Impact of Time-to-Collision Information on Driving Behavior in Connected Vehicle Environments Using A Driving Simulator Test Bed

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Abstract—The aim of this study is to develop a driving simulator test bed for a connected vehicle environment and study the impact of communicating safety messages on driver behavior. This was conducted by enabling a lead vehicle to communicate alert messages to the simulator when certain time-to-collision thresholds were reached. Thirty participants, grouped into aggressive and non-aggressive drivers, were allowed to drive the simulator twice; once with the alert messages, and another without the alert messages. Using time-to-collision as a performance measure, a t-test for dependent samples showed that for non-aggressive drivers, there were no differences in their driving behavior. However for aggressive drivers, their driving behavior showed a significant improvement in their overall safety. The findings not only lend credence to the safety benefits of the connected vehicles technology, but also means that a driving simulator test bed can be harnessed to achieve similar goals as physical test beds.

Index Terms—connected vehicles, V2V, driving simulator, time-to-collision, test bed, aggressive drivers, and driving simulator test bed.

I. INTRODUCTION

Recently, the development of a fully connected transportation network has received special attention from researchers, federal and state government agencies, and public and private stakeholders. The concept of connected vehicles relies on vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication technologies, which require a robust platform to allow for not only creativity and interoperability, but also the ability to interact with the complex human behavior. Connected vehicles research relies on the use of test beds to address the potential problems associated with the development and deployment of V2V and V2I technologies. Test beds for connected vehicles research can also be used for testing real time data capture and management systems, as well as testing the integration and interoperability of the connected vehicles, mobile devices, and highway infrastructure. Along with the physical platforms for test beds, driving simulator test beds can also be harnessed to achieve similar goals. More specifically, driving simulators are a high fidelity human-in-the-loop simulation platform that has a great potential to serve as a connected vehicles test bed.

The ability of driving simulation technology to interact with the complex human behavior is of great interest. However, to fully investigate the benefits of connected vehicles using this technology, the use of test beds is required. The use of a driving simulator test bed for connected vehicles allows for a controlled environment to test real-time data capture and the integration and operability of connected vehicles. With the driving simulator, the development of a simulation test bed for connected vehicles is now possible.

Traffic accidents in the U.S. have declined over the last two decades but continue to cost the country billions of U.S. dollars each year. Intersection collisions alone account for about 50% of the total number of annual accidents [1]. A study of the characteristics of these accidents showed that 75% of intersection accidents resulted from driver error including driver inattention, faulty perception, and vision impaired/obstruction. There has been significant effort to overcome this problem, over the past few years and it is viewed that connected vehicle technology may offer a very promising means to reduce, and maybe totally overcome, the driver error factor in intersection collisions [2]. Part of this can be achieved through providing a properly designed system of collision warning messages to drivers at the right time that will allow drivers a suitable reaction time to overcome any potential collision. However, this is not always the case especially with the complex driving behavior that differs within any driver population based on factors such as, mood, age, and gender among others. These factors affect the way people drive in terms of the headway, speed, and perceived risk that is translated into the minimum time to collision value. Driver aggressiveness is the main attribute that captures the different driving styles of people, therefore two levels of aggressiveness were tested for this study.

From this perspective, a preliminary driving simulator test bed was developed in the driving simulator laboratory at Louisiana State University (LSU) so as to
allow a lead vehicle to communicate warning messages to the simulator vehicle (connected vehicles technology) within the virtual environment. A pilot study was then undertaken with a group of aggressive and non-aggressive drivers to assess which group could most benefit from this technology when approaching intersection stop lines. It was anticipated that a successful driving simulator test bed may impact on the driving behavior of the aggressive drivers, and thereby reduce the number of potential collisions at intersections.

II. Background

Over the past few years there has been targeted significant research effort in connected vehicles technology in order to address operational, safety and environmental related issues. In addition, some studies have focused on the drivers’ behavior and response to the existence of the technology and how they handle the information load in their vehicle. It has been determined that providing too much information in the form of multiple warning and/or information in multiple displays may overwhelm and distract the driver. In fact, too much information being presented affect the drivers’ reaction times and may lead to inappropriate responses in emergency situations [1].

The human information processing capability is limited and may involve errors sometimes [3]. Humans process information using three key components: memory, attention, and decision making. Further, the human memory consists of three subsystems that each have their own limitations as to the information they can receive: sensory storage, working memory, and long-term memory. The first memory subsystem is sensory storage, and this type of memory is based entirely on stimuli. When a stimulus is present, the human memory creates a sensory storage that will last until it has been replaced by another stimulus of similar function. However, as a way to separate different stimuli, humans have four different modes of sensory storage: auditory, visual, tactual, and olfactory. This allows humans to retain various stimuli. The problem with sensory storage is that it is only for short amounts of time [4] because the purpose of sensory storage is to retain the information long enough to pass it along to working memory [3]. Working memory uses a coding system to determine the type of information it receives i.e. visual, phonetic, or semantic [4]. [5]. This type of coding allows the working memory to determine which type of information it received from the sensory storage, and then process that information. However, Yang and Fricker note that “one of the most noticeable limitations of working memory is that it has a very limited capacity. The maximum number of items that can be held in working memory is 7±2 ‘chunks’.” [3]. This is an interesting observation because the findings suggest that if information can be pieced together into meaningful chunks then working memory space can be maximized. As new information enters the working memory, it is held temporarily until it is encoded and stored permanently in the long-term memory. The information stored in the long-term memory can be retrieved either by recall, if the entire stored information has to be retrieved, or recognition, if it is only to find out whether or not a specific piece of information is stored in the long-term memory [6].

With the rapid advances in the transportation system, such as the Advanced Traveler Information Systems (ATIS) and the in-vehicle information systems (IVIS), drivers are prone to have divided attention between the driving and the information processing tasks. In that context, Yang and Fricker [3] conducted an experiment to determine the amount of information that is considered to be too much for a driver to process, and to determine which way of conveyance is most effective. They used a driving simulator to simulate familiar and unfamiliar areas to the subjects. The responses when given twelve different information combinations for both familiar and unfamiliar areas were evaluated. Their findings showed that when a driver is in a familiar area, the need for a visual display (e.g. a map) is not necessary due to the fact that a driver will rely on their prior knowledge of the area. The opposite is observed when the driver is in an unfamiliar area. They also found that a visual display was more effective when accompanied with an auditory message that alerted drivers.

Lloyd et al. [2] studied the most effective means to convey potential collision information at intersections. They began by analyzing the occurrence of collisions at intersections using the National Automotive Sampling System (NASS) crash data, and found that together, driver inattention (28.7%), faulty perception (33.9%), and vision impaired/obstructed (11.1%), accounted for nearly 75% of intersection crashes. This shows that a majority of crashes are caused by a lapse in judgment in some manner. In their study, the authors analyzed different means for conveying the potential collision information and found two types of warning systems that could benefit a large group of people in the most effective manner: heads-up-display (HUD) and haptic cueing. The main finding of this study was that using a combination of these technologies can be the most effective way because drivers could be stimulated with a haptic cue, and then alerted to the situation approaching so that a proper reaction could be performed. However, the warnings have to be simple and short as lengthy and complex messages could rather prove distracting and reduce safety.

In another study, Lloyd et al. [7] explored when and how to present warning messages of a stop when approaching signalized intersections in order for drivers to optimally perform safe reactions. The authors analyzed drivers’ behavior data and focused on four main parameters: throttle lift-off, brake application, steering, and turn signal activation. In their analysis, the authors found that the optimal time to alert drivers when to stop was 15 seconds before reaching the intersection. They also suggested that alerts should be such that they should benefit all drivers, not require specific directional orientation, be compatible with drivers’ response, and have a viable integration with other Collision Avoidance Systems (CAS) and Driver Assistance Systems.
Based on these characteristics, the authors analyzed the effectiveness of both visual and auditory messages. For the auditory messages, the results showed that a tone alert would not benefit all drivers especially drivers with a hearing disability; whereas, a voice command was found to potentially cause a driver to experience attention overload. For the visual messages, HUD was found to be effective but could potentially lead to distraction and compromise safety if not located in a forward view position.

Fitch et al. [8] tested the Connected-Vehicle Collision Avoidance System (CAS) applications using a Wizard-of-Oz technique. The main objective of the study was to test whether to present multiple crash alerts in multiple conflict scenario, or present only one alert to the first conflict and suppress the subsequent alerts. The results of study suggest that presenting multiple unique auditory alerts in a multiple conflict scenario was appropriate to most of the drivers provided. This supports the first part of earlier studies [9]; [10] that state that multiple alerts in multiple conflicts can provide drivers with the appropriate guidance to conduct the appropriate avoidance maneuvers. However, the results conflicted with the second part of the studies which states that any alerts presented after the first alert could confuse and distract the drivers. Therefore, Fitch et al. [8] concluded that their results need to be investigated further.

Jeong et al. [11] conducted a simulation study to evaluate the proposed Inter-vehicle Safety Warning Information System (ISWS) aimed at improving drivers’ attentiveness through providing warning alerts about potential hazards in a connected vehicle environment. They used a crash prone location in the Korean freeway system to collect data about drivers’ behavior in different situations and then transformed into a VISSIM simulation model. The results showed that with a 100% market penetration, the number of rear-end conflicts was reduced by around 84% under level of service D. However, for free flowing conditions, the ISWS did not show any significant impact on drivers’ safety as the conditions are already stable.

### III. METHODOLOGY

In this study, the main focus was on designing a message alert system, based on time-to-collision between two vehicles, in a driving simulator environment and analyzing the driving performance of a sample of aggressive and non-aggressive drivers to determine if there were any safety benefits to either group of drivers.

#### A. Design of Connected Vehicle Test-bed

The following subsections present detailed discussion of aspects of the driving simulator test bed.

**Driving Simulator Features:** The driving simulator at Louisiana State University (LSU), shown in Fig. 1, consists of a full-sized passenger car modeled after a Ford Focus automobile, and combines with a series of cameras, projectors and screens to provide a high fidelity virtual environment. The simulator has an audio software and hardware plus real time one degree of freedom motion in the forward-backward direction so that participants can drive with engine sound, tire sound and noise from the vehicle. The driving process almost mirrors the realistic driving task of an actual vehicle. Participants have to put the car in motion, use mirrors for better visual awareness, and react to other vehicles in traffic. Two computers control the simulation, one screens the image that is being captured by the cameras, and two more are used for data analysis. The simulator is able to gather sensing data such as vehicle speed but has not been programmed to collect any data on the ambient traffic. Also, digital cameras installed within the vehicle, are linked to the application software, Sim Observer, to collect video that is time-referenced with the sensing data. Its flexible scenario creation interface and customizable highway system design tools allow for the driving scenarios to be changed based on weather conditions, roadway surfaces and environments, and also allows for other options to be added by the application software SimVista. The dynamics of the simulator itself can be modified by the application software SimCreator; a graphical simulation and modeling system. In addition to those programs, there exist the JavaScript files, scripted vehicle activity in C/C++ code components, and can be used to call up functions during the simulation to either control aspects of Sim Creator or the SimVista. For this study, the JavaScript files were scripted to allow collection of sensing data for the lead vehicle in addition to that of the simulator. One negative side effect of the simulator is motion sickness, and therefore, some researchers discourage the use of the simulator by participants that suffer from balance disorders such as vertigo and dizziness.

![LSU Driving Simulator](image)

(a) Simulator body
(b) The computers control

Figure 1. LSU Driving Simulator.
Location of the Visual Display: To determine which location in the simulator that the alert messages will be displayed to the drivers, a separate survey was undertaken with the view of identifying the preferred location empirically. A simple questionnaire based on Fig. 2 was designed on “Survey Monkey” website and the LSU Civil Engineering pool of graduate and undergraduate students were asked to choose their preferred location.

Out of the 79 responses received, 42% chose Location 1 as their best location for the visual display, 34% chose Location 2, and the remaining 24% chose Location 3. Displaying the visual information at Location 1 agreed with previous studies [12] that suggested that most drivers comply with the messages displayed at that location and identified that location to be the safest for drivers to mount off-the-shelf GPS devices so as to minimize attention lost to the driving task.

Design of Alert Message System: The alerts were designed as visual text messages that warned the driver of imminent potential crash with the lead vehicle. Based on Yang and Fliker’s study [3], it was decided to omit auditory warnings because drivers were allowed to become familiar with the scenario surroundings before the actual test. The first of two visual warning messages was projected onto the driver’s screen in a yellow font as “SLOW DOWN” when the driver’s minimum time-to-collision (TTC) was down to 3 seconds. This is shown in Fig. 3a.

The second visual warning message, displayed in red font, read “SLOW DOWN- POTENTIAL CRASH” when the TTC further dropped to 1.5 seconds, the minimum TTC required for drivers to safely react [13]. This is shown in Fig. 3b. The generation of these alert messages were programmed using the JavaScript files associated with the driving scenario. For the message size to be readable, a 7” frame that mirrors a HUD was projected onto the middle of the windshield. Three participants were asked to assess the readability of the projected message inside the frame and the text size was edited until the three drivers agreed that it was clear and readable within the 7” frame. This made the test-bed very close to simulate a connected vehicle HUD.

B. Participants

Thirty participants aged between 18 and 58 years of age (mean = 27.3, standard deviation = 8.17), and consisting of five females and twenty-five males were recruited from the Louisiana State University’s community of students and staff. They were all of good general health, and were active drivers with a valid driver’s license. They were recruited using flyers on university bulletin boards and in accordance with the university’s Institutional Review Board’s (IRB) standards. No financial incentive or course credit was offered so all subjects participated out of their own interest. To be able to classify them into aggressive and non-aggressive drivers, participants were asked to complete the Larson Driver’s Stress Profile (LDSP) questionnaire [14] but were not informed of the criteria so as to not influence the scoring of their driving behavior. The LDSP was developed by psychiatrist Dr. John Larson for the AAA foundation for Traffic Safety and is a 40-question Likert scale instrument, grouped into four sub-groups of 10 questions each: Anger, Impatience, Competition, and Punishing Behaviors. Participants scored each question on a 0-3 scale (0 = never; 1 = sometimes; 2 = often; 3 = always). Scores were then summed up and participants with a summed score less than or equal to 21 were classified as non-aggressive drivers, while those with greater scores were classified as aggressive drivers. This criteria was selected based on previous studies by Blanchard et al. (2000) [15] and Loretta et al. (2005) [16]. Consequently, there were 20 non-aggressive and 10 aggressive drivers from the subject pool. The validity of the LDSP questionnaire for determining aggressive and non-aggressive drivers has been thoroughly analyzed by Blanchard et al. (2000) [15] who
found the instrument to be “sound, reliable, and valid scale for use with aggressive driving”.

C. Experiment Design and Procedure

The experiment was designed as a pre-post-test study with all thirty participants required to drive the simulator with and without the alert message system within the developed test bed scenario. The test route consisted of a divided four lane road within urban settings with corresponding road furniture. It had a solid double yellow line down the center, solid white lines on the outside edges, dashed white lines separating the two lanes that go in each direction, and on a flat grade with a posted speed limit of 35 mph. Drives with alert messages resulted in the warning messages being generated as described under ‘Design of Alert Message System’, while drives without the alert messages did not produce any warning messages.

Upon arrival at the driving simulator lab, participants were briefed on the experiment and asked to review the university’s IRB approved consent sheet before signing it. This was then followed by completing the LDSP questionnaire. Participants were then asked to draw a card to determine the order of their drives (with or without alert messages). The drives were randomly determined in order to nullify any learning effect. Each participant was then allowed to practice with the driving simulator until such time that they became familiar with the controls and its operation. The actual test then followed with participants being asked to drive as they would normally on their way to work or college but to always stay in the right-lane, avoid changing lanes or overtaking, and maintain a consistent following distance that they considered as safe.

D. Data Collection and Analysis

Data was collected for only when the vehicles were within 20 seconds of approaching an intersection stop line due to earlier studies [7] suggesting 15 seconds as the minimum time required for drivers to react to warning messages at stop lines. Each participant’s velocity (\(V_l\)), lead vehicle’s velocity (\(V_l\)), and headway distance (\(D_h\)) between the participant’s vehicle and the lead vehicle for both drives were collected at 60 Hz frequency through the proprietary software of the driving simulator. The time-to-collision for each participant (\(TTC_i\)), defined as the time in seconds for the participant’s vehicle (of length \(l\)) to make contact with the lead vehicle, was calculated for each drive and for all the observations as follows:

\[
TTC_i = \frac{D_h - l}{V - V_l} (1)
\]

For each participant, the mean value of \(TTC\) was then computed for each drive so that the final data consisted of one row of data for each participant containing four columns: participant ID; mean TTC for the drive with alert messages; mean TTC for the drive without alert messages; and the difference in means between the TTCs for the two drives. The data were then organized into two separate groups based on aggressive and non-aggressive drivers and analyzed separately.

Because the same participant carried out both drives, the samples were treated as dependent and subjected to a dependent t-test in ANOVA to find whether there were any differences in the driving behavior of the subjects as they were exposed to the alert messages. The paired sample test was appropriate as it did not impose an equal variance assumption on the two drives, and exclusively allots any difference between the mean TTCs for the two drives to the presence of the alert messages. Prior to the t-test, the data was checked for violation of the normality assumption. All statistical analysis were undertaken using SAS Enterprise Guide 4.3.

IV. RESULTS AND DISCUSSION

A formal test of the normality assumption was performed for the difference in means between the TTCs for the two drives for all participants. The result (Shapiro-Wilk’s statistic = 0.9478, \(p = 0.1479\)) was not significant at 0.05 level of significance, and hence, the normality assumption was not rejected. This is a required assumption of the t-test for dependent samples.

The t-test for dependent samples was performed separately for the aggressive and non-aggressive drivers. The null and alternative hypotheses tested in each case were:

- \(H_0\): There is no significant difference between the mean TTC observed without and with alert messages.
- \(H_1\): There is a significant difference between the mean TTC observed without and with alert messages.

Figure 4. TTC profile plot for drivers with and without alert messages.

For non-aggressive drivers, the result \([t (19) = -0.32, p = 0.7561]\) suggests that the null hypothesis cannot be
rejected at a 5% level of significance. On the other hand, for aggressive drivers, the result \[ t(9) = 2.58, p = 0.0297 \] suggests that the null hypothesis can be rejected at the 5% level of significance, leading to the conclusion that the display of alert messages caused a significant difference in the driving behavior of aggressive drivers. Furthermore, Fig. 4 shows the profile plots for the two groups of drivers: TTC values for the drives with and without alert messages.

The profile plot for the non-aggressive drivers suggests that while the difference between the drives with and without alert messages was not significant, the mean TTC for the drives with alert messages was slightly lower than the drives without alert messages. This means that for drives without alert messages, the non-aggressive drivers drove with slightly more caution than they would normally do. Upon analyzing their video data, it was obvious that a few of them tended to drive closer to the lead vehicle during the drive with the alert messages. When interviewed, they expressed that they knew they would be prompted by the alert messages when they were too close to the lead vehicle and that influence their driving behavior.

V. SUMMARY AND CONCLUSION

Connected vehicles technology has been acknowledged to have operational benefits in terms of reducing travel times and delays for the traveling public, as well as lessening the environmental impact in terms of reducing vehicle emissions and air pollution. The deployment of such technology offers an opportunity for economic development by targeting improvements in the areas of traffic operation, safety, and environmental impacts. However, to be able to fully assess its reliability and potential benefits, it requires the use of test beds which will additionally address unforeseen and potential issues associated with the development and deployment of the technology. Simulation-based test beds, harnessing a driving simulator platform, can be utilized to achieve the benefits of a physical test bed and if successful, will provide a cheaper alternative that can be easier controlled for desired effects. For this study, a preliminary driving simulator test bed was developed using the LSU driving simulator and through manipulation of appropriate proprietary software. A survey was conducted to determine where best to display two different alert messages based on the time-to-collision between the simulator and the lead vehicle. A sample of aggressive and non-aggressive drivers were recruited and their driving performance at approaches to intersection stop lines analyzed for differences in drives with the alert messages and drives without. The performance measure used to analyze the drives was time-to-collision since emphasis was on avoiding collisions at intersections. Upon carrying out a t-test for dependent samples for each group of drivers, the results showed that the non-aggressive drivers did not significantly change their driving behavior when exposed to the alert messages. On the other hand, aggressive drivers significantly changed their driving performance by slowing down more at intersections and increasing their time-to-collision. It was also observed that aggressive drivers activated more alerts than the non-aggressive drivers, implying the alert message system was successful in altering their driving style. The successful development of the preliminary driving simulator test bed means future sensitivity tests can be undertaken to ascertain the optimal moment to prompt the activation of the alert messages. The addition of audio prompts to the current visual alert system can also be explored and a larger sample size can be utilized to analyze demographic effects of such technology. It is acknowledged that the present sample size is a limitation of the study. In addition, other driving characteristics such as speed, acceleration and time headways could be analyzed before and after the alert message in order to investigate potential adaptation effects in driving behavior. Furthermore, the preliminary test bed can be enhanced to allow more vehicles to communicate within the generated network of the driving simulator environment, and further benefits of the V2V technology explored.

REFERENCES

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