CONNECTED VEHICLES-INFRASTRUCTURE UTC

Connected Vehicle Enabled Freeway Merge Management - Field Test
UTC Title Page

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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 Vehicles technologies, more proactive traffic management strategies are possible, such as the Freeway Merge Assistance Systems (FMAS), that 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, which will be influenced by situational factors 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. For this, a field test was conducted with naïve human subjects to collect driver behavior data to different types of advisory messages under different traffic scenarios in a controlled environment. The data gathered from the field test indicates that the compliance rate is higher when a large or medium size gap is available for a lane change while the lowest compliance rate was observed for a small gap size scenario. In addition, it was found out that more drivers follow a direct advisory message that advises a lane change, rather than an indirect message which stimulates a lane change through speed control.
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].

Among the many causes, 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 is dependent on the freeway system (32% of total annual vehicle million-miles) [5], various strategies such as ramp metering, variable speed limit, etc. have been implemented to improve freeway merging operation. However, each of these strategies have disadvantages [6] as well as limited capabilities in reducing freeway merge conflicts because of the real-time data collection and dissemination limitations of current traffic surveillance system [7].

The Connected Vehicle (CV) initiative addresses the above limitations by establishing wireless communication between vehicles and also between vehicles and infrastructure. Vehicles will be able to transmit individual vehicular data such as 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 definition of data types and communications used by Connected Vehicle technology [8]. 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 for CV applications. Another enormous advantage of the CV technology is the ability to send customized messages/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 the Connected Vehicle technology, it may be possible to develop new approaches to address freeway merge conflicts. The University of Virginia Center for Transportation Studies (UVA CTS) has developed CV technology enabled Freeway Merge
Assistance System to promote smoother merging operation by minimizing conflicts between the mainline vehicles and on-ramp vehicles. Four algorithms developed under this system are: variable speed limit, lane changing advisory, gap responsive metering and merging control. The overall goal of this system is to either identify existing gaps in the freeway mainline lane or to create gaps in the merging lane for the on-ramp vehicles. Initial results showed that the 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 will greatly impact the performance of the individual algorithms.

The above mentioned four algorithms under the merge assistance system provide personalized advisories to both freeway mainline and merging vehicle drivers. Based on the advisory given, it was assumed that the drivers will take the necessary courses of action to create gaps, change lanes or control the speed of their vehicles. The benefits anticipated from the merge management system in reducing merging conflicts and bottlenecks in merge areas entirely depend on the compliance of drivers. It was assumed during the development and evaluation phase that all drivers comply with all the relayed personalized advisories. However, in real-world scenarios 100% driver compliance may not be possible due to various reasons.

Therefore, the major objectives of the proposed work are 1) to design a field test to investigate driver compliance behavior in a Connected Vehicle Test bed and 2) to understand how the drivers react to the advisories based on different traffic conditions. This will eventually help us investigate further how actual driver compliance affects the benefits anticipated from the merge management system in a Connected Vehicle environment. Various prior research studies 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. As mentioned, the earlier work on the freeway merge management system did not consider any component of driver behavioral factor and situational factor influencing individual compliance, whereas compliance can be attributed to individual driver characteristics to dynamic traffic conditions.

To understand how driver behavior might be affected by personalized advisories, this research investigates how drivers respond to advisories provided under the Freeway Merge Assistance
System. Field tests involving naïve test subjects are one of the preferred ways to collect driver behavioral data, since it provides a more accurate representation of the real road driving environment for the test participants, and the data gathered will be more reliable than that generated using other techniques like driving simulators [9]. Driver compliance data will be collected by conducting a field test in a real-world Connected Vehicle test bed, where multiple traffic scenarios will be created to test subjects under the different strategies.

**FREEWAY MERGE ASSISTANCE SYSTEM**

This section presents a brief overview of the freeway merge assistance system developed by the UVA CTS. With the goal of improving the efficiency and safety of freeway merges, this system is developed to take advantage of the Connected Vehicle technology to address the limitations of current merge management practice. The following are three important fundamental components central to objectives of the system:

I. Dynamic Lane Control: The purpose of this logic is to identify available capacity in lanes and encourage drivers travelling on the mainline lane adjacent to the merging lane to change lanes to the left, thus creating larger and frequent gaps in the merging area. This dynamic lane control logic was implemented by two algorithms:

(A) Lane-level Variable Speed Limit: Based on the mainline traffic density, this algorithm dynamically determines and implements lower speed limit on the right most lane to encourage drivers to move to the left lane for better driving condition, thus creating gaps on the right lane for merging vehicles [10].

(B) Lane Changing Advisory: This algorithm dynamically selects vehicles travelling on right lane to send lane changing advisory for early lane change and thus creates bigger gaps for merging vehicle and reduces conflicts in the ramp merging area [11].

II. Gap-responsive Metering: This algorithm utilizes Connected Vehicle-enabled high-resolution vehicle trajectory data to identify gaps in the mainline lane and implement a dynamic gap-based
ramp metering strategy for on-ramp merging traffic. However, in this dissertation research this algorithm is not considered for evaluation [12].

III. Merge Control: This algorithm utilizes V2V and V2I communication to control longitudinal movements or advise/recommend speed changes for both mainline and ramp vehicles in order to ensure smooth merging in the smallest gap sizes and reduce merging conflicts, thus increasing capacity by reducing minimum headways [13].

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

The anticipated benefits from all these control strategies depend on drivers taking actions based on the advisory messages. There is a need to investigate drivers’ response to these advisories and the consequent impact to the transportation system.

The goal of this research is to conduct a comprehensive evaluation of the freeway merge assistance system and understand how drivers’ responses to the relayed advisories impact the performance of the different algorithms in improving mobility. Understanding driver behavior to personalized advisories will allow transportation system managers to utilize information as traffic management tool and adopt strategies and policies for effective implementation of CV applications.

**METHODOLOGY**

**Facility**
The field-test phase of this study was conducted in the Smart Road, a Connected Vehicle test bed facility located in Blacksburg, Virginia. This University Transportation Center test bed provides an excellent opportunity and necessary resources for the proposed research work. This facility has a 2-lane road instrumented with DSRC-based RSEs along the 2 mile length section. In
addition, this facility also has a small fleet of vehicles equipped with DSRC-based on-board equipment. Though the facility provides a Connected Vehicle enabled controlled environment for testing and conducting research; the length of the facility and limited number of equipped vehicles does not allow a full-fledged experimentation replicating real-world traffic scenarios. With this limitation, the research team has developed a testing plan with detailed description of the required system architecture, scenario development, test procedure steps, test personnel protocol.

Instrumentation

Road-Side Equipment (RSE)
The test bed is equipped with RSEs to provide the necessary I2V and V2I communications. The range of these RSEs varies from 1200 to 1400ft with possibility of less if line-of-sight is obstructed in some cases.

Smart-Road Vehicle Fleet with On-Board Equipment (OBE)
The field testing included three CVI-instrumented vehicles. These CVI-instrumented vehicles will be equipped with the necessary instruments (On-board Equipment -OBEs) including DSRC communications to facilitate testing the three algorithms. The fleet consists of mainly model from GM and NISSAN of recent years. These equipped vehicles are also equipped with in-vehicles information system which is capable of delivering both visual and auditory messages to the drivers. In addition to that these vehicles are instrumented with data acquisition system where all the necessary data (BSMs, video, etc) are stored and the stored data can easily be retrieved at the end of testing. In addition, a couple of non-instrumented vehicles were also available if needed for testing purposes.

Applications
The basic system architecture contains 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.

For the purpose of the testing, the above basic components may have to be modified if needed and two additional types of applications should be developed as below:

5) Three merge applications, one for each of three freeway merge assistance algorithms, to be installed at a remote application server; and

6) One testing control application required for the field testing in a portable laptop.

Figure 1 illustrates the system architecture of the proposed merge management system and the sequential steps that will be followed by the system 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 a start signal of a testing run, will then be sent to the application server, the RSE, and the OBEs sequentially. Finally, all the applications will start running once the start signal is received.

2. The OBE application starts (or continues) broadcasting Basic Safety Messages (BSMs).

3. The RSE application receives BSMs from OBEs and then sends these BSMs to the application server.

4. The application server receives BSMs from 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 will be running in a manual mode, in which an ACM will be generated only when the test administrator initiates 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 RSE, the OBE application displays the selected message on the driver telematics.

7. The test administrator manually records the reaction of a participant driver.

8. The test administrator then sends an end signal to the application server, which will then be relayed to the RSE application and the OBE application. Once this end signal is received, all the applications stop.
9. During each testing run, the centralized database application will keep record of all the BSMs, ACMs, etc. so that these records can be retrieved easily for post-testing processing.

![Figure 1: Merge Management-System Architecture](image)

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 VTTI team for development.

**Application for OBE**

There are three major functions to be performed by the OBE application in each of the instrumented vehicles:

- Broadcasts BSMs to RSEs (and nearby OBEs): All vehicles will broadcast Basic Safety Messages (BSMs) to all nearby vehicles and RSEs. This BSM includes positional data, speed, heading, acceleration/deceleration, etc. for each individual vehicle.
- Displays advisory messages: Another important functionality of the OBE application is to display the received advisory messages for each specific scenario. The messages will be displayed in the in-vehicle telematics in both visual and auditory format.
- Data storage: A database of all the sent BSMs and received ACMs will be maintained by
the data acquisition system installed in each vehicle.

**Application for RSE**
The RSE application will mainly have the role of establishing communication between the OBE and the remote application server. This application will send all the BSMs received from OBEs to the application server and also send the ACMs received from the remote application server back to each individual OBE. DSRC communications will be utilized as the communication method between OBEs and RSEs, and the remote application server and RSEs will be connected through Ethernet network.

**Application Server**
The application server is responsible for hosting and running all the algorithms or use cases. Once vehicular data is received from RSEs, the algorithms in the application server would be executed and final decisions would be made. These decision results would then be sent back to RSEs.

**Central Database Application**
The central database connected with the application server will keep record of all the BSMs sent from the OBEs through a database application. All these BSMs will have timestamp information so that researchers can retrieve these from the database for post-testing data processing. In addition, any ACMs generated as a result of application execution would be stored at the central database as well.

**Applications for Freeway Merge Assistance Algorithms**
Three separate applications will be developed for the three algorithms that will be tested in this project and stored at the application server. These algorithms are (i) Variable Speed Limit Application, (ii) Lane Changing Advisory Application, and (iii) Merging Control Application. The applications are required to meet the necessary requirements and follow the fundamental logic of the algorithms. After development these applications will be fully implementable as a real-world merge management tool in a connected vehicle environment. Detailed logic of these algorithms will be included in a separate software requirement document.

Each of the above applications will have two operating modes: (a) Automatic Mode, and (b) Manual Mode.
- **Automatic Mode**: In this mode the application will perform the necessary operations following the algorithm logic without any manual interference. For example, the decision making process of sending advisory to vehicle(s) will be 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) will have the authority and flexibility to override all the built-in criteria to send advisory or implement control strategy using the testing control application described in the next section. The Test Administrator will be able to send advisories at any time he/she wills to do so.

In the proposed system architecture, the freeway merge applications will be hosted in a remote application server which is connected with the RSE via an existing communication backbone.

**Testing Control Application**

As mentioned previously, the field testing will be conducted using a manual mode of the merge algorithms, which necessitates a testing control application that can be used to “manually” select and send an appropriate advisory message depending on the scenario being tested. The test control application will be installed in a portable device (laptop) so that the test administrator can carry to the test site. Besides, this testing control application will have additional capabilities, described below:

1) Through this testing control application, the test administrator will be able to send signals/instructions necessary to administer a test to all the vehicles. Examples include a signal to start the test run, an instruction to achieve target speed, and so on.

2) Test Administrator can 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 will establish the interconnection between the testing control application in a mobile device and freeway merge applications in the remote application server. Only cellular/wireless communication can provide the flexibility of portability of the test control application to the testing site and a continuous communication between control application and remote server applications.
3) After each advisory is sent, the test administrator should also be able to manually input the participant response into the testing control application, which will be included in the log report. The application will finally generate a log report which will include all the information presented in the Section 6.

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 utilize a simplify system architecture to conduct the field test and collect research data without further delay. Figure-2 represents the proposed 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 was not included. Rather, testing was conducted using only a Test Control Application and OBEs of test vehicles.

Figure 2: Simplified System Architecture
Following are the sequential steps that were followed in the proposed simplified system architecture:

1. The Test Control Application is started by the Test Administrator, who is riding in the participant vehicle. Then the test administrator will select one of the three applications and the specific scenario to be tested.
2. The OBE application will start sending BSMs to other OBEs. The data acquisition system in the vehicles will keep record of all the BSMs sent and received.
3. When the test administrator selects to send an advisory specific to the selected scenario, the on-board display system will show that advisory in both visual and auditory format to the test subject vehicle.
4. In the test control application, Test administrator will record the response of test participant to the advisory displayed.
5. After recording the response the test administrator will send the end signal through the test control application to the OBEs. The OBEs will stop sending BSMs. In addition to that the test control application will also generate a test log report for each test run.

**Design of Field Test**

There is a gap in the knowledge about drivers’ response behavior to these different control strategy advisories within a CV-enabled environment and we could not find any study that has focused specifically on this issue. Therefore, it is necessary to conduct a field test that addresses these problems. The field-test was conducted in the Smart Road facility located in Blacksburg, Virginia. This facility has a 2-lane road instrumented with DSRC-based Road-Side Equipment (RSE) and a small fleet of vehicles equipped with DSRC-based on-board equipment (OBE). However, limitation of resources did not allow a full-fledged experiment replicating real-world traffic scenarios. With these limitations, a simplified architecture was developed to conduct the field-test, which involved OBEs, in-vehicle on-board display and a test application. The test application was developed to allow the experimenter to randomly select test scenario and send advisory to the participant vehicle.
For all the algorithms under the merge management system, gap size is the main factor behind lane change decision making process. An extensive literature review has also indicated lane change and merging operation depends on the available gap size along with other variables such as relative speed of lead and lag vehicle, and the remaining distance of merge area. Since it was not feasible to consider all the 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: (i) Variable Speed Limit (ii) Lane Changing Advisory and (iii) Merging Control Algorithm.

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

Table 1(a): Time and Space Headway for different gap size

<table>
<thead>
<tr>
<th>Gap Type</th>
<th>Time-Headway (sec)</th>
<th>Space-Headway (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small Gap</td>
<td>2.00</td>
<td>88</td>
</tr>
<tr>
<td>Medium Gap</td>
<td>3.00</td>
<td>132</td>
</tr>
<tr>
<td>Large Gap</td>
<td>4.00</td>
<td>176</td>
</tr>
</tbody>
</table>

Table 1(b) Scenario Overview

<table>
<thead>
<tr>
<th>Gap Sizes</th>
<th>Advisory Types</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Variable Speed Limit</td>
</tr>
<tr>
<td>Large Gap (176ft)</td>
<td>Scenario #1</td>
</tr>
<tr>
<td>Medium Gap (132ft)</td>
<td>Scenario #2</td>
</tr>
</tbody>
</table>
Sampling of Test Participants
The sample population was selected to represent the overall demographics of licensed US. driver population so that with a reasonable level of confidence the response nature of the entire driver population can be concluded. As we did not have any direct control in variance estimation and there was no prior information about drivers’ response to these new type of advisories; a conservative assumption of 50% about the compliance proportion was made, 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 10% [17].

Participants were recruited through advertisement on classified websites like Craigslist and local newspaper from Blacksburg and surrounding area in Virginia. Final sample population constituted 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 necessary paperwork and training before the field test. In the training phase, each participant was oriented with the test vehicle, on-board display and a detailed instruction was given about their responsibility and course of actions during 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. Before the beginning of each scenario the three test vehicles were positioned on numbered spot designated specifically for each of them [Figure 3(a)]. Left lane vehicles were driven by confederate drivers and participants drove the right lane vehicle with the experimenter in the front passenger seat. For all scenarios, the left lane lead vehicle was placed on the position with location marker #1.
The lag vehicle on the left lane was placed on three different positions depending on the scenario to be tested. For large, medium and small gap scenarios the lag vehicle was placed on position with location marker #4, #3 & #2 respectively. On the right lane, the participant vehicle was placed with location marker #5, #6 & #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 a right lane and another lane as a 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 sequential driving activities, figure 3(b) illustrates the activity based test track segmentation of the 2000ft 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 necessary length to attain the test speed of 30mph with a moderate acceleration from the starting position. To allow vehicles to travel at uniform speed and get confirmation about their location, the uniform speed zone was utilized. The control interval zone was used to send the advisory and record the participant’s response within this zone. The last section, speed reduction zone, was used for vehicles to safely reduce speed and get prepared to stop.
Scenario Description
To conduct the field test, a detailed field test procedure, test protocol and test script was developed by the research team. The order of the scenarios was randomized to eliminate any bias in the data gathered and minimize the learning effects of the participants. Each of the participants took part in all the nine test scenarios.

Following are the typical procedural steps followed for each scenario run:

- Before the beginning of a particular test scenario, all the three research vehicles were positioned at designated locations for that specific scenario.
- Experimenter on the participant vehicle sent instruction over the radio to all drivers to start driving at the same time and reach the speed of 30 mph.
- Participant driver was instructed to maintain the speed of 30mph and keep driving on the right lane, until any advisory was displayed in the on-board display.
- After all the vehicles drove at the advised speed, the experimenter used the test application to send an advisory to the on-board display.
- Upon receiving the advisory, the participant either complied with the advisory or kept driving on right lane, if they did not feel comfortable following the advisory.
- The participant driver’s reaction to the advisory was recorded by the experimenter.
- At the end of the designated test section, all drivers are instructed to slow down and further instruction is sent for the next scenario.

Following are the brief descriptions of each strategy in the field:

**Variable Speed Limit**
In the VSL scenarios, when all the drivers on both lanes reached the uniform speed of 30 mph, the 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 responding to the advisory rather they should try to change lane and take gaps between the two vehicles on left lane. In case, drivers did not feel comfortable moving to the left lane, they were instructed to keep driving on the right lane. Figure 4(a) illustrates a schematic diagram of this strategy with the VSL advisory shown in the inset on the left bottom corner.

**Lane Changing Algorithm**
For the LCA scenarios, the participant drivers were simply 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 lane and take the available gap on the left lane between the two vehicles, only when they feel comfortable to do so. The gap between the two left lane vehicles was changed from scenario to scenario. Figure 4(b) presents a schematic diagram for this strategy with the LCA advisory shown in the inset on the left bottom corner.

**Merging Control Algorithm**
In the MCA scenarios, the participants received two sequential advisories. The goal of this strategy to help drivers smoothly merge, when adequate gap is not available, by first advising speed changes and then sends lane changing advisory. For example, as shown in figure 2(c), the participant vehicle (green vehicle) on right lane at position 1 does not have enough lag-gap to change lane. In this situation, the merging control algorithm sends acceleration advisory [inset figure 4(c)] to the participant driver. After the participant driver moves to position 2 by
accelerating and have adequate gap to change lane, MCA sends the lane changing advisory. If the driver feels comfortable, he/she complies and takes the gap on the left lane between the two vehicles.

(a)

(b)
Definition of Compliance:

**Lane Changing Advisory:** Compliance for Lane Changing advisory is straightforward. If the participant takes an action to change lane and successfully completes the lane change within the control interval zone, this can be defined as positive compliance or simply as compliance. If the driver ignores it or fails to complete the lane changing action within the control interval zone, it is considered as non-compliance. For example, some drivers did not feel comfortable changing gaps in small gap scenarios and they continued driving on the right lane after getting the LCA advisory; this is simply non-compliance. However, in some cases after getting the advisory, the driver takes initiative to change lane but due to inadequate gap size or some other reason the driver takes longer period of time and fails to change lane within the Control Interval zone but completes the lane change in the speed reduction zone; this was not considered as compliance rather it was considered as non-compliance. The reason that drivers had to complete the lane changing action within a certain zone is because actual freeway merging section has limited length. In real-world if the driver is given an advisory to change lane and he fails to complete the action or take gap between the two vehicles and waits in the merge area for another acceptable gap, essentially the advisory has failed in terms of getting a positive compliance.

**Merging Control Advisory:** The MCA strategy includes two distinct sequential advisories in each test scenario. First the driver receives an acceleration advisory with suggested speed of 35mph.
And then if the driver complies and accelerates to position the vehicle on the right lane to have an adequate gap on the left lane to change lane, the system provides a lane changing advisory. In ideal case, the driver first complies with the acceleration advisory and manages to position the vehicle to get ready to change lane. And after getting the LCA the drivers changes lane. 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 reacted to the acceleration advisory or did not accelerate to the level as suggested by the advisory. But when they were provided with the LCA advisory they complied and changed lane. 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 acceleration advisory but failed to properly position the vehicle on the right lane to get ready for the LCA delivery. In this case, since there was no adequate gap to change lane, the experimenter chose not to send the advisory because in reality the system will also recognize the fact of not having adequate gap on the left lane and hence it will not be sensible or justifiable to provide the driver with a LCA. Driver responses in these cases were recorded as non-compliance because they failed to react in a timely manner. Similar to the definition under LCA strategy, if the drivers did not manage to change lane within the control interval zone, it was recorded as non-compliance even though they finally managed to do so in the speed reduction zone.

**Variable Speed Limit:** Unlike the LCA and MCA scenarios, the definition of compliance is not straightforward. For LCA and MCA scenario the participant just 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 on a freeway merge area to move to the left lane by providing them a lower speed limit only for the rightmost lane. This strategy was evaluated in the traffic simulator VISSIM and results indicated that lower speed limit actually makes some driver to move to left lane, thus creating gaps for the merging vehicle. Since the desired effect of a lower speed limit is not to actually slow down rather move to the comparatively faster left lane, for the Variable Speed Limit strategy compliance is defined as moving to the left lane in response to the new lower speed limit on the right lane. During the pre-test training phase, 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 changing lane they decelerated upon receiving the VSL advisory.

**Post Field-test Questionnaire Survey**
Besides collecting revealed preference data from the field test, a post field-test questionnaire survey was also conducted to collect stated preference data. The SP approach has been widely used for transportation mode choice, route choice and dynamic traffic information study[18], [19]. Due to the limitation of resources, it was not possible to replicate all possible scenarios on the test track. After the field test, the questionnaire survey was provided to the participants to give their response to the different hypothetical situations that will influence drivers’ advisory compliance behavior regarding advisory compliance. The participants responded to a four point Likert scale (0-3), where 0 being strongly disagree and 3 being strongly agree with the statement. First part of the questionnaire collected socio-demographic information and the second part had questions about hypothetical traffic condition 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 is received. The response time is estimated from the difference between the timestamp when an advisory was given and the timestamp when the driver completed the time. The figure illustrates the response time for a given advisory:

The response time gives an indication how quickly the drivers perceive and then react to the advisory. Video data collected from the field test contains the timestamps which was manually retrieved to estimate the response time. Out of the 68 participants, video data is available for 67 participants. In analyzing the response time, response time more than 16 second was not included in the final analysis. Initially the control interval was set to 15 seconds to allow participants react within that time period. However in analyzing response time, maximum 16 second of response time was considered as this equals to approximately 700ft acceleration lane; the assumed length of merging area in developing the FMAS was 730 ft [13].
RESULTS

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

1) Variable Speed Limit
For the VSL scenarios, the compliance rate is similar for the scenarios of large gap sizes (72%) and mid-size gaps (72%). Compliance rate for small gap size scenarios is lowest with more than 55% of the time drivers opted to not following the advisory. The difference of compliance rates between small gap scenarios and both large and mid-gap size scenarios are statistically significant \[ \chi^2 (1, N=68) = 9.78, p < 0.10 \]. This result of compliance rates supports the assumption that drivers are willing to change lane when gaps are comparatively larger and more skeptical about changing lanes where headways between vehicles are small (Figure 3). Earlier simulation evaluation of the VSL strategy indicates that this strategy has potential to improve overall average network performance in condition of high volume and high density traffic on both left and right mainline lanes. Though the compliance rate for small gap scenarios are smallest, 45% compliance rate indicates that in some cases driver will be influenced by lower speed limit to move to left lane thus creating gap for merging vehicle.

2) Lane Changing Advisory
For the LCA strategy, all the participants except one accepted the gaps for scenarios with the largest gap with a compliance rate of 97%. For scenarios with mid-size gap the compliance rate is more than 90 % with only six participants out of 68 did not comply with LCA advisory (figure 3). About 36% of the drivers (25 drivers) did not feel comfortable complying with the lane changing advisory in the scenarios with the smallest gap, which is statistically different\[ \chi^2(1, N=68) = 13.53, p < 0.10 \] with the compliance rate of medium gap scenarios. The gap acceptance behavior for LCA scenarios is similar to that observed for VSL scenarios and supports the notion of drivers’ preference of larger and medium gap sizes. In simulation evaluation, the LCA strategy provided biggest network-wide benefits for biggest gap followed by medium gap and smallest gap strategy resulting in marginal benefits. In addition, sensitivity
The analysis of compliance rate in simulation indicated that at least 90% compliance rate is desirable 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 biggest benefit in low and medium traffic conditions.

3) Merging Control Algorithm

For the MCA scenarios, compliance result indicates that participants were most comfortable in following the advisories for both large gap and mid-size gap scenarios, with non-compliance rate of about 5% in both cases. However, more than 35% of the participant drivers did not comply under small gap scenarios (figure 3), which is significantly different from the response behavior under large \( \chi^2(1, N=68) = 16.23, p < 0.10 \) and medium \( \chi^2(1, N=68) = 18.48, p < 0.10 \) gap scenarios. Though the MCA strategy is a combination of two advisories, drivers did not show greater level of difficulty of complying with the advisories. Simulation evaluation of the MCA strategy showed that significant benefits in terms of network performance can be achieved both at mainline lanes and merging lanes with high compliance rate of 70% or above. Compliance results from the field test indicates that the biggest benefits from the MCA strategy may be achieved under low and medium traffic conditions than under heavy traffic condition. However, a 65% compliance rate under small gap scenarios in the field test indicates that even in highly congested situation drivers are willing to follow proactive speed change advisory to create gaps and then follow lane changing advisory when adequate gaps are available.

![Figure 5: Compliance under VSL, LCA and MCA](image-url)
4) Compliance across gap sizes:
Compliance rates across the scenarios for the three different gaps sizes are similar for both large and medium gap size scenarios. For large gap scenarios, the compliance rate is highest (88%) followed by compliance rate mid-gap size scenarios (85%). And there are no significant \( \chi^2(1, N=204) = 0.551, p > 0.10 \) difference between compliance rates for large gap and medium gap scenarios. On the other hand, about 42% of the drivers did not complied with advisory under small gap scenarios; which has significant difference with the compliance rates of large gap \( \chi^2(1, N=204) = 49.4, p < 0.10 \) and medium gap \( \chi^2(1, N=204) = 39.13, p < 0.10 \). This suggests that drivers will be most comfortable following the advisories in both low and medium traffic congestions. As traffic condition worsens, drivers will be relying more on individual perception, judgment and decision making process rather depending on driver assistive systems. However, compliance under small gap scenario also suggests that some drivers will trust FMAS and will comply with the advisories by taking the advised course of actions. This indicates that this system has the potential to improve merging operation even in high volume traffic condition where the gaps are small and possibility of vehicular conflict is very high.

5) Compliance across strategies:
For compliance across the strategies irrespective of the gap sizes, both LCA (84.3%) and MCA (84.8%) has almost similar compliance rate, with no significant difference. However, VSL has the highest non-compliance rate of 37%, 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 VSL strategy can be attributed to misunderstanding the objective of this advisory. The goal of this advisory is to implement a lower speed limit on the right lane and 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 reduced speed limit advisory, even though they were given specific instructions in the pre-field test training session, about what would be the expected choice for this advisory [Figure 4(a)]. This suggests that it is necessary investigate in a deeper level how drivers understand and then react to a particular type of advisory, and how advisories can be linguistically designed and delivered so that the desired outcomes can be achieved. This also indicates the necessary driver education and training about advancement in transportation technologies.
6) Compliance for different gender groups:

a) Compliance across strategies: For compliance across strategies for different gender groups, similar compliance rate is observable for both LCA and MCA strategies with no significant difference between female and male participants [Figure 7(a)]. For LCA scenarios female participants had a compliance rate of 85% and male participants had a compliance rate of about 83%, with no significant [χ²(1, N=108,96) = 0.0465, p > 0.10] difference in compliance. For MCA scenarios, there was no significant [χ²(1, N=108,96) = 0.0012, p > 0.10] difference in compliance rate, with male participants complied 84% and for female participant complied 85%.
However, for the VSL strategies female participants show a higher compliance rate of 70% compared to 55% compliance rate from male participants, with significant difference \[ \chi^2(1, N=96,108) = 3.4036, p < 0.10 \]

b) Compliance across gaps sizes: For compliance across the three gap sizes for different gender, similar compliance rate is observable for large gap size for both female and male participants with compliance rate of about 89% and 87% respectively, with no significant difference \[ \chi^2(1, N=96,108) = 0.0206, p > 0.10 \]. For medium gap size scenarios, there is significant \[ \chi^2(1, N=96,108) = 2.7749, p < 0.10 \] difference in compliance rate, with female participants exhibit higher compliance rate of 90% followed by male compliance rate of 81% [Figure 7(b)]. Comparing with large and medium gap size scenario, small gap size scenarios have lower compliance rate with 61% for female participants followed by 53% 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 the three gap sizes female participants has the lowest non-compliance rate. If compliance rate is aggregately considered irrespective of gap sizes, the difference in compliance rate between female (80.5%) and male (74.3%) participants is statistically significant\[ \chi^2(1, N=288,324) = 2.9673, p < 0.10 \].
7) Compliance for different age groups

The participants in field test were recruited from different age groups to represent the overall demographics of current licensed US driver population. Recruited participants were divided into four age groups. Though initially it was planned to maintain the actual percentages of US driver population for each groups, due to difficulty in participant recruitment it was not possible to maintain that distribution.

If the compliance rates of different age groups are compared without decomposing to the gender groups, we can observe similar response behavior among all the age groups. Age group 4 has the lowest compliance rate among all the groups. All the other three age groups demonstrated similar compliance rate which ranges from 84% to 79% and there is no statistically significant difference among the compliance rate (Figure 8a). Chi-square test indicates that there is statistically significant difference in compliance rate of age group 4 with all the three other groups age group 1 [χ²(1, N=189,81) = 7.179, p = 0.007376 ], age group 2 [χ²(1, N=135,81) = 6.713, p = 0.009571 ] and age group 3 [χ²(1, N=207,81) = 7.3017, p = 0.006889 ].

When compliance rates within an age group are compared between the male and female participants we can observe similar compliance behavior for age group 1 and 2. In both of these two groups female participants have slightly higher compliance rates than the compliances rate of male participants. However, the difference of compliance rates between male and female participants within each age group has no statistical significance. For age group 3, the
compliance rate of female participants is close to 84% and compliance rate of male participants is approximately 73%. The difference between the compliance rates between male and female participants is found statistically significant \( \chi^2(1, N=117.90) = 2.757, p < 0.10 \). Overall, the compliance rates of both female and male participants are lower compared to all the other groups. Even in this group, female participants have higher compliance rate 66%, compared with 61% compliance rate of the male participants. 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 8: Compliance for different genders: (a) aggregated across age groups, (b) across age groups – male and female
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 highest compliance rates are achieved for large and medium gap size scenarios with no significant difference in compliance rates between these two gap sizes. This indicates that during high and medium traffic conditions when headways between vehicles are relatively large enough so that drivers can comfortably change lane, drivers will be willing to follow the advisories more than that at traffic conditions when gaps between vehicles are comparatively smaller. Though small gap scenarios have 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 deployment of Merge Management strategies, the observed compliance behavior indicates 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 situation, when available gaps are small and there is limited freedom to change lane, 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 highest compliance rates were achieved for both LCA and MCA strategy. By design, the Lane Changing advisory provides very simple and straightforward instruction for the drivers to understand and act accordingly. This strategy can be easily deployed as one of the first Merge Management strategies with minimum resources towards driver education and training. Similar conclusions can be made about the MCA’s effectiveness in improving merging operation. The merging control advisories simply guide the driver to smoothly merge by appropriate speed changes and changing lanes. Participant drivers demonstrated 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 observe significantly low compliance rate comparing with the compliance rates for LCA and MCA. This low compliance rate is due to the fact that the VSL advisory provides a lower speed limit advisory but the goal is to motivate drivers to move to the left lane to create gaps for the merging vehicle. Another approach to deliver this message may to advise drivers about alternate choice(s) in responding to this message. In the case of VSL advisory, the advisory can be delivered as “Reduce your speed to 25 mph or Move to faster left lane”. Therefore, an important
lesson from this study is that it is important to design advisory messages in a way that drivers can readily understand and the desired outcomes are easily achieved.

Age group and gender: Compliance data on both male and female participant drivers indicate that there is no significant difference in most cases. In some cases female participants demonstrated better compliance rate than their male participants. This behavior may be explained may be with the fact that male and female drivers have different level 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 extensive investigation on both laboratory and field setting.

When aggregated compliance rate is considered among the different age groups without decomposing into the two gender groups, it is interesting to see significant difference in compliance rate of older driver participants with the other three age groups. This decrease in compliance rate may be in some cases due to the diminishing driving skills and risk perception with age, however with a very small sample size it is very difficult to reach this conclusion. In addition, it is also need to be proven that the older drivers are lacking in those two critical abilities. Another aspect of lower compliance rates among older drivers may be due to the fact older drivers becoming more cautious and the perception among younger drivers of being immune from the effects of high level risk [20] and consequently being more aggressive in accepting gaps or change lanes.

The compliance rates of female participants within each of four age groups are higher than the compliance rate of the male participants. However the difference of compliance rates between male and female participants was not statistically significant except for the age group 3. Again the higher compliance rate among female drivers can be supported with argument that the female drivers may be more cautious while driving and had better perception 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

1) Variable Speed Limit:
For Variable Speed Limit scenarios, the scenarios with large gap sizes resulted with the lowest average response time of 8.68 sec (s=1.86 sec) [Figure 9]. Scenarios with small gap size resulted an average response time of 8.94 sec (s=1.40 sec). However mid gap size scenarios, the participants reacted most slowly resulting an average response time of 9.01 sec (s=1.82 sec). The difference of response time between the large and mid-size gap scenarios was not statistically significant; \( t(95)=0.8811, p =0.385 \). Similarly the difference of response time between small and large gap scenarios failed to reach statistical significance; \( t(76)=0.6595, p=0.5115 \).

![Figure 9: Response time of Variable Speed limit](image)

2) Lane Changing Advisory
Similar to VSL, for the lane changing advisory, participant drivers more quickly reacted to the large gap scenarios with average response time of 8.43 sec (s = 1.46 sec). For mid gap size scenarios, the participants completed lane change action with an average response time of 8.63 sec (s=1.84 sec). However, for small gap scenarios the participants reacted most slowly with an average reaction time of 8.98 sec (s=1.82). The difference of response time between large and mid-gap size scenario was no found statistically significant; \( t(126)=0.6803, p =0.4975 \). Similarly
the difference of response time between large and small gap scenarios was not statistically significant; t(110)=1.7594, p = 0.0813.

Figure 10: Response time of Lane Changing Advisory

3) Merging Control Advisory
Like the LCA scenarios, participant drivers demonstrated similar trend in behavior in terms of response time. Drivers reacted most quickly for large gap scenarios with average response time of 7.48 sec (s=1.67) and followed by mid gap size scenarios with an average response time of 7.83 sec (s=1.52 sec), and the difference of average reaction time between two scenarios was not statistically significant; t(123)=1.222, p = 0.2241. Similar to LCA, drivers took more time on average to change lane for small gap size scenarios with an average of 8.30 sec (s= 2.13). And the difference of average reaction time between large and small gap scenarios was found statistically significant; t(106)=2.2228, p = 0.0284.
4) Response Time across strategies

If the participants’ advisory response times are compared across the different strategies irrespective of the three gap sizes, we can observe that drivers’ reaction was slowest for the VSL scenarios with an average response time of 8.87 sec (s=1.74 sec). The slow reaction for Variable Speed Limit advisory can be due to at first drivers getting confused with lower speed limit advisory and either slowing down or taking some to think what would be appropriate action to take. The lane changing advisory resulted in average response time of 8.64 sec (s=1.70sec) and significance test indicates no statistically significant difference between average response times of LCA and VSL; t(297)=1.1069, p=0.2692. It is interesting to note that on average driver changed lane quickly under the MCA scenario with an average response time of 7.83 sec (s=1.74 sec). This quick reaction can be explained that by complying with the acceleration advisory, drivers were already placed them in a suitable position for changing lane and after getting the second advisory to change lane, drivers were able to quickly react to that. The difference of reaction time between VSL and MCA was found 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.
5) Response Time across gap sizes

When average response times are compared across the three different gap sizes, irrespective of the strategies, we can observe an increase in the response time with the decrease in the gap size. As observed with each of the specific strategy, the large gap size scenarios have resulted the quickest responses from the participant drivers with average response time of 8.16 sec (s=1.72 sec). For medium gap size scenarios, the participants reacted with an average response time of 8.45 sec (s=1.78 sec). And the difference of average response times between large and medium gap size scenarios was not statistically significant; t(348)=1.524 , p =0.1284. On average, the participant drivers were slowest in reacting with the advisories during the small gap scenarios with average response time of 8.71 sec (s=1.87 sec). The reason participants took longer time to react with the advisories under the small gap size scenarios may be due to participants being more cautious under small size scenarios. Statistical significance test indicates that the difference between average response times of large and small gap size scenarios is statistically significant; t(296)=2.6002, p =0.0098. However, the difference of average response times between medium and small gap size scenarios failed to reach statistical significance, t(288) = 1.2061, p=0.2288.

![Figure 12: Response time of across strategies](image)
6) Response Time for different Gender

a) Response time within strategies: For average response time within strategies across different gender groups, similar response time is observed on average between female (M=7.81 sec, s=1.69 sec) and male (M= 7.84 sec, s=1.85 sec) participants for MCA scenarios. For VSL scenarios, the average response times for female and male participants were 8.93 sec (s=1.89) and 8.79 sec (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 average response time of 8.719 sec (s=1.57 sec) and 8.58 sec (s=1.819 sec) respectively, with statistically significant difference; t(170)=0.5232, p=0.6015.
b) Response time across gap sizes: For comparing average response times within gap sizes for different gender groups irrespective of strategies, we can observe similar trend as observed within specific strategies. As gap size decreased, drivers reacted more cautiously with the advisories by taking more time to change lane. For large gap size scenarios, Female participants reacted slowly (M=8.25 sec, s=1.69 sec) compared with male participants (M= 8.09 sec, s=1.75sec), with no statistically significant difference; t(177)=0.6142, p=0.5399. For medium gap size scenarios, male and female participants have similar average response time of 8.48 sec (s=1.89 sec) and 8.42 sec (s=1.68sec), with no statistical significant difference; t(169)=0.1933, p=0.8469. Both male and female participants reacted with the advisories slowly when compared with large and mid-gap size 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 were not statistically significant; t(117)=0.5910, p=0.5557.

![Figure 15: Response times within gap sizes for different gender](image)

7) Response Time for different age groups
As mentioned earlier, the participants were recruited for different age groups to represent the overall demographics skill of US driver population. Drivers among different age groups have different level of risk perception and may demonstrate different level of aggressive diving behavior [21]. If aggregated average response time is considered without decomposing to gender level, we can observe that age group 1, responded most quickly than all other groups with an average response time of 8.11 sec (s=1.47 sec). Among all the age groups, age group 4 which
includes participants 65 years or older, was slowest (M = 8.90 sec, s = 1.76 sec) on average in responding with the advisories. However, the difference of average response times between age group 1 & 4 failed to reach any statistical significance; t(28)=1.276, p=0.2124. This may due to the small sample size (9 participants) of age group 4. Participants of age group 2 (35-49) reacted slightly quickly compared to age group 4 with an average response time of 8.76 sec (s=2.28 sec). However, the difference of average response times with age group 2 and age group 1 was not found statistically significant; t(34)=1.0448, p=0.3035. Similarly the difference between age group 2 and age 3 average response times failed to reach statistical significance; t(36)=0.7647, p=0.4494.

Another approach of analyzing response times is to decompose into different age groups. Among all male participants of the four age groups, male participants in group 2 have 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 of age group 4. Male participants of age group 1 reacted most quickly (M= 7.88 sec, s =1.35 sec) among all the age groups of both male and female participants. However, the difference of average response time between male participants of age group 1 and age group 2 is not statistically significant; t(18)=1.277, p =0.2178. Among female participants, age group 4 was the slowest in responding with the advisories with average response time of 9.02 sec (s=1.61 sec), followed by the female participants of age group 2 (M = 8.58 sec, s = 2.03sec). However, with a very small sample size of 3 participants for the age group 4, it is not possible to attain any significant conclusion about the response behavior for this age group. Age group 3 female participants were quickest among all the female participants with average response time (M= 8.23 sec, s =1.65 sec). However, the difference of average response time of age group 3 with both age group 2 and age group 1 were not statistically significant.
Discussion on Advisory Response Time

The average advisory reaction time across the different strategies indicates whether drivers reacted quickly or slowly. For both MCA and LCA strategy, we can observe similar trend in the average reaction times across the different gap sizes. As gap size decreases, the average reaction time increases. This can be explained that for large gap size scenarios, the drivers feel comfortable in following the advisories and changing lane as the available lead and lag gaps are bigger than the critical gaps. The average reaction time increases for the medium gap size with the decrease of gap size. This indicates that as gaps are decreasing the drivers are becoming more cautious and their perception of level of risk is also increasing. This results in less risky
driving behavior from the participant drivers and consequently drivers reacting more slowly compared with their reaction for large gap size. Finally, we see that drivers reacted slowest for the small gap size scenarios as the available gap on 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 make sense in a way that before making the final decision to change lane drivers wanted to make sure that they can change lane safely and reduce the conflict with vehicles on the target lane. This may result in drivers checking and ensuring multiple times that their perception of available gap is accurate; which results in higher reaction time on average for small gap scenarios.

For the VSL strategy, we can observe that the average reaction time did not follow the exact trend as for the LCA and MCA scenarios. In addition, when compared across the strategies the As mentioned earlier the variable speed limit strategy provides lower speed advisory to the drivers. Before the beginning of the field test, during the pre-test training phase the drivers were instructed to ignore the lower speed limit and change lane if they feel comfortable. However, some drivers were confused with the lower speed limit during the field test and it resulted in lower compliance rate. Even though some drivers remembered the instruction from the training phase and change lane, they reacted in a slower manner than they did for other two strategies. The reason for slower reaction time may be driver first getting confused with the slower limit advisory and in some cases slow down before changing the lane.

If the average reaction times are compared across the strategies, participant driver react slowest under the VSL strategy; which my due to the confusion and slight slowing down before changing lane as explained above. It is interesting to observe that the drivers reacted with MCA advisory significantly quickly than the other two strategies. The lower reaction time for MCA strategy is due to the fact that drivers already complied with acceleration advisory and placed them in a better position to change lane before getting the second advisory to change lane. In this case, drivers were comfortable with their placement of the vehicle to change lane and required less time to verify their position and changing lane after getting the LCA advisory; this resulted in lowest average response time for MCA scenarios.

When the average reaction times were compared across the gender groups, we can see female participants reacting slower than the male participants for VSL and LCA scenarios. For MCA
scenarios, male and female participants have similar average reaction times. The difference of average reaction times for male and female participants was not statistically significant.

For average reaction time across different gap sizes for male and female participants, we see similar trend as observed for within LCA and MCA strategy; as gap size decreased the average reaction times increased. For large and small gap size scenarios, female participants have higher reaction times on average and only for the medium gap size scenarios male participants have slightly average higher reaction times. However the differences in average reaction times between male and female participants within each gap size were not statistically significant.

When average reaction times are compared within the different age groups, we can see age group 1 has the quickest response and age group 4 has the slowest response among all groups. However, the difference in average response times between these two groups is not significant. The average response time of age group 2 is higher than age group 1 and 3, however again the difference in average response times between the groups are not statistically significant. The slowest average reaction time from age group 4 can be explained that older driver participants demonstrate less risky and aggressive driving behavior than their younger counterparts. Age group 1 participants resulted the quickest response due to the risk taking behavior tendency of younger participants.

**Post Field-test Questionnaire Survey**

1) **Compliance under different traffic condition:**
After the field test, the participants were asked in the survey how they would respond to the advisories under different traffic conditions in the real-world. Participants stated that they are most likely to follow the advisory in medium traffic congestion. Only 3 people (4%) out of the 68 participants stated they will not follow advisory under medium congestion. Under free-flow condition, 90% stated that they will comply with the advisory and 10% stated not following the advisory. The non-compliance responses under free-flow condition may be due to participants not understanding the need of an advisory under such condition, when there are large headways between vehicles. As expected, more than 60% participants stated that they will not follow advisory under heavy-traffic condition, when available gaps are small and there is limited
freedom for lateral movements. The result from the questionnaire survey supports the response behavior demonstrated in the field test in terms of preference of gap sizes to follow an advisory.

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

3) Higher speed lane:
Drivers always try to drive on a lane that would provide them the highest driving utility in terms of both safety and speed. Drives may be motivated to follow an advisory, if they can realize that following the advisory will lead them driving on a comparatively higher speed lane. In the survey, participants were presented with a hypothetical scenario, where by complying with advisory the drivers move to a high speed lane. Most of the participants (about 92%) showed willingness to comply with the advisory, with 32% participants strongly agreed with the statement. Only 7% of participants indicated higher speed lane will not motivate them to comply with the advisory. This supports the notion that some drivers prefer travelling on a higher speed lane. This also indicates the drivers will prefer to comply with FMAS advisories, especially with the VSL advisory where the goal of the lower speed limit advisory is to motivate drivers to move to the comparatively faster left lane.

4) Sense of conflict:
In the survey, participants were asked how they would respond to an advisory if compliance helps avoiding a conflicting situation with another vehicle. All the participants showed consent; 42 participants (about 62%) out of the 68 participants strongly agreed with statement and rest of the 26 participants (about 38%) agreed. It is evident from the results that safety always has a greater utility to the drivers and advisories will be preferred by the drivers in situations where
there are high possibility of conflicts between on-ramp merging vehicle and mainline lane vehicle.

5) Presence of a front vehicle:
The participants were asked with appropriate figure whether having a front vehicle in the same lane will influence their compliance decision. Stated response supports this assumption with 75% of participants stated that the presence of a lead vehicle will influence their compliance behavior and 25% of the participants indicate that having a front vehicle in the same lane will not influence their compliance.

6) Presence of a merging vehicle:
In the survey, participants were presented with a statement with appropriate figure to respond to a hypothetical scenario where they comply with the advisory if the driver can see an approaching on-ramp vehicle. 97% of the participants agreed to the statement with only two participants disagreed with statement. This higher percentage of compliance indicates that in traffic situations where drivers can 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 17: Post field-test questionnaire survey](image-url)
Discussion of Post Field-Test Survey

Due to the limitation of resources and time, it is not feasible to test all the possible traffic scenarios in the field test. The post field test stated preference survey provides valuable insight to drivers’ response behavior under different hypothetical traffic scenarios. It is interesting to observe that the participants stated similar preference in complying with the advisories as they demonstrated in the actual field test. As observed from the field test, the compliance rates for both LCA and MCA scenario for large and medium gap size scenarios were close to 90%. Similarly, in the stated preference survey for both free-flow and medium congestion condition the compliance rate is about 90% or more. In the field test the large gap size represented the free-flow condition and medium gap size represented the medium congestion condition. This indicates that there is significant consistency in drivers’ revealed preference and stated preference. In case of the heavy congestion condition, about 38% of the participants stated that they will comply with advisory, whereas in the field test the average compliance rate is about 57%. Therefore we can observe a similar trend in both the field test and survey response; as traffic condition worsens the compliance rate also decreases.

Higher compliance rate under the network familiarity factor indicates that the drivers are willing to trust and follow the advisories from the system even if they are driving in an unfamiliar environment. In some cases drivers are not aware of particular geometric configuration of the ramp area and may feel uncomfortable 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 is a great motivating factors for drivers to follow the advisories. Merging situations often create sense of conflict in drivers especially during heavily congested situation. All the participants stated that they will follow the advisory if they can sense that complying with the advisory will enhance their current driving condition from the perspective of safety.

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

Similar to previous issue, participants indicated that the presence of a merging vehicle will greatly influence their compliance behavior. This indicates that if the drivers understands or observe the justification of a particular advisory they will follow it most of the times. This is very important in designing a system that will have a very low rate of false-positive detections. If they system sends advisories frequently and the driver cannot perceive the justification of the advisories, it will create a sense of annoyance and mistrust about the system. In this case, the driver may choose to disable the system or discontinue its subscription. So it is very necessary to design, implement and deploy any CV-based mobility applications that has very low rate of false-positive.

**CONCLUSIONS AND RECOMMENDATIONS**

With the Connected Vehicles technology, more sophisticated and advanced traffic management strategies can be developed and deployed to address limitations of current approaches. The Freeway Merge Assistance System is one of the example strategies that take advantages of this technology in improving freeway merging operations. It should be however 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 investigate how drivers actually react to the advisories sent by the Freeway Merge Assistance System 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 feel more comfortable following the advisories when large and medium gaps are 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 still willing to follow the advisory even in a high volume traffic condition. Another significant finding from the field testing was that drivers tend to better comply with a direct advisory message, which directly advises the drivers to make a lane change. On the other hand, an indirect advisory message,
which attempts to indirectly stimulate a lane change through speed control, turned out to be less effective.

In conclusion, the actual drivers’ response data collected and presented in this project is one of the first sets of data that allows for better understanding of the realistic driver compliance rate. Given the significance of proper understanding of drivers’ behavior in developing, evaluating, and deploying connected vehicle mobility applications, continuous effort should be made to gather actual drivers’ behavior data which provides valuable insight in drivers’ decision making process.

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REFERENCES


