications are addressed with an experimental design approach and a consideration of the evaluation results. Chapter 6 is composed of the findings and conclusions, along with a discussion of recommendations for future research.

2. Related Work

This chapter briefly reviews the state-of-the practice of the use of DS in the evaluation of ITS applications from the perspective of drivers. Jamson et al. [1] and Jamson and Smith [2] examined driver's behavioral changes to different traffic patterns in an automated vehicle condition. The authors designed experiments for both light and heavy traffic conditions of 500 and 1,500 vehicles per hour per lane (vphpl), respectively. A total of 48 subject drivers participated in the experiments by operating an automated simulator vehicle. It was observed that the participants performed fewer lane-changing maneuvers during automated driving than during manual driving, even while their travel time increased. Particularly in the light traffic condition, the safety distance between the leading and the following vehicles was reduced, thereby resulting in a potential increase in roadway capacity. However, no significant reduction in safety distance was observed in the heavy traffic condition.

Punzo and Ciuffo [3] incorporated a microscopic traffic simulator, AIMSUN [4], into a driving simulator platform, SCANeR [5], to achieve a high-fidelity simulation modeling framework. SCANeR employs the Virtual Environment for Road Safety (VERA) [6] as the primary driving simulator engine. SCANeR enables realistic driving maneuvers: car-following, lane changing, and route decision, of background traffic in VERA by synchronizing AIMSUN in real-time. Background traffic refers to ambient vehicles that are controlled by the driving simulator. Using the integrated modeling framework, the authors examined the reality of a driving simulator environment for a four-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 background traffic.

Winter et al. [7] conducted a meta-analysis for the driving workload, the effort to manipulate a vehicle, and driver situational awareness, 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 driver 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. The 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 headway and driver situational awareness states: the risk, effort, comfort, and maneuvering difficulty when accelerating, decelerating and steering 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 one minute driving sessions to follow the leading vehicle. The major findings showed that in cases of short headway, 0.6 seconds, the subject drivers felt higher risks when they drove at lower speeds, 30 mph, rather than higher speeds, 60 to 90 mph. In addition, drivers experienced higher levels of discomfort at low speeds with short headways than high speeds with short headways.

Guoy et al. [10] examined how drivers reacted to a platoon of automated vehicles in the vicinity of the subject vehicle. A total of 32 subject drivers participated in the experiments. The results showed that drivers maintain shorter time headways to the leading vehicle while driving next to the platoon. The headways of the design platoon were varied from 0.3 to 1.4 seconds to measure the response to the change of headway. Interestingly, 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 response to 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) assist drivers in decision-making at signalized intersections by providing real-time signal duration information. The model predicted a 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.

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 conditions. 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 provided the subject drivers with improved reality.

Jeihani and Ardeshiri [14] evaluated the effectiveness of dynamic message signs (DMS) by utilizing the driving simulator UC-Win/Road [15]. The authors developed a large-scale three-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, a wide variety of driver behaviors: 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 had significant impact on driver route choice behavior.

In summary, with ever-increasing attention towards driving simulators as viable tools to precisely capture driver 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. From traditional traffic operation strategies to cutting-edge Connected/Automated Vehicles applications, driving simulators have played a critical role for the evaluation of such strategies and applications since the early 2000s. However, the fidelity of ambient-traffic driving behaviors, longitudinal movement and lane changing maneuvers in the driving simulator were often unsuitable for the precise evaluations of several ITS and TSM&O applications that rely heavily on the interaction between the subject driver and ambient traffic. To address this issue, efforts to incorporate an external microscopic traffic simulator, such as VISSIM or AIMSUN, into the driving simulator have been conducted as reviewed in this chapter. By replacing the rudimentary driving behavior logic of ambient traffic 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. In the next chapter, an overview of the NJIT driving simulator is presented from the perspective of its applicability for the precise evaluation of ITS and TSM&O applications.

3. Overview of NJIT Driving Simulator

3.1. Specification and Functionality

The NJIT ITS Resource Center procured an open cockpit driving simulator from Realtime Technologies, Inc. (RTI) in November, 2016. The driving simulator consists of four server computers, a standalone database, vehicle dynamics models enabling the realistic movement of vehicles, and a software package to deal with three-dimensional virtual reality. The simulator makes use of an actual partial vehicle cab with an instrument panel, adjustable driver's seat, pedals, and steering wheel. Three forward LCD panels: one 46-inch front panel and two 60-inch side view panels, create an immersive visual environment, providing a 150-degree forward field of view as shown in **Figure 1(a)**. The host control station is shown in **Figure 1(b)**. The simulator weighs approximately 400 lbs., and its dimensions are 120-inch Width x 100-inch Length x 72-inch Height.

With the open-cockpit configuration, the NJIT driving simulator is designed to maximize its virtual reality by employing the following features:

- Adjustable driver seat and steering wheel, turn signals, column gear selector, air condition controller, and acceleration/brake pedals;
- Dashboard with speedometer, tachometer, gear selector, turn signals, odometer;
- Audio amplifier with external controls and virtual rear- and side- view mirrors;
- An operator station that provides operators with a Graphical User Interface (GUI) to manage the simulation, select driving scenarios, and conduct data analysis; and
- A high-performance computer system with all necessary I/O devices required to effectively control (manage) the operation of the driving simulator.

(a) Driving Simulator

(b) Control Station (Console)

Figure 1. NJIT Driving Simulator: Driving Cockpit and Host Control Station

The open cockpit cab includes the following controls for drivers to conduct realistic manipulations in the simulator:

- Control loaded steering wheel (Force Feedback Steering System)
- Throttle (Active Feedback System)
- Brake (Active Feedback System)
- Gear selector for automatic transmission (P, R, N, D, L1, L2)
- Turn signals
- Seat Belt
- Headlights switch
- Ignition switch (Status Only)

In addition, the dashboard indicators respond to the status of the simulated vehicle and may be controlled from the scenario system. These indicators consist of the following gauges:

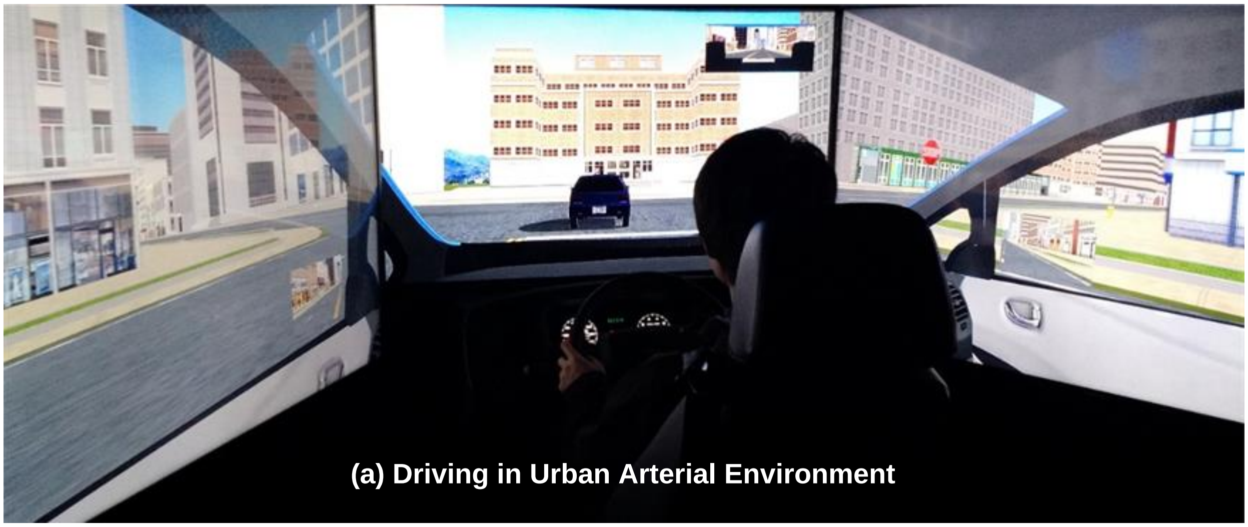
- Speedometer
- Tachometer
- Turn signal indicator
- Engine oil pressure
- Fuel level
- Warning lights

The host channel workstation features a control display also used for development of customized user interface, which interacts with the simulator software: SimCreator®. Rear view mirrors are simulated by inlayed images of the left, center and right mirrors on the simulator screens as shown in **Figure 2**.

Figure 2. Simulator Rear-View Panel

Sample freeway and urban arterial driving environments are shown in **Figure 3(a)** and **Figure 3(b)**, respectively.

(a) Driving in Freeway Environment



(a) Driving in Urban Arterial Environment

Figure 3. Driving Environment: Freeway and Urban Arterial

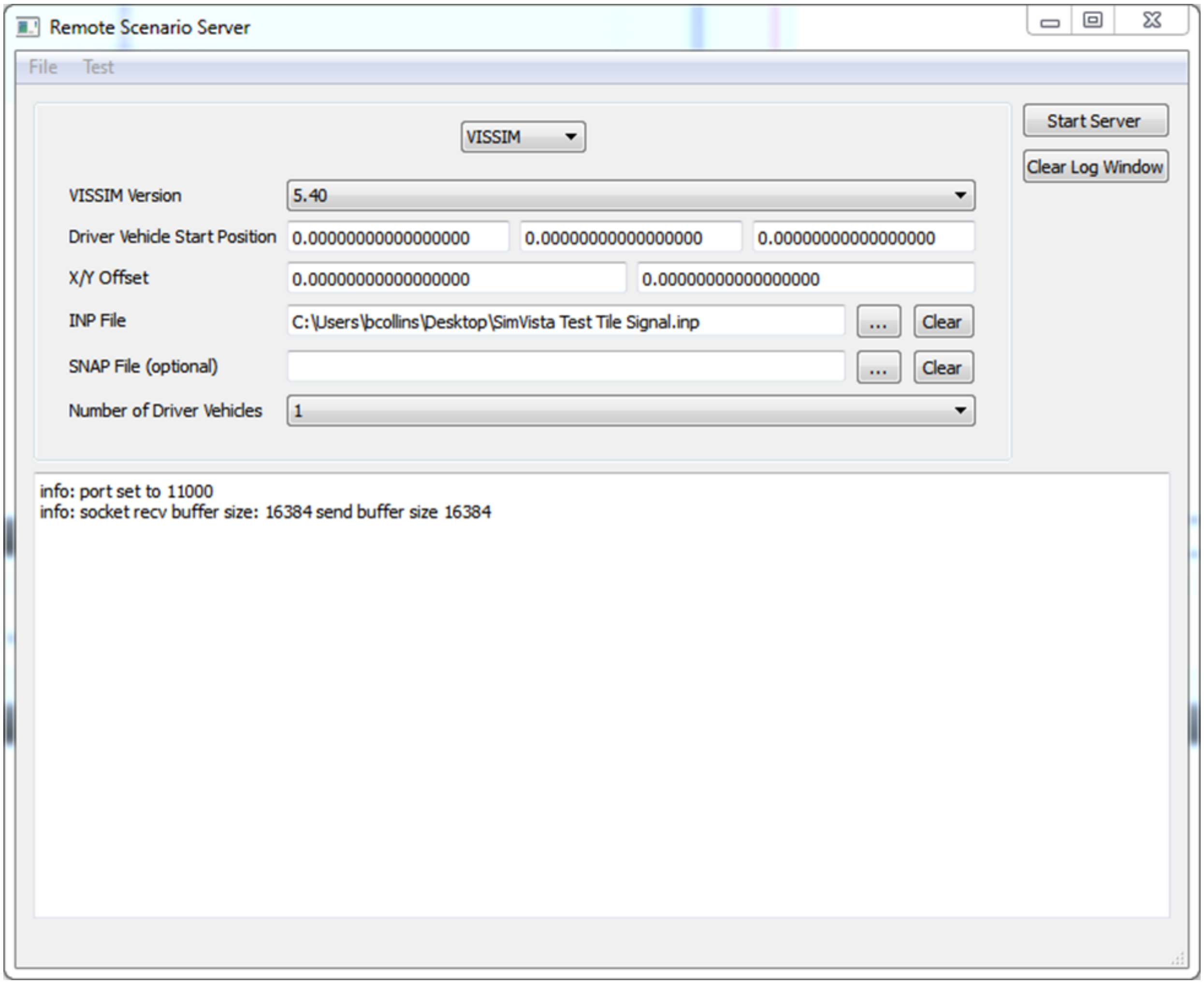
The driving simulator generates vehicle responses as outputs at a 60 Hz update rate (i.e., 1/60 seconds): vehicle speed, acceleration, position, direction, and proximity to specified objects as well as data related to the steering wheel, brake and accelerator pedal. **Table 1** summarizes the select simulation output data that are widely used for simulation-based evaluation. The simulation output can be customized to meet the specific purposes of the experiment.

Table 1. Simulation Results Data

No.	Data Logging Parameter	Unit	No.	Data Logging Parameter	Unit
1	Time	(seconds)	21	Brake Force Sum	(ND)
2	Vehicle Position-Euler Angles (X,Y, Z)	(rad)	22	Meters to MPH Conversion Signal Out	(ND)
3	Vehicle Linear Position Coordinates (X,Y,Z)	(M)	23	Rear Left Corner-Wheel Speed	(rad/s)
4	Vehicle Speed	(m/s)	24	Rear Right Corner-Wheel Speed	(rad/s)
5	Vehicle Acceleration Rate-	(m/s^2)	25	Front Left Corner Wheel Speed	(rad/s)
6	Acceleration to Pitch Conversion Factor	(ND)	26	Front Right Corner Wheel Speed	(rad/s)
7	Vehicle Pitch Linear Position Filter Signal Out	(ND)	27	Power Train-Brake Torque Rear Left	(Nm)
8	Vehicle Steering Wheel Position	(rad)	28	Power Train-Brake Torque Rear Right	(Nm)
9	Vehicle Dynamics Aero-Force	(ND)	29	Power Train Brake Torque Front Left	(Nm)
10	Vehicle Dynamics to LBS Conversion-Factor	(ND)	30	Left Alley Switch	(ND)
11	Vehicle Dynamics Gain	(ND)	31	Right Alley Switch	(ND)
12	Power Train- Engine Torque	(Nm)	32	Take Down Switch	(ND)
13	Power Train Engine RPM	(RPM)	33	Left Directional Switch	(ND)
14	Brakes-Pressure Front	(Bar)	34	Right Directional Switch	(ND)
15	Brakes Pressure Rear	(Bar)	35	Signal-Park Gear Switch	(ND)
16	Vehicle Gas Offset	(ND)	36	Reverse Gear Switch	(ND)
17	Vehicle Brake Offset	(ND)	37	Neutral Switch	(ND)
18	Vehicle Brake Gain	(ND)	38	Drive Gear Switch	(ND)
19	Vehicle Gas Saturation	(ND)	39	Seat Belt Switch (ND)	(ND)
20	Brake Saturation-Signal	(ND)	40	High Beam Switch	(ND)

3.2. Integrating with Microscopic Traffic Simulator

One state-of-the art feature distinguishing the NJIT driving simulator from similar is the capability to integrate with an external microscopic traffic simulator. As briefly reviewed in the previous chapter, continuous efforts have been made to build an integrated framework using a driving simulator and a traffic simulator to improve the fidelity of the driving simulator. By incorporating a traffic simulator that is able to conduct reliable driving behaviors, such as lane changing, car following, and route choice, the fidelity of ambient traffic behavior in the driving simulator can be dramatically improved. The high-fidelity driving behavior enables precise and realistic evaluation of ITS and TSM&O applications that involve interactions between subject drivers and ambient traffic. The NJIT driving simulator is equipped with an external proprietary interface, as shown in **Figure 4**, enabling real-time interaction between the driving simulator and a traffic simulator.



VISSIM

VISSIM Version: 5.40

Driver Vehicle Start Position: 0.0000000000000000 0.0000000000000000 0.0000000000000000

X/Y Offset: 0.0000000000000000 0.0000000000000000

INP File: C:\Users\bcollins\Desktop\SimVista Test Tile Signal.inp

SNAP File (optional):

Number of Driver Vehicles: 1

```
info: port set to 11000
info: socket recv buffer size: 16384 send buffer size 16384
```

Figure 4. Interface for microscopic traffic simulator integration

The NJIT driving simulator supports both VISSIM and AIMSUN for real-time integration. The NJIT research team has extensive experience with using VISSIM for evaluating a wide spectrum of ITS and TSM&O applications such as variable speed limit, dynamic lane use, speed harmonization, adaptive traffic control system, and cooperative adaptive cruise control. These applications can then be transplanted into the driving simulator to examine the impacts from the perspective of drivers.

4. ITS Applications

4.1. In-Vehicle Signal Assistance

In-vehicle Signal Assistance (ISA) is a Connected Vehicles (CV) application utilizing vehicle to infrastructure (V2I) communications. Vehicles equipped with the ISA application receive real-time signal phase and timing (SPaT) data from the intersection as the vehicles approaches. With the SPaT data, the ISA application conveys the current signal status to the driver via a graphical display unit (e.g., an opt-in LCD panel or head-up display, an external smartphone or tablet PC). Depending on the embedded logic, the ISA application provides the driver with an advisory speed to deal with: 1) dilemma zone; 2) emissions and fuel consumption reduction (i.e., eco-driving); and 3) delay and stop mitigation.

A high-level architecture of the ISA application is shown in **Figure 5**. A Road-Side Unit (RSU) receives SPaT data from the traffic signal controller and broadcasts it via wireless communication. Under the current connected vehicle standard, the wireless communications conveying SPaT messages utilize Dedicated Short Range Communication (DSRC) at 5.9 GHz bandwidth. However, depending on the communication range, using non-DSRC communications such as WiFi and 4G/LTE network is also available for the implementation of ISA. The SPaT messages disseminated from the RSU are delivered to drivers that are equipped with on-board units (OBU). OBU receive the SPaT message from a nearby RSU and process the message to produce driver-friendly information such as the current signal phase: green, red, or yellow, at the next intersection and an advisory speed. Drivers in the equipped vehicles access the real-time SPaT information through an in-vehicle display unit.

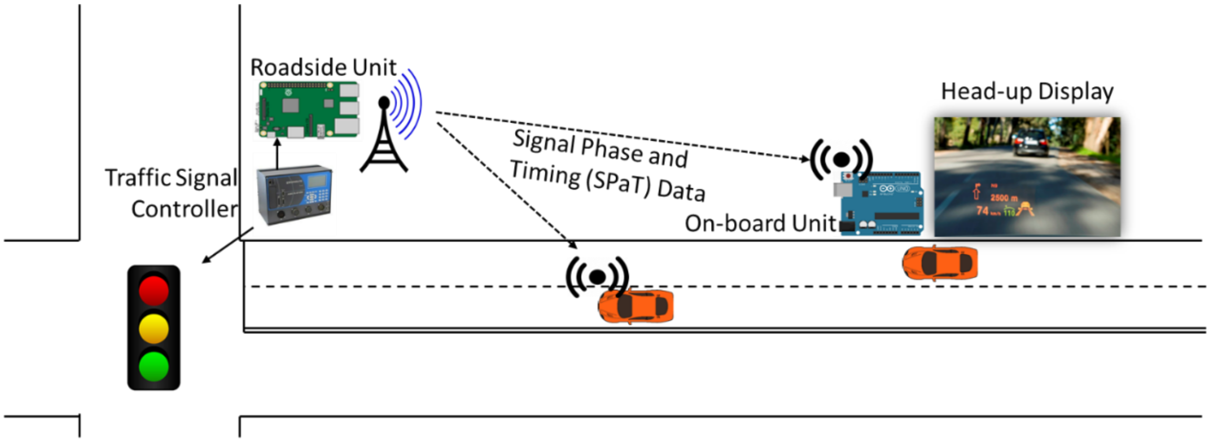


Figure 5. Conceptual Framework of In-vehicle Signal Assistance

4.1.1. Assistance Information

The concept of ISA was applied to the NJIT driving simulator. A four-way signalized intersection was constructed in the virtual world. The intersection was equipped with a virtual RSU to disseminate SPaT messages with a one-second update interval. An OBU in the subject vehicle is manipulated by the human driver who receives the SPaT message. As soon as a new simulation starts, the current signal status of the next intersection driver is displayed via a HUD unit, shown on the windshield of the subject vehicle as illustrated in **Figure 6**.

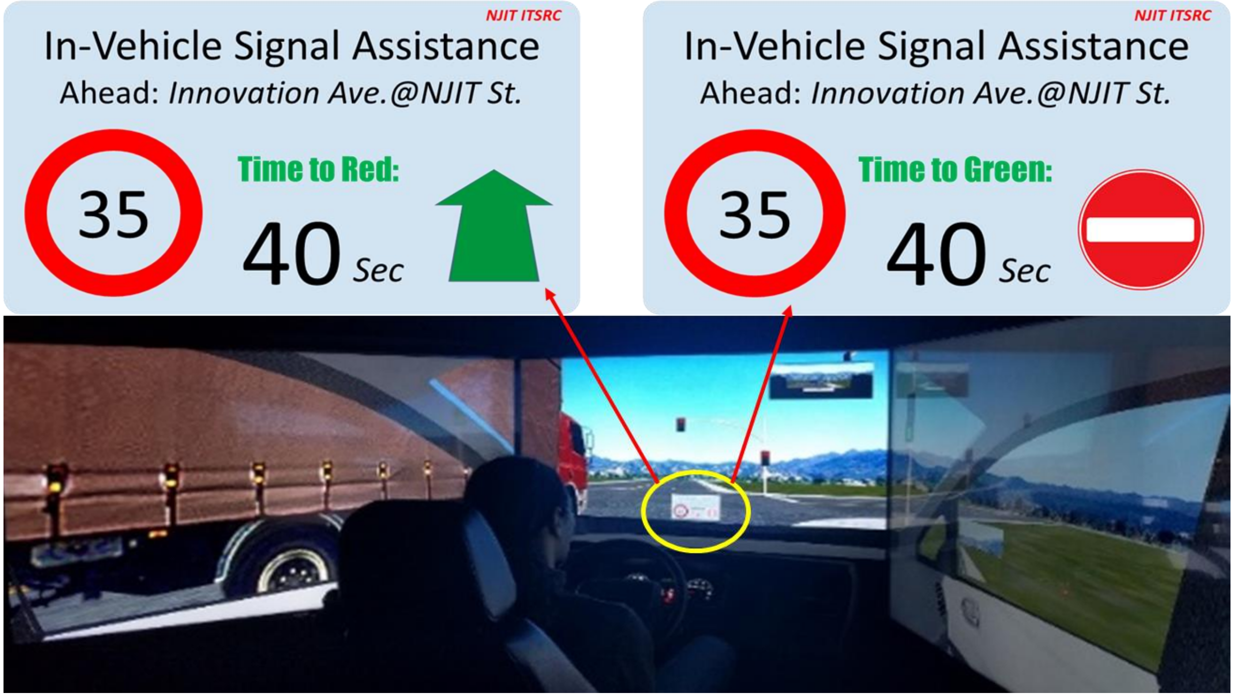


Figure 6. Advisory Information by ISA

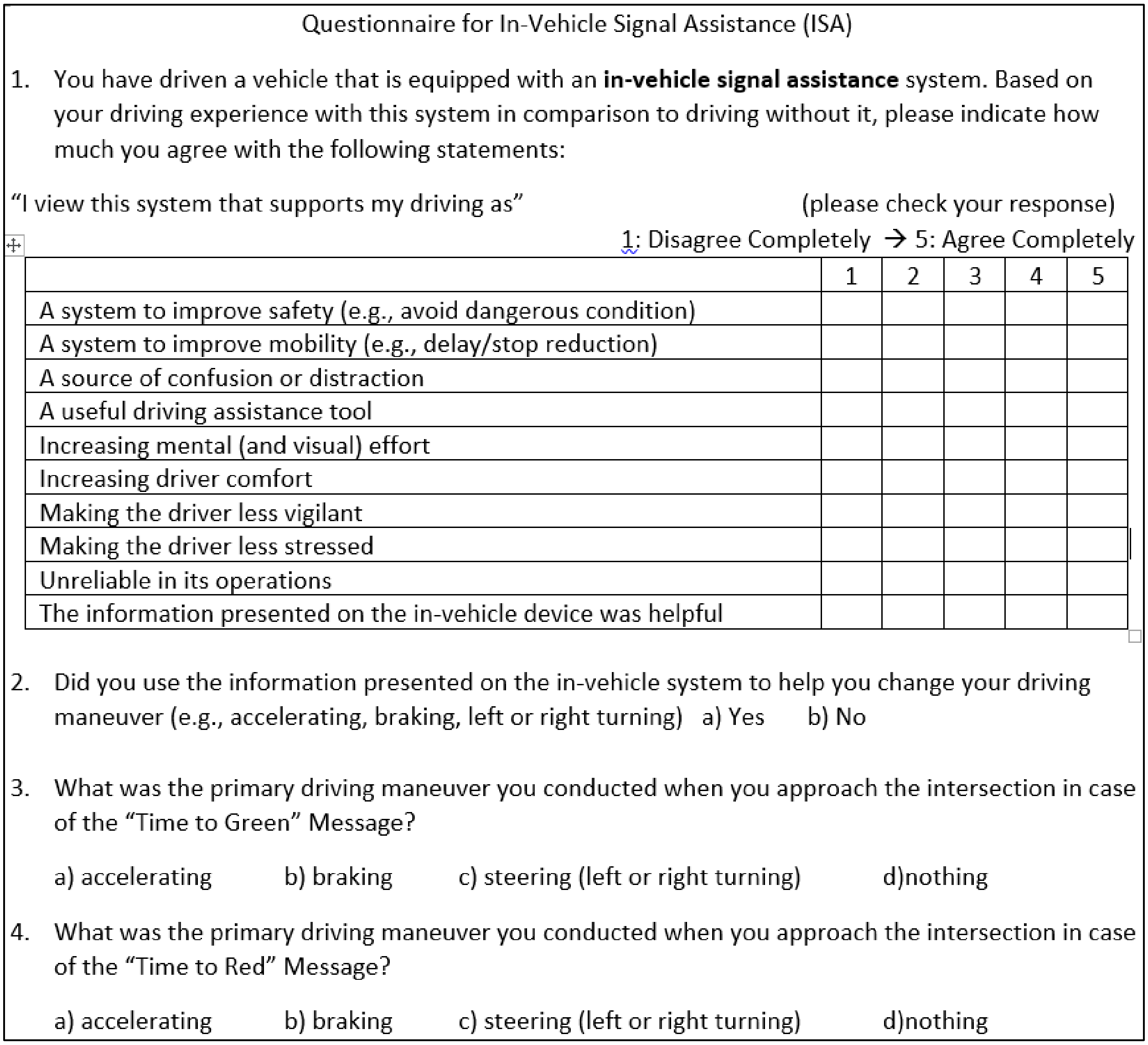
4.1.2. Experiment Design

The virtual test site developed for the experiment consisted of one signalized intersection as shown in **Figure 7**. Subject drivers participating in the experiment freely select the most proper driving maneuvers: accelerating, braking, lane changing, to safely cross the downstream intersection. The intersection operates as fixed time, however, the length of the green phase for each experiment is randomly selected. The random phase length helps subject drivers avoid experiencing a potential learning effect for the changing signal phases. The congestion level around the test intersection is designed to be moderate with ambient traffic of 600 to 800 vehicles per hour for each street approach with approximately 5% truck traffic.

Five distinctive scenarios were provided to individual subject drivers. The experimental factors for each scenario, such as traffic congestion level, length of green, and the start location of the subject vehicle, are then randomly determined prior to the beginning of each simulation within the pre-defined ranges of experiment factors. For each specific selected scenario, the subjects then drive the test site with and without the ISA application.

Figure 7. ISA simulation test bed

To examine the effectiveness of the ISA application, both quantitative and qualitative measures are captured for the subject driver, given dilemma zone conditions. For the quantitative measures, the simulator records driving maneuvers such as accelerating, braking, and lane changing until the subject vehicle passes the intersection. Combined with each simulation time-stamp, high-resolution (e.g., 0.1 seconds interval) driving data including speed, travel distance, acceleration/deceleration rate, steering wheel angle, etc., is archived into a database for post-processing. For the qualitative analysis to examine the performance of the ISA application from the human factor perspective, the project team developed a questionnaire, shown in **Figure 8**, to capture how drivers feel and react in response to the cases of driving with and without ISA. The first question set was developed to investigate the usefulness of the ISA application from the perspective of drivers in terms of safety and mobility. Associated with the first question, the second question was intended to capture the compliance of drivers in response to the information provided through the ISA application. The third and fourth questions were designed to observe the behavior of the drivers when the ISA information is provided. The results of the experiments are discussed in Chapter 5.



Questionnaire for In-Vehicle Signal Assistance (ISA)

1. You have driven a vehicle that is equipped with an **in-vehicle signal assistance** system. Based on your driving experience with this system in comparison to driving without it, please indicate how much you agree with the following statements:

"I view this system that supports my driving as" (please check your response)

1: Disagree Completely → 5: Agree Completely

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

2. Did you use the information presented on the in-vehicle system to help you change your driving maneuver (e.g., accelerating, braking, left or right turning) a) Yes b) No

3. What was the primary driving maneuver you conducted when you approach the intersection in case of the "Time to Green" Message?

a) accelerating b) braking c) steering (left or right turning) d)nothing

4. What was the primary driving maneuver you conducted when you approach the intersection in case of the "Time to Red" Message?

a) accelerating b) braking c) steering (left or right turning) d)nothing

Figure 8. Questionnaire for the ISA evaluation

4.2. Freeway Merge Assistance

4.2.1. Overall Framework

Freeway merge segments may cause dangerous roadway conditions due to safety-critical conflicts between high-speed vehicles operating on the mainline and low-speed vehicles entering from the ramp. While the right-of-way in the merge segment is given to the mainline vehicle, it is observed that vehicles on the ramp frequently ignore the right-of-way rule, thereby resulting in adverse impacts on the mainline with respect to safety, such as near-miss crashes, and mobility, such as phantom queues and delays.

Freeway merge assistance (FMA) has gained attention as one of the viable ITS technologies to achieve safe and smooth merge maneuvers for vehicles entering the mainline. The FMA application provides an advisory speed range to any entering driver 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. In the state-of-the practice, such vehicular information is either directly captured by high-end radar sensor (e.g., Wavetronix Matrix) or indirectly estimated by analyzing data obtained from detectors (e.g., inductive loop, video detector, etc.). It is also worth noting that Vehicle-to-Vehicle (V2V) communications are applicable for capturing real-time vehicular information given by connected vehicle environments in the future.

In this project, a radar-based detection unit was employed to estimate the arrival time of mainline vehicles, as depicted in the overall architecture of the FMA system shown in **Figure 9**. Once the detector that is located 600-feet upstream of the merge point captures the speed and position of a mainline vehicle, the roadside unit then estimates its arrival time at the merge point.

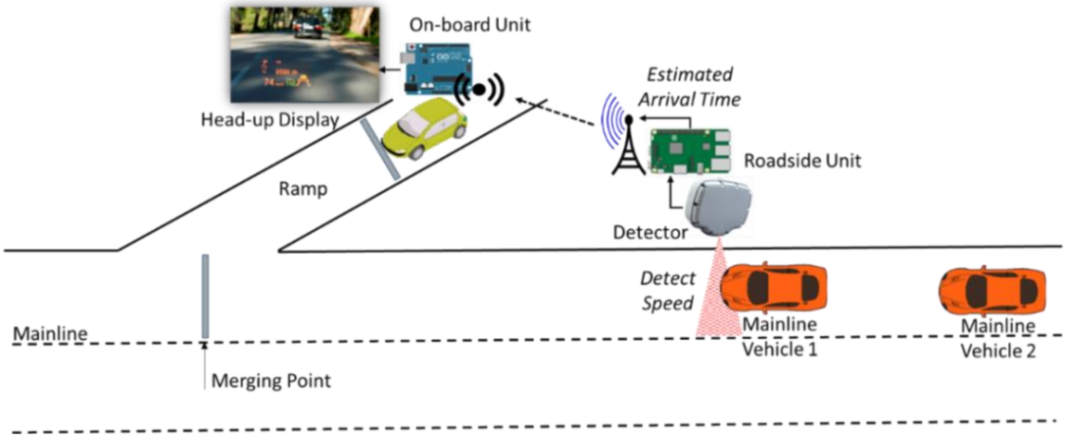


Figure 9. Conceptual Framework of Freeway Merge Assistance

Using a wireless communications link, the estimated arrival time is sent to an on-board unit equipped in a vehicle that is located on the ramp. Using the estimated arrival time of the mainline vehicle, the on-board unit implements the merge assistance algorithm and displays the advisory speed range via a head-up display unit. The details of the merge assistance algorithm is discussed in the next section.

4.2.2. Merge Assistance Algorithm

The FMA application provides an entering vehicle on the ramp with a recommended range of speed enabling the driver to enter the mainline in a safe manner. Once a ramp vehicle passes over the trigger point, say 600 feet upstream from the merge point, the algorithm calculates the estimated arrival time of the ramp vehicle at the merge point, denoted by t0. Using the instantaneous speed and position information of vehicles on the mainline, the algorithm estimates the arrival time of each individual mainline vehicle, i, at the merge point, denoted by ti (i=1,2, …. n) as graphically illustrated in **Figure 10**.

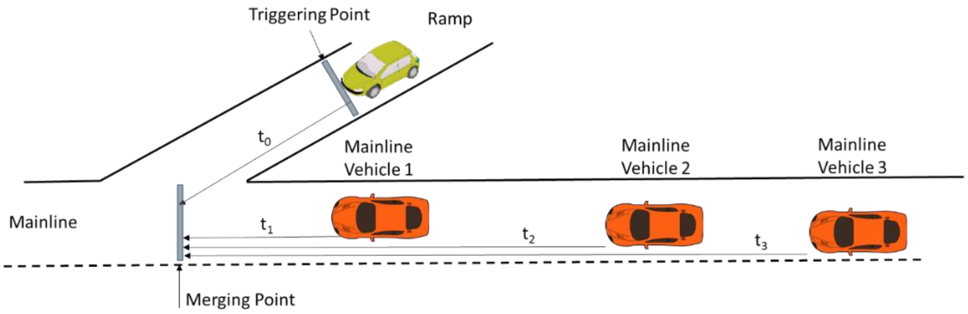


Figure 10. Arrival Time Estimation

Time-space diagrams conceptually depicting the trajectories of vehicles approaching the merge point are shown in **Figure 11**. The basic idea of the merge assistance algorithm is to detect a condition satisfying: $t_0 = t_i$, which indicates a collision between a mainline and ramp vehicle at the merge point. Once a collision condition is anticipated, as shown in **Figure 11(b)**, the algorithm adjusts the ramp vehicle speed to avoid the collision based on the mainline vehicle arrival time t_i, as shown in **Figure 11(c)**.

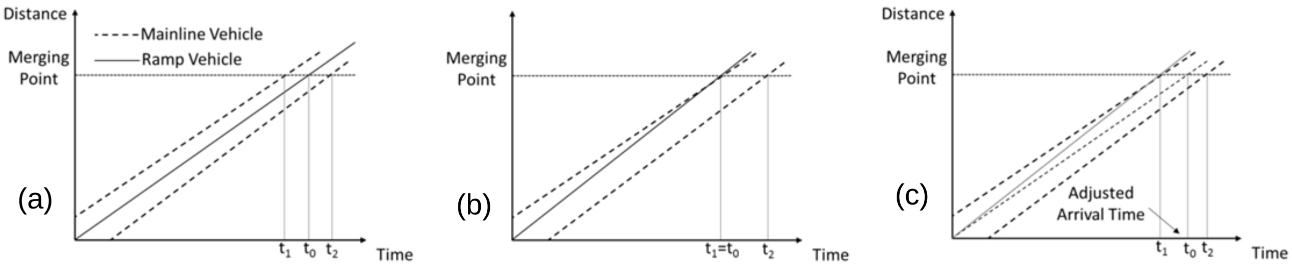


Figure 11. Collision Detection Approach

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 12(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 arrival time, denoted by t_0-h and t_0+h, respectively, as shown in **Figure 12(b)**. In case the arrival time of a mainline vehicle is within the arrival time boundary of the ramp vehicle as shown in **Figure 12(c)**, the algorithm first attempts to adjust the arrival time by providing a speed advisory to the driver of the ramp vehicle conceptually depicted in **Figure 12(d)**. Thus, the range of advisory speeds given to the ramp vehicle is determined by finding the safe arrival time of the ramp vehicle to avoid any conflict with the mainline vehicles within the safety headway boundaries.

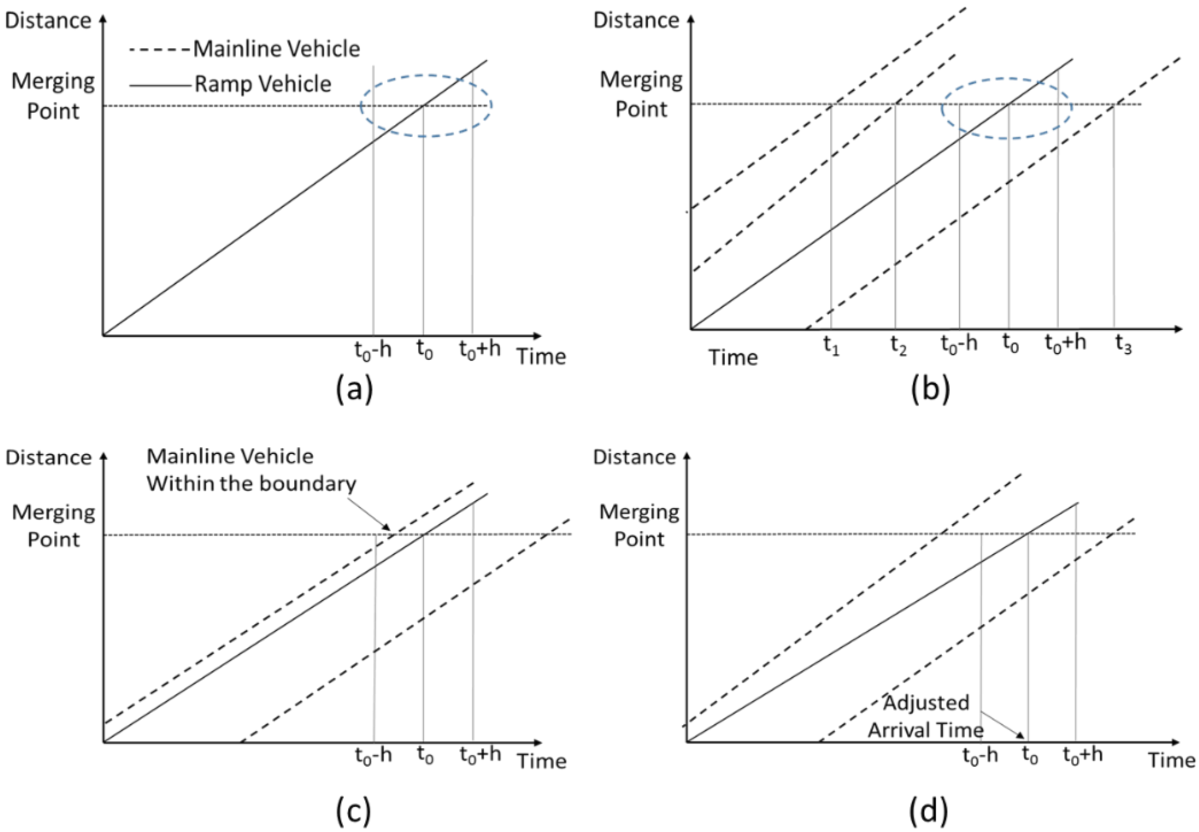


Figure 12. Advisory speed range determination

Depending on the arrival time of the mainline vehicles at the merge point, the advisory speed calculation can be grouped into five cases as illustrated in **Figure 13**. In Case 1, shown in **Figure 13(a)**, no mainline vehicles were identified approaching the merge point; thus, there is no need to adjust the arrival time of the ramp vehicle. In Case 2 and Case 3, a mainline vehicle is anticipated to be within either the upper (i.e., t0+h) or the lower (i.e., t0-h) safety boundary, as shown in **Figure 13(b)** and **Figure 13(c)**, respectively. In both cases, the arrival time of the ramp vehicle was adjusted through a recommended speed advisory to avoid the conflict, thereby resulting in a safe merge condition. In Case 4, depicted in **Figure 13(d)**, two mainline vehicles have potential conflicts within the safety boundary. In this case, the arrival time of the ramp vehicles was again adjusted through a speed advisory to avoid both conflicts. In Case 5, depicted in **Figure 13(e)**, an attempt to adjust the arrival time of the ramp vehicle is considered as failed; as there is no advisory speed range that would enable a safe merge. In this case, the algorithm produces a warning message to assist the ramp driver to stop before entering the mainline.

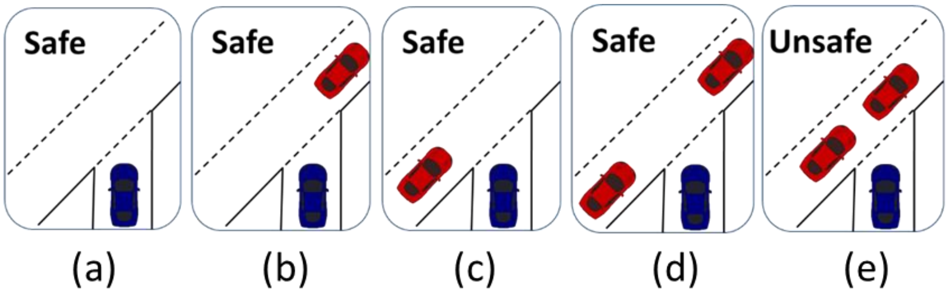


Figure 13. Cases for Advisory Speed Information

The FMA application graphically displays the speed range through a Head-up Display (HUD) unit. **Figure 14** 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 Case 1 yields a free entering condition, the upper and lower speed boundaries are tied to the speed limits of the mainline, 65 MPH, and the ramp, 35 MPH, as depicted in **Figure 14(a)**. In Case 2, the ramp driver must delay his arrival time to avoid an anticipated conflict caused by a mainline vehicle in the upper boundary. The upper and lower speed boundaries are depicted in **Figure 14(b).** In Case 3, the ramp driver must change his arrival time to avoid an anticipated conflict caused by a mainline vehicle in the lower boundary. The upper and lower speed boundaries are depicted in and **Figure 14(c).** Similarly, in Case 4, 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 14(d)**. In Case 5, there is no safe ramp speed range to avoid a conflict so a warning message for the ramp vehicle driver to prepare to stop is displayed, as depicted in **Figure 14(e)**.

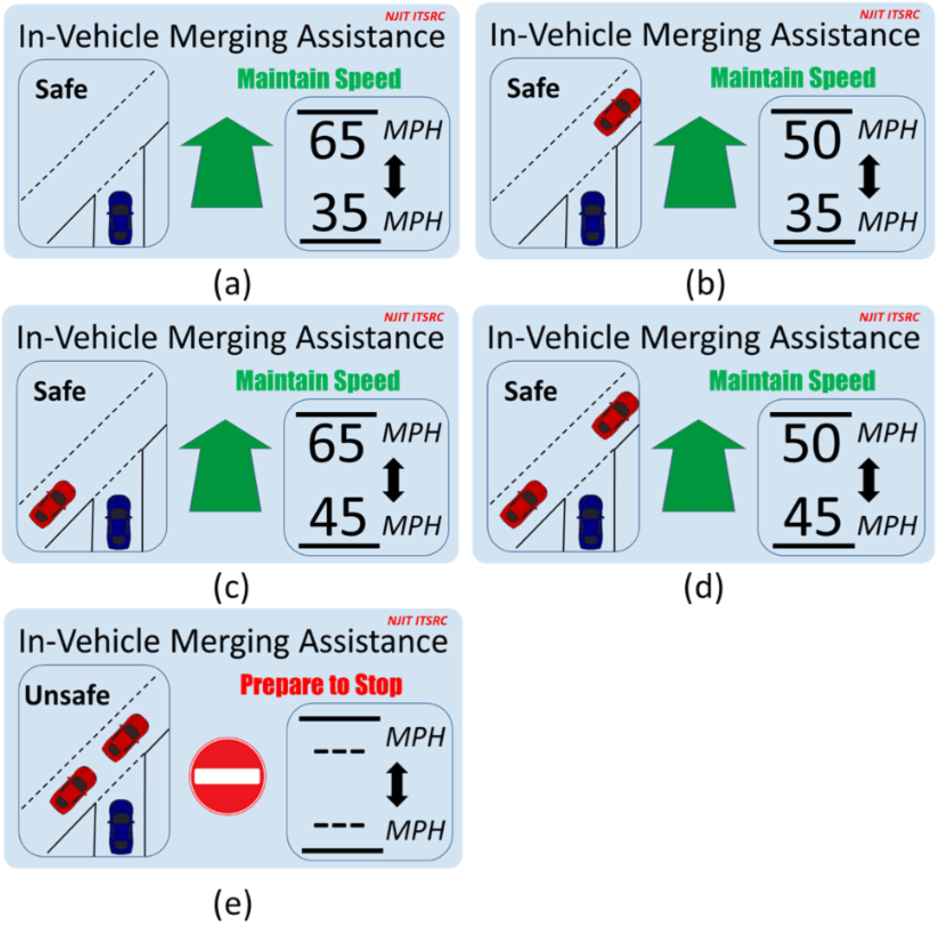


Figure 14. HUD images for the advisory information

4.2.3. Simulation model for FMA experiment

A bird's eye view of a virtual test site for the evaluation of the FMA application is shown in **Figure 15**. The on-ramp of the test site merges with a two-lane freeway with a 65 MPH speed limit through a 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 downhill segment with approximately 2% grade prior to the merge. Combined with the 200-foot acceleration lane, the downhill 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 merge area. A real-world condition similar to the virtual test site is shown in **Figure 16**.

Figure 15. FMA simulation test site

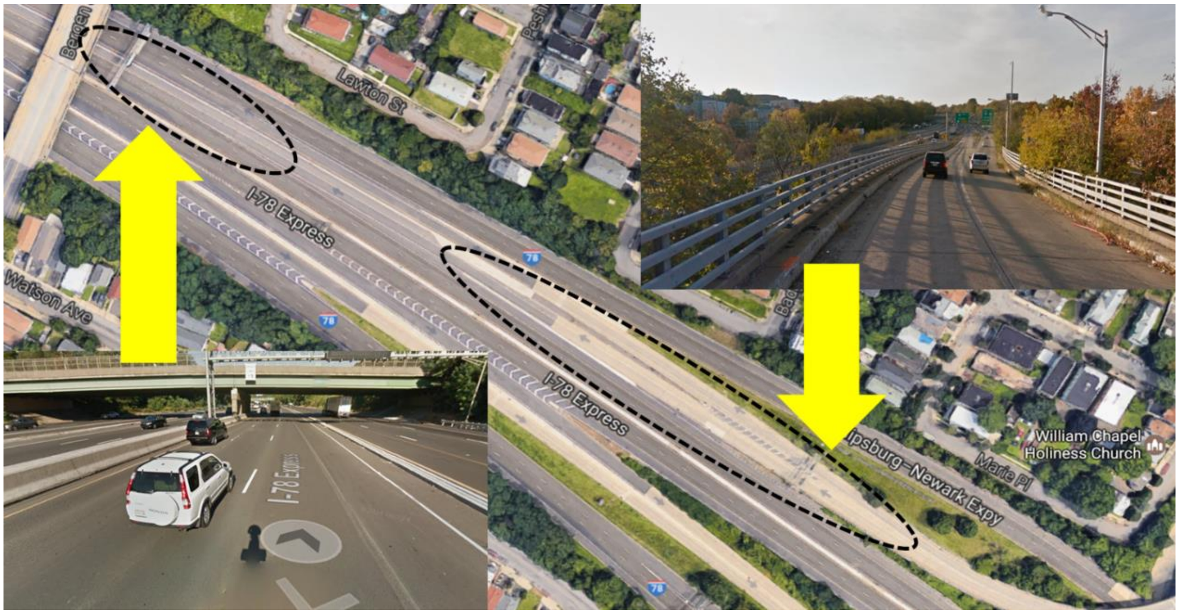
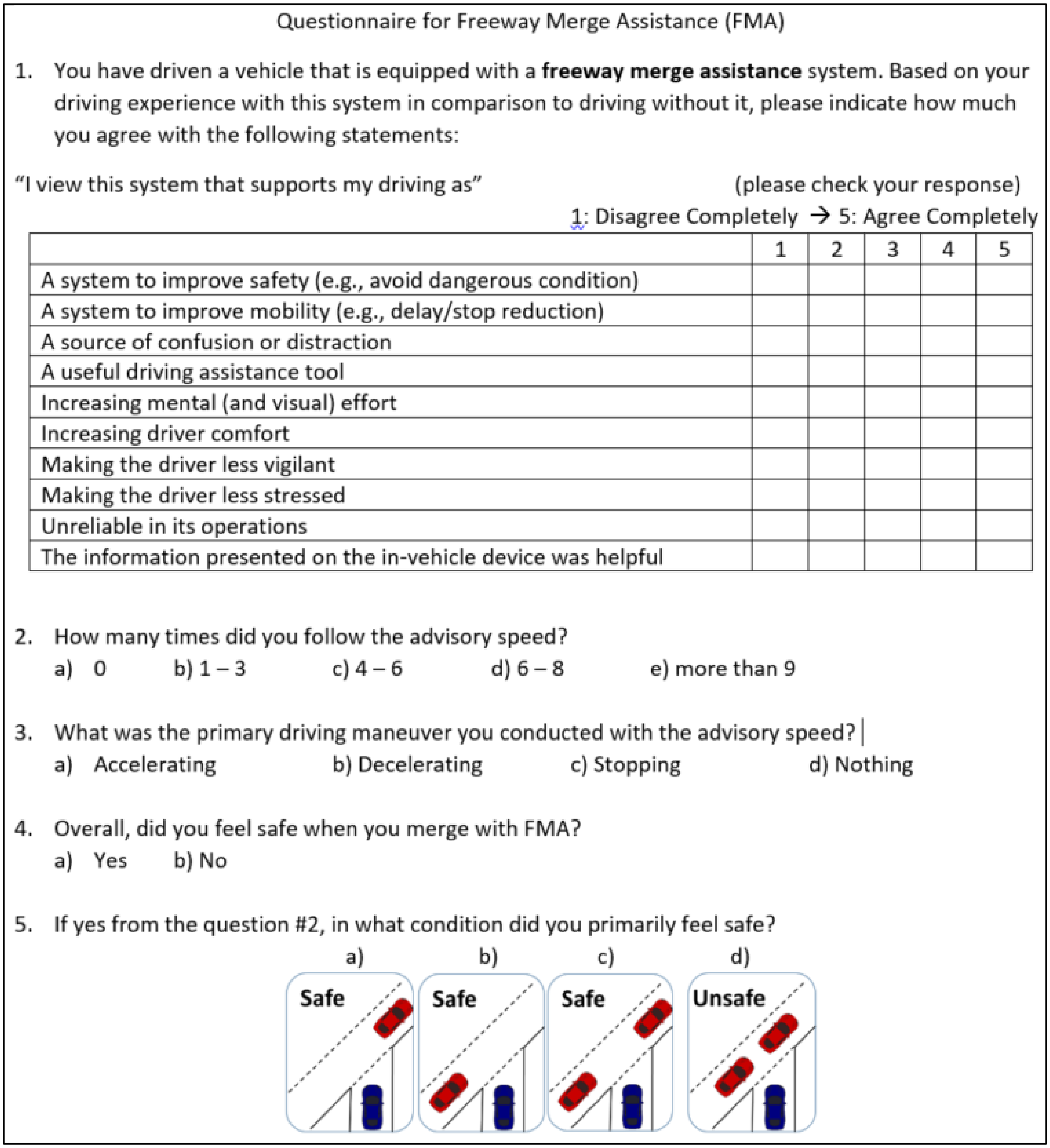


Figure 16. Real-world short merge case

Traffic volume on the mainline was randomly selected by the driving simulator within the range of 1200 and 1800 vehicles per hour per lane with 5% truck traffic. Five scenarios dealing with different traffic volume conditions on the mainline were presented to individual subject drivers. For each scenario, a subject driver manipulates the ramp vehicle until he/she completes the merging maneuvers with or without the FMA application.

The effectiveness of the FSA application was examined by analyzing both quantitative and qualitative measures captured from each subject driver. Similar to the ISA experiment presented in the previous chapter, the driving simulator automatically collects quantitative measures: speed, acceleration rate, and position, with 60 Hz (i.e., 0.016 seconds) intervals. With respect to the qualitative analysis for the usefulness of the FMA application, a set of five questions was given to the subject drivers who completed the experiment. The questionnaire for the evaluation of the FMA application is shown in **Figure 17**. The first question set, like the ISA experiment, was 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 questions are: to analyze the acceptance of drivers for the advisory information provided; and to capture the actual reactions of drivers in response to the information, respectively. The fourth and fifth questions attempt to determine the most useful case that improved the safety of the drivers when they used the FMA application. The results are summarized in Chapter 5.



Questionnaire for Freeway Merge Assistance (FMA)

1. You have driven a vehicle that is equipped with a **freeway merge assistance** system. Based on your driving experience with this system in comparison to driving without it, please indicate how much you agree with the following statements:

"I view this system that supports my driving as" (please check your response)

1: Disagree Completely → 5: Agree Completely

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

2. How many times did you follow the advisory speed?
   a) 0 b) 1 – 3 c) 4 – 6 d) 6 – 8 e) more than 9

3. What was the primary driving maneuver you conducted with the advisory speed?
   a) Accelerating b) Decelerating c) Stopping d) Nothing

4. Overall, did you feel safe when you merge with FMA?
   a) Yes b) No

5. If yes from the question #2, in what condition did you primarily feel safe?
   a) Safe b) Safe c) Safe d) Unsafe

Figure 17. Questionnaire for FMA Evaluation

5. Evaluation

5.1. Subject Drivers

The project team recruited subject drivers within the NJIT community to perform small-scale proof-of-concept evaluation tests for both ISA and FMA applications. Ten volunteers with valid driver licenses, who had no mental and physical health problems, participated in the experiments. Participants included both male and female drivers with an age distribution from less than 25 years old to greater than 35 years old. Most drivers had five or more years of experience and drove on a daily basis. In addition, most drivers had never been involved in a crash. . The characteristics of the subject drivers are summarized in **Table 2**.

Table 2. Subject Driver Characteristics

Driver Characteristic				
Gender	**Male**		**Female**	
	60%		40%	
Age Distribution [years]	**<25**	**26-30**	**31-35**	**35+**
	20%	30%	30%	20%
Experience with Car Crashes	**Yes**		**No**	
	20%		80%	
Driving Experience [years]	**< 1**	**1-5**	**5-15**	**15+**
	10%	20%	40%	30%
Frequency of Driving	**Daily**	**Once per Week**	**Occasionally**	
	70%	10%	20%	

Each subject driver conducted preliminary free driving sessions prior to the actual experiments in order to familiarize himself or herself with the virtual reality constructed by the driving simulator. Several subject drivers reported simulation sickness at the beginning of the warm-up period. Thus, the length of the warm-up period varied depending on the individual driver; overall, male drivers spent up to 30 minutes in warm-up, while a female driver took approximately 50 minutes for the same warm-up stage. Including the warm-up period, the total experiment test time for each subject driver ranged from 90 minutes to 120 minutes including 5 to 15 minutes of break time, depending on the individual driver.

5.2. In-Vehicle Signal Assistance

This project examined the qualitative effectiveness of the ISA application by analyzing the subject driver responses to the ISA questionnaire presented in Chapter 4. The summary results of the questionnaire are presented in **Table 3** and key findings are discussed in this section.

Table 3. Responses to Questionnaire for In-Vehicle Signal Assistance (ISA)

Responses to In-Vehicle Signal Assistance (ISA) Questionnaire					
Question 1: Based on your driving experience with this system in comparison to driving without it, please indicate how much you agree with the following statements					
I view this system that supports my driving as:	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
A system to improve safety	0%	0%	30%	20%	50%
A system to improve mobility	0%	0%	10%	20%	70%
A source of confusion or distraction	40%	20%	10%	30%	0%
A useful driving assistance tool	0%	0%	10%	20%	70%
Increasing mental (and visual) effort	0%	30%	40%	30%	0%
Increasing drive comfort	20%	10%	30%	20%	20%
Making the driver less vigilant	10%	10%	20%	60%	0%
Making the driver less stressed	0%	10%	10%	50%	30%
Unreliable in its operations	50%	40%	10%	0%	0%
The information presented on the in-vehicle device was helpful	0%	0%	0%	30%	70%
Question 2: Did you use the information presented on the in-vehicle system to help you change your driving maneuver (e.g., accelerating, braking, left or right turning)?				Yes	No
				80%	20%
		Accelerating	**Braking**	**Steering**	**Nothing**
Question 3: What was the primary driving maneuver you conducted when you approached the intersection in case of the “Time to Green” message?		60%	20%	0%	20%
Question 4: What was the primary driving maneuver you conducted when you approached the intersection in case of the “Time to Red” message?		60%	30%	10%	0%

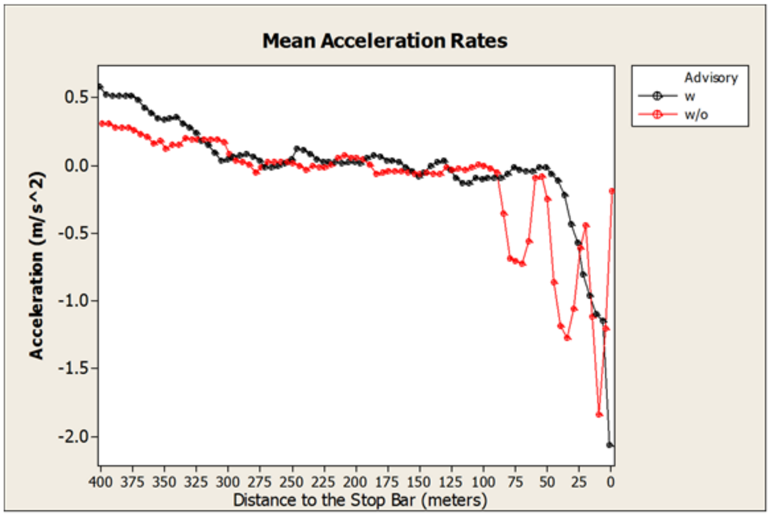
Between 70% and 90% of subject drivers agreed that the ISA application is a useful tool for improving the safety and mobility of their driving conditions. However, 30% of subject drivers responded that the ISA application often either distracted their driving or caused them to become confused. Nevertheless, the overall findings revealed that subject drivers agreed that the ISA application positively assisted their driving experience.

Interestingly, 30% of subject drivers responded that the ISA application had increased their mental focus and concentration efforts while manipulating the subject vehicle. Compared to their experiences driving without the ISA application, the drivers had to conduct additional effort causing them to pay attention to the information from the ISA application, which might be redundant. As a result, 30% of subject drivers disagreed that the ISA application helped increase their driver comfort while 40% of participants agreed that it did help. In addition, it appeared that the ISA application enables the subject drivers to feel less nervous when crossing an intersection. Every experiment for the ISA evaluation was designed to occur within a dilemma zone condition. Thus, with the ISA application providing the remaining green time information, the subject drivers were able to conduct preemptive maneuvers to avoid potentially dangerous conditions caused by a dilemma zone, thereby resulting in less vigilant and less stressful driving conditions.

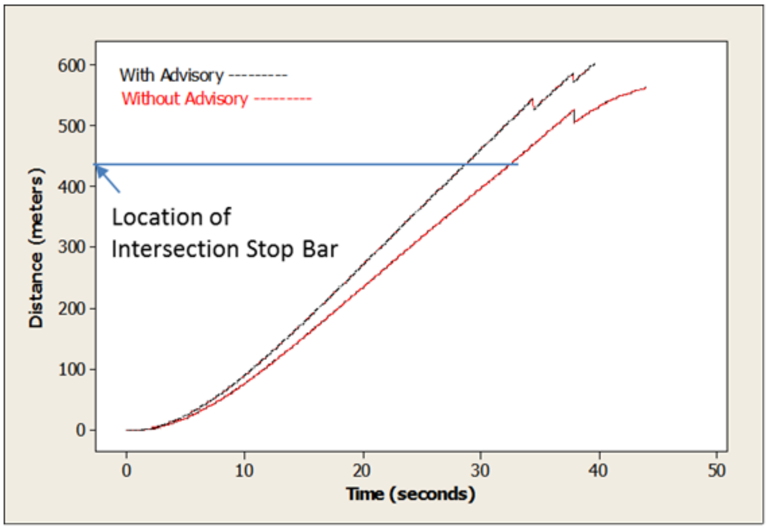
The reliability of the ISA application was also examined and zero subject drivers agreed that the ISA application was unreliable. Similarly, all of the subject drivers who participated in the experiments agreed that the information from the ISA application was helpful in determining proper driving maneuvers to safely cross the intersection, given dilemma zone conditions.
The actual behavior that the subject drivers performed in response to the received ISA information was also investigated. In case of the “Time to Green” message with the remaining red time information, 60% accelerated, 20% reduced their speed, and 20% maintained their driving speed. It is noteworthy that the majority of subject drivers increased their speed even though they were aware that the next signal phase was currently red. Regarding this phenomena, the project team observed that the subject drivers continued pushing the accelerator as soon as the simulation began during the experimental phase of the study. This was believed to occur be because the subject vehicle is stopped at the start of the simulation, while the ambient traffic are moving. This condition causes the subject drivers to accelerate to reach a prevailing speed similar to the ambient traffic. In the cases where the “Time to Green” message is displayed during this initial acceleration period, the subject drivers did not pay attention to the message, even as they were aware of the consequences that they need to eventually stop at the intersection. Given the “Time to Red” message with the remaining green time information, 30% of the subject drivers braked to stop the car, while 60% accelerated to pass through the intersection before the green signal ended.

The actual longitudinal driving behavior of subject drivers were examined by analyzing the profiles of acceleration/deceleration rates with and without the ISA application and the time space diagram as shown in **Figure 18. (a)** and **Figure 18. (b),** respectively. As clearly shown in **Figure 18(a)**, subject drivers that were assisted by the ISA application maintained stable longitudinal movements by performing monotonically continuous decelerating maneuvers as they approached the stop bar of the target intersection (i.e., distance to the stop bar less than 50 meters). On the other hand, the subject drivers without the ISA application repeatedly accelerated and decelerated as they moved closer to the intersection, thereby resulting in jittering maneuvers for the longitudinal movement, which likely caused discomfort for the drivers.

The trajectory result obtained from the time-space diagram shown in **Figure 18.** **(b)** is also of interest. The ISA application enabled the drivers to move the ISA-equipped vehicles faster, by producing travel time savings of as much as 5 seconds, on average. With the observations discovered from the acceleration profile and trajectory data, the ISA application assisted drivers with conducting smooth driving maneuvers and, in turn, improved the safety, mobility, and comfort of drivers when crossing an intersection.



(a) Acceleration profile



(b) Time-space diagram

Figure 18. Acceleration profile and time-space diagram with and without ISA

5.4. Freeway Merge Assistance

This project examined the qualitative effectiveness of the FMA application by analyzing the subject driver responses to the FMA questionnaire presented in Chapter 4. The summary results from the questionnaire are presented in **Table 4** and key findings are discussed in this section.

Table 4. Responses to Questionnaire for Freeway Merge Assistance (FMA)

Responses to Freeway Merge Assistance (FMA) Questionnaire					
Question 1: Based on your driving experience with this system in comparison to driving without it, please indicate how much you agree with the following statements					
I view this system that supports my driving as:	**Strongly Disagree**	**Disagree**	**Neutral**	**Agree**	**Strongly Agree**
A system to improve safety	0%	0%	30%	30%	40%
A system to improve mobility	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 drive 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%
Question 2: How many times did you follow the advisory speed?	**0**	**1-3**	**4-6**	**6-8**	**9 +**
	0%	0%	0%	30%	70%
Question 3: What was the primary driving maneuver you conducted with the advisory speed?	**Accelerating**	**Braking**	**Steering**	**Nothing**	
	80%	10%	0%	10%	
Question 4: Overall, did you feel safe when you merged with FMA?				**Yes**	**No**
				90%	10%
Question 5: If yes from question #4, in what condition did you primarily feel safe?	**Case 2**	**Case 3**	**Case 4**	**Case 5**	**None**
	60%	10%	20%	0%	10%

The FMA application was effective in improving the safety and mobility of driving conditions when performing freeway merges. Most subject drivers responded that the FMA application enabled drivers on the on-ramp to make safe and smooth merges on 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. Through conducting post-experiment interviews with the drivers, 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 for drivers.

The FMA application increased driver mental focus when conducting merge maneuvers, as 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 effort. As a result, only 30% of subject drivers felt comfortable with the FMA application.

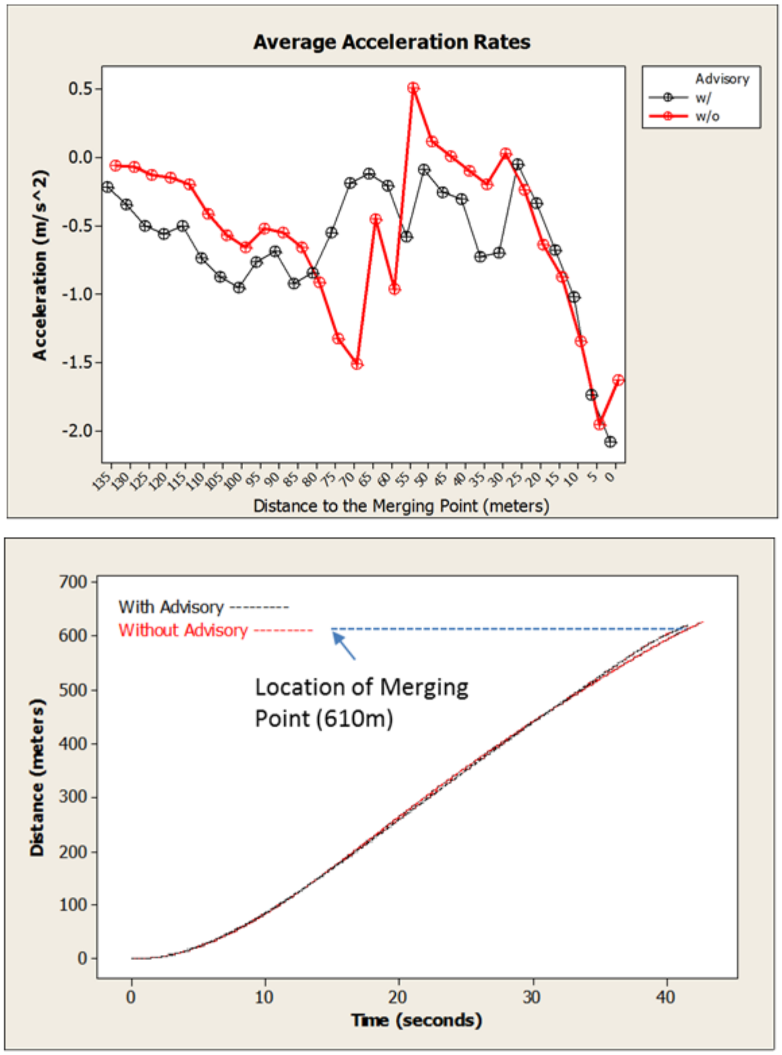
The FMA application appeared to help reduce driver stress by relieving their vigilance when they attempt to merge onto the mainline in spite of the additional mental effort that the subject drivers experienced. In cases without the FMA application, 60% of subject drivers stated that they felt uncomfortable when approaching the mainline to conduct merge maneuvers due to their uncertainty at the merge point. The uncertainty is mainly caused by a lack of sufficient situational awareness for the merge. 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 merge 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.

In response to the question that the information provided by the FMA application is unreliable, the majority of the subject drivers (strongly) disagreed. As a result, the FMA application appears to convey useful information enabling the subject drivers to merge onto the mainline in a safe and smooth manner.

It was discovered that the high reliability of the advisory information leads to higher compliance rates for the subject drivers. Most subject drivers followed the provided information more than 4 times out of 5, or 80% compliance rate. 30% of subject drivers also followed the provided information 3 times out of 5 or 60% compliance rate. Following the advisory information, the primary driving maneuver that the subject drivers performed was accelerating. The advisory speed information is a function of prevailing traffic conditions in and around the merge segment as addressed in Chapter 4. Depending on the mainline traffic condition, the 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 or 35 mph. Thus, the speed of the subject vehicle at which the FMA application conducts advisory speed estimation is relatively low. Given such a low speed, it is easy for the FMA application to reduce the arrival time of the ramp vehicle by increasing its approach speed to avoid 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 merges, particularly in Case 1 scenarios where there is no forecasted conflict with mainline vehicle.

The project team also captured individual drivers' driving maneuvers with and without the FMA application as shown in Error! Reference source not found.. 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/sec^2 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.



(a) Acceleration Profile

(b) Time-space diagram

Figure 19. Acceleration profile and time-space diagram with and without FMA

With the projected situational awareness provided by the FMA application, the subject drivers with the FMA 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 merge point). Without the FMA application however, subject drivers were unable to perform any proactive maneuverings until they arrived at the merge 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 maneuvers within approximately 200-foot ahead of the merge point, which would result in unsmooth longitudinal movements as shown in Error! Reference source not found.**(a).** Unlike an acceleration profile, no significant difference was observed from the time-space diagram as demonstrated in Error! Reference source not found.**(b)**, indicating no mobility impacts were improved by the FMA application.

6. Conclusions and Recommendations

6.1. Conclusions

In technical partnership with NJDOT, the ITS Resource Center at NJIT initiated a procurement process for a state-of-the art driving simulator in late 2014. Starting with a comprehensive review of the technical specifications of various driving simulators available in the market, the NJIT project team made efforts to find the most suitable driving simulator that properly envisioned NJDOT's plans for the implementations of ITS and TSM&O applications. The procurement process completed in September 2016 and the complete set of the driving simulator became operational in November 2016 with the following features:

- Monitor and automatically record the driver's behavior (e.g., lane departure, steering wheel movement, and eye blinking) as well as the vehicle dynamics (e.g., speed, acceleration/deceleration, vehicle headway, and applied forces/power) in real-time;
- Provide a driving environment and experience as close to actual driving as possible, with a comfortable seat, steering wheel, dashboard, acceleration pedal, brake pedal, etc.;
- Provide software tools for scenario design, selection, and modification, and simulation data analysis;
- Test different vehicle dynamics, e.g. for sedans, SUVs, and trucks;
- Be compatible with other add-on tools available in the market (e.g., eye tracking systems).
- Handle various scenarios operating in the following conditions: rural/urban highways, monotonous/moderate/complex roadway geometry, low/moderate/heavy traffic, night/day time driving, different weather conditions including adverse weather with winter driving conditions, etc.;
- Provide a user-friendly intuitive GUI for building driving scenarios designs that are handling the following parameters: traffic signage location, shape, caption, color, and dimensions; various traffic signal control logics and sensing devices; ambient traffic volume; various vehicle types (e.g. passenger car, bus, truck, tractor-trailer, etc.); weather condition; illumination condition; real-time interactions with background traffic; and
- Provide programming flexibility allowing for integration with off-the-shelf microscopic traffic simulators to achieve a high-fidelity simulation environment.

Utilizing the above features, the NJIT project team examined the applicability of the NJIT driving simulator as a viable tool for the evaluation of ITS and TSM&O applications. To this end, this project constructed two virtual test environments dealing with the evaluation of 1) In-Vehicle

Signal Assistance (ISA) using Signal Phase and Timing (SPaT) data and 2) Freeway Merging Assistance (FMA). Via SPaT messages, ISA provides drivers with the real-time traffic signal status of the next intersection through a HUD unit. 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. Obviously, both applications require advanced modeling capabilities, such as SPaT message dissemination, approaching vehicle detection, HUD simulation, and arrival time estimation, which are beyond the off-the-shelf functions provided by the driving simulator.

The NJIT driving simulator provided operators with great flexibility to customize the driving simulator to any given scenario. The project team successfully performed the customizations to achieve high-fidelity experiment test beds for both ISA and FMA applications as addressed in Chapter 4. Thirteen subject drivers were recruited and the final group of ten participants was selected for inclusion in the experiments after the team screened all subject applicants to detect any potential problems such as simulation sickness. The project team designed a questionnaire for the subjects based on a Likert Scale (16) and then conducted experiments with the human subjects. As discussed in Chapter 5, the effectiveness of both the ISA and FMA applications were evaluated by accurately capturing the diverse driving behaviors of the subject drivers.

Despite the seamless capabilities of the NJIT driving simulator that were proven through this project, modeling virtual reality in a timely manner remains a challenge. The primary reasons for the challenge are: 1) the enormous time and effort required for collecting a proper data set; 2) a lack of skilled manpower to conduct the modeling; and 3) recruiting the number of human subjects sufficient for a valid statistical analysis. In addition, the experiments in this project were conducted without integration of the microscopic traffic simulator.

The interactions between the subject vehicle and the ambient traffic for the evaluation of both the ISA and FMA applications were insignificant enough to be implemented by customizing the driving simulator. However, it would be beneficial to integrate a traffic simulator to achieve realistic ambient traffic behavior, depending on the ITS application. The project team will conduct VISSIM-based integration for the evaluation of proper ITS and TSM&O applications in the future.

Upon completing the evaluations of the proposed applications, the project team was able to achieve the following objectives that were previously established for this project:

- Review of the state-of-the-practice for the evaluations of both ISA and FMA applications using a driving simulator in Chapter 2.
- Development of a high-fidelity simulation environment for the ISA and FMA applications in Chapter 4.
- Examination of the effectiveness of the ISA and FMA applications by using the findings from the experiments in Chapter 5.

- Gaps and challenges discovered during the ITS application evaluations and a discussion of the next steps in Chapter 6.

6.2. Recommendations

Virtual reality provided by a driving simulator will be a useful tool and will aid in a variety of ITS and TSM&O applications supporting the scope of the ITS Resource Center. Therefore, the project team recommends that NJDOT conduct further analysis for the following application areas, where the use of a driving simulator will be especially useful:

- **Evaluation of Active Traffic Management and Connected Vehicle applications:** Driver behaviors (reactions) are one of the crucial components enabling a precise evaluation of Active Traffic Management strategies and Connected Vehicle applications. The state-of-the-art driving simulators are being used to study various Active Traffic Management (ATM) strategies, specifically emphasizing drivers' reactions to the dynamic features of ATM strategies. A few cutting-edge research efforts have been conducted recently to use driving simulators to assess the impact of human factors on Connected Vehicle (CV) applications by forming a virtual cyber physical system based on a human-in-the-loop simulation approach. The performance of major ATM strategies and CV applications rely heavily on travelers' instantaneous feedback: e.g., compliance to dynamically posted (variable) speed limits or advisories in Dynamic Speed Limit(DSpL) applications, or driver acceptance for advisory route information from the Advanced Traveler Information System (ATIS) application in CV. Thus, it is worth investigating 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. Driving simulators will provide a cost-effective and worry-free approach to conducting such investigations.
- **Investigation of driver response to adaptive traffic control system (ATCS):** NJDOT has recently deployed ATCS on several major arterials. It has been recognized, based on both the experience from recent deployment and the feedback from the professional community, that driver expectancy of consistent phase sequencing at intersections may present a safety problem when deploying ATCS. The ATCS allows flexible, demand-driven phase sequencing, so phases may be skipped from one cycle to another. If a driver expects a phase to go through, he or she may perceive the ATCS operation as 'flawed' or 'illogical' if the phase is skipped or does not appear in the expected sequence. The driver may then react based on the expected signal operation, thereby producing an adverse impact on traffic safety. A driving simulator equipped with advanced modules to handle ATCS enables the researchers to capture the drivers' reaction to the dynamic phase sequencing of ATCS, which will be useful for developing the proper ATCS deployment specifications and requirements, as well as for public outreach and traveler information.
- **Safety audit for work zone lane closure plan and road diet activities:** Major road work activities often include lane closures. In addition, road diet, conversion of lanes from

motorized to bicycle traffic, sidewalks, or on-street parking, are sometimes implemented with the objective of reducing vehicle speeds on urban streets. These strategies are also expected to reduce the frequency and severity of motor vehicle crashes. While the reconfiguration of lane utilization for work zones is often inevitable, and a more permanent reconfiguration is desired when creating a bicycle/pedestrian facility, the impact of such reconfigurations on driver behavior has not been fully examined. The use of driving simulators makes it possible to capture driver reactions to alternative lane reconfiguration strategies as part of work zone and road diet plans.

References

[1] Jamson H, Merat N, Carsten O, Lai F. Fully-automated driving: The road to future vehicles. InProc. of Sixth International Driving Symposium on Human Factors in Driver Assessment, Training and Vehicle Design 2011 Dec.

[2] Jamson H, Smith P. Drivers' perception of and response to brake failure. InProceedings of the Second International Driving Symposium on Human Factors in Driver Assessment, Training and Vehicle Design, Park City, Utah, 21.-24. Juli 2003 2003 Jul 21 (pp. 231-238).

[3] Punzo V, Ciuffo B. Integration of driving and traffic simulation: Issues and first solutions. IEEE transactions on intelligent transportation systems. 2011 Jun;12(2):354-63.

[4] AIMSUN 6. Microsimulator and Mesosimulator in AIMSUN 6. User's Manual. Transport Simul. Syst. 1997–2008, Transp. Simul. Syst., Barcelona, Spain, Jan. 2009.

[5] SCANeR II User's Guide v2.18a, Oktal, Paris, France, Nov. 28, 2006

[6] TEST scarl, Centro Regionale di Competenza 'Trasporti.' [Online]. Available: www.crdctest.it/on-line/en/Home.html

[7] De Winter JC, Happee R, Martens MH, Stanton NA. Effects of adaptive cruise control and highly automated driving on workload and situation awareness: A review of the empirical evidence. Transportation research part F: traffic psychology and behaviour. 2014 Nov 30;27:196-217.

[8] Hart SG, Staveland LE. Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research. Advances in psychology. 1988 Dec 31;52:139-83.

[9] Siebert FW, Oehl M, Pfister HR. The influence of time headway on subjective driver states in adaptive cruise control. Transportation research part F: traffic psychology and behaviour. 2014 Jul 31;25:65-73.

[10] Gouy M, Wiedemann K, Stevens A, Brunett G, Reed N. Driving next to automated vehicle platoons: How do short time headways influence non-platoon drivers' longitudinal control?. Transportation research part F: traffic psychology and behaviour. 2014 Nov 30;27:264-73.

[11] Islam MR. Safety and efficiency benefits of traffic signal countdown timers: a driving simulator study (Doctoral dissertation).

[12] Sun J, Ma Z, Li T, Niu D. Development and application of an integrated traffic simulation and multi-driving simulators. Simulation Modelling Practice and Theory. 2015 Dec 31;59:1-7.

[13] PTV AG, VISSIM 5.40 User Manual. Karlsruhe, Germany, 2011.

[14] Jeihani M, Ardeshiri A. Exploring Travelers' Behavior in Response to Dynamic Message Signs (DMS) Using a Driving Simulator. 2013 Oct.

[15] Forum 8, UC-win/Road New Features, http://www.forum8.co.jp/english/uc-win/ucwinroad-e1.htm. 2013

[16] Brown S. Likert scale examples for surveys. ANR Program evaluation, Iowa State University, USA. 2010 Dec.

Appendix: Experiment Questionnaire

General & Health Information

Name:

Age:

Gender: Male Female

Please complete the questionnaire by circling the answers where applicable

1. Do you have a valid driver's license?

a) Yes b) No

2. Have you been involved in any accident(s) within the past 3 years?

a) Yes b) No

3. If yes, please state the number of crash(s) involved in and the type.

____

____

4. Do you need to wear glasses or contact lenses while driving?

a) Yes b) No

5. Do you have any health problems that affect your driving?

a) Yes b) No

If yes, please explain: ______________________________________

6. Do you experience any inner ear, dizziness, vertigo, or balance problems while driving?

a) Yes b) No

7. How often do you drive?

a) Daily b) Once a week c) Occasionally

8. For how long have you been driving?

a) Less than 1yr b) Between 1 - 5 yrs c) Between 5-15 yrs d) More than 15 yrs

Questionnaire for In-Vehicle Signal Assistance (ISA)

1. You have driven a vehicle that is equipped with an in-vehicle signal assistance system. Based on your driving experience with this system in comparison to driving without it, please indicate how much you agree with the following statements:

"I view this system that supports my driving as" (please check your response)

1 : Disagree Completely → 5: Agree Completely

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

2. Did you use the information presented on the in-vehicle system to help you change your driving maneuver (e.g., accelerating, braking, left or right turning)

a) Yes b) No

3. What was the primary driving maneuver you conducted when you approach the intersection in case of the "Time to Green" Message?

a) Accelerating b) Braking c) Steering (left or right turning) d) Nothing

4. What was the primary driving maneuver you conducted when you approach the intersection in case of the "Time to Red" Message?

a) Accelerating b) Braking c) Steering (left or right turning) d) Nothing

Questionnaire for Freeway Merge Assistance (FMA)

1. You have driven a vehicle that is equipped with a freeway merge assistance system. Based on your driving experience with this system in comparison to driving without it, please indicate how much you agree with the following statements:

"I view this system that supports my driving as" (please check your response)

1 : Disagree Completely → 5: Agree Completely

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

2. How many times did you follow the advisory speed?

a) 0 b) 1 – 3 c) 4 – 6 d) 6 – 8 e) more than 9

3. What was the primary driving maneuver you conducted with the advisory speed?

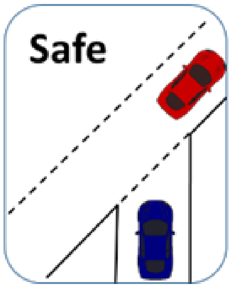
a) Accelerating b) Decelerating c) Stopping d) Nothing

4. Overall, did you feel safe when you merge with FMA?

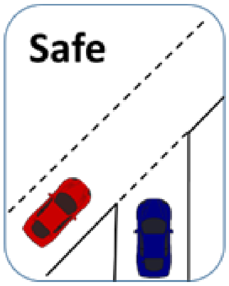
a) Yes b) No

5. If yes from the question #5, in what condition did you primarily feel safe?

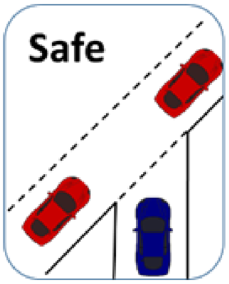
a)



b)



c)



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