



**CONNECTED
VEHICLE/INFRASTRUCTURE
UNIVERSITY TRANSPORTATION
CENTER (CVI-UTC)**

**Connected Vehicle Enabled Freeway Merge
Management - Field Test**

Connected Vehicle Enabled Freeway Merge Management – Field Test

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Connected Vehicles/Infrastructure UTC

The mission statement of the Connected Vehicle/Infrastructure University Transportation Center (CVI-UTC) is to conduct research that will advance surface transportation through the application of innovative research and using connected-vehicle and infrastructure technologies to improve safety, state of good repair, economic competitiveness, livable communities, and environmental sustainability.

The goals of the Connected Vehicle/Infrastructure University Transportation Center (CVI-UTC) are:

- Increased understanding and awareness of transportation issues
- Improved body of knowledge
- Improved processes, techniques and skills in addressing transportation issues
- Enlarged pool of trained transportation professionals
- Greater adoption of new technology

Abstract

Freeway congestion is a major problem of the transportation system, resulting in major economic loss in terms of traffic delays and fuel costs. With connected vehicle (CV) technologies, more proactive traffic management strategies are possible. The Freeway Merge Assistance System (FMAS) can implement innovative ramp management strategies by providing personalized advisories to individual drivers to ensure smoother merging. The benefits anticipated from these strategies will completely depend on the advisory compliance of the drivers; this, in turn, will be influenced by situational as well as individual behavioral factors.

The purpose of this research was to investigate drivers' responses to this new generation of personalized in-vehicle advisory messages. A field test was conducted with naïve human subjects to collect driver behavior data about different types of advisory messages under different traffic scenarios in a controlled environment. The data gathered from the field test indicated that the compliance rate was higher when a large- or medium-size gap was available for a lane change. The lowest compliance rate was observed for a small-gap scenario. In addition, it was discovered that more drivers would follow a direct advisory message that advised a lane change rather than an indirect message which was meant to stimulate a lane change through speed control.

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Table of Contents

Background.....	1
Freeway Merge Assistance System	2
Methodology.....	4
Facility.....	4
Instrumentation.....	4
Roadside Equipment (RSE).....	4
Smart Road Vehicle Fleet with Onboard Equipment (OBE)	4
Applications	4
Application for OBE.....	6
Application for RSE	6
Application Server.....	7
Central Database Application.....	7
Applications for Freeway Merge Assistance Algorithms.....	7
Test Control Application	7
Field Testing Environment	8
Simplified System Architecture for Testing.....	8
Design of Field Test	9
Sampling of Test Participants	10
Field Experiment.....	11
Lane Configuration.....	11
Smart Road Segmentation	11
Scenario Description	12
Variable Speed Limit (VSL).....	13
Lane Changing Advisory (LCA).....	13
Merging Control Advisory (MCA).....	13
Definition of Compliance.....	15
Lane Changing Advisory.....	15
Merging Control Advisory	15
Variable Speed Limit.....	16

Participant Questionnaire Survey.....	16
Definition of Response Time.....	16
Results.....	17
Advisory Compliance Behavior.....	17
Variable Speed Limit.....	17
Lane Changing Advisory.....	17
Merging Control Advisory.....	18
Compliance Across Gap Sizes.....	18
Compliance Across Strategies.....	19
Compliance for Different Gender Groups.....	20
Compliance for Different Age Groups.....	22
Discussion of Compliance Behavior.....	23
Advisory Response Time.....	25
Variable Speed Limit.....	25
Lane Changing Advisory.....	25
Merging Control Advisory.....	26
Response Time Across Strategies.....	27
Response Time Across Gap Sizes.....	28
Response Time for Different Genders.....	29
Response Time for Different Age Groups.....	30
Discussion on Advisory Response Time.....	32
Participant Stated Preferences Survey.....	33
Compliance under Different Traffic Conditions.....	33
Network Unfamiliarity.....	34
Higher-Speed Lane.....	34
Sense of Conflict.....	34
Presence of a Front Vehicle.....	34
Presence of a Merging Vehicle.....	35
Discussion of Participant Stated Preferences Survey.....	35
Conclusions and Recommendations.....	37
References.....	37

List of Figures

Figure 1. Merge management system architecture.	6
Figure 2. Simplified system architecture.	9
Figure 3. Smart Road lane configuration.	12
Figure 4. Activity-based test track segmentation.	12
Figure 5. VSL scenario description.	14
Figure 6. LCA scenario description.	14
Figure 7. MCA scenario description.	14
Figure 8. Compliance under VSL, LCA, and MCA.	18
Figure 9. Compliance across gap sizes.	20
Figure 10. Compliance across strategies.	20
Figure 11. Compliance for different genders across strategies.	21
Figure 12. Compliance for different genders across gap sizes.	21
Figure 13. Compliance aggregated across age groups.	23
Figure 14. Compliance for different genders aggregated across age groups.	23
Figure 15. Response time of VSL.	25
Figure 16. Response time of LCA.	26
Figure 17. Response time of MCA.	27
Figure 18. Response time across strategies.	28
Figure 19. Response time across gap sizes.	29
Figure 20. Response times within strategies for different genders.	29
Figure 21. Response times within gap sizes for different genders.	30
Figure 22. Response time for different genders aggregated across age groups.	31
Figure 23. Response time for different genders aggregated across age groups.	32
Figure 24. Participant stated preferences questionnaire.	35

List of Tables

Table 1. Time and Space Headway for Different Gap Size.	10
Table 2. Scenario Overview.	10

Background

Freeway traffic congestion is a significant problem within the transportation system. Congestion is not only a major factor of economic loss in terms of delays and fuel costs, it also adversely impacts the environment. Growth in passenger travel and freight movement already poses significant challenges to the current transportation system, and these numbers are projected to grow substantially, further aggravating the traffic congestion problem. According to the Urban Mobility Report 2012 [1], the total cost in 2011 of congestion was \$121 billion, which is 20% more than that reported for the year 2010 [2].

Merging conflicts [3] contribute heavily to freeway congestion by creating bottlenecks within freeway ramp areas [4]. Since a significant portion of the total annual highway travel depends on the freeway system (32% of total annual vehicle miles) [5], various strategies (e.g., ramp metering, variable speed limit, etc.) have been implemented to improve freeway merging operations. However, each of these strategies has disadvantages [6] as well as limited capability to reduce freeway merge conflicts. This is due to the real-time data collection and dissemination limitations of the current traffic surveillance system [7].

The Connected Vehicle (CV) initiative addresses these limitations by establishing wireless communication between vehicles and also between vehicles and the infrastructure. Vehicles will be able to transmit individual vehicular data (e.g., speed, location, acceleration, vehicle type, vehicle length, vehicle ID, etc.) to nearby vehicles and infrastructure. The Society of Automotive Engineers (SAE) J2735 standard provides the definitions of data types and communications used by CV technology [8]. The Federal Communications Commission (FCC) has allocated 75 MHz of spectrum at 5.9 GHz for Dedicated Short-Range Communications (DSRC) to support the communication needs of CV applications.

Another enormous advantage of CV technology is the ability to send customized messages and advisories to targeted vehicles. With these new capabilities, more proactive and advanced strategies can be developed and deployed to address various transportation problems.

With the new capabilities offered by this technology, it should be possible to develop new approaches to address freeway merge conflicts. Under a previous project, the University of Virginia Center for Transportation Studies (UVA CTS) has developed the CV-enabled Freeway Merge Assistance System (FMAS) to promote smoother merging operations by minimizing conflicts between the mainline vehicles and the on-ramp vehicles.

Four algorithms were developed for this system: variable speed limit, lane changing advisory, gap-responsive metering, and merging control advisory. The overall purpose of FMAS is (1) to identify existing gaps in the freeway mainline lane, and (2) to create gaps in the merging lane for the on-ramp vehicles. Initial results showed that these algorithms can significantly improve the overall network performance. In addition, a simulation evaluation in an integrated CV test bed indicated

that the performance of the underlying communication network greatly impacts the performance of the individual algorithms. These four algorithms can provide personalized advisories to both freeway mainline drivers and to merging vehicle drivers. Based on the advisory given, drivers take the necessary course of action: create a gap, change lanes, or control the speed of the vehicle.

The benefits anticipated from the merge management system (reducing merging conflicts and bottlenecks in merge areas) depend entirely on the compliance of drivers. It was assumed during the development and evaluation phase that all drivers would comply with all relayed personalized advisories. However, in real-world scenarios 100% driver compliance may not be possible.

Therefore, the two major objectives of the current study were (1) to design a field test to investigate driver compliance behavior in a CV test bed, and (2) to understand how the drivers react to the advisories based on different traffic conditions. This helped us investigate further how actual driver compliance affects the benefits anticipated from the merge management system in a CV environment.

Various prior research studies have investigated how information at broader levels impacts travel behavior and thus network performance. However, there is a gap in the current knowledge about how individual drivers will react to advisories specifically targeting them. Variability in driver compliance can significantly affect the outcomes of these mobility applications. The earlier work on the freeway merge management system did not consider any components of driver behavioral factors or situational factors that would influence individual compliance.

Compliance can be attributed to individual driver characteristics in dynamic traffic conditions. To understand how driver behavior might be affected by personalized advisories, this research investigated how drivers respond to advisories provided under the FMAS. Field tests involving naïve test subjects are one of the preferred ways to collect driver behavioral data, since field testing provides a more accurate representation of the real-road driving environment for the test participants. Field tests also provide more reliable data than other techniques like driving simulators [9]. Driver compliance data were collected by conducting a simplified field test of the FMAS on a real-world CV test bed. Multiple traffic scenarios were created and run manually to test subjects' responses under the different algorithms.

Freeway Merge Assistance System

This section presents a brief overview of the full FMAS as developed previously by the UVA CTS. With the goal of improving the efficiency and safety of freeway merges, this system takes advantage of CV technology to address the limitations of current merge management practices. Three components are fundamental to the objectives of the system: dynamic lane control, gap-responsive metering, and merge control.

- **Dynamic Lane Control.** The purpose of dynamic lane control is to identify available capacity in lanes and encourage drivers traveling in the mainline lane (adjacent to the

merging lane) to change lanes to the left, thus creating larger and more frequent gaps in the merging area. The dynamic lane control logic is implemented by two algorithms, lane-level variable speed limit and lane changing advisory.

- *Lane-level Variable Speed Limit.* Based on the mainline traffic density, this algorithm dynamically determines and implements a lower speed limit for the right-most lane to encourage drivers to move to the left lane for better driving conditions, thus creating gaps in the right lane for merging vehicles [10].
- *Lane Changing Advisory.* This algorithm dynamically selects vehicles traveling in the right lane and sends them a lane changing advisory for early lane change, thus creating bigger gaps for merging vehicles and reducing conflicts in the ramp merging area [11].
- **Gap-responsive Metering.** This algorithm utilizes CV-enabled, high-resolution vehicle trajectory data to identify gaps in the mainline lane and implements a dynamic gap-based ramp-metering strategy for on-ramp merging traffic. This algorithm was evaluated under another project [12].
- **Merge Control.** This algorithm utilizes vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication to control longitudinal movements or advise and recommend speed changes for both mainline and ramp vehicles. Such communication should ensure smooth merging in the smallest gap sizes and reduce merging conflicts, thus increasing capacity by reducing minimum headways [13].

The FMAS was evaluated under an integrated CV simulation environment developed by Park et al. (2011) [14]. The integrated framework provided a realistic simulation of a CV environment by coupling a microscopic traffic simulator and a wireless communication simulator and following a communication protocol based on WAVE/DSRC standards and simulating SAE J2735 message sets.

The anticipated benefits of FMAS seen in simulation depend on drivers taking actions based on the advisory messages. Thus, there is a need to investigate drivers' responses to these advisories and the consequent impact to the transportation system. The goals of this research were to conduct a comprehensive evaluation of the FMAS and to understand how drivers' responses to the relayed advisories impact the performance of the different algorithms in improving mobility. Understanding driver behavior toward personalized advisories will allow transportation system managers to utilize this information as a traffic management tool and to adopt strategies and policies for effective implementation of CV applications.

Methodology

Facility

The field-test phase of this study was conducted on the Virginia Smart Road, a CV test bed facility located in Blacksburg, Virginia. The Smart Road is a two-lane, closed test track instrumented with DSRC-based roadside equipment (RSE) along its 2-mile length. In addition, a small fleet of vehicles equipped with DSRC-based onboard equipment is available. Though the Smart Road provides a CV-enabled, controlled environment for testing and conducting research, its length and the limited number of equipped vehicles do not allow a full-fledged replication of real-world traffic scenarios. Within these limitations, the research team developed plans for a simplified test of the FMAS, including scenario development, test procedure steps, and test personnel protocol. The research team also created a detailed description of the required system architecture as it would be widely implemented in practice.

Instrumentation

Roadside Equipment (RSE)

The test bed is equipped with RSEs to provide the necessary infrastructure-to-vehicle (I2V) and V2I communications. The range of these RSEs varies from 1,200 to 1,400 feet, which may lessen if line of sight is obstructed.

Smart Road Vehicle Fleet with Onboard Equipment (OBE)

The field testing utilized three CVI-instrumented vehicles. The fleet consisted mainly of recent year models from GM and Nissan. These vehicles were equipped with onboard equipment (OBE) for DSRC communications as well as an in-vehicle information device that can deliver both visual and auditory messages to drivers. In addition, these vehicles were instrumented with a data acquisition system (DAS) which stores all the necessary data (basic safety messages [BSMs], video, etc.). This data can be easily retrieved later after the testing for post-hoc analyses.

Applications

The basic system architecture consists of the following four components:

- 1) One application for OBEs;
- 2) One application for RSEs;
- 3) One application for the application server; and
- 4) One application for the central database.

Additional applications for the testing included:

- Three merge applications, one for each of three freeway merge assistance algorithms, to be installed on a remote application server;
- One test control application required for the field testing on a portable laptop.

Figure 1 illustrates the system architecture of the proposed merge management system and the procedure the system follows for each test run.

1. The test control application is started by the test administrator. The test administrator then selects one of three freeway merge applications to run and a related scenario to be tested. This selection, which serves as the start signal of a testing run, is sent to the application server, the RSE, and the OBEs, sequentially. All the applications start running once the start signal is received.
2. The OBE application starts (or continues) broadcasting BSMs.
3. The RSE application receives BSMs from the OBEs and then sends these BSMs to the application server.
4. The application server receives BSMs from the RSEs and runs a selected freeway merge application to generate an advisory message in an a-la-carte message (ACM) format. *Note that, during the testing, the freeway merge applications were run in manual mode, in which an ACM was generated only when the test administrator initiated a signal for this based on the selected scenario.* Finally, the generated ACM is sent back to the RSE.
5. The RSE application receives an ACM from the application server and sends the received ACM to the OBEs in appropriate target vehicles.
6. Upon receiving the ACM from the RSE, the OBE application displays the selected message to the driver through the in-vehicle telematics.
7. The test administrator manually records the reaction of the participant driver.
8. The test administrator sends an end signal to the application server. The end signal is then relayed to the RSE application and the OBE application. Once this end signal is received, all applications stop.
9. During each test run, the centralized database application records all the BSMs, ACMs, etc., so that these records can be retrieved easily for post-test processing.

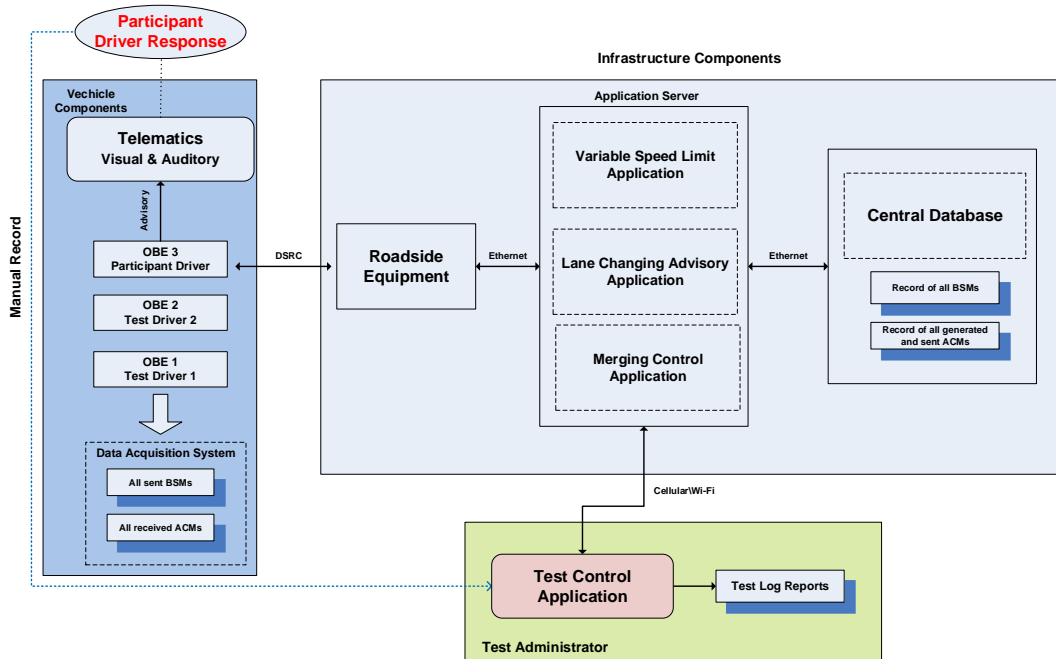


Figure 1. Merge management system architecture.

Brief descriptions of the applications are provided below. Note that detailed descriptions of all these applications with pseudo-codes were prepared and sent to the Virginia Tech Transportation Institute (VTTI) team for development.

Application for OBE

The OBE application performs three major functions in each of the instrumented vehicles:

- Broadcasting BSMs to the RSEs (and nearby OBEs): Vehicles broadcast BSMs to nearby vehicles and RSEs. The BSM includes positional data, speed, heading, acceleration/deceleration, etc. for each individual vehicle.
- Displaying advisory messages: Another important functionality of the OBE application is to display the received advisory messages for each specific scenario. The messages are displayed via the in-vehicle device in both visual and auditory formats.
- Storing data: A database of all the sent BSMs and received ACMs is maintained by the DAS installed in each vehicle.

Application for RSE

The RSE application mainly has the role of establishing communication between the OBE and the remote application server. This application sends all the BSMs received from OBEs to the application server, and also sends the ACMs received from the remote application server back to each individual OBE. DSRC communications are utilized as the communication method between

OBEs and RSEs, and the remote application server and RSEs are connected through an Ethernet network.

Application Server

The application server is responsible for hosting and running all the algorithms. Once vehicular data is received from the RSEs (via the OBEs), the algorithms in the application server is executed and final decisions are made. These decision results are then sent back to the RSEs.

Central Database Application

The central database connected with the application server keeps records of all the BSMs sent from the OBEs through a database application. All BSMs have timestamp information so that researchers can retrieve this data from the database for post-test data processing. In addition, any ACMs generated as a result of application execution are stored in the central database as well.

Applications for Freeway Merge Assistance Algorithms

Three separate applications were developed for the three algorithms that were tested in this project: Variable Speed Limit, Lane Changing Advisory, and Merging Control Advisory. The applications are required to meet the necessary requirements and follow the fundamental logic of the algorithms. After development, these applications are fully implementable as a real-world merge management tool in a CV environment.

Each of the above applications has two operating modes, Automatic Mode and Manual Mode:

- **Automatic Mode:** In this mode, the application performs the necessary operations following the algorithm logic without any manual interference. For example, the decision-making process of sending an advisory to vehicles is based on the criteria provided in the algorithm. If deployed in a real-world scenario, this operating mode will be utilized to apply the built-in strategies in the logic of the algorithm.
- **Manual Mode:** The purpose of manual mode is only for the system development phase and field testing of this project. In the manual mode, the test administrator (UVA #3) has the authority and flexibility to override all the built-in criteria to send an advisory or implement a control strategy using the test control application. The test administrator can send advisories at any time in the course of a run.

In the proposed system architecture, the freeway merge applications were hosted on a remote application server that is connected with the RSE via an existing communication backbone.

Test Control Application

The field testing was conducted using the manual mode of the algorithms. This necessitated a test control application that could be used to “manually” select and send an appropriate advisory message, depending on the scenario being tested. The test control application was installed in a portable device (laptop) so that the test administrator could carry it to the test site. In addition, this test control application had additional capabilities:

- 1) Through the test control application, the test administrator could send signals or instructions necessary to administer a test to all vehicles. Examples include a signal to start the test run, an instruction to achieve target speed, and so on.
- 2) The test administrator could manually select and send different advisory messages (specific for each scenario) to the participant vehicle through communication with the application server. A cellular or wireless network was used to establish the interconnection between the test control application in a mobile device and the freeway merge applications on the remote application server. Only cellular/wireless communication could provide the flexibility of portability for the test control application at the testing site and continuous communication between control application and remote server applications.
- 3) After each advisory was sent, the test administrator was able to manually input the participant's response into the test control application so it could be included in the log report. The final log report was generated by the application.

Field Testing Environment

Simplified System Architecture for Testing

Since it was not possible to have a fully operational system that supports the proposed Merge Management System within the current time frame, we decided to use a simplified system architecture to conduct the field test and collect research data without further delay. Figure 2 represents the simplified system architecture, in which the test control application is directly connected to an OBE in the participant vehicle through Ethernet. In this simplified architecture, RSEs, the application server with three merge management applications, and the central database system were not included. Rather, testing was conducted using only a test control application and the OBEs of the test vehicles.

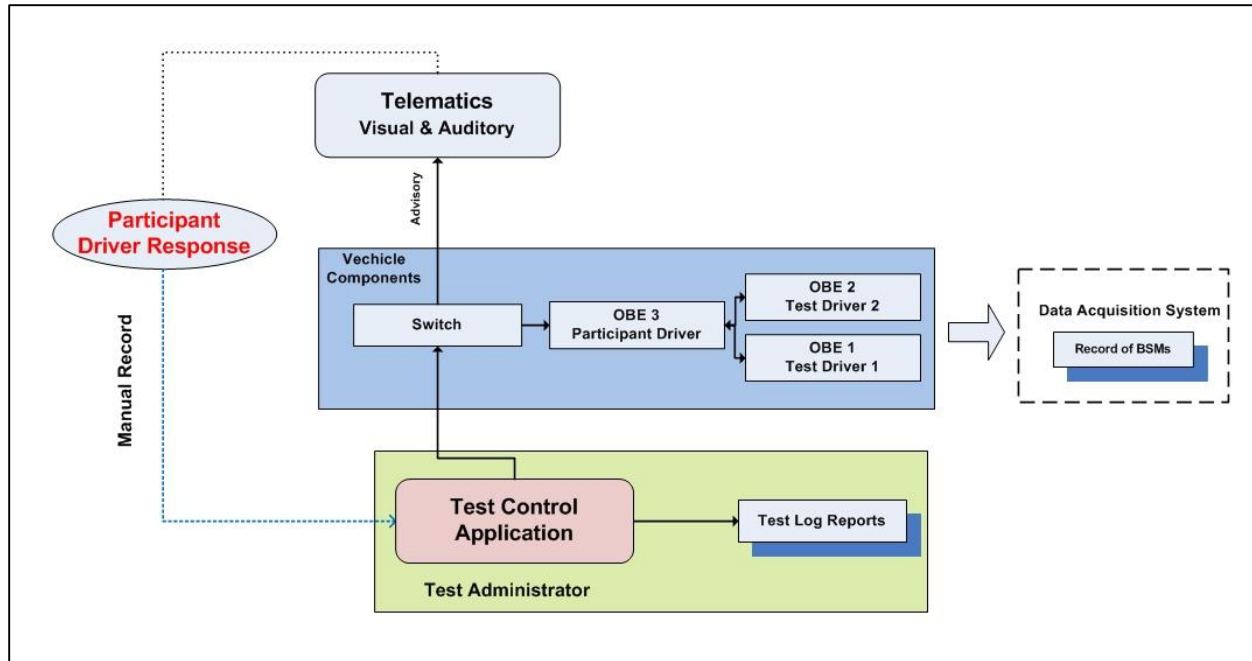


Figure 2. Simplified system architecture.

These are the sequential steps followed by the proposed simplified system architecture:

1. The test control application is started by the test administrator, who is riding in the participant vehicle. The test administrator selects one of the three applications and the specific scenario to be tested.
2. The OBE application sends BSMs to other OBEs. The DASs in the vehicles record all BSMs sent and received.
3. When the test administrator sends an advisory specific to the selected scenario, the in-vehicle display presents that advisory in both visual and auditory formats.
4. In the testing control application, the test administrator records the response of the test participant to the displayed advisory.
5. After recording the response, the test administrator sends the end signal through the test control application to the OBEs. The OBEs stop sending BSMs, and the test control application generates a test log report for each test run.

Design of Field Test

There is a gap in the current knowledge about how drivers respond behaviorally to different control strategy advisories within a CV-enabled environment. We could not find any study that focused specifically on this issue. Therefore, it was necessary to conduct a field test that addressed this question. The field test was conducted at the Virginia Smart Road facility located in Blacksburg, Virginia. The Smart Road provides a two-lane, closed test track instrumented with DSRC-based RSE units and a small fleet of vehicles equipped with DSRC-based OBEs. Limited resources did not allow a full-fledged experiment replicating real-world traffic scenarios. Therefore, a simplified

architecture was developed to conduct the field test, which involved OBEs, an in-vehicle display, and a test application. The test application was developed to allow the experimenter to randomly select test scenarios and send advisories to the participant vehicle.

For all the algorithms under the merge management system, gap size is the main factor in the lane change decision-making process. An extensive literature review indicated that the lane change and merging operation depends on the available gap size, along with other variables such as the relative speed of the lead and lag vehicles, and the remaining distance of the merge area. Since it was not feasible to consider all of these factors for scenario development due to complexity and limited resources, only gap size was considered for scenario development. The algorithms that were evaluated in the field test were (a) Variable Speed Limit (b) Lane Changing Advisory, and (c) Merging Control Advisory.

For the scenario development, the mean time-headways for high, medium, and low traffic conditions found by Ye and Zhang [15] were adopted to define the small, medium, and large gap sizes, respectively, and were converted to space-headways. For vehicles traveling at 30 mph, the different proposed gap sizes (in terms of time-headway and space-headway) are shown in Table 1. Based on the three levels of gap size and three application types, a set of nine testing scenarios was developed as shown in Table 2.

Table 1. Time and Space Headway for Different Gap Size

Gap Type	Time-Headway (s)	Space-Headway (ft.)
Small Gap	2.00	88
Medium Gap	3.00	132
Large Gap	4.00	176

Table 2. Scenario Overview

Gap Sizes	Advisory Types		
	Variable Speed Limit	Lane Changing Advisory	Merging Control Advisory
Large Gap (176 ft.)	Scenario #1	Scenario #4	Scenario #7
Medium Gap (132 ft.)	Scenario #2	Scenario #5	Scenario #8
Small Gap (88 ft.)	Scenario #3	Scenario #6	Scenario #9

Sampling of Test Participants

The sample population was selected to represent the overall demographics of the licensed U.S. driver population. This was done so that, with a reasonable level of confidence, the response nature of the entire driver population could be determined. Because we did not have any direct control in variance estimation and there was no prior information about drivers' responses to these new type

of advisories, we made a conservative assumption of 50% for the compliance proportion, as suggested by Krejcie and Morgan [16]. The sample size was estimated to be 68 with a confidence interval of 90% and margin of error of 10% [17].

Participants were recruited through advertisements on classified advertisement websites like Craigslist and local newspapers from Blacksburg and the surrounding areas in Virginia. The final sample population consisted of participants from all age groups, with 36 male and 32 female participants. Eligible participants were scheduled for the field test at a specific time on the Smart Road facility. Upon arriving at the facility, the participants went through the necessary paperwork and training before the field test. In the training phase, each participant was oriented to the test vehicle and the onboard display, and detailed instructions were given about their responsibilities and the expected or proper actions to take for each advisory in the field test.

Field Experiment

Lane Configuration

The current geometric configuration of the Smart Road does not allow replicating a freeway merge area with an on-ramp section and merging lane. As a result, the existing lane configuration was modified to conduct the field test with merge assistance strategies. Left-lane vehicles were driven by confederate drivers. Participants drove the right-lane vehicle with the experimenter in the front passenger seat. Before the beginning of each scenario, the three test vehicles were positioned at designated, numbered location markers (Figure 3). For all scenarios, the left-lane lead vehicle was placed at location marker #1. The lag vehicle in the left lane was placed at three different positions, depending on the scenario to be tested. For large-, medium-, and small-gap scenarios, the lag vehicle was placed at location marker #4, #3, and #2, respectively. In the right lane, the participant vehicle was placed at location markers #5, #6, and #7 for small-, medium-, and large-gap size scenarios, respectively.

Smart Road Segmentation

Based on the lane configuration of the Smart Road, one lane served as the right lane and another lane as the left lane of a freeway segment. In addition, it was identified that there would be four specific activities during a scenario run. Based on the general sequence of driving activities, Figure 4 illustrates the activity-based test track segmentation of the 2,000-foot section:

1. Reaching target speed – Speed Gain Zone (Activity-1)
2. Driving at uniform speed – Uniform Speed Zone (Activity-2)
3. Sending/receiving/reacting to advisory – Control Interval Zone (Activity-3)
4. Reducing speed – Speed Reduction Zone (Activity-4)

The speed gain zone provided the necessary length to attain the test speed of 30 mph with moderate acceleration from the starting position. The Uniform Speed Zone allowed vehicles to travel at uniform speed and get confirmation about their location. The Control Interval Zone was used to

send the advisory and record the participant's response within this zone. The Speed Reduction Zone was used for vehicles to safely reduce speed and prepare to stop.

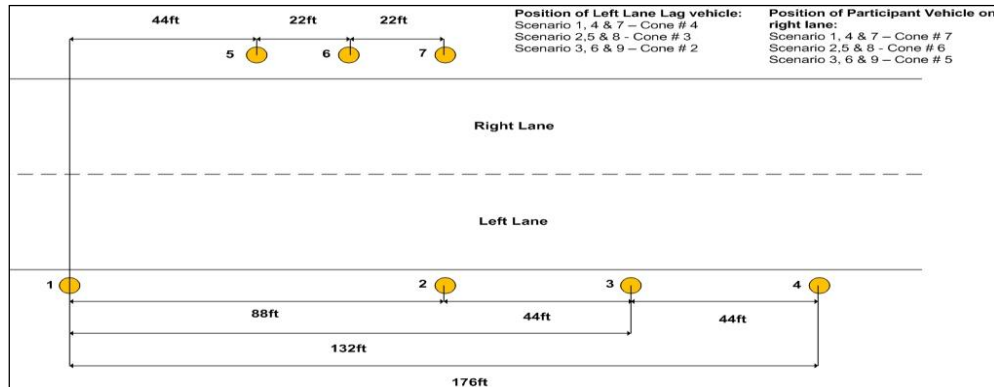


Figure 3. Smart Road lane configuration.

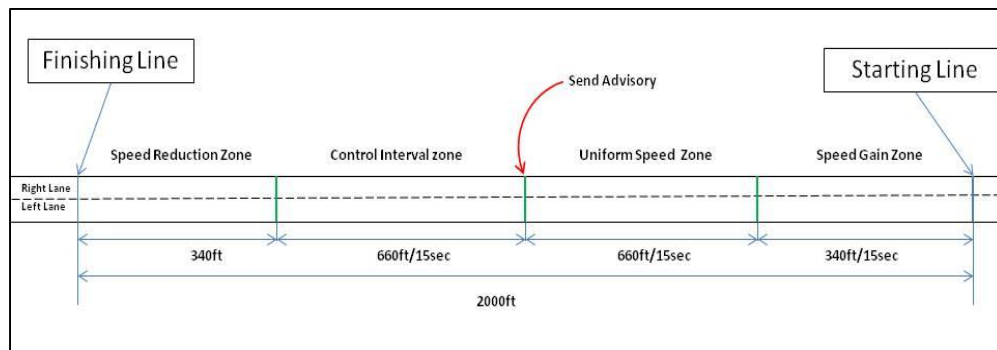


Figure 4. Activity-based test track segmentation.

Scenario Description

To conduct the field test, a detailed field test procedure, test protocols, and a test script were developed by the research team. The order of the scenarios was randomized to eliminate any bias in the data gathered and to minimize the learning effects of the participants. Each of the participants took part in all nine test scenarios.

The typical procedure for each scenario was as follows:

1. Before the beginning of a particular test scenario, the three research vehicles were positioned at the designated locations for that specific scenario.
2. The experimenter in the participant vehicle sent instructions over the radio to all drivers to start driving at the same time and reach the speed of 30 mph.
3. The participant driver was instructed to maintain the speed of 30 mph and keep driving in the right lane until any advisory was displayed by the onboard display.
4. After all the vehicles reached the advised speed, the experimenter used the test application to send an advisory to the onboard display.

5. Upon receiving the advisory, the participant either complied with the advisory or continued driving in the right lane if he or she did not feel comfortable following the advisory.
6. The participant driver's reaction to the advisory was recorded by the experimenter.
7. At the end of the designated test section, all drivers were instructed to slow down and further instruction was sent for the next scenario.

Following are brief descriptions of each field scenario.

Variable Speed Limit (VSL)

In the VSL scenarios, when all the drivers in both lanes reached the uniform speed of 30 mph, a lower speed limit advisory of 25 mph was sent by the experimenter. During the training phase, the participants were instructed to not decrease speed in response to the advisory; rather, they should try to change lanes and enter the gaps between the two vehicles in the left lane. In case the drivers did not feel comfortable moving to the left lane, they were instructed to keep driving in the right lane. Figure 5 illustrates a schematic diagram of this strategy with the VSL advisory shown in the inset on the left bottom corner.

Lane Changing Advisory (LCA)

For the LCA scenarios, the participant drivers were sent a lane change advisory after all the vehicles reached the speed of 30 mph. During the training, the participant drivers were instructed to change lanes and take the available gap in the left lane between the two vehicles, but only when they felt comfortable to do so. The gap between the two left-lane vehicles was changed from scenario to scenario. Figure 6 presents a schematic diagram for this strategy with the LCA advisory shown in the inset on the left bottom corner.

Merging Control Advisory (MCA)

In the MCA scenarios, the participants received two sequential advisories. The goal of this strategy was to help drivers merge smoothly when an adequate gap was not available by first advising speed changes and then sending a lane change advisory. For example, as shown in Figure 7, the participant vehicle (green vehicle) in the right lane at Position 1 does not have enough lag-gap to change lane. In this situation, the merging control advisory sends an acceleration advisory (inset Figure 7) to the participant driver. After the participant driver moves to Position 2 by accelerating and leaving an adequate gap to change lanes, the MCA sends a lane changing advisory. If the driver feels comfortable, he or she complies and takes the gap in the left lane between the two vehicles.

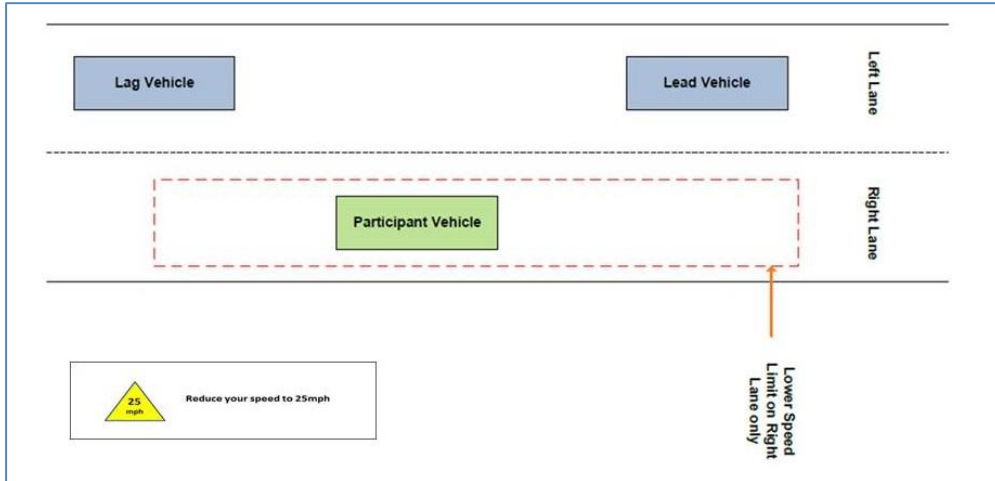


Figure 5. VSL scenario description.

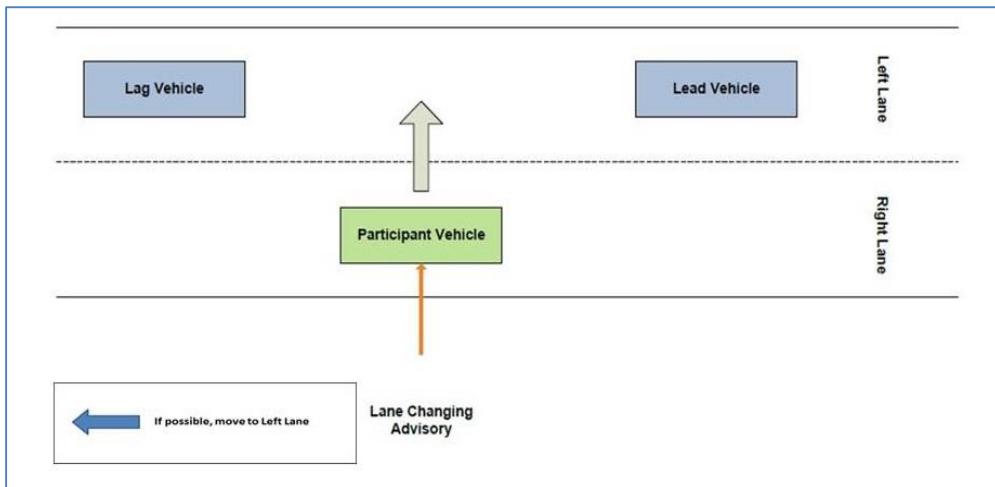


Figure 6. LCA scenario description.

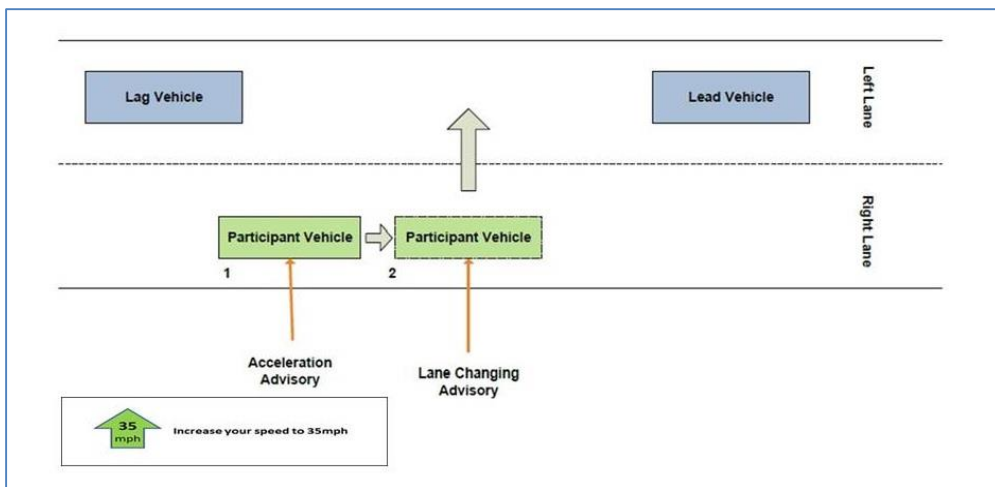


Figure 7. MCA scenario description.

Definition of Compliance

Lane Changing Advisory

Compliance for the LCA is straightforward. Positive compliance, or simply compliance, occurs when the participant takes action to change lanes and successfully completes the lane change within the control interval zone. Non-compliance occurs when the driver ignores the advisory or fails to complete the lane change within the Control Interval Zone. For example, some drivers did not feel comfortable changing lanes in the small-gap scenarios, and they continued driving in the right lane after receiving the LCA advisory. This is simply non-compliance. In some cases, after getting the advisory, the driver took initiative to change lanes but took too long and failed to change lanes within the Control Interval Zone, completing the maneuver only after entering the the Speed Reduction Zone. This is also considered non-compliance. Although drivers may have taken more time due to inadequate gap size or for some other reason, compliance was defined as completing the lane change within a certain zone because the actual freeway merging section has limited length. In the real world, if the driver is given an advisory to change lanes and fails to complete the action (or to take the gap between the two vehicles), the driver waits in the merge area for another acceptable gap. Essentially, this means the advisory has failed in terms of getting a positive compliance from the driver.

Merging Control Advisory

The MCA strategy includes two distinct sequential advisories in each test scenario. First, the driver receives an acceleration advisory with a suggested speed of 35 mph. If the driver complies, accelerates to position the vehicle in the right lane, and has an adequate gap in the left lane to change lanes, the system provides a lane changing advisory. In an ideal case, the driver first complies with the acceleration advisory, positions the vehicle to get ready to change lanes and, after getting the LCA, the driver changes lanes. This is defined as compliance to the MCA advisory and this is how the drivers were instructed to react in the training phase.

In some cases during the field test, drivers did not react to the acceleration advisory or did not accelerate to the level suggested by the advisory. But, when they were provided with the LCA advisory, they complied and changed lanes. These responses were also considered as compliance if they completed the lane changing action within the Control Interval Zone. In other cases, drivers complied with the acceleration advisory but failed to properly position the vehicle in the right lane to get ready for the LCA delivery. In this case, since there was no adequate gap to change lanes, the experimenter chose not to send the advisory because the system will recognize an inadequate gap in the left lane and it would not make sense to provide the driver with an LCA. Driver responses in these cases were recorded as non-compliant because the drivers failed to react in a timely manner. Similar to the definition used with the LCA scenario, if the drivers did not manage to change lanes within the Control Interval Zone, the response was recorded as non-compliance. This was done even though they finally managed to change lanes in the Speed Reduction Zone.

Variable Speed Limit

The definition of compliance in the VSL scenario is not as straightforward. For the LCA and MCA scenarios, the participant had to literally follow the advisory and take the advised action. However, for the Variable Speed Limit scenario, participants received a slower speed limit advisory, which made the drivers confused. The Variable Speed Limit was developed to encourage rightmost lane drivers in a freeway merge area to move to the left lane by providing a lower speed limit specific to that lane.

This strategy was evaluated in the traffic simulator VISSIM and results indicated that the lower speed limit actually caused some drivers to move to left lane, thus creating gaps for the merging vehicle. Since the desired effect of the lower speed limit for the right lane is not for the driver to actually slow down, but rather move to the comparatively faster left lane, compliance for the Variable Speed Limit strategy is defined as moving to the left lane in response to the new lower speed limit for the right lane. During the pre-test training phase, the experimenter clearly explained and demonstrated the desired response behavior to the participants. They were instructed to move to the left lane whenever they received a slower speed limit advisory. However, during the test, it was evident that some drivers did not clearly understand this definition of compliance and, rather than changing lanes, they decelerated upon receiving the VSL advisory.

Participant Questionnaire Survey

The field test collected the participating drivers' preference data. A questionnaire survey was also conducted after the field test to collect drivers' stated preference data. The stated preference approach has been widely used for transportation mode choices, route choices, and dynamic traffic information studies [18-19]. Due to limited resources, it was not possible to replicate all possible traffic scenarios on the test track. Therefore, the survey was provided to the participants to ascertain their responses to various hypothetical situations. Participants' answers indicated what influenced their compliance behavior regarding the MCA, LCA, and VSL scenarios using a four-point Likert scale ranging from 0 to 3 (0 =strongly disagree and 3 = strongly agree with the statement). The first part of the questionnaire collected socio-demographic information and the second part contained questions about hypothetical traffic conditions and situations.

Definition of Response Time

Response time is defined as the time required by a participant to complete a lane change action after an advisory was received. The response time is estimated from the difference between the timestamp when the advisory was given and the timestamp when the driver completed the action.

The response time gives an indication of how quickly the drivers perceive, and then react to, the advisory. Video data collected from the field test contain the timestamps, which were manually retrieved to estimate the response time.

Out of the 68 participants, video data are available for 67 participants. In analyzing the response times, it was decided that response times more than 16 seconds would not be included in the final

analysis. Initially, the control interval was set to 15 seconds to allow participants to react within that time period. However, in analyzing response times, a maximum of 16 seconds of response time was considered; this equals an approximately 700-foot acceleration lane. The assumed length of the merging area in developing the FMAS was 730 feet [13].

Results

Advisory Compliance Behavior

The following section discusses the results from the data gathered from nine test scenarios completed on the Smart Road. All 68 participants participated in all nine scenarios. Collected data were analyzed for each advisory type to understand how different gap sizes and strategies influenced drivers' compliance.

Variable Speed Limit

With the VSL scenarios, the compliance rate was similar for both large gaps (72%) and medium gaps (72%). The compliance rate for small gaps was lowest, as more than 55% of the time drivers opted not to follow the advisory. The difference in compliance rates between the small-gap scenarios and both the large- and medium-gap scenarios is statistically significant, $\chi^2(1, N = 68) = 9.78, p < 0.10$.

This result supports the assumption that drivers are willing to change lanes when gaps are comparatively larger but are more skeptical about changing lanes where headways between vehicles are small (Figure 8). Earlier simulation evaluation of the VSL strategy indicates that this strategy has potential to improve overall average network performance in conditions of high-volume and high-density traffic in both left and right mainline lanes. Though the compliance rate for small-gap scenarios was the lowest, a 45% compliance rate indicates that in some cases drivers will be influenced by the lower speed limit to move to the left lane, thus creating a gap for merging vehicles.

Lane Changing Advisory

For the LCA scenarios, all participants except one accepted the gaps for the scenarios; the large gap had a compliance rate of 97%. For scenarios with the medium gap, the compliance rate was more than 90%; only 6 participants out of 68 did not comply with the LCA advisory (Figure 8). About 36% (25 drivers) did not feel comfortable complying with the LCA in the scenarios with the small gap, which is different with statistical significance, $\chi^2(1, N = 68) = 13.53, p < 0.10$, from the compliance rate of medium-gap scenarios.

The gap acceptance behavior for LCA scenarios was similar to that observed for VSL scenarios, and supports the notion that drivers prefer large and medium gap sizes. The simulation evaluation indicated that the LCA strategy provided the biggest network-wide benefits for the large gap, followed by the medium gap; the small gap strategy resulted in marginal benefits. In addition, sensitivity analysis of the compliance rate in simulation indicated that at least a 90% compliance

rate would be necessary to achieve significant benefits from this strategy. Higher compliance rates for large- and medium-gap scenarios in the field test support the simulation result that the LCA strategy will provide the biggest benefits in low and medium traffic conditions.

Merging Control Advisory

For the MCA scenarios, compliance results indicated that participants were most comfortable in following the advisories for both large-gap and medium-gap scenarios; the non-compliance rate was about 5% in both cases. However, more than 35% of the participant drivers did not comply under small-gap scenarios (Figure 8), which differs significantly from the response behavior under the large-gap scenario, $\chi^2(1, N = 68) = 16.23, p < 0.10$, and the medium-gap scenario, $\chi^2(1, N = 68) = 18.48, p < 0.10$.

Though the MCA strategy is a combination of two advisories, drivers did not show a greater level of difficulty in complying with it. Simulation evaluation of the MCA strategy showed that significant benefits, in terms of network performance, can be achieved both in mainline lanes and merging lanes with a high compliance rate of 70% or above. Compliance results from the field test indicated that the biggest benefits from the MCA strategy may be achieved under low and medium traffic conditions rather than under heavy traffic conditions. However, a 65% compliance rate under small-gap scenarios in the field test indicated that, even in highly congested situations, drivers were willing to follow proactive speed change advisories to create gaps, and then to follow a lane changing advisory when adequate gaps were available.

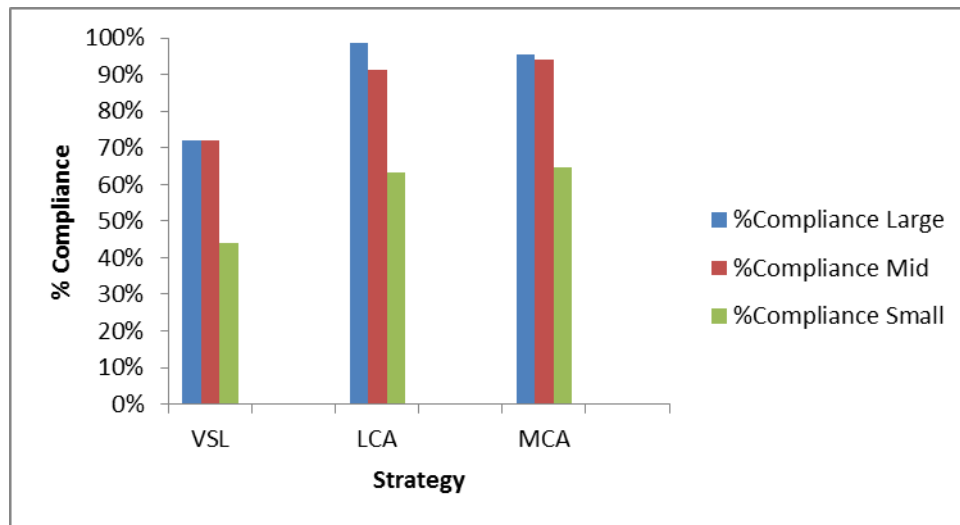


Figure 8. Compliance under VSL, LCA, and MCA.

Compliance Across Gap Sizes

Compliance rates across the scenarios for the three different gaps sizes are similar for both large- and medium-gap scenarios (Figure 9). For large-gap scenarios, the compliance rate was highest (88%), followed by the compliance rate for medium-size scenarios (85%). There are no significant differences between the compliance rates for large-gap and medium-gap scenarios, $\chi^2(1, N = 204)$

= 0.551, $p > 0.10$. On the other hand, about 42% of the drivers did not comply with the advisory during the small-gap scenarios. This differs significantly from the compliance rates of the large gap-scenarios, $\chi^2(1, N = 204) = 49.4, p < 0.10$, and medium-gap scenarios, $\chi^2(1, N = 204) = 39.13, p < 0.10$.

The difference suggests that drivers will be most comfortable following the advisories in both low and medium traffic congestion. As traffic conditions worsen, drivers will rely more on individual perception, judgment, and decision-making processes rather than depending upon driver assistive systems. However, compliance rates under the small-gap scenario also suggest that some drivers will trust FMAS and will comply with the advisories by taking the advised course of action. This indicates that this system has the potential to improve merging operations even in high-volume traffic conditions where the gaps are small and the possibility of vehicular conflict is very high.

Compliance Across Strategies

Across the strategies, and without respect to gap sizes, both LCA (84.3%) and MCA (84.8%) showed almost identical compliance rates, with no significant difference. VSL had the highest non-compliance rate of 37%, which was significantly different from the non-compliance rate for LCA, $\chi^2(1, N = 204) = 23.28, p < 0.10$, and MCA, $\chi^2(1, N = 204) = 24.52, p < 0.10$.

The higher non-compliance rate for the VSL strategy can be attributed to drivers' misunderstanding of the objective of this advisory. The goal of this advisory was to implement a lower speed limit for the right lane to encourage drivers to make earlier discretionary lane changes (i.e., to move to the left lane with higher speed limit). However, some participants interpreted the advisory simply as a reduced speed limit advisory, even though they were given specific instructions in the pre-field test training about what would be the expected choice for this advisory (Figure 10).

This suggests that it is necessary to investigate at a deeper level how drivers understand and then react to a particular type of advisory. Further investigation needs to discover how advisories can be linguistically designed and delivered so that the desired outcomes can be achieved. This also indicates the necessity for driver education and training about advancements in transportation technologies.

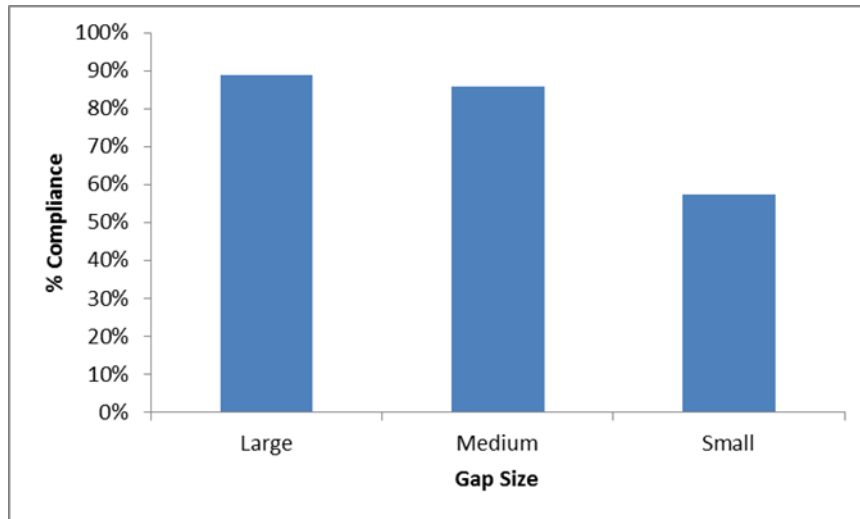


Figure 9. Compliance across gap sizes.

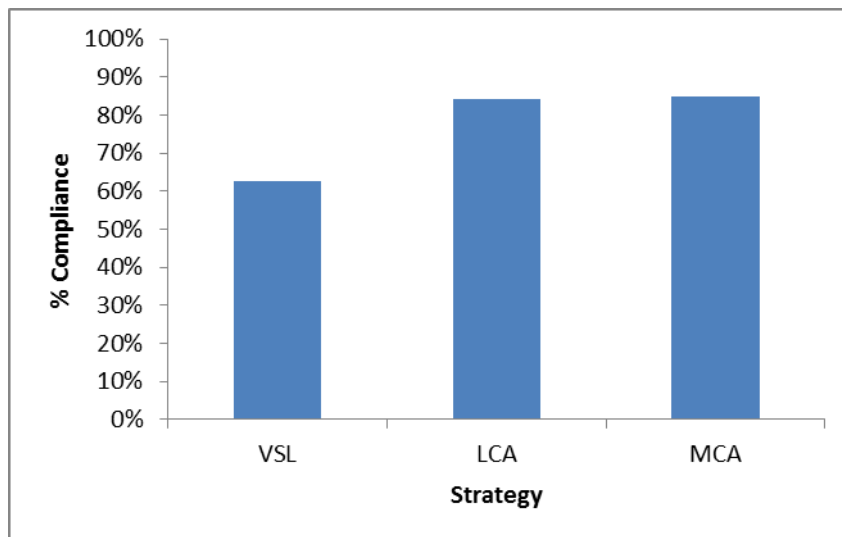


Figure 10. Compliance across strategies.

Compliance for Different Gender Groups

Compliance across strategies. Similar compliance rates were observed across gender for both the LCA and MCA strategies, with no significant difference between female and male participants (Figure 11). For LCA scenarios, female participants had a compliance rate of 85% and male participants had a compliance rate of about 83%, with no significant difference in compliance, $\chi^2(1, N = 108,96) = 0.0465, p > 0.10$. For MCA scenarios, there was no significant difference in compliance rate, $\chi^2(1, N = 108,96) = 0.0012, p > 0.10$. Male participants complied 84% of the time and female participants complied 85% of the time. However, for the VSL strategies female participants showed a higher compliance rate of 70% compared to a 55% compliance rate from male participants, with significant difference, $\chi^2(1, N = 96,108) = 3.4036, p < 0.10$.

Compliance across gap sizes. Compliance across the three gap sizes (by gender) demonstrates similar compliance rates for large gaps by both female and male participants; the compliance rates

of about 89% and 87%, respectively, showed no significant difference, $\chi^2(1, N = 96,108) = 0.0206$, $p > 0.10$. For medium-gap scenarios, there were significant differences in compliance rates, $\chi^2(1, N = 96,108) = 2.7749$, $p < 0.10$, with female participants exhibiting a higher compliance rate of 90%, followed by a male compliance rate of 81% (Figure 12). Compared to large- and medium-gap scenarios, small-gap scenarios had a lower compliance rate, with 61% compliance for female participants followed by 53% compliance for male participants; however, this difference not significant, $\chi^2(1, N = 96,108) = .9526$, $p > 0.10$. It is obvious from the data that for all three gap sizes female participants had the lowest non-compliance rate. If compliance rate is aggregately considered irrespective of gap size, the difference in compliance rate between female (80.5%) and male (74.3%) participants is statistically significant, $\chi^2(1, N = 288,324) = 2.9673$, $p < 0.10$.

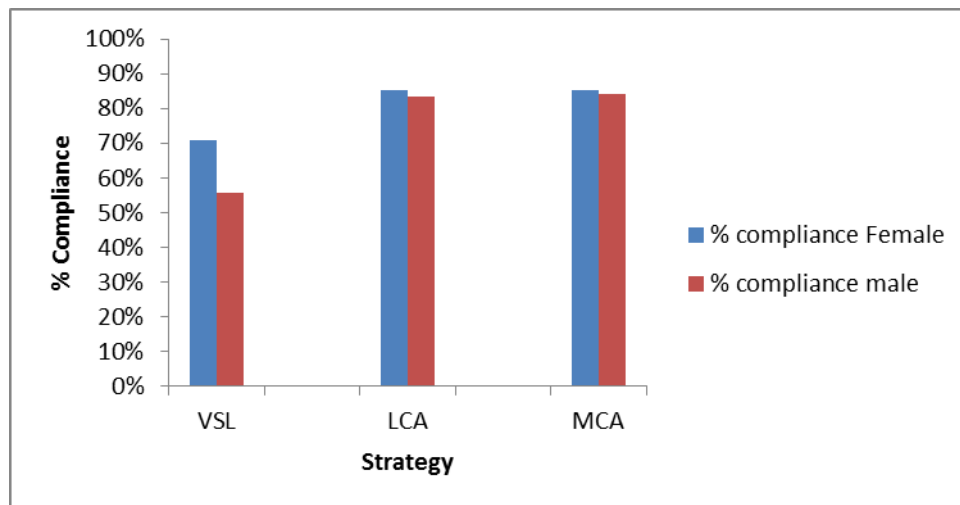


Figure 11. Compliance for different genders across strategies.

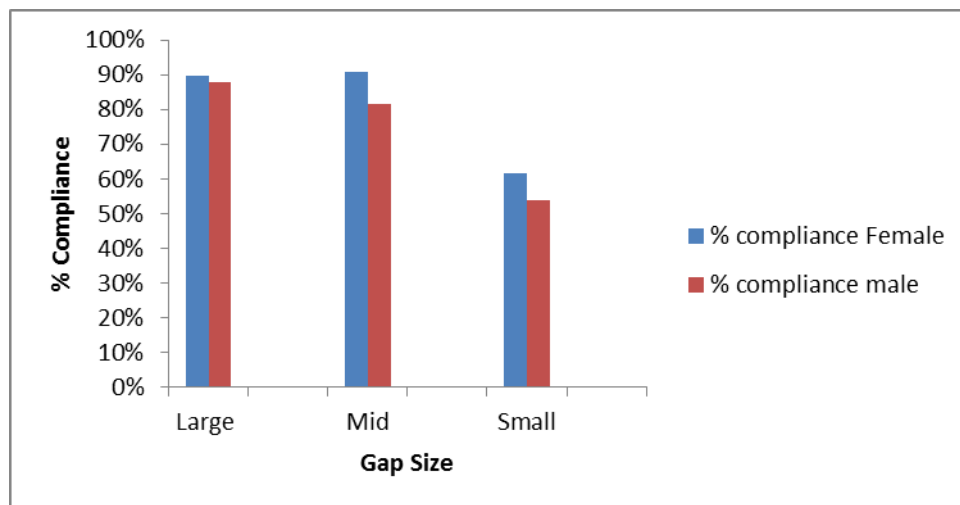


Figure 12. Compliance for different genders across gap sizes.

Compliance for Different Age Groups

Participants in the field test were recruited from different age groups to represent the overall demographics of the current licensed U.S. driver population, then divided into four age groups: age group 1(19–34), age group 2 (35–49), age group 3 (50–65), and age group 4 (65+). Initially, the plan was to maintain the actual percentages of the U.S. driver population for each group. However, due to difficulty in the recruitment process, it was not possible to maintain that distribution.

Comparing the compliance rates of different age groups (without decomposing to gender groups), indicates similar response behaviors among all the age groups. Age group 4 had the lowest compliance rate. The other three age groups demonstrated similar compliance rates, which ranged from 84% to 79%, and there was no statistically significant difference among them (Figure 13). A chi-squared test indicated that there was a statistically significant difference between the compliance rate of age group 4 and the three other groups: age group 1, $\chi^2(1, N = 189,81) = 7.179$, $p = 0.007376$; age group 2, $\chi^2(1, N = 135,81) = 6.713$, $p = 0.009571$; and age group 3, $\chi^2(1, N = 207,81) = 7.3017$, $p = 0.006889$.

Comparing compliance rates within an age group between male and female participants demonstrated similar compliance behaviors for age groups 1 and 2 (Figure 14). In both of these groups, female participants showed slightly higher compliance rates than those of the male participants. However, the difference between compliance rates for males and females within each age group had no statistical significance.

For age group 3, the compliance rate of females was close to 84%, and the compliance rate of males was approximately 73%. The difference between the compliance rates of male and female participants was found to be statistically significant, $\chi^2(1, N = 117,90) = 2.757$, $p < 0.10$. Overall, the compliance rates of both female and male participants in age group 3 were lower than those of all the other groups. Even in this group, female participants had a higher compliance rate (66%) than that of the male participants (61%). However, this difference in compliance rates is not statistically significant, $\chi^2(1, N = 27,54) = 0.0596$, $p > 0.10$, and it would not be prudent to reach conclusion about the response behavior with a very small sample size.

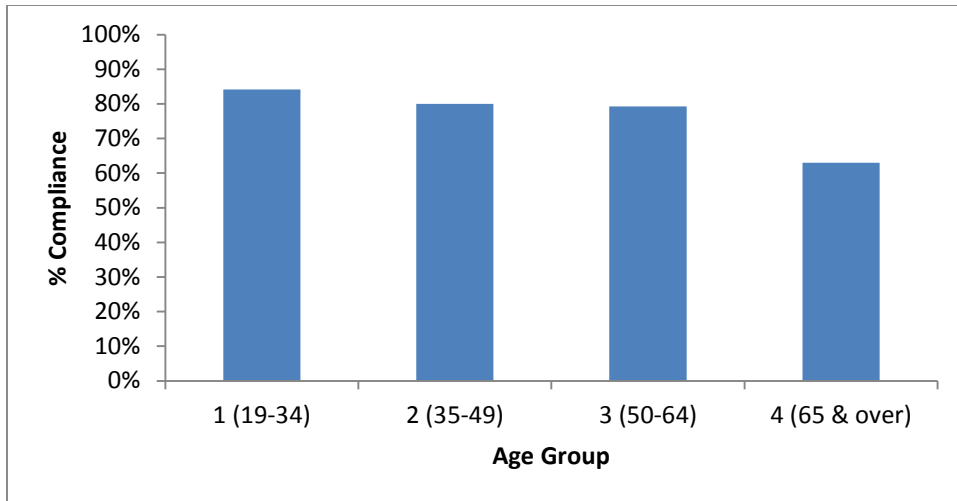


Figure 13. Compliance aggregated across age groups.

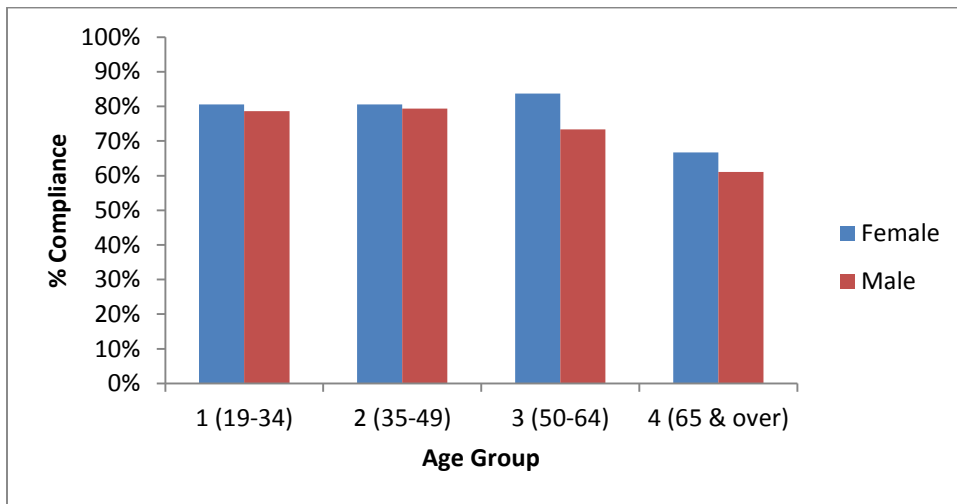


Figure 14. Compliance for different genders aggregated across age groups.

Discussion of Compliance Behavior

Gap size preferences/compliance under different traffic conditions. Based on the data gathered from the field test, it is evident that the highest compliance rates were achieved for large- and medium-gap scenarios, with no significant difference in rates between these two gap sizes. This indicates that, during high and medium traffic conditions, when headways between vehicles are relatively large enough that drivers can comfortably change lanes, drivers are willing to follow the advisories more than during traffic conditions when the gaps between vehicles are comparatively smaller. Though small-gap scenarios resulted in the lowest compliance rates, it implies that some drivers were comfortable changing lanes in conditions when available gaps were relatively smaller. The gap acceptance behavior demonstrated by the participants in the field test is similar to what is usually observed in real-world traffic conditions. From the perspective of the deployment of merge management strategies, the observed compliance behavior indicates that the highest benefits will be achieved during low and medium traffic flow conditions, as drivers are most likely to follow the advisories during these conditions. And even in highly congested situations, when available

gaps are small and there is limited freedom to change lanes, some participant drivers will comply with the advisories and will take the advised actions.

Effectiveness of strategies. From the field test data, we can see that the highest compliance rates were achieved for both the LCA and MCA strategies. By design, the LCA provides very simple and straightforward instructions for drivers to understand and act accordingly. This strategy can be easily deployed as one of the first merge management strategies with minimum resources required for driver education and training. Similar conclusions can also be made about the MCA's effectiveness in improving merging operation. The merging control advisories simply guide the driver to smoothly merge using appropriate speed changes and lane changes.

Participant drivers demonstrated the same compliance rate for the MCA as they did for the LCA, even though the former is a two-advisory strategy. However, in the case of VSL, we observed a significantly lower compliance rate when compared with the compliance rates for LCA and MCA. This lower compliance rate is due to the fact that VSL provides a lower speed limit advisory, but the goal is to motivate drivers to move to the left lane to create gaps for merging vehicles. Another approach to deliver this message may be to advise drivers about alternate choice(s). In the case of the VSL advisory, it can be delivered as "Reduce your speed to 25 mph or move to faster left lane." Therefore, an important lesson learned from this study is that it is important to design advisory messages in a way that drivers readily understand. This, in turn, will make the desired outcomes easy to achieve.

Age group and gender. Compliance data on both male and female drivers indicate that there is no significant difference in most cases. In some cases, female participants demonstrated better compliance rates than their male counterparts. This behavior may be explained by the fact that male and female drivers have different levels of risk perception. Though research studies have shown that in some cases male drivers are likely to demonstrate risky driving behavior, risky driving behavior may not necessarily mean higher advisory compliance rate. Though not statistically significant, higher female compliance rate may indicate they were more aware of the dynamic traffic condition than their male counterparts and were able to follow the advisories more frequently. However, to reach a strong conclusion regarding gender effect on compliance behavior, it is necessary to conduct an extensive investigation using both laboratory and field settings.

Comparing the aggregated compliance rate among the different age groups (without decomposing into the two gender groups) shows a significant difference in the compliance rates of older drivers when compared with the other three age groups. In some cases, this decrease in compliance rate may be due to the diminishing driving skills and changes in risk perception that come with age. However, with a very small sample size, it is very difficult to reach this conclusion. In addition, it also needs to be proven that older drivers are lacking in these two critical abilities. Another aspect of lower compliance rates among older drivers may be due to the fact older drivers have become more cautious than their younger counterparts. The perception exists among younger drivers that

they are immune to the effects of high-level risk [20] and, consequently, drive more aggressively when accepting gaps or changing lanes.

The compliance rates of the female participants in all four age groups are higher than the compliance rates of the male participants. However, the difference between male and female participants was not statistically significant except for age group 3. Again, the higher compliance rate among female drivers can be supported with the argument that the female drivers may be more cautious while driving and had better perceptions of the risk of lane changing. This awareness of the situation may have led them to accept the gaps more frequently than male participants.

Advisory Response Time

Variable Speed Limit

For Variable Speed Limit scenarios, the scenarios with large gap sizes resulted in the lowest average response time of 8.68 seconds ($s = 1.86$ sec.) (Figure 15). Scenarios with small gap size resulted in an average response time of 8.94 seconds ($s = 1.40$ sec.). However, during the medium-gap scenarios, the participants reacted most slowly, resulting in an average response time of 9.01 seconds ($s = 1.82$ sec.). The difference in response time between the large- and medium-gap scenarios was not statistically significant; $t(95) = 0.8811$, $p = 0.385$. Similarly, the difference in response time between small- and large-gap scenarios failed to reach statistical significance; $t(76) = 0.6595$, $p = 0.5115$.

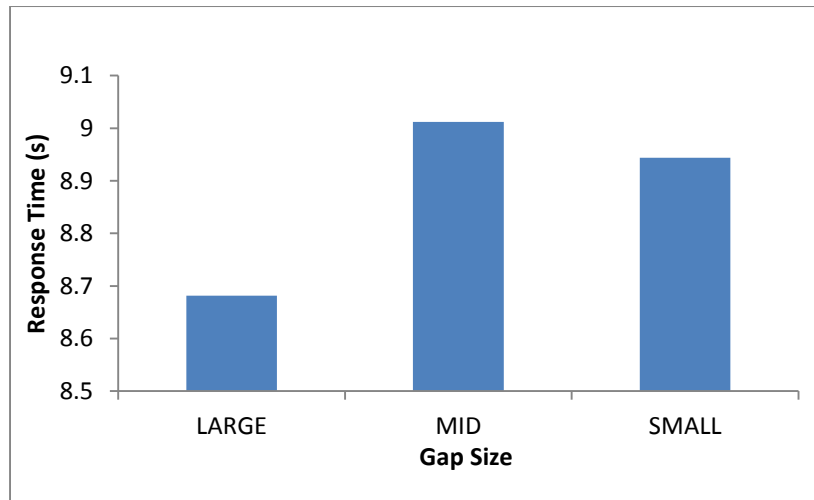


Figure 15. Response time of VSL.

Lane Changing Advisory

As for VSL, participant drivers reacted more quickly to the LCA during the large-gap scenarios, with average response time of 8.43 seconds ($s = 1.46$ sec.) (Figure 16). For medium-gap scenarios, the participants completed lane changes with an average response time of 8.63 seconds ($s = 1.84$ sec.). However, for small-gap scenarios, the participants reacted most slowly, with an average reaction time of 8.98 seconds ($s = 1.82$ sec.). The difference in response time between large and

medium-gap scenarios was not found to be statistically significant, $t(126) = 0.6803$, $p = 0.4975$. Similarly, the difference in response time between large- and small-gap scenarios was not statistically significant; $t(110) = 1.7594$, $p = 0.0813$.

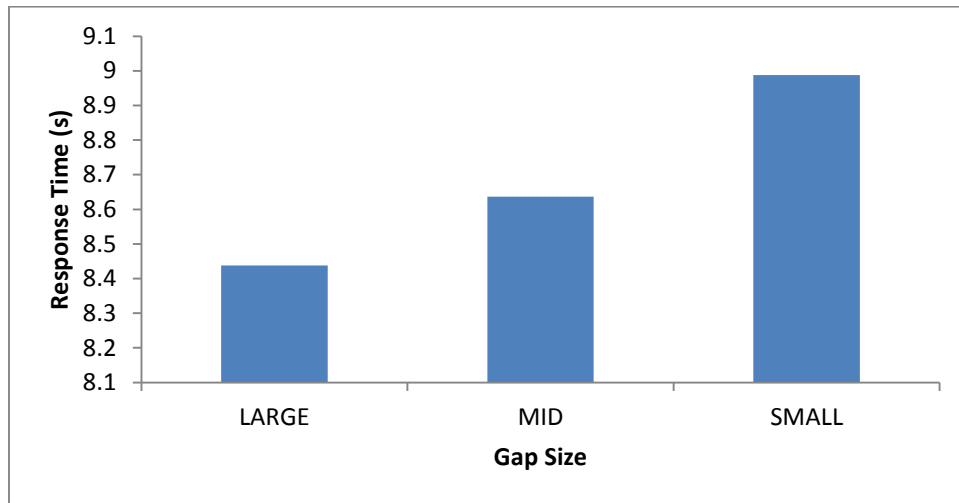


Figure 16. Response time of LCA.

Merging Control Advisory

Like the LCA scenarios, in the MCA scenarios participant drivers demonstrated a similar trend in behavior in terms of response time (Figure 17). Drivers reacted most quickly for large-gap scenarios, with average response time of 7.48 seconds ($s = 1.67$ sec.); this was followed by medium-gap scenarios, with an average response time of 7.83 seconds ($s = 1.52$ sec.). The difference of average reaction times between the two scenarios was not statistically significant; $t(123) = 1.222$, $p = 0.2241$. Similar to LCA, drivers took more time to change lanes for small-gap scenarios, with an average of 8.30 seconds ($s = 2.13$ sec.). The difference of average reaction times between large- and small-gap scenarios was found to be statistically significant; $t(106) = 2.2228$, $p = 0.0284$.

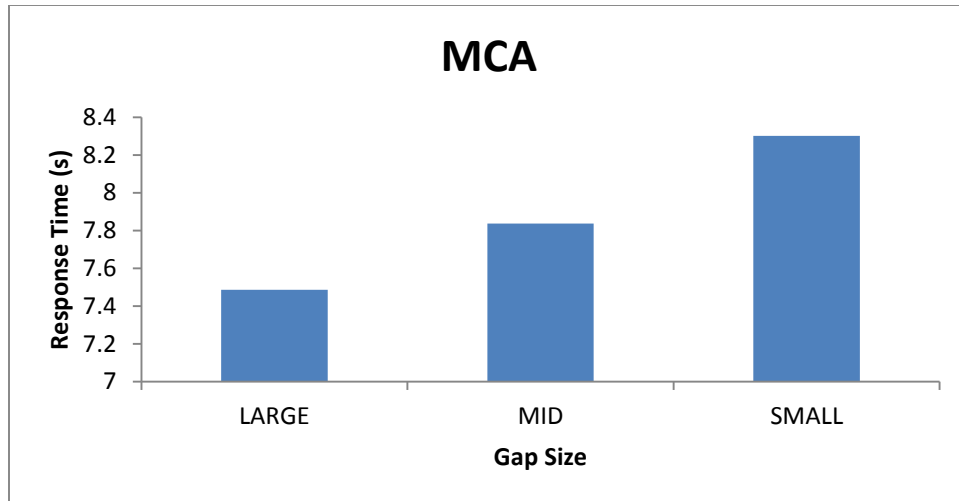


Figure 17. Response time of MCA.

Response Time Across Strategies

Comparing the participants' advisory response times across the different strategies (without respect to the three gap sizes) indicates that drivers' reactions were slowest for the VSL scenarios, with an average response time of 8.87 seconds ($s = 1.74$ sec.) (Figure 18). The slow reaction for the VSL advisory can be due, at first, to drivers being confused by the lower speed limit advisory and either slowing down or taking some time to think what would be the appropriate action to take. The LCA resulted in an average response time of 8.64 seconds ($s = 1.70$ sec.); a significance test indicated no statistically significant difference between the average response times of LCA and VSL; $t(297) = 1.1069$, $p = 0.2692$.

It is interesting to note that, on average, a driver changed lanes quickly under the MCA scenario, with an average response time of 7.83 seconds ($s = 1.74$ sec.). This quick reaction can be explained thus: by complying with the acceleration advisory, drivers were already placed in a suitable position for changing lanes, and after getting the second advisory to change lanes, drivers were able to quickly react to that. The difference in reaction times between VSL and MCA was found to be statistically significant, with $t(295) = 5.0276$ and $p < 0.0001$. Similarly, the difference between LCA and MCA average reaction time was statistically significant; $t(340) = 4.3449$, $p < 0.0001$.

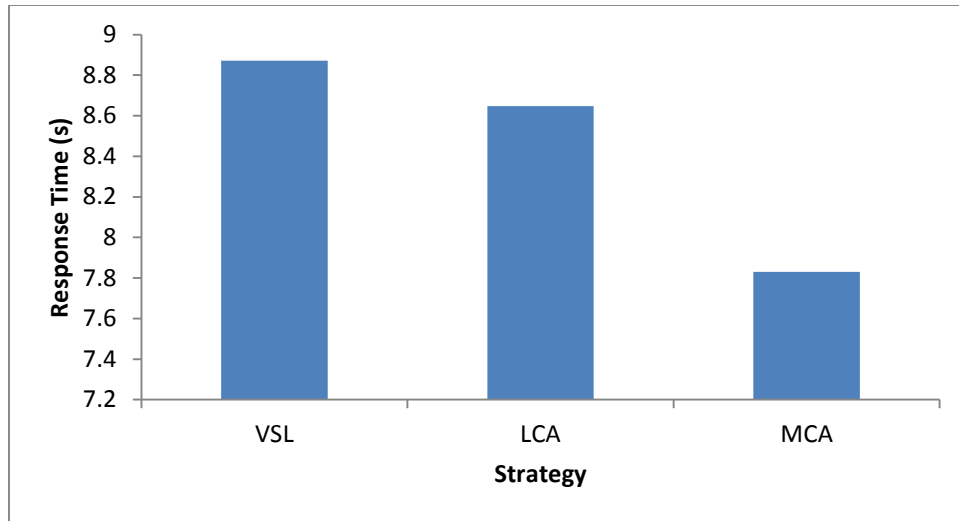


Figure 18. Response time across strategies.

Response Time Across Gap Sizes

Comparing average response times across the three different gap sizes (without respect to the strategies) indicated an increase in the response time related to the decrease in the gap size (Figure 19). As observed with each of the specific strategies, the large-gap scenarios resulted in the quickest responses from the participant drivers, with an average response time of 8.16 seconds ($s = 1.72$ sec.). For medium-gap scenarios, the participants reacted with an average response time of 8.45 seconds ($s = 1.78$ sec.). And the difference in average response times between the large- and medium-gap scenarios was not statistically significant; $t(348) = 1.524$, $p = 0.1284$.

On average, the participant drivers were slowest in reacting to the advisories during the small-gap scenarios, with an average response time of 8.71 seconds ($s = 1.87$ sec.). The reason participants took more time to react to the advisories under the small-gap scenarios may be due to participants being more cautious. A statistical significance test indicated that the difference between the average response times of large- and small-gap scenarios is statistically significant; $t(296) = 2.6002$, $p = 0.0098$. However, the difference of the average response times between medium- and small-gap scenarios failed to reach statistical significance, $t(288) = 1.2061$, $p = 0.2288$.

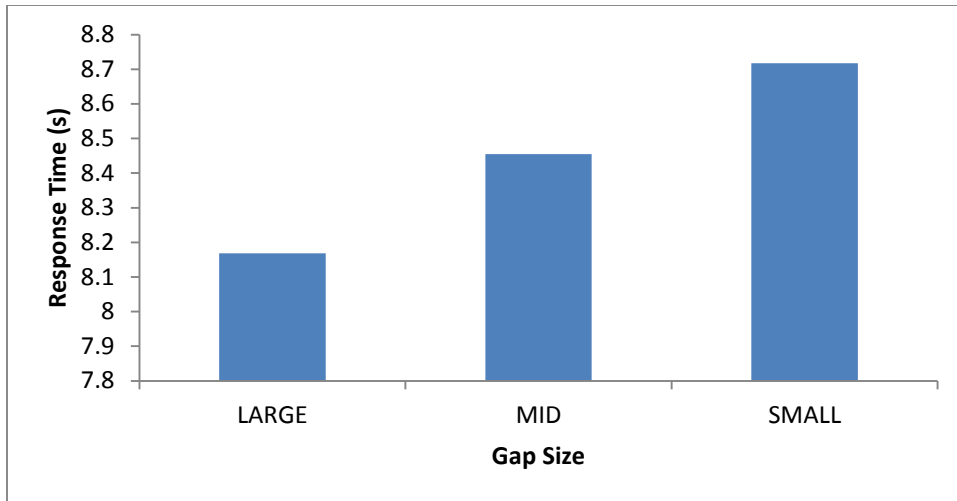


Figure 19. Response time across gap sizes.

Response Time for Different Genders

Response time within strategies. For the average response time within strategies (and across different gender groups), similar response times were observed for female ($M = 7.81$ sec., $s = 1.69$ sec.) and male ($M = 7.84$ sec., $s = 1.85$ sec.) participants for MCA scenarios (Figure 20). For VSL scenarios, the average response times for female and male participants were 8.93 seconds ($s = 1.89$ sec.) and 8.79 seconds ($s = 1.58$ sec.), with no statistical significance, $t(170) = 0.5187$, $p = 0.6046$. Female and male participants reacted similarly for the LCA scenarios, with an average response time of 8.719 seconds ($s = 1.57$ sec.) and 8.58 seconds ($s = 1.819$ sec.), respectively, and without a statistically significant difference, $t(170) = 0.5232$, $p = 0.6015$.

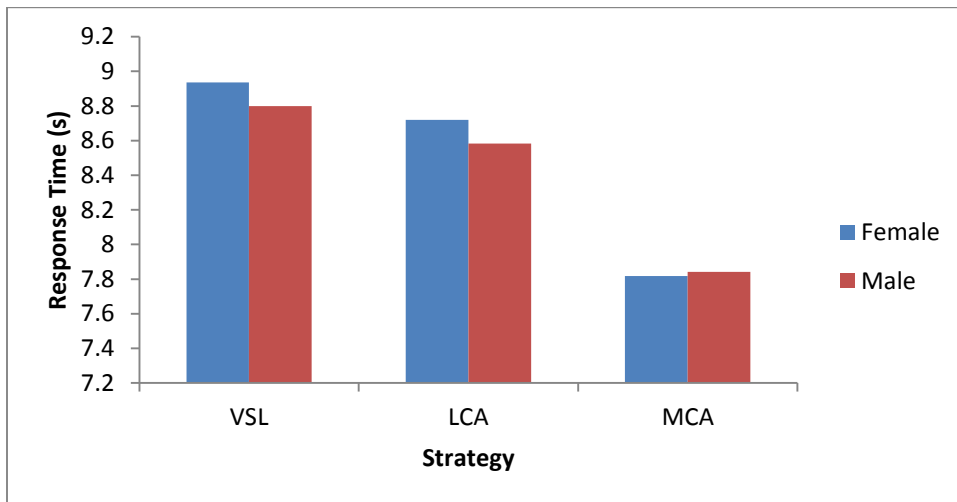


Figure 20. Response times within strategies for different genders.

Response time across gap sizes. Comparing average response times within gap sizes for different gender groups (without respect to strategies), similar trends occurred within specific strategies (Figure 21). As gap size decreased, drivers reacted more cautiously with the advisories by taking

more time to change lanes. For large-gap scenarios, female participants reacted slowly ($M = 8.25$ sec., $s = 1.69$ sec.) compared with male participants ($M = 8.09$ sec., $s = 1.75$ sec.), with no statistically significant difference, $t(177) = 0.6142$, $p = 0.5399$. For medium-gap scenarios, male and female participants had similar average response times of 8.48 seconds ($s = 1.89$ sec.) and 8.42 seconds ($s = 1.68$ sec.), with no statistical significant difference, $t(169) = 0.1933$, $p = 0.8469$. Both male and female participants reacted slowly to the advisories when compared with large- and medium-gap scenarios. During small-gap scenarios, male participants ($M = 8.61$ sec., $s = 1.76$ sec.) reacted more quickly than the female participants ($M = 8.81$ sec., $s = 1.98$ sec.). However, the difference between average response times was not statistically significant, $t(117) = 0.5910$, $p = 0.5557$.

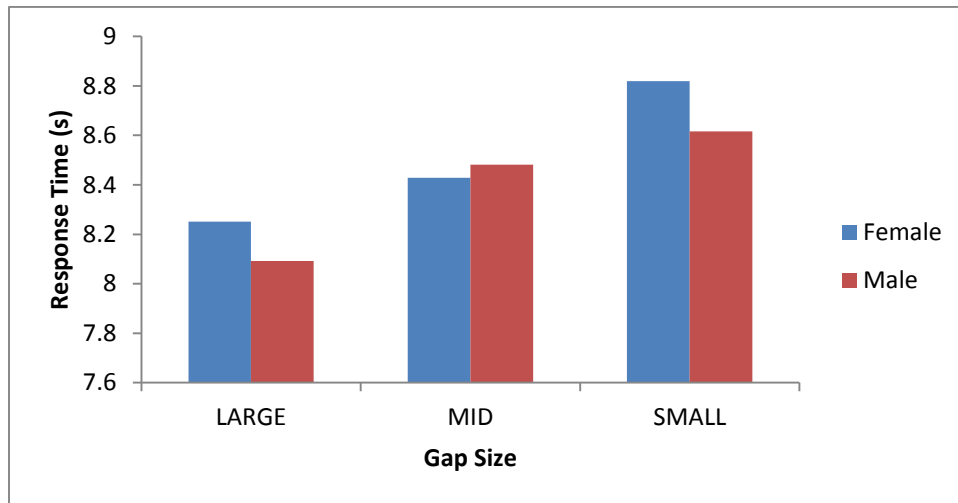


Figure 21. Response times within gap sizes for different genders.

Response Time for Different Age Groups

As mentioned earlier, the participants were recruited for different age groups to represent the overall age demographics of the U.S. driver population. Drivers among different age groups have different levels of risk perception and may demonstrate different levels of aggressive driving behavior [21]. When aggregated average response times are considered (without decomposing to gender level), age group 1 responded more quickly than all the other groups, with an average response time of 8.11 seconds ($s = 1.47$ sec.) (Figure 22). Among all the age groups, age group 4, which consisted of participants 65 years or older, was the slowest ($M = 8.90$ sec., $s = 1.76$ sec.) in responding to advisories. However, the difference in average response times between age groups 1 and 4 failed to reach any statistical significance, $t(28) = 1.276$, $p = 0.2124$. This may be due to the small sample size (9 participants) in age group 4. Participants of age group 2 (35–49) reacted slightly more quickly compared with age group 4, with an average response time of 8.76 seconds ($s = 2.28$ sec.). However, the difference between the average response times of age groups 1 and 2 was not found to be statistically significant, $t(34) = 1.0448$, $p = 0.3035$. Similarly, the difference between the average response time of age groups 2 and 3 failed to reach statistical significance, $t(36) = 0.7647$, $p = 0.4494$.

Another approach to analyzing response times by gender is to decompose the data into different age groups (Figure 23). Among all male participants of the four age groups, male participants in group 2 had the highest average response time ($M = 8.98$ sec., $s = 2.54$ sec.), followed by the average response time ($M = 8.84$ sec., $s = 1.86$ sec.) of male participants in age group 4. Male participants in age group 1 reacted most quickly ($M = 7.88$ sec., $s = 1.35$ sec.) among all the groups, both male and female. However, the difference in average response times between male participants of age groups 1 and 2 is not statistically significant, $t(18) = 1.277$, $p = 0.2178$. Among female participants, age group 4 was the slowest in responding to the advisories, with an average response time of 9.02 seconds ($s = 1.61$ sec.), followed by the female participants of age group 2 ($M = 8.58$ sec., $s = 2.03$ sec.). However, with a very small sample size of 3 participants for age group 4, it is not possible to make any significant conclusions about the response behavior for this age group. Age group 3 female participants were the quickest among all the female participants with average response time ($M = 8.23$ sec., $s = 1.65$ sec.). However, the differences between average response times for age groups 3 with both group 2 and group 1 were not statistically significant.

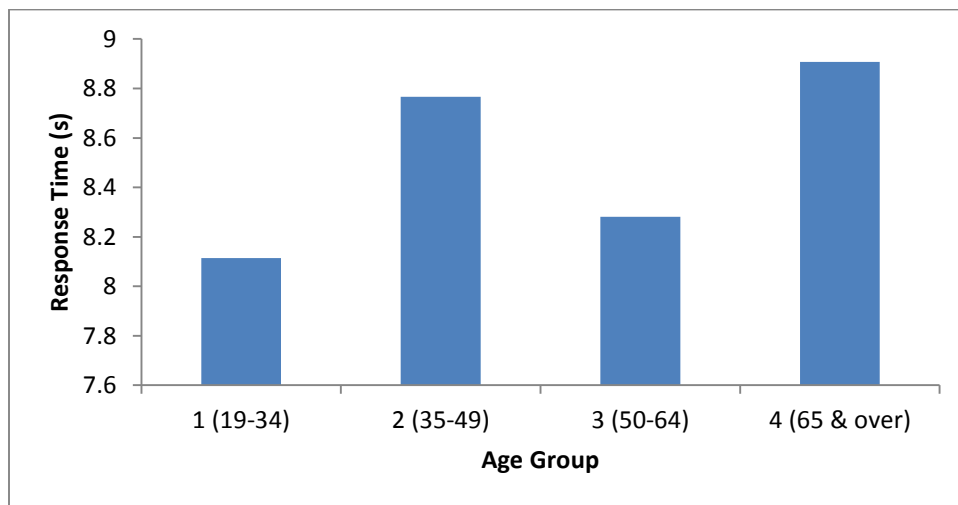


Figure 22. Response time for different genders aggregated across age groups.

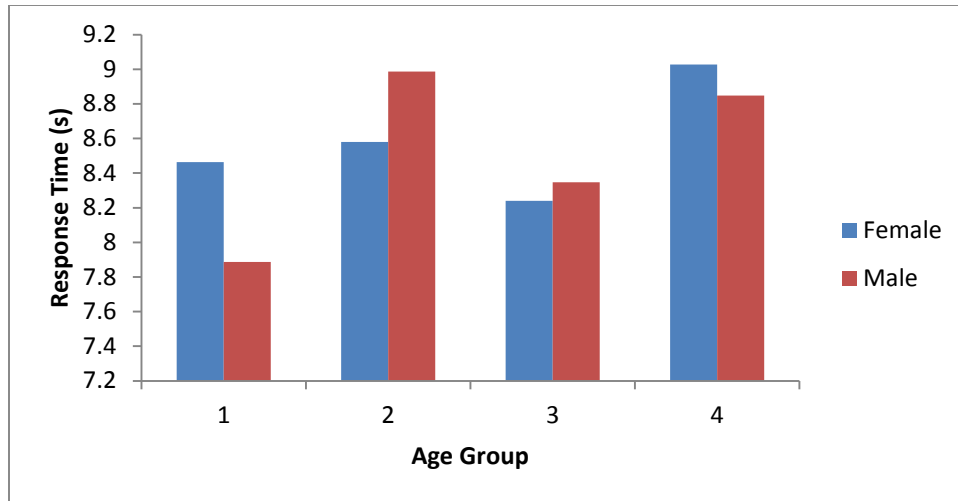


Figure 23. Response time for different genders aggregated across age groups.

Discussion on Advisory Response Time

The average advisory reaction time across the different strategies indicated whether drivers reacted quickly or slowly. For both MCA and LCA strategies, we observed similar trends in the average reaction times across the different gap sizes. As gap size decreased, the average reaction time increased. This can be explained that, for large-gap scenarios, the drivers felt comfortable following the advisories and changing lanes, as the available lead and lag gaps were bigger than the critical gaps. The average reaction time increased for the medium gap with the decrease of gap size. This indicated that, as gaps decreased, the drivers became more cautious and their perception of level of risk also increased.

This resulted in less-risky driving behavior from the participant drivers; consequently, drivers reacted more slowly compared to their reactions for large gap size. Finally, we saw that drivers reacted the slowest for the small-gap scenarios as the available gap in the target lane decreased. Though one can expect drivers to react more quickly for small gap size, higher reaction time for small gap size scenarios makes sense in a way. Before making the final decision to change lanes, drivers wanted to make sure that they could change lanes safely and reduce the conflict with vehicles in the target lane. This may have resulted in drivers checking and ensuring multiple times that their perception of the available gap was accurate, which resulted in a higher average reaction time for small-gap scenarios.

For the VSL strategy, we observed that the average reaction time did not follow the same trend as it did for the LCA and MCA scenarios. As mentioned earlier, the variable speed limit strategy provided a lower speed advisory to the drivers. Before the beginning of the field test, during the pre-test training phase, drivers were instructed to ignore the lower speed limit and change lanes if they felt comfortable. However, some drivers were confused by the lower speed limit during the field test, and it resulted in a lower compliance rate. Even though some drivers remembered the instruction from the training phase and changed lanes, they reacted in a slower manner than they did for the other two strategies. The reason for the slower reaction time may be that the driver first

got confused with the slower limit advisory and, in some cases, slowed down before changing lanes.

Comparing average reaction times across the strategies determined that participant drivers reacted the slowest under the VSL strategy; this may be due to the confusion and a slight slowing down before changing lanes. It is interesting to observe that drivers reacted to the MCA advisory significantly more quickly than to the other two strategies. The lower reaction time for the MCA strategy was due to the fact that drivers had already complied with the acceleration advisory and that placed them in a better position to change lanes before getting the second advisory to change lanes. In this case, drivers were sufficiently comfortable with the placement of their vehicles to change lanes, and they required less time to verify their positions and to change lanes after getting the LCA advisory. This resulted in the lowest average response time for the MCA scenarios.

When the average reaction times were compared across the gender groups, female participants reacted slower than the male participants for VSL and LCA scenarios. For MCA scenarios, male and female participants had similar average reaction times. The difference between the average reaction times for male and female participants was not statistically significant.

Examining the average reaction time across different gap sizes for male and female participants detects a similar trend to that observed for the LCA and MCA strategies: as gap size decreased, the average reaction times increased. For large- and small-gap scenarios, female participants had higher reaction times. It was only for the medium-gap scenarios that male participants had slightly average higher reaction times. The differences in average reaction times between male and female participants within each gap size were not statistically significant.

Comparing average reaction times within the different age groups showed that age group 1 had the quickest response and age group 4 had the slowest response. However, the difference in average response times between these two groups was not significant. The average response time for age group 2 was higher than age groups 1 and 3; again, the differences in average response times between the groups were not statistically significant. The slowest average reaction time from age group 4 can be explained this way: older driver participants demonstrated less risky and aggressive driving behavior than their younger counterparts. Age group 1 participants demonstrated the quickest responses due to the risk-taking behavioral tendency of younger participants.

Participant Stated Preferences Survey

Compliance under Different Traffic Conditions

After the field test, the participants were asked in a survey how they would respond to the advisories under different traffic conditions in the real world. Participants stated that they were most likely to follow the advisory in medium traffic congestion. Only 3 people (4%) out of the 68 participants stated they would not follow advisories under medium congestion. Under free-flow conditions, 90% stated that they would comply with the advisory, and 10% stated they would not.

The non-compliance responses under free-flow conditions may be due to participants' not understanding the need for an advisory under such conditions when there are large headways between vehicles. As expected, more than 60% of participants stated that they would not follow advisories under heavy traffic conditions, when available gaps were small and there was limited freedom for lateral movements. The result from the questionnaire survey supports the response behavior demonstrated in the field test in terms of the impact of preference for gap sizes indicating a willingness to follow an advisory.

Network Unfamiliarity

Advisory compliance may also be influenced by the fact of how familiar the drivers were with the geometric configuration of the merging area. Some drivers may not have been comfortable following advisories on unfamiliar roads and may have ignored any advisory. In the survey, participants were presented with a scenario asking whether or not they would follow the advisory on an unfamiliar network or roadway where they have had little or no experience traveling. About 86% of participants strongly agreed with the statement, indicating that in most cases they would be comfortable following advisories on unfamiliar roads. Higher compliance indicated that the drivers would trust the merge assistance system, and that it will be effective for both commuter and non-commuting drivers.

Higher-Speed Lane

Drivers always try to drive in a lane that provides them the highest driving utility in terms of both safety and speed. Drivers may be motivated to follow an advisory if they realize that following the advisory will lead them to driving in a comparatively higher-speed lane. In the survey, participants were presented with a hypothetical scenario, where, by complying with the advisory they could move to a higher-speed lane. Most of the participants (about 92%) showed a willingness to comply with the advisory, with 32% of participants strongly agreeing with the statement. Only 7% of participants indicated that a higher-speed lane would not motivate them to comply with the advisory. This result implies that the majority of drivers would comply with the VSL advisory, of which the goal is to motivate drivers to move to the comparatively faster left lane by lowering the speed limit of the right most lane.

Sense of Conflict

In the survey, participants were asked how they would respond to an advisory if their compliance would help to avoid a conflict situation with another vehicle. All the participants showed consent: 42 participants (about 62%) out of the 68 participants strongly agreed with the statement and the remaining 26 participants (about 38%) agreed. It is evident from the results that safety always has a greater utility to drivers, and advisories will be preferred by drivers in situations where a high possibility of conflict between merging vehicles and mainline lane vehicles exists.

Presence of a Front Vehicle

The participants were asked, while viewing an appropriate diagram, whether having a front vehicle in the same lane would influence their compliance decision. Stated responses supported this

assumption, with 75% of participants stating that the presence of a lead vehicle would influence their compliance behavior and 25% of the participants indicating that having a front vehicle in the same lane would not influence their compliance.

Presence of a Merging Vehicle

In the survey, participants were presented with a statement (and an appropriate diagram) to respond to a hypothetical scenario to learn if they would comply with the advisory if they could see a vehicle approaching from the on-ramp. Ninety-seven percent of the participants agreed with the statement, with only two participants disagreeing with it. This higher percentage of compliance indicates that, in traffic situations where drivers actually realize the necessity to comply, they will follow the advisory. The small percentage (2%) of non-compliance indicates that some drivers may not be comfortable following the advisory in any situation. Rather, they would rely on their own decision-making process.

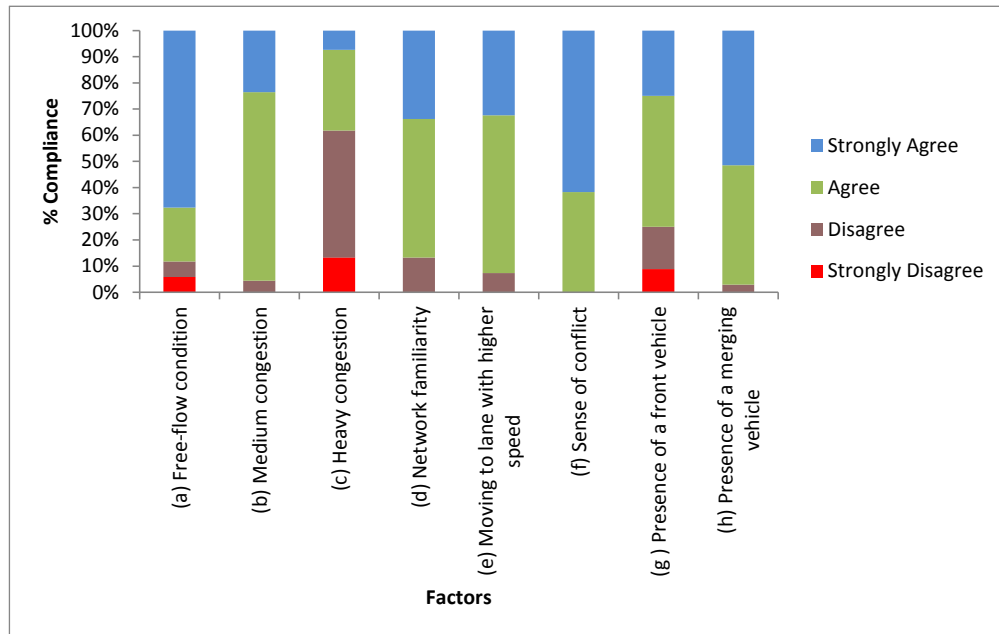


Figure 24. Participant stated preferences questionnaire.

Discussion of Participant Stated Preferences Survey

Due to the limitation of resources and time, it was not feasible to test all the possible traffic scenarios in the field test. The stated preferences survey following the field test provided valuable insight into drivers' response behavior under different hypothetical traffic scenarios (Figure 24). It was interesting to observe that the participants' stated preferences for complying with the advisories were the same as those they actually demonstrated in the field test.

As observed during the field test, compliance rates for both the LCA and MCA scenarios for large- and medium-gap scenarios were close to 90%. Similarly, in the stated preferences survey for both free-flow and medium-congestion conditions, the compliance rate was 90% or more. In the field

test, the large gap size represented the free-flow condition and the medium gap size represented the medium-congestion condition. This indicated that there was significant consistency in drivers' revealed preferences and stated preferences. In the case of the heavy congestion condition, about 38% of the participants stated that they would comply with the advisory, whereas in the field test the average compliance rate was about 57%. Therefore, we observed a similar trend in both the field test and survey response: as traffic conditions worsen, the compliance rate also decreases.

Higher compliance rates tested under the network familiarity factor indicate that the drivers were willing to trust and follow the advisories from the system even if they were driving in an unfamiliar environment. In some cases, drivers were not aware of the particular geometric configuration of the ramp area and may have felt uncomfortable driving during high traffic conditions. The advisories from the merge assistance system will warn drivers of on-ramp vehicles or help initiate smoother merging of vehicles in ramp areas.

As discussed earlier, the perception of risk proved a great motivating factors for drivers to follow the advisories. Merging situations often create a sense of conflict in drivers, especially during heavy congestion. All the participants stated that they would follow the advisory if they could sense that complying with it would enhance their current driving condition from the perspective of safety.

According to car following theory, a following vehicle responds to stimuli from the front vehicle, either by adjusting speed, acceleration, or spacing, and in some cases by changing lanes. Similarly, the presence of a front vehicle in the same lane may influence the compliance behavior of the target vehicle driver. Stated preference data support this assumption, as 75% of the drivers indicated that they would comply with advisories in this type of situation.

Similarly, participants indicated that the presence of a merging vehicle would greatly influence their compliance behavior. This indicates that if drivers understand or observe the justification of a particular advisory, they will follow it most of the time. This is very important in designing a system that will have a very low rate of false-positive detections. If the system sends advisories frequently and the driver cannot perceive the justification for them, it will create a sense of annoyance and mistrust regarding the system. In this case, the driver may choose to disable the system or discontinue a subscription to it. Thus, it is essential that any CV-based mobility application be designed, implemented, and deployed with a very low rate of false positives.

Conclusions and Recommendations

With CV technology, more sophisticated and advanced traffic management strategies can be developed and deployed to address the limitations of current approaches. The FMAS is one of the example strategies that take advantage of this technology by improving freeway merging operations. It should be noted that, in developing and evaluating any mobility applications, proper understanding of drivers' behavior is a must to ensure the applicability and efficiency of the mobility applications in the real world.

In this project, we investigated how drivers actually reacted to the advisories sent by FMAS by conducting a field test of different gap size scenarios with naïve participants. Based on the data gathered from the field test, it is evident that drivers felt more comfortable following the advisories when large and medium gaps were available, which represent low and medium traffic conditions respectively. Though the small gap size scenarios resulted in the lowest compliance rates, this is still meaningful in that “some” drivers are willing to follow the advisory even in a high-volume traffic condition. Another significant finding from the field testing was that drivers tend to comply better with a direct advisory message that explicitly advises drivers to make a lane change. On the other hand, an indirect advisory message, which attempts to implicitly stimulate a lane change through speed control, turned out to be less effective.

In conclusion, the data set collected and presented in this project is one of the first to provide actual driver response data that will allow for a more realistic understanding of driver compliance rates to advisory messages. Given the significance of the proper understanding of drivers' behavior in developing, evaluating, and deploying CV mobility applications, more effort should be made to gather actual drivers' behavioral data, which provides valuable insight into drivers' decision making.

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