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A driving simulator study to evaluate the impact of portable changeable message signs (PCMS) on driver speed characteristics

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A DRIVING SIMULATOR STUDY TO EVALUATE THE IMPACT OF PORTABLE CHANGEABLE MESSAGE SIGNS (PCMS) ON DRIVER SPEED CHARACTERISTICS

By

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ABSTRACT

This research project examined the effects of sequential Portable Changeable Message Signs (PCMS) on driver behavior in work zones. PCMS are temporary traffic control (TTC) devices, part of Intelligent Transportation Systems, which supplement static signs to provide advance warning and real-time information to drivers. Text and number based messages are displayed on the PCMS for which detailed evaluation has not been carried out before. This research fills this gap using a driving simulator (DS) supplemented by objective and subjective surveys. A work zone on I-44 in rural Missouri was replicated in the DS using video recordings and GIS (Geographical Information System) data. The DS experiment consisted of five scenarios (0-4). The control scenario (scenario-0) was compared to scenarios 1-4. In the DS, evaluation of the four message signs displayed on the PCMS used by the Missouri Department of Transportation (MoDOT) and their effects on drivers' speed was carried out. The results from the experiment showed significant decrease in speed of driver as a result of the type of messages displayed by the PCMS. From the objective analysis results, message sign-4 (MS-4) saw the maximum decrease in the speeds of drivers when compared to the control scenario. The subjective (survey) results showed that MS-2 was the most preferred message as it displayed a specific speed limit for the participants to follow. Also, the 85^{th} percentile speeds before the construction zone closely matched with the displayed speed for MS-2. The results obtained from the subjective survey reinforced the fact that PCMS were effective in reducing the speed of the drivers.

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1. INTRODUCTION

1.1. BACKGROUND

Work zones pose a significant risk in terms of safety of both construction workers and drivers. To minimize this risk Portable Changeable Message Signs (PCMS) are used. PCMS, an example presented in Figure 1.1, are also known as Dynamic Message Signs (DMS), Variable Message Signs (VMS) and Changeable Message Signs (CMS). The basic premise for deployment of these signs is to provide the travelling public with real-time traffic information such as slowing/stopped traffic conditions due to work zones (construction, repair and maintenance of highways). PCMS help alert the drivers to what may lie ahead in work zones (Wang and Dixon, 2003). PCMS are also used for incident management and to increase drivers' compliance with posted speed limits (Horowitz and Weisser, 2003).

Figure 1.1 Example of a PCMS

Work zones are vulnerable to crashes, especially fatal crashes. Figure 1.2 shows the number of work zone fatalities between 1994 and 2010. In 2010, 87,606 crashes occurred in which 37,476 people were injured in work zones. Further, 514 crashes were fatal causing 576 deaths in work zones (FHWA 2011). Though the work zone fatalities have decreased in the past 10 years, the total number of injury crashes and fatalities is still alarming. In work zone studies (Garber et al. 2002; Chambless et al; 2002), speeding was found as one of the main factors responsible for fatalities and injuries (33% of the total fatalities and injuries).

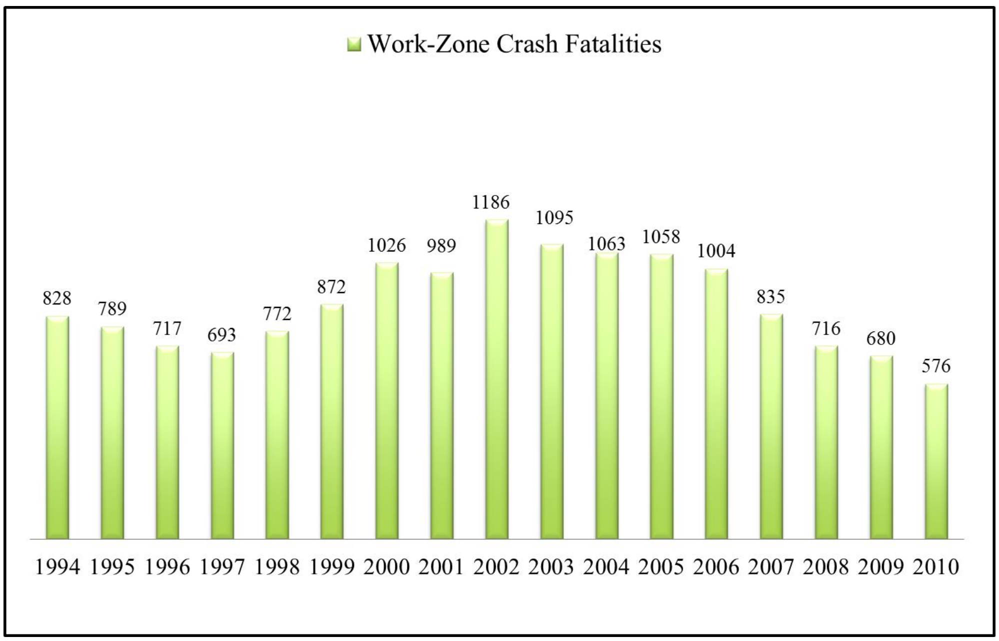


Figure 1.2 Work zone crash fatalities from 1994 to 2010

The losses due to work zone crashes are aplenty. Work zone crashes constitute about 10% of overall congestion, which roughly translates to annual fuel loss of over 700 million dollars. In 2010, the total amount of fuel loss estimated was 1.9 billion gallons. Additionally due to work zone activities, congestion causes loss of around 3.7 billion hours and 2.3 billion gallons of fuel every year. Furthermore, work zone activities on freeways contribute about 482 million hours of non-recurring delay (FHWA 2011). These losses caused by work zone crashes have raised an urgent need to make work zones safer and cause minimal delay.

1.2. PROBLEM STATEMENT

In recent years, PCMS have been broadly employed as part of Temporary Traffic Control (TTC) measure across the world (United States, China, UK, etc.), thereby advising motorists of unexpected traffic and routing conditions (FHWA 2009). When used appropriately, in conjunction with static signs, these signs can command additional attention from drivers, thus increasing safety and reducing crashes in work zones (FHWA 2003). Further, PCMS can provide a wide variety of real time information to motorists, making them another useful tool for traffic engineers to impact driver behavior and increase work zone safety. Text, number, and graphic based PCMS are now deployed by DOTs to provide traffic information to passengers.

The primary objective of this research project was to evaluate the use of PCMS to determine their potential for reduction of speeding in work zones, thereby reducing the current high number of crashes in work zones. This project focused on vehicle speeds before and after a PCMS and before the start of a construction zone. A driving simulator was used as a tool to analyze the speeding behavior of drivers. Therefore, the study analyzed drivers’ speed characteristics (mean, variance, and the 85^{th} percentile speed). This project also determines the effectiveness of PCMS by using speed as the measure of effectiveness.

1.3. THESIS ORGANIZATION

This thesis is organized into six sections as follows.

Section1: Introduction to the research project. This chapter also includes the background and the research problem statement.

Section 2: Objective, Scope and Methodology. This chapter includes the main objectives of the research project, the scope, the future implications and the methodology followed.

Section 3: Literature Review. This chapter contains extensive literature review carried out regarding the usage of PCMS in highway work zones, studies conducted to analyze the effectiveness of PCMS, human factors in highway safety, measures of effectiveness employed by various researchers and the statistical approaches used.

Section 4: DOT Survey Results. This chapter discusses the DOT survey results.

Section 5: Objective and Subjective Analysis. This chapter presents the results of analysis of driving simulator and post experiment questionnaire data.

Section 6: Conclusion and Recommendations. This chapter draws conclusions from the results obtained and provides recommendations.

2. OBJECTIVES, SCOPE AND METHODOLOGY

2.1. RESEARCH OBJECTIVES

The main objective of this research project was to analyze the effectiveness of PCMS placed sequentially in highway work zones using a driving simulator and their impact on driver behavior. The research also studied drivers' comprehension of each message and their reaction before and after each sign. These objectives were completed through data collection from the simulator and pre-driving and post-driving questionnaires. The other objectives are:

1. To identify and review common practices followed by the Departments of Transportation (DOT) in the United States, other agencies and researchers both nationally and internationally to assess the research carried out.
2. To examine the effectiveness of different messages displayed on the PCMS by using a driving simulator.
3. Assess the driver perception of different PCMS.

The first of the above objective was accomplished by reviewing the literature and surveying the common practices among DOTs using an online survey questionnaire. The second objective was accomplished by developing scenarios in a driving simulator. This task was achieved by conducting experiments in the driving simulator and collecting vehicle speed data along the highway and analyzing the speed data by using statistical methods. The results were obtained from the post-experiment surveys and analysis using different statistical approaches.

2.2.RESEARCH SCOPE

Speeding was found as the main cause for work zone crashes (Li, 2011; Garber et al. 2002; Chambless et al; 2002). Any reduction in drivers' speed (if any) before the construction zone as a result of PCMS can be helpful in reducing the severity of crashes thereby saving lives. This is a strong motivation for this study.

The use of a driving simulator helps researchers conduct experiments in a controlled environment, enable reproducibility and standardization; ease in data collection and the possibility of dangerous and hazardous driving are annulled. The drawbacks of performing the experiments in a driving simulator are limited physical, perceptual and behavioral fidelity. The results obtained from this research study was not compared to any field data, but growing evidence suggests that driving simulator measures are predictive of on-road performance (Pradhan and Hammel, 2005). Extensive data analysis keeping these limitations in mind will yield results that are relatively (if not absolutely) comparable to realistic driver behavior.

The ongoing research combines qualitative and quantitative analysis of the participants' behavior in a driving simulator when exposed to different messages on the PCMS. A factorial analysis was carried out to design the experiment for testing the behavior of participants from various age groups and different gender.

The analysis was carried out for 1000 feet before each PCMS and 1000 feet after each PCMS. 800 feet was considered as an adequate length to analyze the impact on driver behavior as a result of PCMS (Boyle and Mannering, 2004). This criterion was used a baseline to evaluate the effectiveness of PCMS. The same MS was displayed on all the four PCMS for a given traffic condition. The experiments performed in the driving simulator replicated this exact same procedure; hence a particular scenario contained a same MS displayed on all the four PCMS. All the MS were tested only for light traffic, as testing them under medium and heavy traffic conditions would cause a confounding effect (change in driver behavior either due to the traffic or the message signs).

2.3. RESEARCH METHODOLOGY

Figure 2.1 presents the research methodolgy. Participants were recruited from different age groups and tested in a driving simulator. In addition to this, state DOTs were surveyed on the best practices and the usage of PCMS. This section explains in detail the DOT survey, the driving simulator setup, the analysis of data obtained from the simulator, and the questionnaires (pre-screening, pre-driving and post- driving) used.

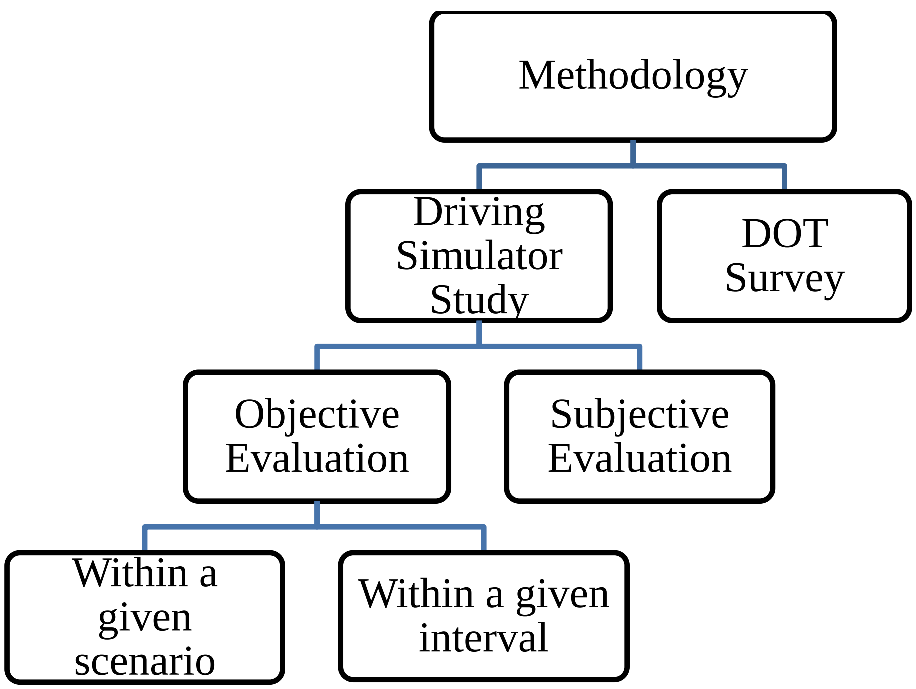


Figure 2.1 Research methodology

2.3.1. DOT Survey. The purpose of the DOT survey was to study the on-going best practices regarding the implementation of PCMS and its effects on driver behavior.

The objectives of the survey were:

1. To analyze the conditions when PCMS were used.
2. To determine the criteria for the selection of type of message.
3. Measures of effectiveness employed to examine the PCMS when compared to the static signs.
4. To determine the performance evaluation for PCMS.

Based on the above objectives, a survey was developed online. The survey also asked for any challenges and suggestions regarding PCMS evaluation. An email was sent to highway agencies and DOTs in the United States responsible for PCMS implementation, its operation and evaluation. Follow-up emails were sent to maximize the comprehension of the recorded response and to gather additional information to enhance the ongoing research.

The first objective was to review the states for the conditions under which they prefer using PCMS rather than conventional static signs. This objective concentrated basically on the reason why PCMS were deployed in work zones. The second objective was used to gain knowledge about the common practices (best practices) employed by agencies in selecting the displayed messages. The third objective concentrated on the various measures of effectiveness used by agencies to evaluate the effects of PCMS when compared to static signs. Questions pertaining to speed reduction, safety and driver behavior were asked. The fourth objective was an attempt to learn about the existing methods of evaluation for the PCMS's performance evaluation.

The DOT survey was conducted for eight weeks in March and April 2012. Twenty-four DOTs out of more than fifty responded.

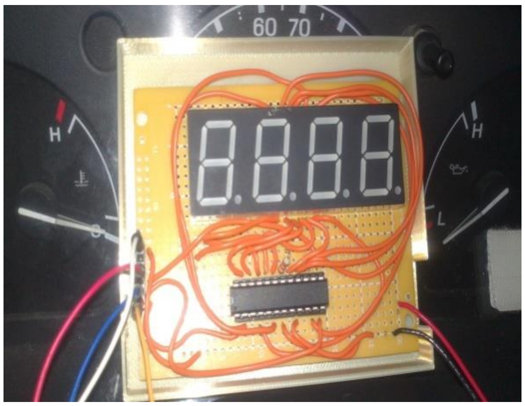
2.3.2. Driving Simulator Study.

2.3.2.1. Missouri S&T driving simulator. The driving simulator at Missouri S&T is a fixed-base driving simulator with a Ford ranger pickup making up the cabin (Figure 2.2a). The cabin includes a steering wheel assembly (Figure 2.2b), a LED 7-segment display (Figure 2.2c) based microcontroller (Figure 2.2d) that also acted as the data acquisition system and the speedometer, three LCD projectors (Figure 2.2e) having 3000 lumens each, a projection screen (Figure 2.2a) and a master computer. The speedometer assembly is illustrated in Figure 2.2f. The steering wheel is encompassed with force feedback to ensure realistic driving. The data acquisition board records the speed, vehicle position, acceleration, deceleration and the steering angle.

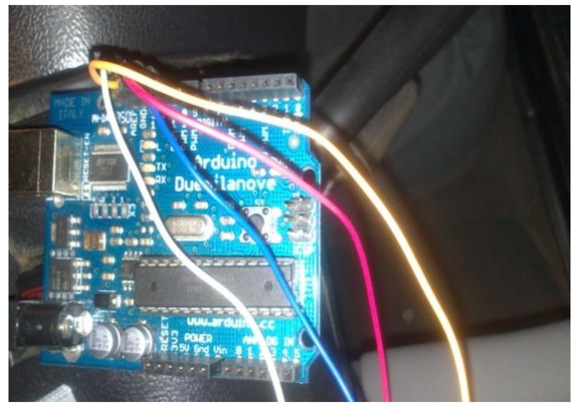
The projection screen has an angle of 52.5°, an arc width of 25 feet and a height of 6.6 feet from the ground. The field of view is 115°. The force feedback mechanism, the spring force, and the degree of rotation of the steering can be controlled. The steering mechanism can also be adjusted to a particular game engine as needed.

(a) Cabin

(b) Steering

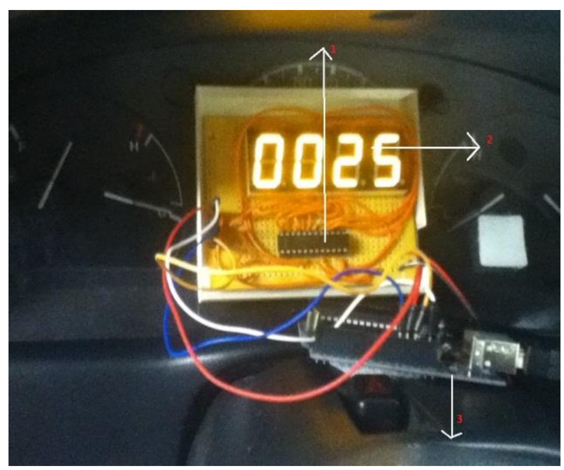


(c)Seven segment display



(d)Arduino board

(e) LCD projectors



(f)Speedometer assembly

Figure 2.2. Driving simulator components

The pixelation on the three projectors is the same (1280 x 1024) and this reduces the distortion of the ongoing simulation.

2.3.2.2. Virtual work-zone setup. The virtual work zone setup replicated 6.2 miles of the I-44 (interstate) westbound highway for a resurfacing project near Waynesville, Missouri. This I-44 section is a rural divided four-lane highway with a speed limit of 70 mph that connects St. Louis with Springfield. The highway was terrain mapped starting from mile marker 166.2 westbound till 159.0 (that included a mile of the construction zone). The first PCMS was placed at mile marker 166.0; the second PCMS was placed in between mile markers 164.4 and 164.2; the third PCMS was placed between mile markers 162.8 and 162.6; the fourth PCMS was between mile markers 162.0 and 161.8. The construction zone started at 160.4. From the construction zone, the first PCMS was 5.6 miles, the second PCMS was 3.9 miles; the third PCMS was placed 2.3 miles and the fourth PCMS was placed 1.5 miles. For a given scenario, same messages were displayed on all the four PCMS. Table 2.1 shows the different message signs used by MODOT. In the real world scenario; Message-sign-1 (MS-1) (used when average speed of the vehicles are 50-70 mph) was used for low traffic conditions (volume of traffic less than 1000 vehicles/hr/lane measured at a given point). Message-sign-2 (MS-2) (used when average speed of vehicles is 20-50 mph) and message-sign-3 (MS-3) (used when the average speed of vehicles is 5-20 mph) were used for medium traffic condition (volume of traffic ranging from 1000-1800 vehicles/hr/lane measured at a given point). Message-sign-4 (MS-4) (used when the average speed of vehicles is less than 5 mph) was used for heavy traffic conditions (volume of traffic greater than 1800 vehicles/hr/lane measured at a given point). Figure 2.3 illustrates the work zone setup.

Table 2.1 Message-signs used in the I-44 work zone and scenarios

Scenario/Message Type	PCMS#1	PCMS#2	PCMS#3	PCMS#4
Control Scenario (No message)	No Message Displayed	No Message Displayed	No Message Displayed	No Message Displayed
Scenario-1 (Message Sign-1) MS-1	CAUTION WORKZONE AHEAD REDUCE SPEED AHEAD	CAUTION WORKZONE AHEAD REDUCE SPEED AHEAD	CAUTION WORKZONE AHEAD REDUCE SPEED AHEAD	CAUTION WORKZONE AHEAD REDUCE SPEED AHEAD
Scenario-2 (Message Sign-2) MS-2	SPEED AHEAD 30 MPH 11 MIN TO END OF WZ	SPEED AHEAD 30 MPH 7 MIN TO END OF WZ	SPEED AHEAD 30 MPH 4 MIN TO END OF WZ	SPEED AHEAD 30 MPH 2 MIN TO END OF WZ
Scenario-3 (Message Sign-3) MS-3	PREPARE TO STOP 16 MIN TO END OF WZ	PREPARE TO STOP 11 MIN TO END OF WZ	PREPARE TO STOP 7 MIN TO END OF WZ	PREPARE TO STOP 4 MIN TO END OF WZ
Scenario-4 (Message Sign-4) MS-4	PREPARE TO STOP STOPPED TRAFFIC AHEAD	PREPARE TO STOP STOPPED TRAFFIC AHEAD	PREPARE TO STOP STOPPED TRAFFIC AHEAD	PREPARE TO STOP STOPPED TRAFFIC AHEAD

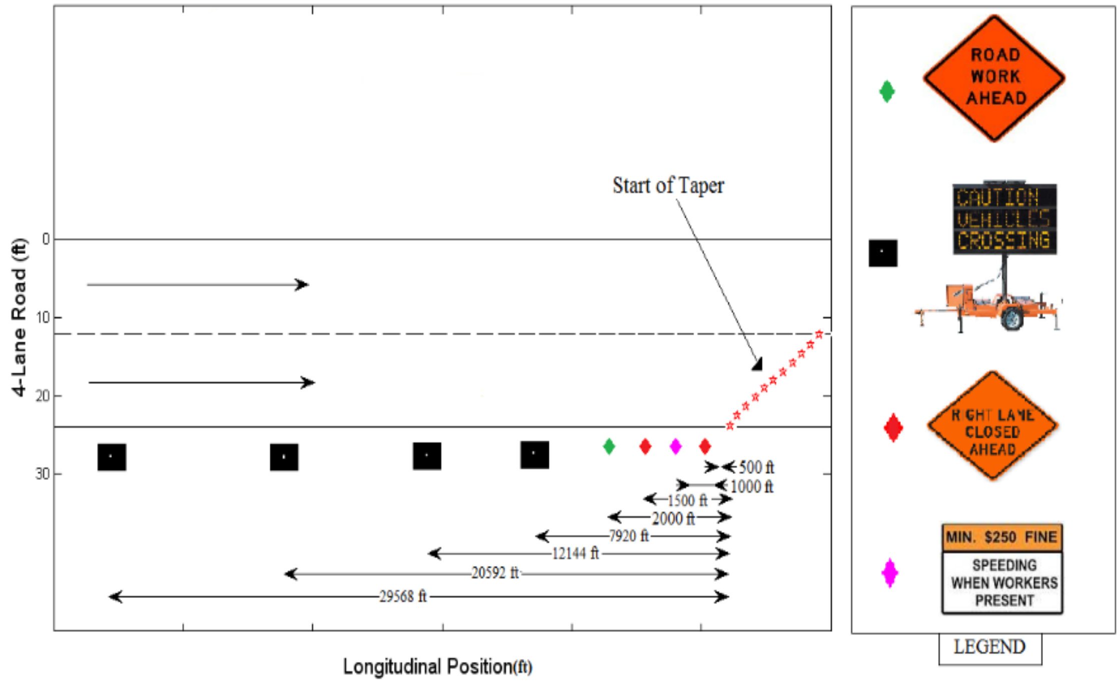


Figure 2.3 Work zone setup

2.3.2.3. Participant recruitment. Participants were recruited initially through campus emails, flyers and through the Missouri S&T's online news and information service (e-connection). Questions in pre-screening questionnaire inquired about the participants' health, prior symptoms of motion sickness, and their validity to drive in the United States. The participants were from Missouri S&T and surrounding areas. All the participants had encountered PCMS before and none of them were familiar with the driving simulator. The pre-screening questionnaire contained questions pertaining to their health that would impede their driving performance in the driving simulator. Questions pertaining to correctness of vision, motion sickness, and their prior experience with a driving simulator were asked.

2.3.2.4. Pre-driving and post-driving questionnaire. All the participants who agreed to participate in the project completed two forms presented in APPENDIX A, prior to the start of the experiment. In the pre-driving questionnaire, questions regarding their driving habits which included the vehicle they drove, number of years of driving experience, alcohol or drug consumption during the past 24 hours, etc. were put forth to the participants. Participants with a valid US driver's license were only allowed to participate in the experiment. Participants who experienced motion sickness, nausea and any discomfort during the simulation were turned away and were not allowed to complete the experiment. Two participants complained about nausea and motion sickness and hence were unable to complete the experiment. Three participants had expired driver license and again were not allowed to participate in the experiments. Overall, 52 participants were selected to participate in the driving simulator. The gender split was 50-50. The drivers were between the ages of 18-62. The mean age of the male participants was 32.6 and the mean age of the female participants was 36.4. From the sample population, two age groups were defined, age group-1 (16-40 years) was dominated by male participants (14 male and 12 female), whereas age group-2 (41-66 years) was dominated by female participants (12 male and 14 female).

Each participant who completed all the scenarios was asked to complete a post driving questionnaire. The participants were asked to identify the messages they came across during the experiment and were further asked to describe each of the messages in detail. Further the participants were asked to rate the messages according to its effectiveness (1 being the least effective and 4 being the most effective). Participants were also asked if they were misled by some messages and if they interpreted the messages incorrectly. In addition to the above questions, the questionnaire inquired about the actions taken by the participants after watching the PCMS. The participants were further asked to rank the messaging signs based on the following criteria: i) usefulness of the information displayed, ii) the timing of the message displayed (whether it was early or late), iii) the visibility of the messages (distorted or clear), iv) the size of the font displayed (small or big), v) frequency of updating the message, vi) length of the message displayed, vii) reliability of the message, viii) distance between each messaging sign, ix) the PCMS effect on driving speed, x) driving safety improvement, and xi) recommendation (recommendation for implementation in the work zone).

2.3.2.5. Experimental setup. The selected participants were first given a small presentation about the simulator. They were asked to drive normally and given the traffic conditions and adhere to all the traffic laws. The working of the simulator, the controls inside the simulator, and what was expected of them once they were inside the driver cabin were all explained to them. As the participants had not encountered a driving simulator before, the participants first drove through a test scenario to get them accustomed to the working of the simulator and get adjusted to the controls. Participants who requested for extra time to get familiarized with the working of the simulator were made to go through an additional trial run to familiarize them with the working of the simulator.

2.3.2.6. Data collection methodology. Data collection included vehicle speed data continuously from the simulator. This data was then supplemented with driver surveys. Vehicle speeds were analyzed 1000 feet upstream to 1000 feet downstream of each PCMS. The analysis of speeds helped understand the extent to which drivers slowed down as a result of PCMS. Simulator data were collected continuously and later discretized to obtain 0.1 second interval data. As a result of four PCMS in each scenario, data from eight sections (intervals) along the work zone were analyzed.

The data obtained from the simulator were extensively screened to check for any unusual behavior or error in the data recording. If the data were found to be unusual or for some reason if the data collection was not complete for the entire run, those data were discarded. Three data sets were discarded due to the incomplete data collection and the participant's data were not considered for further analysis.

2.3.2.7. Data analysis methodology. The analysis was carried out for 1000 feet before each PCMS and 1000 feet after each PCMS. This criterion was used as a baseline to evaluate the effectiveness of PCMS. The same MS was displayed on the all the four PCMS for a given traffic condition. The experiments performed in the driving simulator replicated this exact same procedure; hence a particular scenario contained a same MS displayed on all the four PCMS. All the MS were tested only for light traffic, as testing them under medium and heavy traffic conditions would cause a confounding effect (change in driver behavior either due to the traffic or the message signs).

The Design of Experiment (DOE) followed a split-plot design. The driving simulator experiment was set up such that each participant drove through five scenarios. The main plot factors were age and gender. Gender had two levels, male and female. The sub-plot factors were the scenarios (where a particular message sign was displayed on the four PCMS) and the eight intervals (1000 feet before and 1000 feet after each of the four PCMS). Boyle and Mannering (2004) found that 800 feet was an adequate length to analyze the impact on driver behavior as a result of PCMS. One thousand feet, therefore, provided adequate length for analysis for different types of driving behavior.

In total, nine intervals of interest were defined. The first interval (interval-0) indicated the starting mean speeds of vehicles and was excluded from the statistical analysis. The remaining eight intervals were defined before and after each of the four PCMS on the simulated highway, which replicated the work zone on I-44. Each interval was 1000 feet in length, adequate to study the impact and response of drivers as a result of the PCMS

The drivers speed, acceleration/deceleration, position and steering angle were the main variables measured during the driving simulator experiment, for use of objective evaluation. The vehicle speed was used as a criterion for determining the effectiveness of PCMS. This speed was measured before each PCMS and after each PCMS to determine the effectiveness of PCMS on speed, once it was sighted by the driver.

Analysis of Variance (ANOVA) was carried out to test the statistical significance of gender, age-group, message sign, and interactions on the mean speeds. The 85th percentile speed was calculated by plotting the cumulative distribution of the speeds for a particular interval. The statistical significance (null hypothesis) of the independent variable (factors) or the interactions of two or more variables on the mean speed was rejected if the p-value was less than or equal to the chosen significance level of 0.05. The entire data analysis was carried out in the Statistical Analysis System (SAS 9.3™) software.

Pairwise comparison of least square means (LSM) for different intervals was performed if the p-value in the ANOVA table was significant. LSM are predicted values based on the model fitted, across values of a categorical effect where other model factors are held constant by setting them to the least square estimate of their mean. If the experiment is balanced where each combination of factors (i.e., independent variables) is replicated an equal number of times, least square means will be same as the regular means. The LSM was carried out using the Tukey adjustment, which controls the experiment-wise error rate and provides good control over the Type-1 error rate (false positive).

Tukey's honestly significant difference (HSD) was also used for pairwise comparison in addition to the LSM method. The main idea of HSD is to compute the difference between two means using a statistical distribution defined by the "Q" distribution. "Q" is a table value or the studentized range statistic (in similar lines with the "t" value of a t-test). The value for HSD is calculated by using the following formula:

$$HSD = Q\sqrt{\frac{MS_{error}}{n}} \quad (1)$$

MSerror = Mean square error (MSE) obtained from the ANOVA table.

n = number of drivers = 52

$Q_{k,\ df,\alpha} = Q_{8,336,0.05} = 4.31$

k = number of intervals = 8

df = error degrees of freedom from ANOVA table = 336

α = significance level = 0.05

The ANOVA table consists of the Source of Variation and the degrees of freedom and the p-value explained below.

1. Source of Variation: This includes the various factors affecting the response variable and their interaction with each other.
2. Degrees of Freedom (df): It is the number of independent comparisons that can be made among the elements of a sample. It explains the number of levels of a treatment that are free to change. The formula for calculating the degrees of freedoms for main effects are (a-1) where "a" is the number of levels for the factor A. For a two way interaction, the degrees of freedom are calculated by (a-1) x (b-1), where "a" and "b" are the levels of factors A and B.
3. Sum of Squares (SS) or Treatment Sum of Squares: In analysis of variance, this is the sum of squares that accounts for the variability in the response variable (e.g., speed) due to the different treatments that have been applied.
4. Mean square: The ratio of sum of squares to that of degrees of freedom describes the mean square term. It defines the mean of the squares of the response variable for a given factor as follows:

   $MS_{treatments} = SS_{treatments} / df$.
5. Level of significance (α): The probability of rejecting the null hypothesis in a statistical test when it is true. The statistical significance (null hypothesis) of the factors or the interactions of two or more variables on the mean speed is rejected if the p-value was less than equal to the chosen significance level of (e.g., 0.05).

The analysis was first carried out for interactions. If the interactions were significant, further analysis was not carried out. If interactions were not significant, the main effects were tested. If a main plot factor (or their interactions) or a sub-plot factor (or their interactions) was found to be significant (p-value < α), further analysis was carried out. Our primary variables of interest were the scenario and the interval (sub-plot factor) and their respective interaction with other variables. Figure 2.4 shows the elements in a box plot.

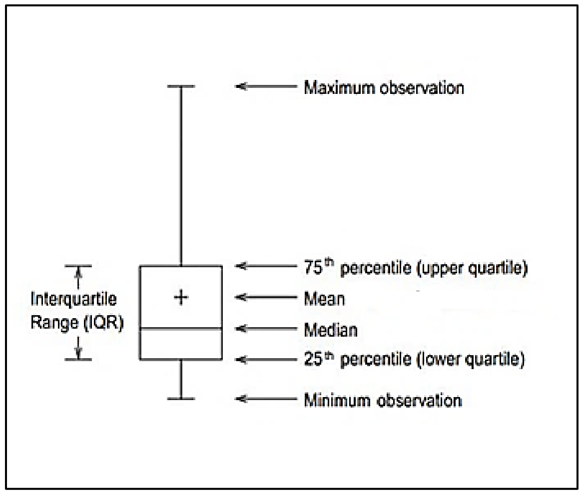


Figure 2.4 Box plot annotation

The null hypothesis (H_O) for analysis of intervals assumed that the mean speeds across these intervals were equal. The alternate hypothesis (H_A) assumed that the mean speeds across any interval is unequal for a given message sign. The results were analyzed at a significance level of 0.05 (accept H_O if p-value > 0.05, and accept H_A if p-value < 0.5). The H_O and H_A for the experiment are defined below:

$$H_O: \mu_1 = \mu_2 = \ldots\ldots = \mu_i$$

$$H_A: At\ least\ one\ \mu_i\ (mean\ speed)\ differed\ from\ the\ other$$

where

$$\mu_i = mean\ speed\ for\ the\ i^{th}\ interval\ for\ the\ scenario\ (i\ varies\ from\ 1\ to\ 8)$$

Interactions between the main plot factors (age*gender) and interactions between the main plot and sub-plot (interval * gender, interval * age, and interval * age * gender) were also analyzed to see if there was any significant change in speeds within the scenario. Since interval was our primary variable of interest, only significant interactions of interval with the other two factors were studied. Only the significant factors and their interactions have been presented.

The last interval after the PCMS was analyzed for the five scenarios. The control scenario was included for comparison with the other scenarios that included the PCMS.

The null hypothesis (H_O) for analysis of intervals assumed that the mean speeds across these scenarios at the final interval were equal. The alternate hypothesis (H_A) assumed that the mean speeds are unequal across scenarios. The results were analyzed at a significance level of 0.05 (accept H_O if p-value > 0.05, and accept H_A if p-value < 0.5). The H_O and H_A for the experiment are defined below.

$$H_O: \mu_1 = \mu_2 = \ldots\ldots = \mu_i$$

$$H_A: At\ least\ one\ \mu_i\ (mean\ speed)\ differed\ from\ the\ other$$

where

$$\mu_i = mean\ speed\ for\ the\ i^{th}\ scenario\ for\ the\ \ (i\ varies\ from\ 0\ to\ 4).$$

3. LITERATURE REVIEW

3.1. HIGHWAY WORKZONES AND PCMS

Despite the diligent efforts of the different transportation agencies in the United States, highway work zone safety still remains a concern. Work zones are typically marked by signs, channelizing devices, barriers, pavement markings, and working vehicles (FHWA 2009).

PCMS deployment in highway work zones is playing an increasingly important role in improving highway safety, and operations in use of existing facilities (Roshandeh & Puan, 2009). In terms of traffic warning, regulation, routing and management, they are intended to affect the drivers' speed in work zones by providing them with advanced real time information regarding the ongoing work activities, traffic information, or any incident occurring in the work zone ahead (Levinson, 2003). A PCMS, however, does not replace already existing static signs on the highway; they mainly supplement the existing static signs specified by the Manual on Uniform Traffic Control Devices (MUTCD).

3.2. EVALUATION OF EFFECTIVENESS OF PCMS

Evaluating PCMS requires unique considerations not typically necessary in other transportation improvement projects. PCMS are intended to reduce delays and risks associated with incidents or unique conditions. As incidents can occur at any time, measures focusing on peak-period needs are not well suited for PCMS evaluation. It is preferable to use measures that consider the impact of the incident and other unique operational conditions (Hatcher, et al. 1998). Additionally, driver response to PCMS is necessary to implement an effective system. Thus, consideration of driver reactions to

PCMS is essential in creating performance measures. These qualitative measures are sometimes difficult to compare but are just as imperative as other more quantitative indicators.

From the review of past studies, it is noted that three general approaches are commonly used to investigate the effects of PCMS systems. They are: driver questionnaire surveys, laboratory simulation experiments, and field studies. Driver questionnaire surveys collect respondents' opinion through a list of multiple choices or open-ended questions. In most projects, no field driving performance data are collected. Results from one site are not always transferable to other sites due to differences in network characteristics, attitudes and experiences of drivers. However, a questionnaire survey is still considered an economical method that could be quickly adapted to a new study and yield valuable results. Specifically, the surveys employing revealed preference (or stated preference or driver feedback) technique may be able to provide more accurate results, since participants are normally asked to describe how they actually behaved under given conditions. Driving simulation measures drivers' responses to artificially introduced stimuli in a simulated driving environment. Participating drivers, sitting behind a steering wheel of a test vehicle, usually experience some degree of virtual driving in a laboratory setting with no risks. By its nature, laboratory simulation allows researchers a lot more freedom to experiment with nearly every possible variation such as a PCMS. As variables examined in the experiment are under strict control, the experiments are mostly repeatable and results can be thoroughly analyzed by statistical methods.

3.3. FIELD STUDIES CARRIED OUT ON PCMS

A large number of field studies were carried out to test the effectiveness of PCMS. Benekohal and Shu (1992) studied the messages placed in the work activity area was effective in reducing the average speed of the cars at a point just after the CMS but was no longer effective downstream. Richards and Dudek (1986) stated that the CMS could result in only modest reductions (less than 10 mph) when used alone, and the device would lose their effectiveness if operated continuously for long periods with the same message.

Carden and Meekums (1998) presented their evaluation of the UK Midlands Driver Information System and estimated that huge reduction in vehicle delay was obtained in most cases where the Variable Message Sign (VMS) technology was used. However, when severity of the incidents was low, or the alternate routes were already congested, some increases in travel times were observed.

Garber and Srinivasan (1998) studied the effectiveness of PCMS in controlling the vehicle speeds in work zone and concluded that PCMS was effective when used with a radar in reducing the speed of drivers in a work zone. They also stated that the complete isolation of the CMS effect is not possible and the driver behavior is always influenced by the traffic, road geometry and intensity of the activity in the construction zone. Wang et al., (2003) in their evaluation showed that PCMS with radar effectively tended drivers to return to their original speeds after passing the signs. Huebschman and Garcia (2003), argued that PCMS are actually no more effective than traditional message panels (static signs) when it comes to work zone management. Firman and Li (2009) conducted field experiments in Kansas for a resurfacing work-zone project where portable VMS and a temporary static sign with the message “Road Work Ahead” were used. The results, however, showed that the static sign was more significant in reducing the speed of passenger cars and truck speeds in one-way of the two-lane work zones. Edara and Sun (2011) recently conducted field surveys to analyze the benefits of Dynamic Message Signs (DMS) on Missouri’s rural corridors and concluded that about 90% of the surveyed motorists said they took action provided by the DMS. Speed reductions of 3.64 mph and 1.25 mph were observed for the first and second sites near the DMS placed upstream of the work zone. The speed reductions were statistically significant. McCoy and Pesti (2002) found that drivers ignored signs on the PCMS and the reliability of the signs was in question as they could not find any reason to slow down when the locations of the messages were too far (4 miles away) from one another.

3.4. STATED PREFERENCE STUDIES

Stated preference methods are data sets based on participants’ information about their preferences - taken from questionnaires. Significant research has been carried out to determine the effectiveness of PCMS by the Stated Preference (SP) survey method. Researchers have studied the drivers’ response to these messages via questionnaires.

Wardman & Bonsall (1997) in a SP study at the University of Leeds recorded drivers’ response to VMS messages to study the effect of the displayed text messages on different route choices. A self-reported SP questionnaire was used. Logit analysis of these studies revealed the importance of relative journey times and of the precise phrasing of the VMS. Chatterjee and Mcdonald (2004) reinforced the above by stating that only one-fifth of the drivers diverted as compared to the results based on SP surveys in London by conducting field trials. Peeta and Ramos (2006) tried three different SP survey methods:

an on-site survey, a mail-back survey, and an Internet based survey to investigate driver response attitudes to traffic information provided through VMS. They concluded that there is a high correlation between the information provided (route choice and speed limits) on the VMS and driver response.

3.5. DRIVING SIMULATOR STUDIES

Godley (2002) summarized that speed was shown to be a valid dependent variable for measuring driver responses to various scenarios in a simulated environment. Ulfarsson (2002) conducted studies on effectiveness of DMS on speed reduction and traffic flow management on the I-90 corridor. They found that DMS significantly reduced mean speeds, but significantly increased speed variation and drivers accelerated, compensating for lower speeds, with the speed reduction effect diminished 10 km from the DMS. Yang and Waters (2005) performed a study to evaluate the information provided related to traffic flow in work zones to drivers through DMS. A questionnaire study along with a driving simulator study was performed. The study revealed that younger drivers tend to respond and comprehend the message more quickly than older subjects. Their study results suggested that static, one-framed messages with more specific wording and no abbreviations were preferred, and amber or green and green-amber combinations were the most favored colors. Also, younger subjects took less response time to the DMS stimuli with higher accuracy than older subjects and there were no significant gender differences. Boyle and Mannering (2004) conducted experiments to obtain driver's speed behavior under different advisory information using a driving simulator. Four conditions were evaluated with in-vehicle information, driving message sign information, driving with both in-vehicle information and driving message sign and just driving message sign information. Their results suggested that there were significant changes in the speed just for shorter distances (less than 800 ft), and nothing significant was observed for longer distances regardless of the travel-information.

Ullman and Dudek (2005) conducted a study of PCMS in work-zones to examine the level of comprehension of messages by the motorists, and provided recommendations based on the length and the redundancy of the messages. Their results indicated that different information displayed on sequentially placed PCMS was more difficult to comprehend than on one DMS with a bi-phasic message. Clark (2008) conducted a driving simulator study on drivers of different ages on the understanding of the VMS and concluded that though the older drivers slowed down after reading the messages displayed, their responses were inaccurate and the response time was significantly higher than those of the drivers between ages 20-40 years. McAvoy (2011) employed a driving simulator and an eye-tracking device to assess the effectiveness of Dynamic Speed Signs (DSS) and Variable Speed Limits (VSL) in reducing work-zone speed. Thirty-nine students between the ages of 16 and 25 years participated in the study. They stated that “SLOW DOWN to 45 mph” message lowered work-zone speed by about 18 mph more than the VSL with a speed limit of 45 mph; however, the message “SLOW DOWN” lowered speed by only 2 mph more than the VSL. Simulator studies have been carried out by McAvoy (2011) to evaluate the effectiveness of Dynamic speed signs (DSS) and concluded that the DSS was not a distraction to the driver. Dudek and Ullman (2005) carried out a study that examined the use of PCMS in work-zones but quantitative data was not recorded. Hence, the actual behavior of the participants in terms of speed was not understood.

3.6. SUMMARY

From the literature review it is clear that some studies have investigated the impact of PCMS on driver behavior, especially its effect on speed. Only a few studies, however, have examined the effects in a controlled environment in a driving simulator to study the driver behavior, their responses to PCMS and the different messages displayed. Hence the design of our research project with a DS included an experiment to study the impact of PCMS on driver behavior in a controlled environment. This study was intended to look into how participants react to multiple PCMS placed before a construction zone and to study the speed profile of the participants before and after each PCMS. It was also intended to look into the variance in the speed of the participants at each interval and therefore to study how participants perceived the PCMS and to what extent the PCMS affects the driving speed of the participant. Although the effects of multiple PCMS on speed have been studied previously by other researchers, the effect of each PCMS on speed in a multiple PCMS system has not been investigated thus far. This is the first study that examines the behavior of a driver before and after each PCMS for different age groups and gender, using rigorous statistical analysis. This study also examines and analyzes the speed variation for different message signs of a same message type.

4. DEPARTMENT OF TRANSPORTATION SURVEY RESULTS

4.1. DOT SURVEY RESULTS

The Department of Transportation survey was conducted online and was developed using the Qualtrics™ software. The survey was sent to all DOTs in the United States. Thirty three DOTs took the survey but only twenty four DOTs completed the entire survey. The results of the survey are presented below.

4.1.1. Conception of PCMS. The DOTs were inquired about the year of conception of PCMS in their respective states. Figure 4.1 shows the usage of PCMS in number of years. New Hampshire, Minnesota, Iowa and Missouri Departments of Transportation have used the PCMS for more than thirty years. Michigan, Delaware, North Carolina, Arizona, Hawaii, Oklahoma, Texas, Oregon, New York, Wisconsin, Indiana and Arkansas have used the PCMS ranging from 21-30 years. It can be inferred that PCMS have been used by DOTs for traffic control for more than two decades.

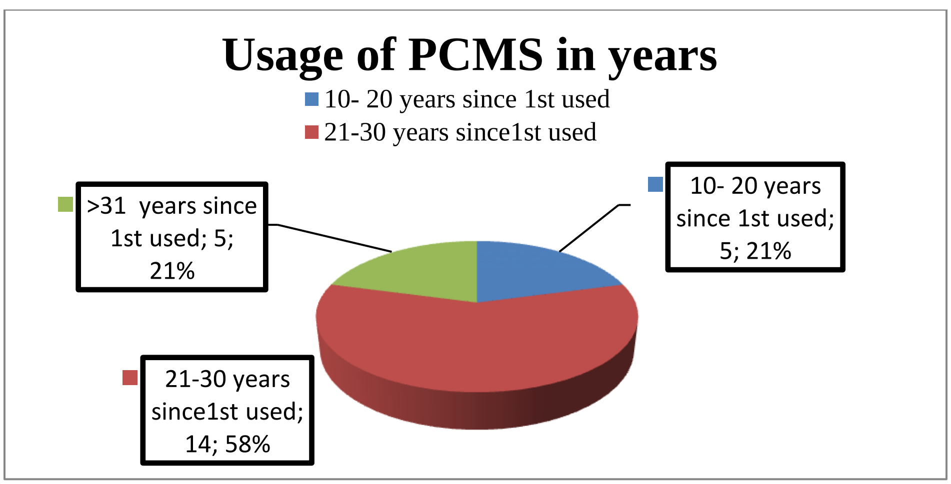


Figure 4.1 Conception of PCMS

4.1.2. Usage of PCMS by Facilities. The next question inquired about the classification of highways on which PCMS have been used. The DOTs were asked if the usage of PCMS was restricted to freeways or work zones or if they were used at any locations other than the obvious choices. Twenty one (88%) DOTs responded by stating that they used PCMS on both freeways and work zones. 2 (8%) DOTs said they used the PCMS only in work zones and 1 (4%) responded saying they used PCMS only in freeways. Figure 4.2 illustrates the usage of PCMS. It can be inferred that the usage of PCMS are mainly to traffic management of freeway work zones.

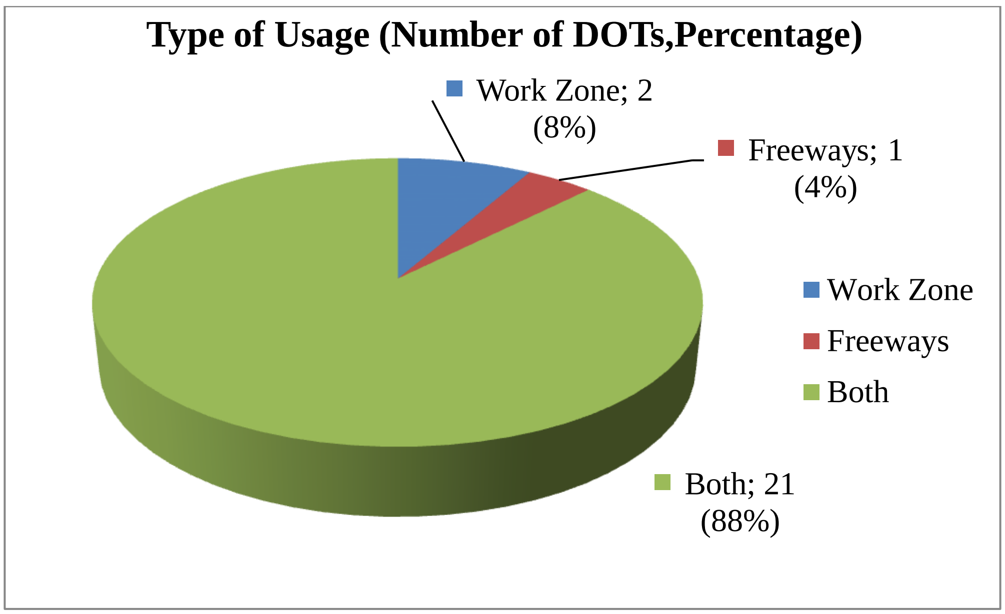


Figure 4.2 Facility usage of PCMS

4.1.3. Usage of PCMS by Purpose. Various DOTs had different purposes for the usage of PCMS. This section contains detailed information about how different agencies use PCMS.

Michigan DOT uses PCMS as an incident management system and to provide drivers with real-time information regarding the activities in the construction zone. New Hampshire DOT uses PCMS for incident management planning on a congested freeway and is currently working towards providing a comprehensive safety infrastructure by implementing PCMS.

Delaware DOT uses PCMS in work zones to inform the travelling public of upcoming road work, major traffic detours, road closures, incident management and other purposes. They use fixed or overboard Dynamic Message Signs (DMS) for congestion management and incident management.

North Carolina DOT uses fixed DMS for work zone information. They use it for work zone applications where general and specific information about the activities of work zone are displayed and sometimes include the travel time information.

Missouri DOT uses PCMS to provide real-time information about conditions ahead, providing information to assist road users in making decisions prior to the point where the actions must be taken. Some typical applications include significant drop in vehicular traffic, queuing, information about adverse environmental conditions, ramp/lane/roadway closures, crash or incident management and changes in road patterns.

Oklohoma DOT uses PCMS in work zone system called “Smart Work Zone”. A smart work zone consists of PCMS, radar detection queuing within the work zone. When the queuing is detected, messages are sent to PCMS to inform the incoming traffic and a speed limit is specified according to the traffic congestion downstream. They use smart work zones on all interstate projects. PCMS are also used for informing the traffic about future construction activities, in rural areas for highway closure and reconstruction activities, maintenance activities, AMBER (kidnap or child abduction) and weather alerts.

PCMS are primarily used by Texas DOT to manage travel, to control and divert traffic, and to inform drivers about current and anticipated highway conditions. This includes information about traffic crashes, weather issues and highway construction. Federal and state guidelines are followed to ensure the messages displayed are reliable, clear and easily understood. The DOT also uses PCMS to inform drivers about AMBER alerts, Texas Silver Alert Program, and the Endangered Missing Person programs. These requests are taken from the Department of Public Safety-Division of Emergency Management (DPS-DEM) in Austin.

North Dakota DOT uses PCMS for emergency operations such as flooded roads around the Devils Lake region. Rising lake waters cause roads to sink and yields them unusable; DMS are extensively used in this situation to communicate alternate routes to travelers.

Oregon, New York, Wisconsin, Indiana and Arkansas DOTs use the PCMS for incident management on freeways, display complex messages in work zones such as future closures, detours, etc. They are also used to supplement the static signs in the work zones.

It can be inferred from the DOT survey that PCMS are commonly used for providing drivers’ with real time information regarding incident management in work zones, weather alerts and alternate routes.

4.1.4. Message Type Displayed. The DOTs were asked about the type of messages displayed on the PCMS. The options provided were: i) Only text, ii) Only Graphic, iii) Text and Graphic, iv) Text and Numbers, v) Graphic and Numbers, and vi) Text, Graphic and Numbers. Figure 4.3 illustrates the different message types displayed on each PCMS.

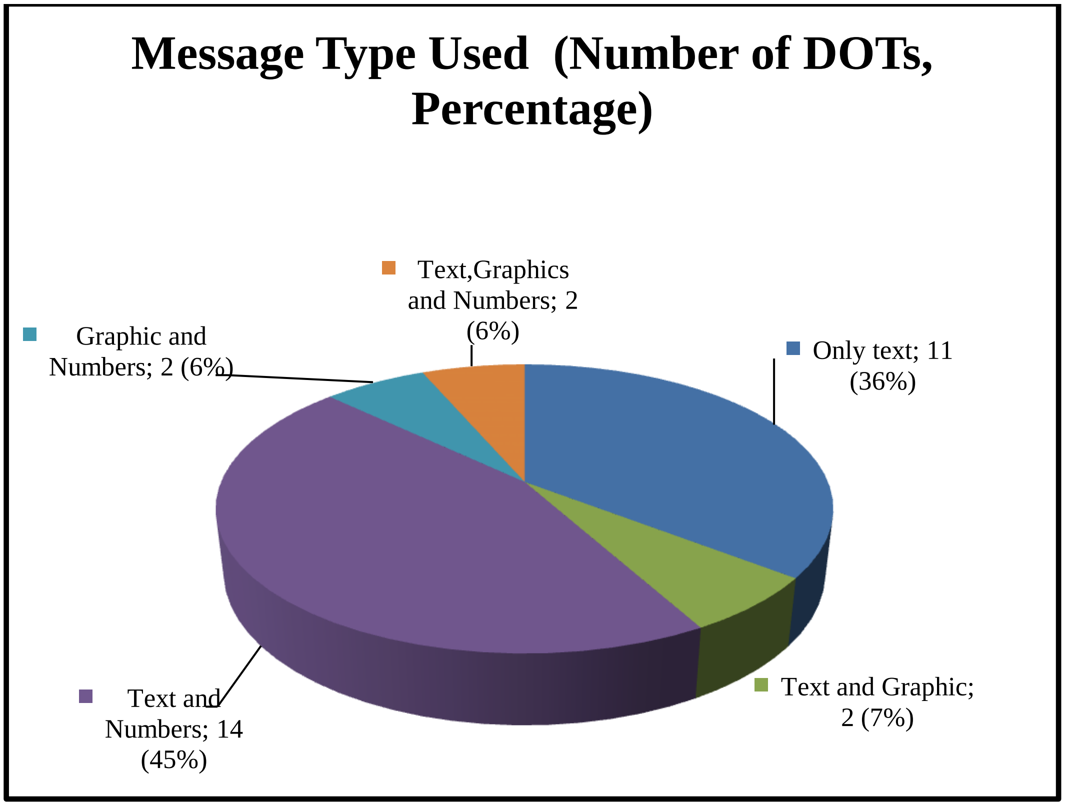


Figure 4.3 Message type used

Some agencies use more than a single type of message. The most commonly used message type is “text and numbers”; 14 (45%) of the DOTs preferred this message type over the others. The next commonly used message type is“only text”; 11 (36%) of the DOTs used this message type. The third most commonly used choice of message type is “text, graphic and numbers” and “graphic and numbers”; 2(6%) each. Though the survey yielded no DOTs using just graphic PCMS, literature review revealed the usage of “only graphic” PCMS. Li (2009) reviewed and evaluated the effectiveness of only graphic PCMS in rural areas of Kansas.

Michigan, Iowa, Oklahoma and Indiana DOTs use both the “only text” and “text and numbers” message type as their display medium to provide real-time information to drivers.

North Carolina, Minnesota, Mississippi, Hawaii, Missouri, Texas and Oregon DOTs use “text and numbers” message type as their display medium. Iowa DOT is the only agency to use “graphic and numbers” and “text, graphics and numbers” as their message type display on the PCMS. We can infer from the study that the most commonly used type of message is “text and numbers”.

4.1.5. Criteria Used for Location of PCMS. Location of the PCMS depends on various factors. The DOTs were enquired if they followed particular criteria when setting up the PCMS on different classes of highways.

Missouri and Michigan DOTs place the PCMS where it is visible to the driver from at least half a mile in both day and night time conditions. This is carried out so that the drivers will have ample time to respond to the message. It is also placed in level with the shoulder perpendicular to the highway.

North Carolina DOT follows the Roadway Standard Drawings as well as TTC Control plans for their PCMS location in work zones. The location also depends on a specific usage of the PCMS and type of facility they are located for their advanced placement.

Minnesota DOT follows the best visibility criterion which included a straight section of the highway. However, they are not placed near major junctions or merging sections as they will cause more roadblocks due to passengers slowing down in order to read the messages.

Oklahoma DOT prefers the location of PCMS to be about two miles upstream of the work zone. The second PCMS (if active) has a radar detector about half a mile or one mile from the work zone. Once in the work zone, PCMS and radar detectors are placed every quarter of a mile. Their other preferred locations were major interchanges, interstate highways, sight distance, and volume of traffic.

North Dakota DOT (NDDOT) follows several criteria for the placement of PCMS. The factors that affected their position are; clear zone, roadway geometry, operating speeds, location of utilities, and location of multiple PCMS if placed prior to a road closure ramp. The agency states that the PCMS should be placed at least 3000 feet before the ramp and at least 1000 feet before a static road closure sign. PCMS, if placed at a particular location for long duration, should be made sure it is not tampered with. The above mentioned guidelines or other design guidelines do not apply to installations in unique situations or as the NDDOT practice and procedure evolves. In case of emergency situations, public safety becomes the main criterion and the PCMS should be deployed as quickly as possible.

Oregon DOT’s PCMS location in a work zone is determined by the work zone traffic control designer. Sometimes, two or more signs are included within a project just in case the contractor determines a need for them.

Indiana DOT places their PCMS 1000 feet in advance of the detour exit for a road or a ramp closure. For a lane closure, it is placed 1 mile or 1000 feet in advance of the detour exit.

Arkansas, New York, Texas, Maine, Delaware, Iowa and New Hampshire DOTs have no set specific criteria and their placements of the PCMS is site and condition specific. Iowa DOT does not have their PCMS placed at equal intervals before the work zone.

Most DOTs have no specific criteria for placing the PCMS and it is usually determined by the site of the work zone and the conditions in which the PCMS were placed.

4.1.6. Evaluation of PCMS. The deployment of PCMS initiated a question about its evaluation. Surprisingly only two DOTs has carried out the evaluation of PCMS during the time of the survey. Texas and Minnesota DOTs have carried out an evaluation of PMCS out of the twenty-four DOTs that responded to the survey.

Minnesota DOT did not conduct a detailed study to evaluate the effectiveness of PCMS. Qualitative data was measured by detecting slower driver speeds which was attributed to reading the messaging signs. This was considered a proof that drivers followed the PCMS. They also stated that the speed reduction was sometimes extreme and instances of drivers complaining about the same. Minnesota DOT used public surveys to evaluate and obtain feedback regarding the effectiveness of PCMS. The main criteria for evaluating the effectiveness were the observed traffic behavior which indicated a high level of effectiveness. The agency just evaluated the early warning of the PCMS. No studies were carried out to study the impact on driver behavior. The

Minnesota DOT also carried out a driving simulator study to evaluate the clarity of the PCMS against a video based traffic simulation.

The results of evaluation of PCMS of Texas DOT were presented under literature review.

4.1.7. Summary DOT Survey. From the DOT survey it can be inferred that PCMS have been in usage for more than two decades, but extensive evaluation of driver behavior with respect to speed characteristics has not been carried out. There is a need to determine these PCMS that are more effective and also to make sure the information displayed on the PCMS is perceived correctly by the drivers. The DOT survey provided no useful feedback on the measure of effectiveness used by the DOTs or the methods used to evaluate the effectiveness of PCMS.

5. OBJECTIVE AND SUBJECTIVE EVALUATIONS

The objective evaluations included quantitative data from the simulator and involved the comparison of mean speeds for different message signs. The subjective analysis involved a post-experiment questionnaire (feedback survey) where participants evaluated the driving simulator based on their experience with the DS. Subjective evaluations were carried out in addition to the quantitative evaluation. These evaluations were carried out mainly to study each participant's perception about the effectiveness of the PCMS and how PCMS impact his/her driving. Fifty two participants' data was analyzed for both the objective and subjective analysis. Extensive data analysis was carried out on the data obtained from the simulator. The participants were divided into two age groups (levels), first age group ranged 16-40 year old and second age group ranged 40-66 year old.

5.1. OBJECTIVE EVALUATION

ANOVA was carried out to find the significant factors (main effects) and their interactions with other factors (e.g., Table 5.1). If the p-value of the interaction or the main effect is found to be significant (p-value less than the given significance level), it was further analyzed. The factor "interval" and its interaction with other factors are of interest. If the interaction "interval * gender" is significant, it means for at least one interval the mean speeds of male and females are significantly different. If the interaction was found to be significant, box plots of speeds were plotted for "interval*gender" (e.g., Figure 5.1). Then the least square means (LSM) and honestly significant difference (HSD) values are calculated using Tukey's method (e.g., Table 5.2). The difference in the mean speeds is compared to the HSD value. If the difference in the mean speeds for a given pair of intervals (e.g., the values in the parenthesis in Table 5.2) is greater than the HSD value, the mean speeds are said to be significantly different between the two intervals. The MS_{error} (MSE) value is obtained from the ANOVA table. MSE evaluates the difference between an estimator and a true value. It is used to determine to what extent the model does not fit the data. The MSE is needed to calculate the HSD along with the “Q value”.

5.1.1. Control Scenario. The control scenario had no messages displayed and was used for free flow traffic. From Table 5.1, the results yielded p-value of the interaction (gender * interval) being significant (<0.0001). Further, to analyze the interaction effect (gender * interval), box plots of mean speeds of male and female participants are plotted for different intervals. Though the interaction (gender * age) is significant, it is not further analyzed as age is not significant and did not show significant interaction with interval. The MSE from the ANOVA table is 4.22. The HSD value is obtained from equation 1.

$$HSD = 4.33\sqrt{\frac{4.22}{52}} = 1.22$$

Table 5.1 Statistical significant results for control scenario

Source	Degrees of Freedom	p-value
Gender	1	**<0.0001**
Gender*Age	1	**0.0397**
Interval	7	**<0.0001**
Gender*Interval	7	**<0.0001**

p-value- probability of rejecting the null hypothesis for a given significance level

Bold indicate statistically significant at 0.05 level of significance

Table 5.2 illustrates the LSM and HSD values of mean speeds from interval-1 to interval-8. The differences in mean speeds between intervals are presented in the parenthesis below the p-value and are compared to the HSD value. If the difference in the mean speeds is lower than the HSD value, there is no significant difference between the intervals. For example, the difference in the mean speed of interval-1 and that of interval-8 is 6.08 mph (Table 5.2) which is greater than the HSD value of 1.22, hence the p-value is less than the significance level of 0.05 and the difference between the two mean speeds is highly significant. The p-values for the eighth interval are highly significant (< 0.0001) and different when compared to the remaining intervals. The posted speed limit was 70 mph (interval-0). From the results, it can be observed that the mean speeds of the drivers do not change from interval-1 to interval-7. The mean speed of the participants is 62.55 mph for the eighth interval. This decrease in speed is assumed to be due to the static signs observed by the drivers.

Figure 5.1 shows the box plot for the interaction “interval * gender”. The plot indicates that overall speed of female drivers is greater than the male drivers for the control scenario. But the final speed (interval-8) is the same for both the male and the female participants. The mean speed plot along with the 85^{th} percentile speed of the control scenario is shown in Figure 5.2. The 85^{th} percentile speed remained above the speed limit of 70 mph, which indicated many participants did not feel the need to slow down. It can be observed that there is a drop in the final speed at interval-8, which can be attributed to the fact that the start of the construction zone and the static signs became visible to the participants

Table 5.2 Mean, standard deviation and p-values for LSM and HSD: control scenario

Interval	Mean	Standard Deviation	2	3	4	5	6	7	8
	Miles per hour		p-values and differences between the mean speeds (HSD = 1.22, α = 0.05)						
1	68.63	3.47	0.0735 (1.22)	**0.0008 (1.8)**	**<.0001 (2.41)**	0.2709 (1.02)	0.9999 (0.04)	**0.0046 (1.63)**	**<.0001 (6.08)**
2	69.85	4.48	-	0.8979 (0.58)	0.1082 (1.19)	0.9992 (0.2)	**0.0223 (1.26)**	0.9889 (0.41)	**<.0001 (7.3)**
3	70.43	4.12	-	-	0.8277 (0.63)	0.5761 (0.78)	**0.0001 (1.84)**	0.9999 (0.17)	**<.0001 (7.88)**
4	71.04	2.76	-	-	-	**0.0217 (1.39)**	**0.0001 (2.45)**	0.5338 (0.78)	**<.0001 (8.493)**
5	69.65	2.86	-	-	-	-	0.1106 (1.06)	0.8436 (0.61)	**<.0001 (7.10)**
6	68.59	2.56	-	-	-	-	-	**0.0010 (1.67)**	**<.0001 (6.04)**
7	70.26	2.64	-	-	-	-	-	-	**<.0001 (7.71)**
8	62.55	1.84	-	-	-	-	-	-	-

"-"= not applicable

p-value- probability of rejecting the null hypothesis for a given significance level

Bold indicate statistically significant at 0.05 level of significance and HSD = 1.22

Values in parenthesis represent the difference between the mean speeds

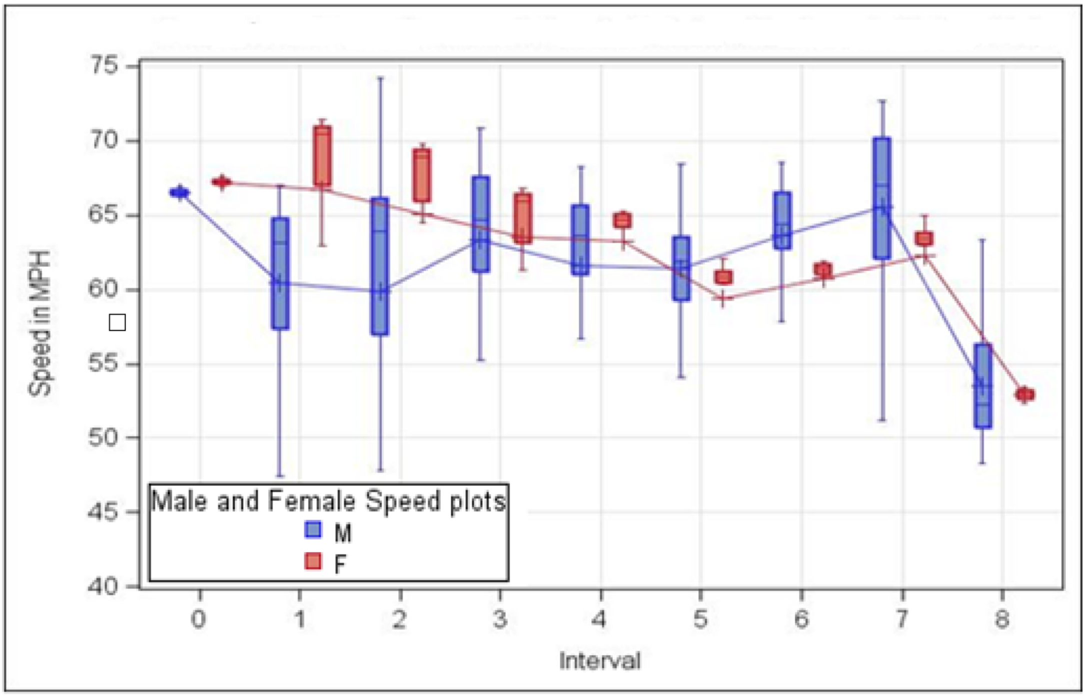


Figure 5.1 Box plot comparison for control scenario

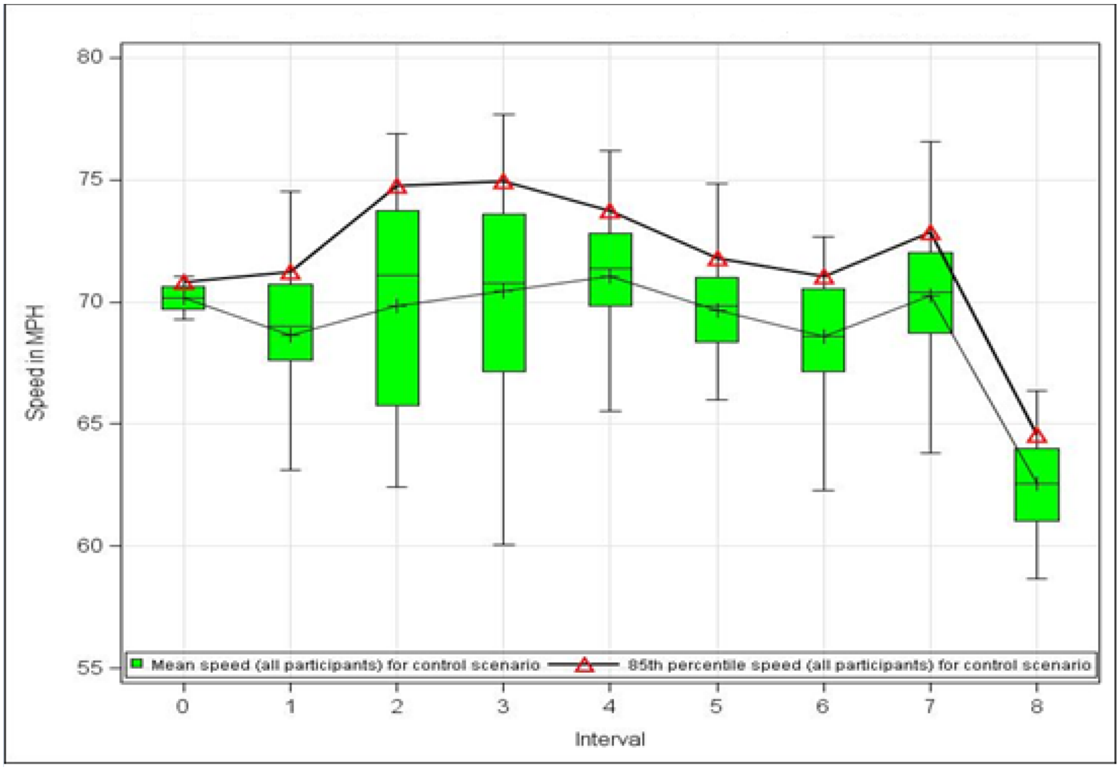


Figure 5.2 Comparison of mean speeds and 85th percentile speed for control scenario

5.1.2. Scenario-1. Scenario-1 had Message sign-1, "CAUTION WORK ZONE AHEAD, REDUCE SPEED AHEAD", displayed on all the four PCMS. The message displayed was intended for free flow traffic.

The results of analysis presented in Table 5.3 yielded a p-value of the interaction (gender * interval) as significant (< 0.0001). Box plots of mean speeds of male and female participants are plotted for different intervals. The MSE from the ANOVA table is 19.58. The HSD value is 2.64.

Table 5.3 Statistical significant results for scenario-1

Source	Degrees of Freedom	p-value
Interval	7	**<0.0001**
Gender*Interval	7	**<0.0001**

p-value- probability of rejecting the null hypothesis for a given significance level

Bold indicate statistically significant at 0.05 level of significance

Table 5.4 shows the LSM and HSD values of mean speeds from interval-1 to interval-8 for scenario-1. From the LSM we can infer that the mean speeds at interval-8 are significantly different when compared to mean speeds at other intervals, whereas the mean speeds of first seven intervals do not differ from each other significantly.

Figure 5.3 shows the box plot of mean speeds for interaction “interval * gender”. The plot indicates that female participants initially started at higher speeds but then decreased speed once spotting the PCMS. The overall mean speeds of female participants are greater than the male participants for scenario-1. But the box plots indicate that the variance in speed for female participants are much lesser when compared to the male participants, which again can be assumed to be due to female drivers perceiving the message displayed similarly and only slowing down when approaching the construction zone.

The mean speeds (Figure 5.4) in the interval-8 (53.20 mph) are much lesser when compared to the control scenario (62.55 mph). This showed that message sign-1 did have an impact in reducing the final speed, i.e., the speed before the construction zone.

Table 5.4 Mean, standard deviation and p-values for LSM and HSD: scenario-1

Interval	Mean	Standard Deviation	2	3	4	5	6	7	8
	Miles per hour		p-values and difference between the mean speeds (HSD = 2.64, α = 0.05)						
1	63.57	8.59	0.9483 (1.11)	1.000 (0.13)	0.9311 (1.15)	**0.0114 (3.16)**	0.7932 (1.56)	0.9997 (0.36)	**<.0001 (10.37)**
2	62.46	9.42	-	0.9472 (0.98)	1.000 (0.04)	0.2531 (2.05)	0.9999 (0.32)	0.7400 (1.47)	**<.0001 (9.26)**
3	63.44	5.93	-	-	0.9288 (1.02)	**0.0113 (3.03)**	0.7907 (1.3)	0.9998 (0.49)	**<.0001 (10.44)**
4	62.42	5.92	-	-	-	0.2868 (2.01)	1.000 (0.28)	0.6992 (1.51)	**<.0001 (9.22)**
5	60.41	5.50	-	-	-	-	0.4874 (1.73)	**0.0020 (3.52)**	**<.0001 (7.21)**
6	62.14	4.96	-	-	-	-	-	0.4796 (1.79)	**<.0001 (8.94)**
7	63.93	5.55	-	-	-	-	-	-	**<.0001 (10.73)**
8	53.20	4.21	-	-	-	-	-	-	-

"-"= not applicable

p-value- probability of rejecting the null hypothesis for a given significance level

Bold indicate statistically significant at 0.05 level of significance and HSD = 2.64

Values in parenthesis represent the difference between the mean speeds

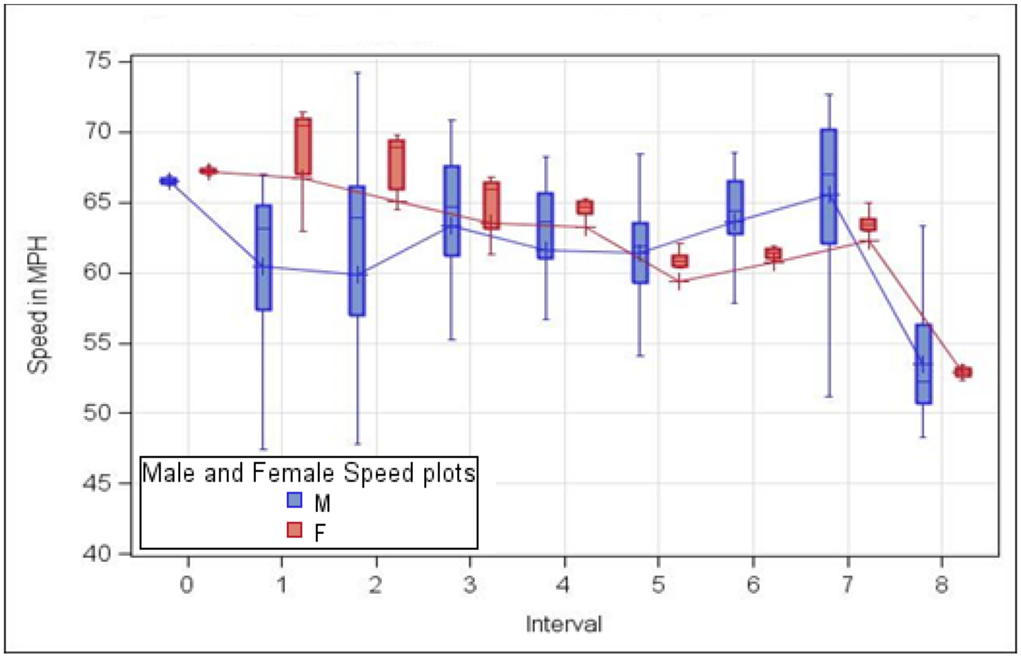


Figure 5.3 Box plot comparison for scenario-1

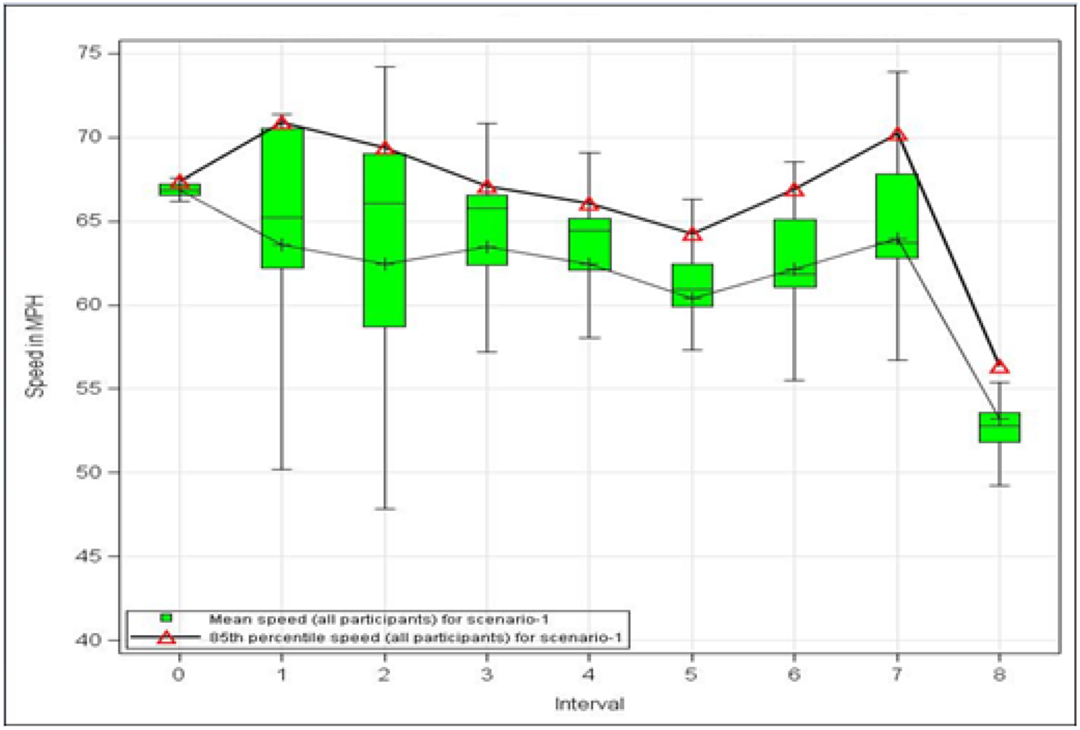


Figure 5.4 Comparison of mean speeds and 85th percentile speeds for scenario-1

5.1.3. Scenario-2. Scenario-2 had Message Sign-2, "SPEED AHEAD 30 MPH, 11,7,4,2 MIN TO END OF WZ ", displayed on all the four PCMS. This message had a specific speed limit displayed for the participants to follow.

The Table 5.5 yielded p-value for the interaction (gender * interval) as significant (< 0.0001). Box plots of mean speeds of male and female participants are plotted for different intervals. The MSE is 30.035. The HSD value is 3.29.

Table 5.5 Statistical significant results for scenario-2

Source	Degrees of Freedom	p-value
Gender	1	**0.0002**
Interval	7	**<0.0001**
Gender*Interval	7	**<0.0001**

p-value- probability of rejecting the null hypothesis for a given significance level

Bold indicate statistically significant at 0.05 level of significance

Table 5.6 shows the LSM and HSD values of mean speeds from interval-1 to interval-8 for scenario-2. From the LSM values we see that the mean speed of interval-8 is significantly different when compared to the other intervals. For this scenario we observe that the mean speeds for other intervals are significantly different from each other. Huge variation in the mean speed is observed for the first seven intervals (Figure 5.6). This might be due to the speed limit and time to “end of the work-zone” displayed on the PCMS. This suggests that some participants follow the speed limit of 30 mph displayed on the messaging sign while other participants slow down when they were near the construction (this can be attributed to the time being displayed on the PCMS along with the speed limit).

Figure 5.5 shows the box plot of mean speeds for interaction “interval * gender”. We can notice that there is a huge variation in the mean speeds of male participants from interval-1 to interval-7 (before PCMS#4). The male participants eventually start to slow down when they are closer to the construction zone and less variation in mean speed is observed at interval-8. Less variation is observed in the female participants from interval-1 to interval-7. Female participants only slowed down when they are near the construction zone and also remembered the speed to follow. There is a gradual decrease in speed for both male and female participants, slowing down completely near the construction zone. The final mean speeds remained almost equal for both male and female participants. Figure 5.6 shows the 85^{th} percentile speed and the mean speeds. The 85^{th} percentile speed at interval-8 (30.67 mph) matched the displayed speed on the PCMS. The mean speeds at interval-8 were less than the displayed speed which implied that participants followed the message sign.

Table 5.6 Mean, Standard deviation and p-values for LSM and HSD: scenario-2

Interval	Mean	Standard Deviation	2	3	4	5	6	7	8
	Miles per hour		p-values and difference between the mean speeds (HSD = 3.29, α = 0.05)						
1	48.92	8.54	**0.0018 (5.11)**	**0.0021 (4.99)**	**<.0001 (11.96)**	**<.0001 (10.77)**	**<.0001 (10.21)**	**<.0001 (11.78)**	**<.0001 (22.43)**
2	43.81	13.21	-	1.000 (0.12)	**<.0001 (6.25)**	**0.0003 (5.36)**	**0.0012 (5.1)**	**<.0001 (6.67)**	**<.0001 (17.32)**
3	43.93	11.96	-	-	**<.0001 (6.37)**	**0.0002 (5.78)**	**0.0010 (5.22)**	**<.0001 (6.79)**	**<.0001 (17.44)**
4	37.56	11.31	-	-	-	0.9996 (0.59)	0.9888 (1.15)	1.000 (0.42)	**<.0001 (11.07)**
5	38.15	12.31	-	-	-	-	1.000 (0.56)	0.9949 (1.01)	**<.0001 (11.66)**
6	38.71	12.11	-	-	-	-	-	0.9518 (1.57)	**<.0001 (12.22)**
7	37.14	10.33	-	-	-	-	-	-	**<.0001 (10.65)**
8	26.49	2.99	-	-	-	-	-	-	-

"-"= not applicable

p-value- probability of rejecting the null hypothesis for a given significance level

Bold indicate statistically significant at 0.05 level of significance and HSD =3.29

Values in parenthesis represent the difference between the mean speeds

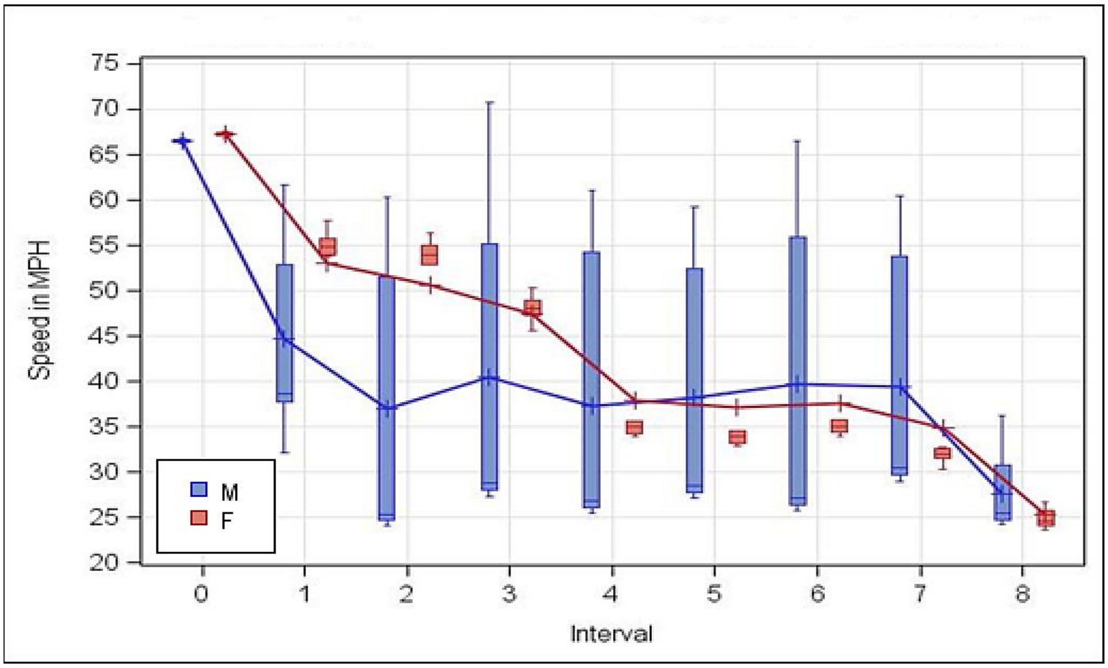


Figure 5.5 Box plot comparison for scenario-2

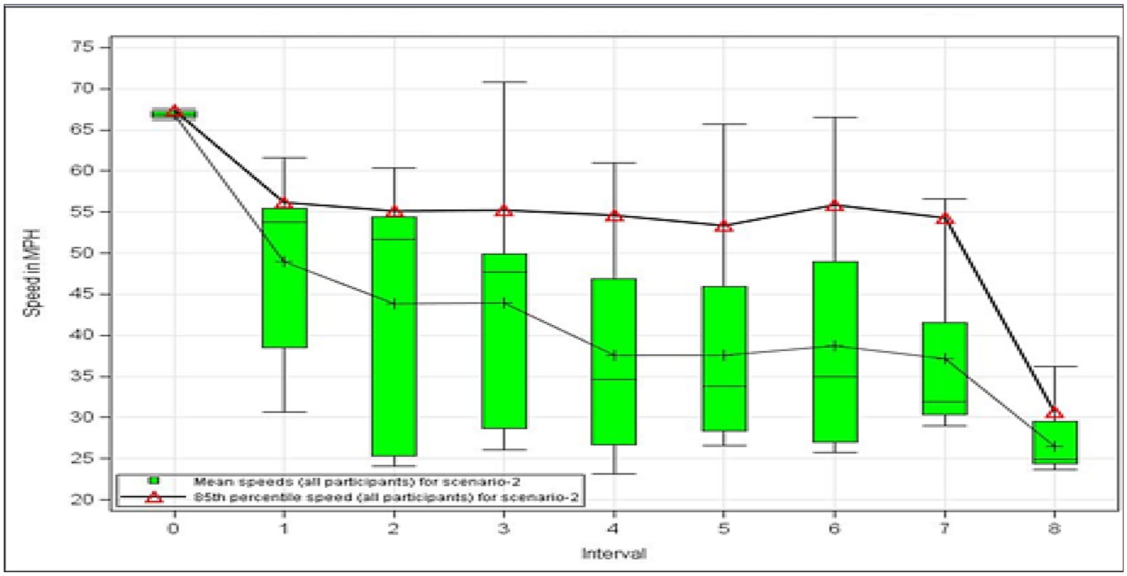


Figure 5.6 Comparison of mean speeds and 85th percentile speeds for scenario-2

5.1.4. Scenario-3. Scenario-3 had Message Sign-3, “PREPARE TO STOP, 16,11,7,4 MIN TO END OF WZ ”, displayed on all the four PCMS. The message displayed warned the drivers to stop ahead. The quantitative values displayed were the time needed to reach the end of work zone. Table 5.7 yielded p-value of the interaction (gender * interval) as significant (< 0.0001). Box plots of mean speeds of male and female participants are plotted for different intervals. The MSE is 31.73. The HSD value is 3.36. For this scenario age was not a significant factor.

Table 5.7 Statistical significant results for scenario-3

Source	Degrees of Freedom	p-value
Interval	7	**<0.0001**
Gender*Interval	7	**<0.0001**

p-value- probability of rejecting the null hypothesis for a given significance level

Bold indicate statistically significant at 0.05 level of significance

Table 5.8 shows the LSM and HSD values of mean speeds from interval-1 to interval-8 for scenario-3. It is interesting to see that interval-5, interval-7 and interval-8 have mean speeds that are significantly different from the other intervals. It is assumed that participants find no reason to stop or slow down. There is a decrease in the mean speeds of the drivers' after sighting PCMS#1 and PCMS#2 but there is an increase after PCMS#2 and before PCMS#3.

Figure 5.7 shows the box plot of mean speeds for interaction "interval*gender". There is a huge variation in the mean speeds of male participants from interval-1 to interval-5 (before PCMS#3). Less variation of mean speeds is observed at interval-7 for male participants, which suggested that majority of male participants slowed down when they are near the construction zone. Less variation is observed in the speeds of the female participants from interval-1 to interval-7, which suggested that majority of the female participants follow the message alike. There is an increase in speed at interval-5 for both male and female participants and it is assumed to be due to the fact that the end of work zone was downstream and they did not find the need to slow down. The final mean speeds is almost equal for both male and female participants.

Figure 5.8 shows the 85^{th} percentile speed and the mean speeds. The mean speeds increase interval-1 to interval-5 and start to decrease only when they are near the construction zone.

Table 5.8 Mean, standard deviation and p-values for LSM and HSD: scenario-3

Interval	Mean	Standard Deviation	2	3	4	5	6	7	8
	Miles per hour		p-values and difference between the mean speeds (HSD = 3.36, α = 0.05)						
1	43.08	9.80	1.000 (0.08)	0.9996 (0.48)	0.4329 (2.18)	**<.0001 (6.69)**	0.8253 (1.39)	**0.0334 (3.76)**	**<.0001 (19.99)**
2	43.00	6.91	-	0.9990 (0.56)	0.3905 (2.26)	**<.0001 (6.77)**	0.7901 (1.47)	**0.0406 (3.68)**	**<.0001 (19.91)**
3	43.56	6.97	-	-	0.7759 (1.70)	**<.0001 (6.21)**	0.9812 (0.91)	**0.0059 (4.28)**	**<.0001 (20.47)**
4	45.26	4.71	-	-	-	**0.0012 (4.51)**	0.9987 (0.79)	**<.0001 (5.94)**	**<.0001 (22.17)**
5	49.77	6.43	-	-	-	-	**<.0001 (5.30)**	**<.0001 (10.45)**	**<.0001 (26.68)**
6	44.47	5.27	-	-	-	-	-	**<.0001 (5.15)**	**<.0001 (21.38)**
7	39.32	5.11	-	-	-	-	-	-	**<.0001 (16.23)**
8	23.09	2.61	-	-	-	-	-	-	-

"-"= not applicable

p-value- probability of rejecting the null hypothesis for a given significance level

Bold indicate statistically significant at 0.05 level of significance and HSD = 3.36

Values in parenthesis represent the difference between the mean speeds

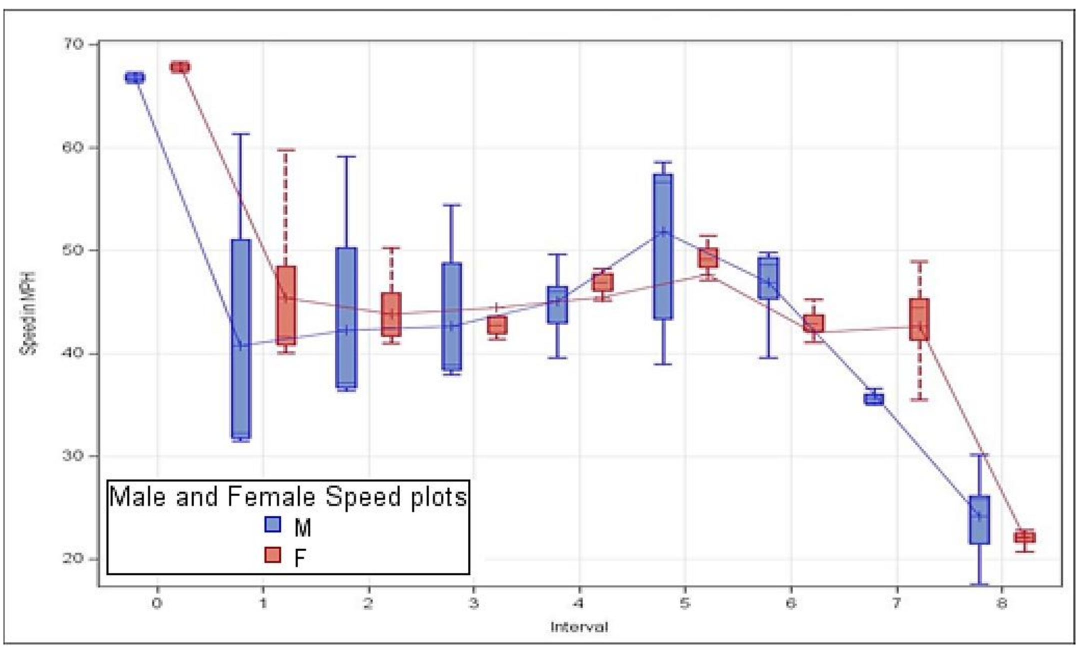


Figure 5.7 Box plot comparison-scenario-3

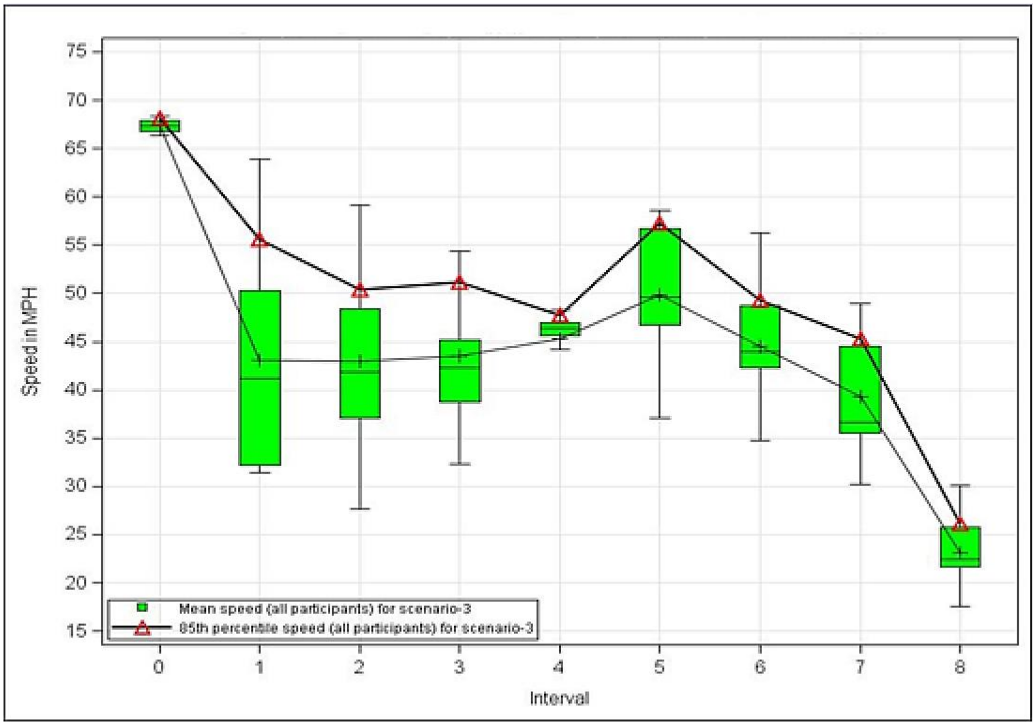


Figure 5.8 Comparison of mean speeds and 85th percentile speed for scenario-3

5.1.5. Scenario-4. Scenario-4 had Message sign-4, “PREPARE TO STOP, STOPPED TRAFFIC AHEAD”, displayed on all the four PCMS. This message displayed warned the drivers to stop ahead. There was no quantitative value displayed on this message.

The statistical analysis (Table 5.9) performed yielded sub-plot factor ‘interval * gender’ significant (< 0.0001). The MSE from the ANOVA table is 10.05. The HSD value is 3.36. For this scenario, age was not a significant factor.

Table 5.9 Statistical significant results for scenario-4

Source	Degrees of Freedom	p-value
Interval	7	**<0.0001**
Gender*Interval	7	**<0.0001**

p-value- probability of rejecting the null hypothesis for a given significance level

Bold indicate statistically significant at 0.05 level of significance

Table 5.10 shows pairwise comparisons for scenario-4. Interval-1 and interval-2 have mean speeds of 36.60 MPH and 37.77 mph and no significant difference in the mean speed is observed before and after PCMS#1. But there is a significant difference of mean speed between interval-3 (mean speed of 41.33 mph) and interval-4 (mean speed of 36.11 mph). The difference in speeds before and after PCMS#2 is almost 5 mph. The final speed at interval-8 is 13.64 mph, which mostly suggested that the severity of the messages is understood by the participants.

Speed plot of the mean speeds for “interval * gender” is illustrated in Figure 5.9. The mean speeds of male participants are slightly greater than the female participants. The final speeds (interval-8) were almost equal for both genders.

Plot of mean speeds and 85th percentile speeds of scenario-4 is illustrated in Figure 5.10. The 85th percentile speed for the third interval is slightly higher than the other intervals. But there is a huge decrease in the speed from interval-8 to interval-7 which inferred the overall effectiveness of the 4 PCMS for scenario-4. This also suggests that for scenario-4, the combined effect of the message decreased the speeds of the participants significantly.

Table 5.10 Mean, standard deviation and p-values for LSM and HSD: scenario-4

Interval	Mean	Standard Deviation	2	3	4	5	6	7	8
	Miles per hour		p-values and difference between the mean speeds (HSD = 3.36, α = 0.05)						
1	36.60	5.17	1.000 (0.08)	**<.0001 (4.73)**	0.9975 (0.49)	0.8673 (0.83)	0.9762 (0.59)	0.1739 (1.57)	**<.0001 (22.96)**
2	37.77	5.76	-	**<.0001 (3.56)**	0.2040 (1.66)	0.9999 (0.34)	0.9916 (0.58)	0.9953 (0.40)	**<.0001 (24.13)**
3	41.33	5.45	-	-	**<.0001 (5.22)**	**<.0001 (3.90)**	**<.0001 (4.14)**	**<.0001 (3.16)**	**<.0001 (27.69)**
4	36.11	6.05	-	-	-	0.4495 (1.32)	0.7112 (1.08)	0.0286 (2.06)	**<.0001 (22.47)**
5	37.43	4.85	-	-	-	-	**0.9999 (0.24)**	**0.9388 (0.74)**	**<.0001 (23.79)**
6	37.19	4.71	-	-	-	-	-	0.7647 (0.98)	**<.0001 (23.55)**
7	38.17	5.08	-	-	-	-	-	-	**<.0001 (16.23)**
8	13.64	1.71	-	-	-	-	-	-	-

"-"= not applicable

p-value- probability of rejecting the null hypothesis for a given significance level

Bold indicate statistically significant at 0.05 level of significance and HSD = 3.36

Values in parenthesis represent the difference between the mean speeds

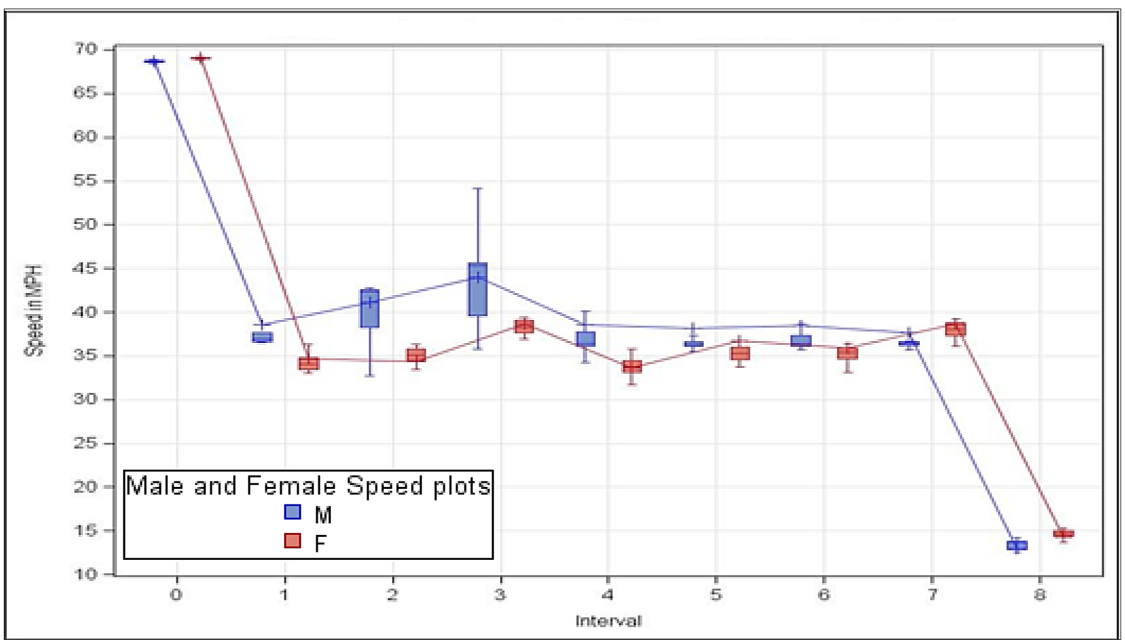


Figure 5.9 Box plot comparison for scenario-4

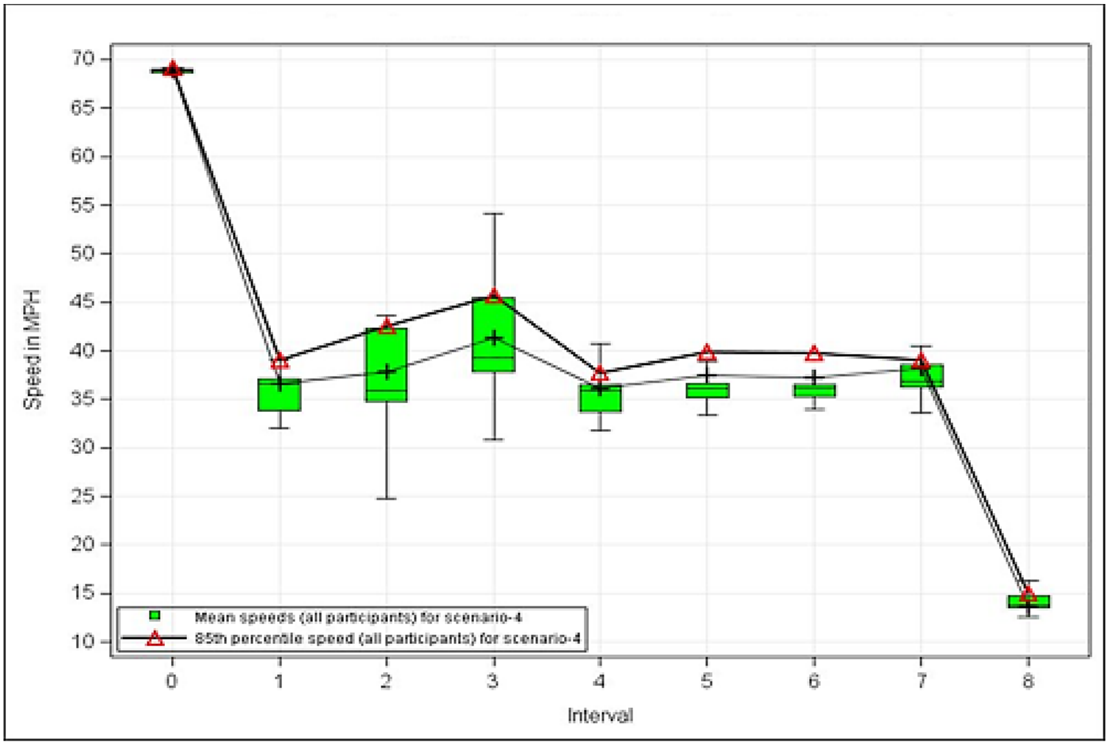


Figure 5.10 Comparison of mean speeds and 85th percentile speeds for scenario-4

5.2. DATA ANALYSIS ACROSS THE SCENARIOS

The driver behavior just before the start of the construction zone is important to analyze as it impacted the speeds of vehicles entering the construction zone. The fourth PCMS is located upstream closest to the construction zone and provided an opportunity to analyze the speed characteristics. The last interval after the PCMS is therefore analyzed for the five scenarios; the control scenario is included for comparison with other scenarios that included the PCMS.

Interval-8 ranged from the fourth PCMS#4 to 1000 feet downstream from it. The statistical analysis performed yielded main plot factor ‘gender’ and sub-plot factor ‘message-sign’ significant based on the p-value (< 0.0001). Results from the ANOVA conducted for different scenarios are presented in Table 5.11. The significant values are marked in bold.

The interaction, 'gender * message-sign' is significant (< 0.0001). Further analysis is carried out to analyze the pairwise comparison between each scenario for the final interval. LSM and HSD are calculated by Tukey's method to observe the pairwise comparison and also analyze the significant p-values between them.

Table 5.11 Statistical significant results for interval-8

Source	Degrees of Freedom	p-value
Message-Sign	4	**<0.0001**
Gender*Message-Sign	4	**0.0079**

p-value- probability of rejecting the null hypothesis for a given significance level

Bold indicate statistically significant at 0.05 level of significance

Table 5.12 summarizes the pairwise comparison for the various message signs for the final interval. The mean speed across all the four message signs is significantly different from each other. The maximum mean speed is observed in the control scenario, which was expected, followed by scenarios 1-4. The mean speeds for scenarios 0-5 are 62.55 mph, 53.20 mph, 26.49 mph, 23.09 mph and 13.64 mph, respectively.

Mean speeds plotted for gender is illustrated in Figure 5.11. From the plot, it can be observed that the difference in speeds between the genders is minimal. It can be observed from the mean speeds (Figure 5.12), that each message is perceived differently by the participants. This also indicates that message sign-4 had the maxmum effect on the drivers' speed resulting in the maximum reduction of the final speed.

Table 5.12 Mean, Standard Deviation and p-values for LSM and HSD: interval-8

Scenario	Mean	Standard Deviation	2	3	4	5
	Miles per hour		p-values and difference between the mean speeds (HSD = 1.51, α = 0.05)			
Control	62.55	1.84	**<.0001 (9.35)**	**<.0001 (36.04)**	**<.0001 (39.46)**	**<0.001 (48.91)**
1	53.20	4.21	-	**<.0001 (26.71)**	**<.0001 (30.11)**	**<.0001 (39.56)**
2	26.49	2.99	-	-	**<.0001 (3.40)**	**<.0001 (12.85)**
3	23.09	2.61	-	-	-	**<.0001 (9.45)**
4	13.64	1.71	-	-	-	-

"-"= not applicable

p-value- probability of rejecting the null hypothesis for a given significance level

Bold indicate statistically significant at 0.05 level of significance and HSD = 1.51

Values in parenthesis represent the difference between the mean speeds

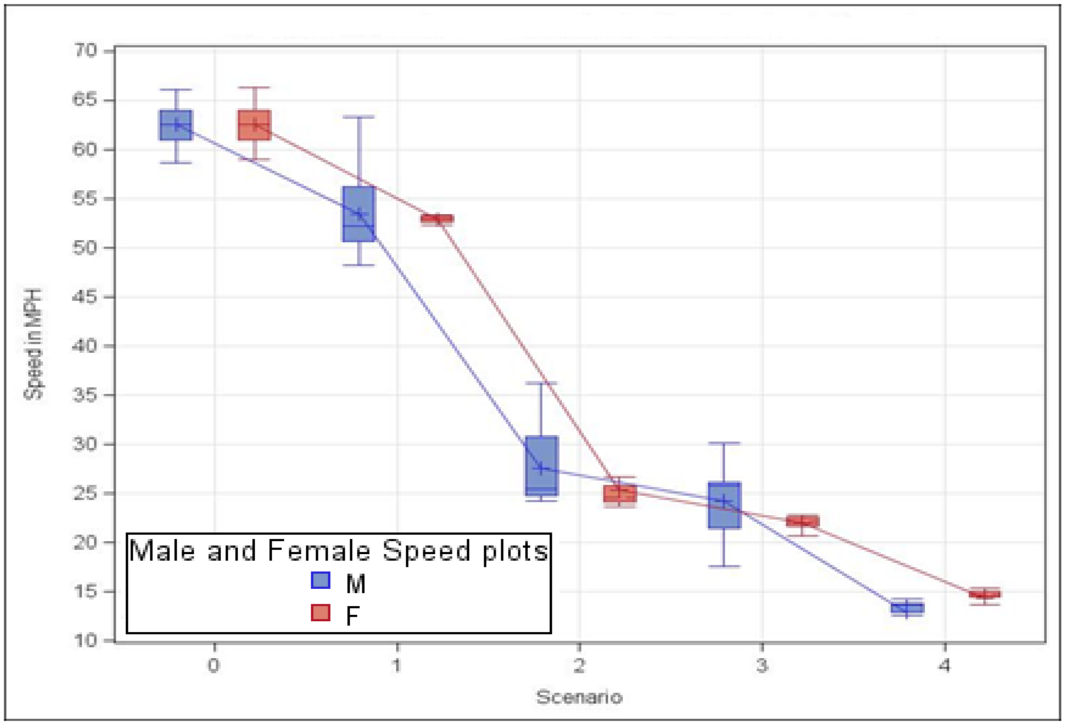


Figure 5.11 Comparison of speeds for interaction (gender*interval) - interval8

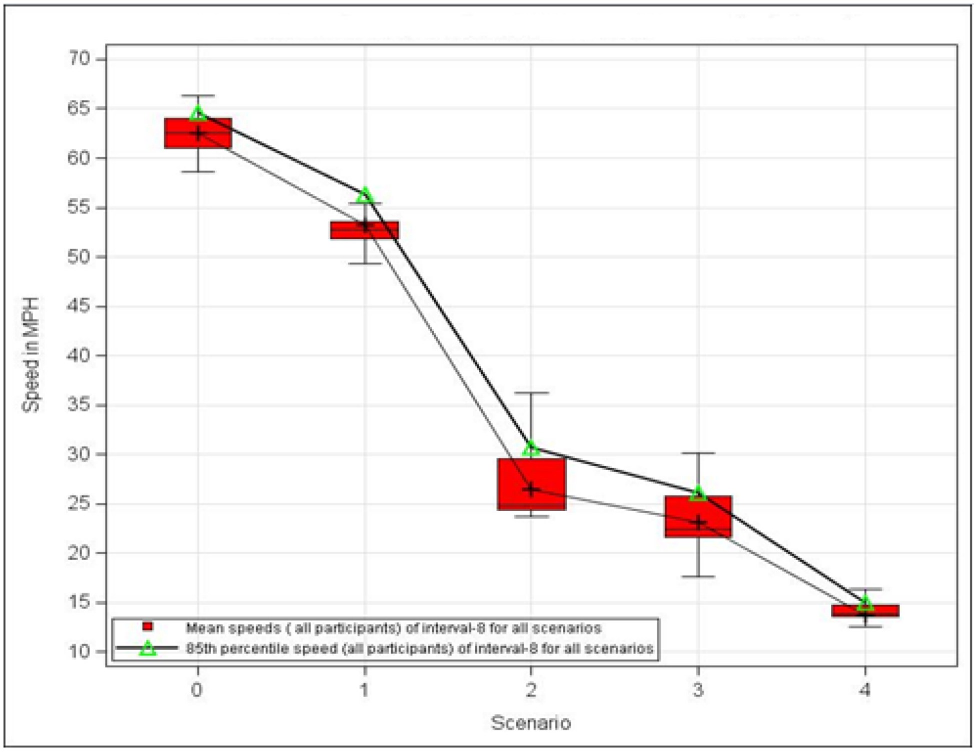


Figure 5.12 Mean speeds and 85th percentile speed for the final interval

5.3. SPEED PROFILE FOR SCENARIOS

The speed profiles of all the scenarios are shown in Figure 5.13. The control scenario did not see any significant change in speeds across intervals as discussed earlier. The only significant decrease is observed in the final speed and which can be attributed to the start of static signs before the construction zone.

For scenario-1, the observed mean speeds for all intervals are much lower than the control scenario and is significantly lower at the final interval. But it can be deduced that MS-1 did have an impact in reducing the speed of the participants. There is a slight increase in mean speeds at interval-3, this can be attributed to the fact that participants expected a “Work Zone Ahead” after seeing the first PCMS and did not see a work zone.

For scenario-2, the observed mean speeds are lower when compared to control scenario and scenario-1. Again we see a slight increase of mean speeds at interval-3, which again is assumed to be due to participants not sighting the work zone after the first PCMS. There is a significant decrease in the mean speed at the final interval when compared to control scenario and scenario-1.

For scenario-3 there is an appreciable decrease of speed at interval-1 but a slight increase is observed until interval-5. This increase in the speed maybe due to participants not finding a reason to stop when they observe the messaging signs as they did not see the start of a taper or a construction zone. But the mean speed decreases from interval-6 (before PCMS#3) as participants start nearing the construction zone.

Scenario-4 also sees a similar trend as scenario-3; at interval-3 there is an increase of speed as participants did not find either “stopped traffic” or the need the stop. But the mean speed doesn’t change significantly from interval-4 to interval-7. The participants start to slow down as they near the construction zone. The final speed is very low and lowest compared to other scenarios.

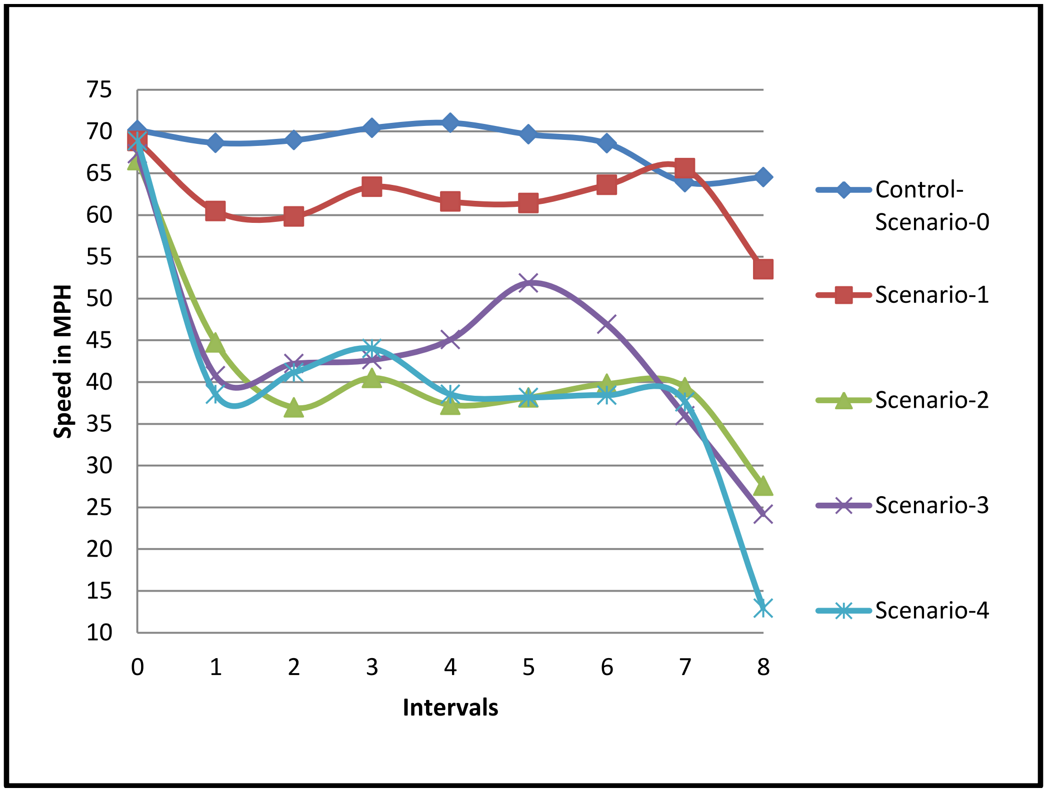


Figure 5.13 Mean speed profile for nine intervals for various scenarios

Message Sign: 0: Control Scenario – No message.

Message sign-1: "CAUTION WORK ZONE AHEAD: REDUCE SPEED AHEAD"

Message sign-2: "SPEED AHEAD 30 MPH: 11,7,4,2 MINS TO END OF WZ"

Message sign-3:"PREPARE TO STOP: 16, 11, 7, 4 MIN TO END OF WZ"

Message sign-4:"PREPARE TO STOP: STOPPED TRAFFIC AHEAD"

5.4. SUBJECTIVE SURVEY RESULTS

A subjective evaluation was carried out in addition to the quantitative objective evaluation. A total of 52 participants participated in the subjective evaluation. This evaluation was carried out to evaluate participants' perception about the effectiveness of the PCMS and how PCMS impacted their driving. The following results provide an insight into the driver's perception and understanding of the message signs.

Participants were asked to rate the different message signs according to their effectiveness and the ability to convey the most accurate information to the drivers. The mean ratings of the message signs are illustrated in Figure 5.14. Rating 4 was considered to be the most effective message and 1 was considered to be the least effective of the four message signs. The results suggested MS-2 was considered to be most effective (mean rating score of 2.24) by the participants which in turn suggested that MS-2 provided accurate information to the drivers. The other messages almost had equal mean ratings which suggested that they did not provide accurate information to the drivers and possibly the drivers were confused as to what action to take. MS-1 provided the least clear message as it only alerted the drivers and no action was required from them. Participants preferred MS-2 as an action was required in terms of a definite speed to be followed, whereas the other three messages seemed ambiguous for the participants as no specific action was required.

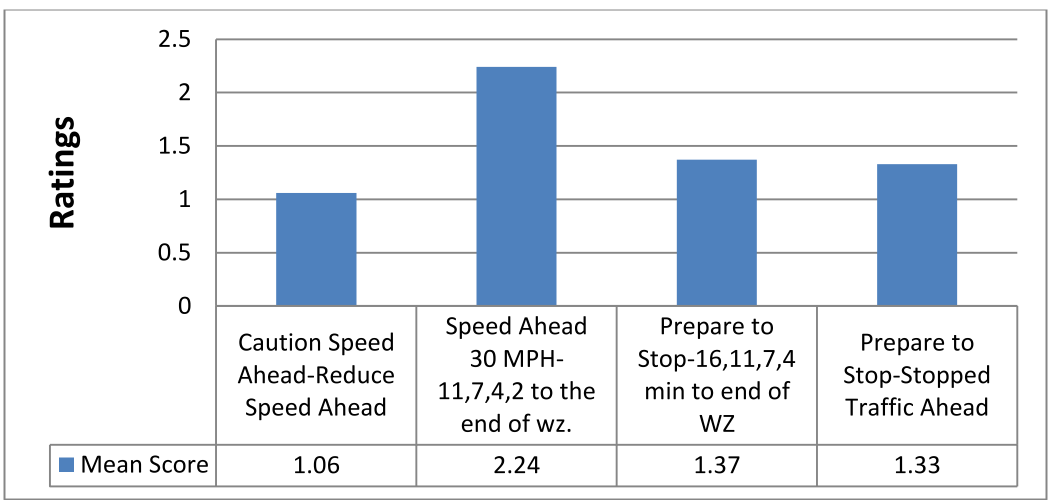


Figure 5.14 Mean ratings of message signs

Next, the participants were asked about the actions taken after sighting, reading and comprehending the PCMS. Figure 5.15 illustrates the actions taken by the participants. Fifty-two (100%) participants slowed down after sighting the PCMS. This indicates that all the participants adhered to the PCMS and slowed down after sighting the PCMS. Thirty-five (67%) participants said they looked for more information when they sighted the message. This can be attributed to the ambiguity of messages 1, 3 and 4. Forty (76%) changed the lane when they saw the message, as there was no traffic on the simulated highway, this behavior can be attributed to the start of taper and closing of the right lane at the start of the construction zone.

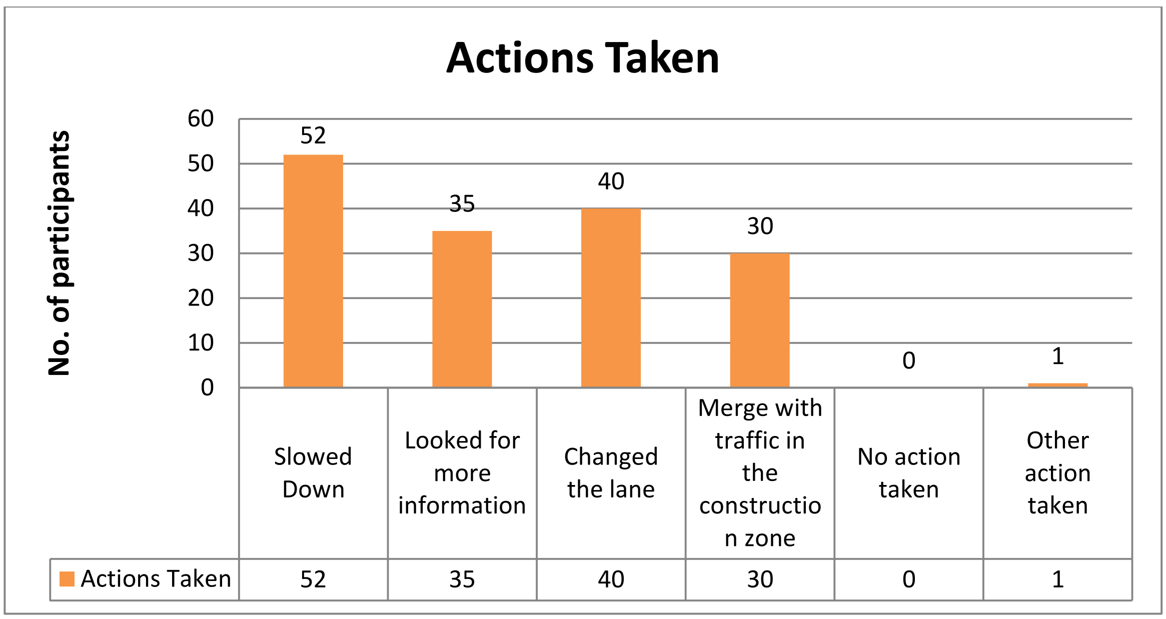


Figure 5.15 Action taken by the participants after sighting the PCMS

Figure 5.16 shows the participants' ability to recall the messages observed. Thirty-seven (71%) of participants were able to recall all the observed messages correctly. This high percentage might be attributed to the fact that participants knew beforehand what they were being tested upon and paid more attention to the message signs than usual. Only one person failed to recall MS-1 (Caution Work Zone Ahead: Reduce Speed Ahead), three people failed to recall MS-2 (Speed Ahead 30 mph: 11, 7, 4, 2 min to end of wz) four people failed to recall MS-3 (Prepare to Stop: 16, 11, 7, 4 min to end of wz) and 8 people failed to recall MS-4 (Prepare to Stop: Stopped Traffic Ahead). This might be attributed to the similarity between MS-3 and MS-4 which contains the same first phase of the two phase message. Participants might have perceived this as a repetition of the experiment.

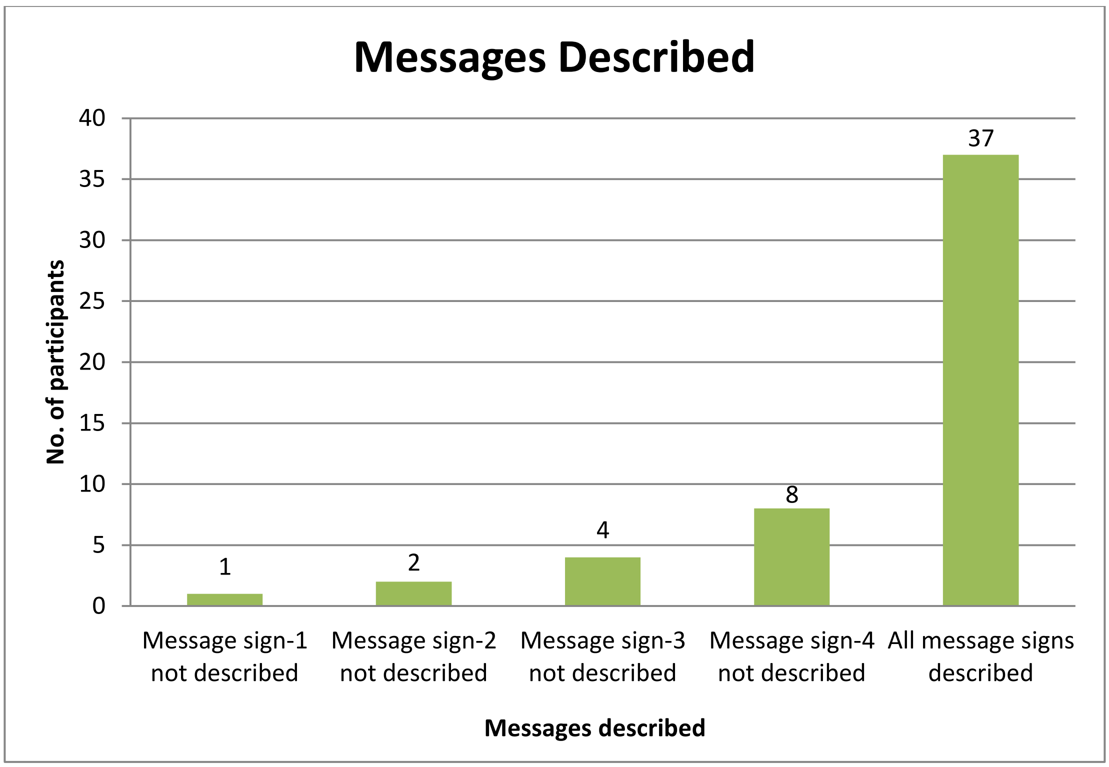


Figure 5.16 Participant's ability to recall the observed messages

5.5. SUMMARY

From the objective evaluation, the observed mean speeds were the lowest for MS-4 (used when the average speed of vehicles is less than 5mph in the construction zone). Statistical analysis yielded gender and interval as the main factors of significance for all the scenarios, which suggests that each message was perceived differently by male and female participants. Age was not found to be a significant factor for all scenarios. From the subjective evaluation it was deduced that MS-2 (used when the average speed of vehicles is between 20-50 mph in the construction zone) was the most effective since it displayed a particular speed limit for the participants to follow. This was reinforced by observing the 85th percentile for MS-2 (30.67 mph) from the objective evaluation, which was almost equal to the displayed speed limit on the PCMS (30 mph). The mean speed for MS-2 in the final interval was 26.47 mph, which was lower than the displayed speed. But the mean speed for MS-4 was 13.64 mph, which was greater than the average mean speeds intended for the usage of MS-4. It can be deduced from the objective and subjective evaluations that MS-2 is the most effective message sign.

6. CONCLUSIONS AND RECOMMENDATIONS

The research project presents a subjective and objective study to evaluate the effectiveness of PCMS using a driving simulator (DS). The objective evaluation used speed as the main criterion and to examine the effects of different message-signs on driving speed characteristics. The objective evaluation considered the variables of gender, age and message signs. Five scenarios were tested: control scenario without any message and the remaining four scenarios with different messages (Table 2.2). The four PCMS placed in a sequential configuration replicated a work zone setup on I-44 in Missouri. These scenarios were used to analyze the driver's speed before and after each PCMS.

From the objective evaluation using the driving simulator, it was observed that the speed did not vary significantly for the first seven intervals of all the scenarios. In terms of the speed, significant difference was found on the last interval after the fourth PCMS was placed before the construction zone.

On a virtual highway replicated in the DS with a 70 mph speed limit for the control scenario, the mean speed of drivers in the last interval was observed as 62.55 mph. The mean speed of drivers in the final interval for scenario-1 ("Caution Work Zone Ahead: Reduce Speed Ahead", displayed on each of the four PCMS) was 53.20 mph, a decrease of 9.35 mph from the control scenario. The mean speed of drivers in the final interval for scenario-2 ("Speed ahead 30 mph; 11, 7, 4, 2 min to end of wz", displayed on each of the four PCMS), was 26.49 mph, which indicated a decrease of 36.06 mph from the control scenario. The mean speed of drivers in the final interval for scenario-3 ("Prepare to stop; 16, 11, 7, 4 min to end of wz", displayed on each of the four PCMS) was 23.09 mph, which was a decrease of 39.46 mph. For scenario-4, ("prepare to stop; stopped traffic ahead", displayed on each of the four PCMS) the mean speeds for the final interval was 13.64 mph, a decrease of 48.91 mph from the control scenario. It can be concluded that all the message signs reduce the speed of the participants before the start of the construction zone. Scenario-4 had the highest speed reduction, when compared to all the other scenarios, followed by scenario-3, scenario-2 and scenario-1.

The 85th percentile speed of 30.67 mph after the fourth PCMS (the last interval) for message sign-2 (MS-2) was observed to be very close to the speed displayed on the PCMS. From this observation, it can be inferred that drivers comply with a certain speed limit displayed on the PCMS and the messages that do not provide the drivers with specific speed values are difficult to follow.

Statistical analysis of the collected data from the DS showed that age group was not significant but gender played an important role. From the analysis of variance, it was observed that female participants exhibited lesser variations in speeds for the majority of the intervals (1000 ft before and after each PCMS).

The subjective analysis yielded scenario-2 (message sign-2) as the most effective among all message signs. The participants preferred the usage of message sign-2 (MS-2) because it specified a certain speed value to follow. All the participants who were involved in the experiments adhered to the message and slowed down to around 30 mph. Only messages that are clear and can be adhered to should be displayed. PCMS with ambiguous values are least effective. From the objective and subjective analysis the usage of MS-2 is recommended, where the drivers are given a certain speed limit to follow.

6.1. FUTURE WORK

The suggested future work for this study is given as follows:

1. Study the impact of different locations of PCMS on driver behavior and determine the best criterion for the locations.
2. It is also suggested to study the impact of placing fewer than four PCMS on driver speed characteristics.
3. PCMS can also be evaluated by using different message signs on different PCMS for a given scenario.
4. Different interval lengths can be adopted to study the effects of PCMS, during different times of the day to examine any difference in the speed reduction pattern.

APPENDIX A.

DRIVING SIMULATOR QUESTIONNAIRES

1. Pre-Screening Questionnaire

Screening Questionnaire (General and Health Information)

Please complete the questionnaire by providing as much information as required

1. Do you hold a **valid** US driver's license?

☐Yes ☐No

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

☐Yes ☐No

3. Have you been involved in an accident in a work zone?

☐Yes ☐No

4. If your answer is yes to questions 3 or 4, please state the number of crash(s) you have been involved in and also state the type of crash(s).

5. Do you have a history of radial keratotomy, [laser] eye surgery, or any other ophthalmic surgeries?

☐Yes ☐No

If yes, which ones? ______________________________________

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

☐Yes ☐No

7. Are you night blind?

☐Yes ☐No

8. Are you color blind?

☐Yes ☐No

If 'yes', state the colors that you are deficient in:

____

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

☐Yes ☐No

If yes, please state which.

10. Does driving through work zones increase your stress?

☐Yes ☐No

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

☐Yes ☐No

12. Do you have a history of motion sickness?

☐Yes ☐No

13. Do you have a history of claustrophobia?

☐Yes ☐No

14. Are you suffering from any lingering effects of stroke, tumor, head trauma, or infection?

☐Yes ☐No

15. Do you or have you ever suffered from epileptic seizures?

☐Yes ☐No

16. Do you have a history of migraines?

☐Yes ☐No

17. Do you have any problems while driving during night time?

☐Yes ☐No

18. Have you had any experience with a driving simulator before?

☐Yes ☐No

2. Pre-Driving Questionnaire

1. Age: ______years

2. Gender: ☐Male ☐Female

3. Have you consumed alcohol during the last 24 hours?
   ☐Yes ☐No

4. Have you consumed recreational drugs during the last one week?
   ☐Yes ☐No

5. How often do you drive?
   ☐Daily ☐Once a week ☐Occasionally

6. State the number of years you have been driving: _________ [years]

7. During which time of the day do you usually drive? (Mark all those applicable)
   ☐Day ☐Night ☐Dawn ☐ Dusk

8. Do you drive frequently on *Interstate Highways*?
   ☐Yes ☐No

9. What type of vehicle do you drive most often (check one)?
   ☐ Passenger Car ☐ Pick-Up Truck ☐ Sport utility vehicle ☐ Van or Minivan
   ☐ Motorcycle ☐ Other:

10. Have you ever come across a portable changeable message sign as shown below in a work zone?

☐Yes ☐No

11. Level of education
☐ Secondary Education ☐ College Graduate ☐ University graduate

Note: Pregnant women are not allowed to participate because of federal regulations since the risk to pregnant women and unborn child is not known.

3. Post Driving Questionnaire

1. Did you see the portable changeable message signs on the highway when you drove through the work zone?
   ☐Yes ☐No

If the answer is YES, then, continue the survey. If the answer is NO, stop the survey.

2. Did you understand the message displayed on the 1st, 2nd, 3rd and the 4th PCMS?
   ☐Yes ☐No

3. If yes to the above question, please describe the problem on each of the PCMS as you remember?

4. Did the PCMS grab your attention in terms the task to be performed?
   ☐Yes ☐No
5. Did you adhere to the message displayed on the PCMS?
   ☐Yes ☐No

6. What actions did you take after watching the PCMS? (select all that apply)
   ☐ Slowed down ☐ Looked for more information

   ☐ Changed the lane ☐ Merge with traffic in the construction zone

   ☐ No action taken ☐ please mention other the action below:

7. Which one of the following message(s) did you observe? (Select all that apply)
   ☐ CAUTION WORK ZONE AHEAD, REDUCE SPEED AHEAD

   ☐ SPEED AHEAD 30 MPH, 11,7,4,2 MIN TO END OF WORK ZONE

   ☐ PREPARE TO STOP, 16,11,7,4 MIN TO END OF WORK ZONE

   ☐ PREPARE TO STOP, STOPPED TRAFFIC AHEAD

8. Which one of the messages displayed do you think will be the most effective PCMS? (rank from 1 to 4, 1 being the most effective and 4 being the least effective)
   ☐ CAUTION WORK ZONE AHEAD, REDUCE SPEED AHEAD

   ☐ SPEED AHEAD 30 MPH, 11,7,4,2 MIN TO END OF WORK ZONE

   ☐ PREPARE TO STOP, 16,11,7,4 MIN TO END OF WORK ZONE

   ☐ PREPARE TO STOP, STOPPED TRAFFIC AHEAD

9. Did any PCMS (comprehension) mislead you while driving? If so, please explain how and why?

10. Do you prefer the use of a PCMS to alert drivers about the traffic conditions ahead of you in the work zones in addition to the static signs?
    ☐Yes ☐No

11. Based on today's experience with the PCMS, in what situation do you think the PCMS can be most effective? (Select all that apply)
    ☐ Day time with high traffic ☐ Day time with low traffic volume
    ☐ Night time with high traffic ☐ Night time with low traffic volume

12. In the driving simulator, what was your approximate driving speed in the work zone _______ [mph]

13. In the following, please fill the bubble that represents your most suitable answer about the PCMS

	1	**2**	**3**	**4**	**5**	
Increased traffic congestion	O	O	O	O	O	Reduced traffic congestion
Information displayed was not useful	O	O	O	O	O	Information displayed was useful
Information provided very early	O	O	O	O	O	Information provided very late
Increased the chance of collisions	O	O	O	O	O	Reduced the chance of collisions
Increased the time in congestion	O	O	O	O	O	Reduced the time in congestion
Other vehicles block the view of PCMS	O	O	O	O	O	Other vehicles did not block PCMS
Text (font) size very	O	O	O	O	O	Text (font) size very

small						big
Messages displayed not updated frequently	O	O	O	O	O	Messages displayed updated frequently
Messages displayed too long	O	O	O	O	O	Messages displayed too short
Messages displayed difficult to read	O	O	O	O	O	Messages displayed easy to read
Messages displayed not clear	O	O	O	O	O	Messages displayed clear to understand
Messages displayed were not reliable	O	O	O	O	O	Messages displayed were reliable
Too long a distance between signs	O	O	O	O	O	Too short a distance between signs
Did not affect my driving speed	O	O	O	O	O	Affected my driving speed
Did not affect lane change behavior	O	O	O	O	O	Affected my lane change behavior
Did not improve driving experience(Safety)	O	O	O	O	O	Improved driving experience(Safety)
Not recommended	O	O	O	O	O	Strongly recommended

14. Any other comments, please mention below:

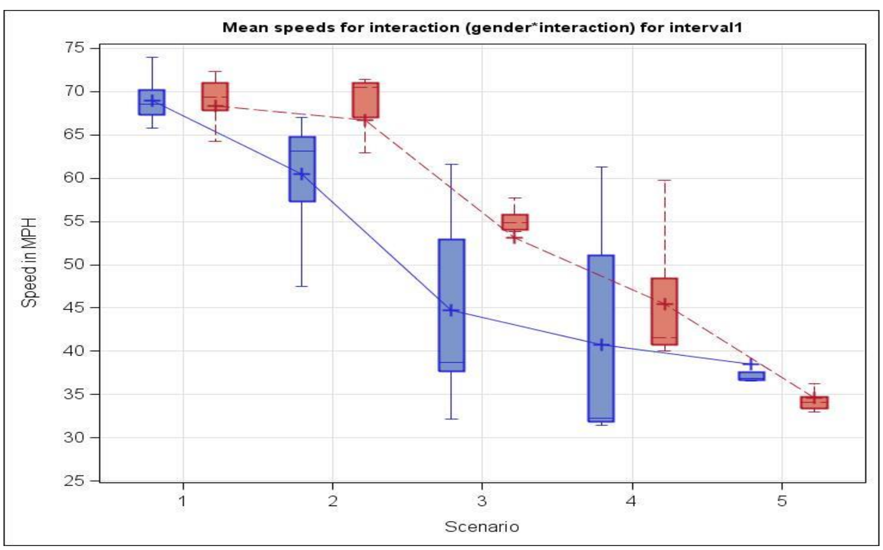
APPENDIX B.

RESULTS OF SPEEDS ACROSS SCENARIOS

1. Interval-1

Source	Degrees of Freedom	Type III SS	Mean Square	F-ratio	Prob > α
Gender	1	568.95159	568.95159	11.10	**0.0010**
Age	1	0.42008	0.42008	0.01	0.9280
Gender*Age	1	47.12237	47.12237	0.92	0.3389
Message-Type	**4**	**38321.30421**	**9580.32605**	**186.91**	**<.0001**
Gender*Message-Type	**4**	**1322.70278**	**330.67570**	**6.45**	**<.0001**
Age*Message-Type	4	132.06047	33.01512	0.64	0.6317
Gender*Age*Message-Type	4	93.41191	23.35298	0.46	0.7682

ANOVA table for Interval-1 across various scenarios.

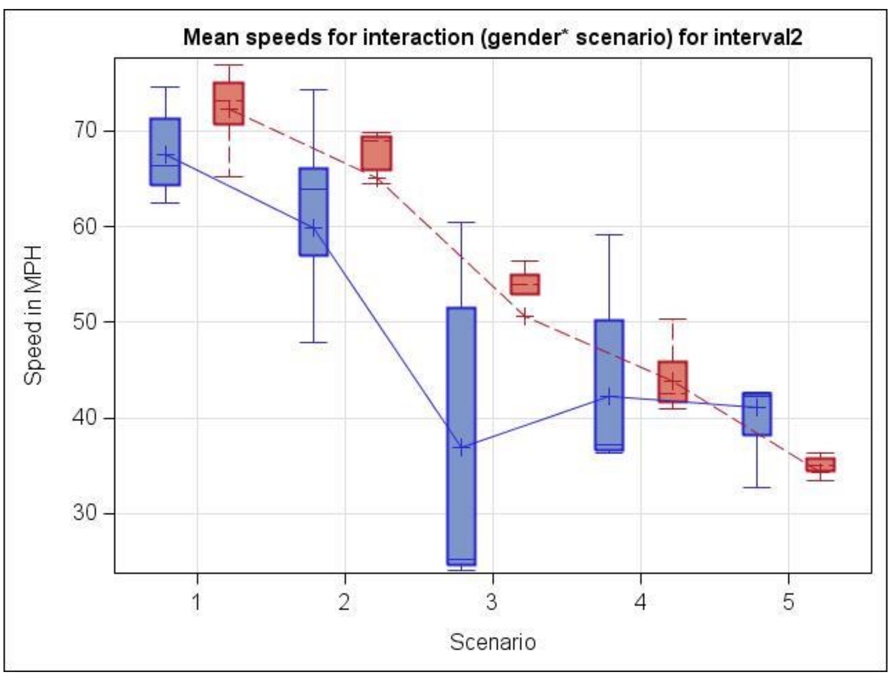


Comparison of Mean speeds for gender*scenario interaction

2. Interval-2

Source	Degrees of Freedom	Type III SS	Mean Square	F-ratio	Prob > F
Gender	**1**	**850.89428**	**850.89428**	**14.62**	**0.0002**
Age	1	7.77579	7.77579	0.13	0.7151
Gender*Age	1	16.71260	16.71260	0.29	0.5926
Message-Type	**4**	**39885.58924**	**9971.39731**	**171.35**	**<.0001**
Gender*Message-Type	**4**	**2680.78319**	**670.19580**	**11.52**	**<.0001**
Age*Message-Type	4	128.69577	32.17394	0.55	0.6972
Gender*Age*Message-Type	4	85.73289	21.43322	0.37	0.8310

ANOVA table for Interval-2 across various scenarios.

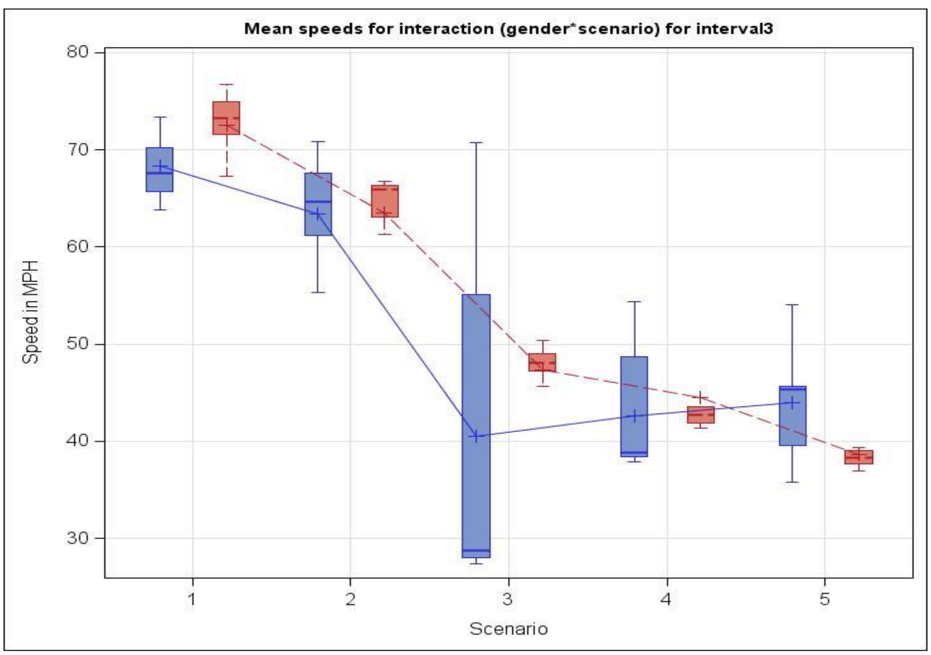


Comparison of Mean speeds for gender*scenario interaction

3. Interval-3

Source	Degrees of Freedom	Type III SS	Mean Square	F-ratio	Prob > F
Gender	1	133.94819	133.94819	2.73	0.0999
Age	1	12.89133	12.89133	0.26	0.6087
Gender*Age	1	21.38428	21.38428	0.44	0.5097
Message-Type	**4**	**36901.18298**	**9225.29575**	**188.21**	**<.0001**
Gender*Message-Type	**4**	**1029.57189**	**257.39297**	**5.25**	**0.0005**
Age*Message-Type	4	56.05565	14.01391	0.29	0.8869
Gender*Age*Message-Type	4	45.10404	11.27601	0.23	0.9213

ANOVA table for Interval3 across various scenarios.

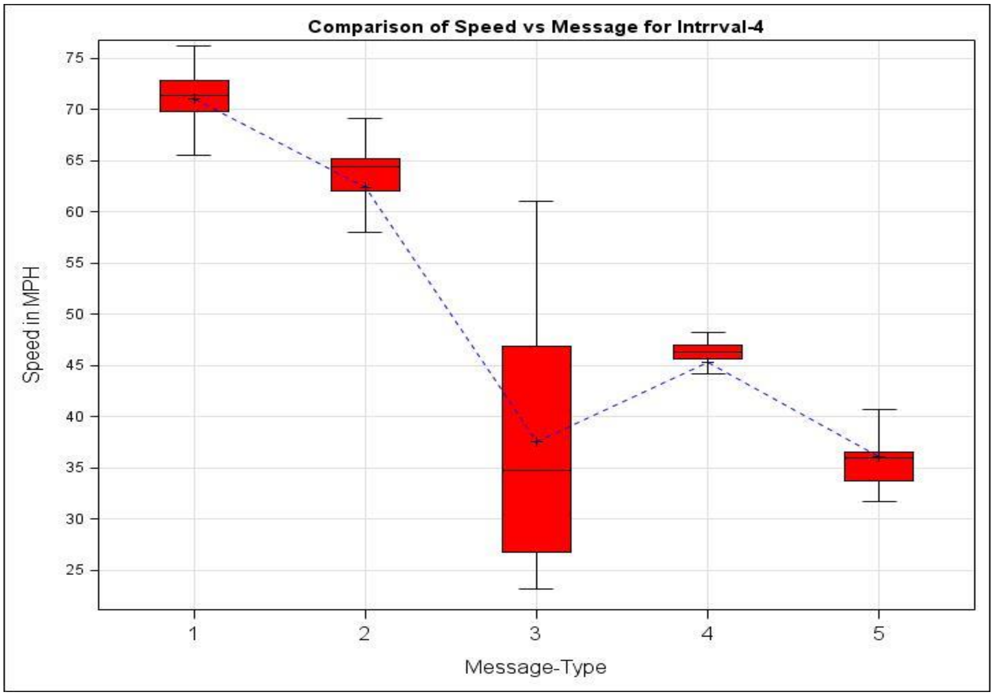


Comparison of Mean speeds for gender*scenario interaction

4. Interval-4

Source	Degrees of Freedom	Type III SS	Mean Square	F-ratio	Prob > F
Gender	1	35.87553	35.87553	0.76	0.3859
Age	1	22.26126	22.26126	0.47	0.4944
Gender*Age	1	5.76450	5.76450	0.12	0.7279
Message-Type	**4**	**49199.73887**	**12299.93472**	**258.95**	**<.0001**
Gender*Message-Type	4	291.57896	72.89474	1.53	0.1937
Age*Message-Type	4	161.18936	40.29734	0.85	0.4962
Gender*Age*Message-Type	4	9.50856	2.37714	0.05	0.9953

ANOVA table for Interval4 across various scenarios.

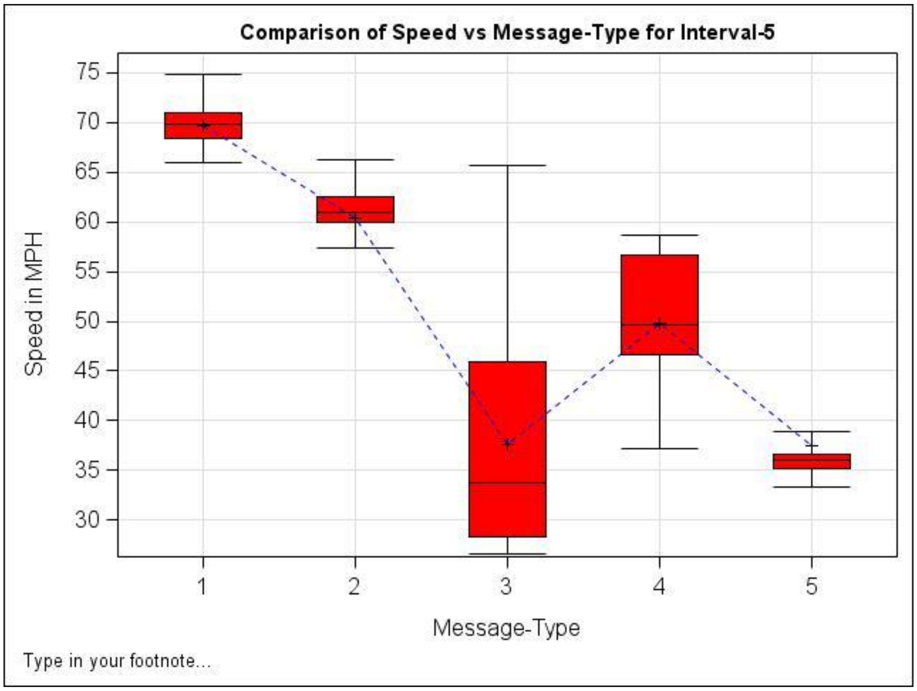


Comparison of Mean speeds for interval-4 across various scenario

5. Interval-5

Source	Degrees of Freedom	Type III SS	Mean Square	F-ratio	Prob > F
Gender	1	188.99688	188.99688	3.92	0.0491
Age	1	0.07408	0.07408	0.00	0.9688
Gender*Age	1	0.17498	0.17498	0.00	0.9520
Message-Type	**4**	**40519.59386**	**10129.89847**	**210.12**	**<.0001**
Gender*Message-Type	4	120.89582	30.22396	0.63	0.6439
Age*Message-Type	4	155.55093	38.88773	0.81	0.5223
Gender*Age*Message-Type	4	20.62391	5.15598	0.11	0.9800

ANOVA table for Interval5 across various scenarios.

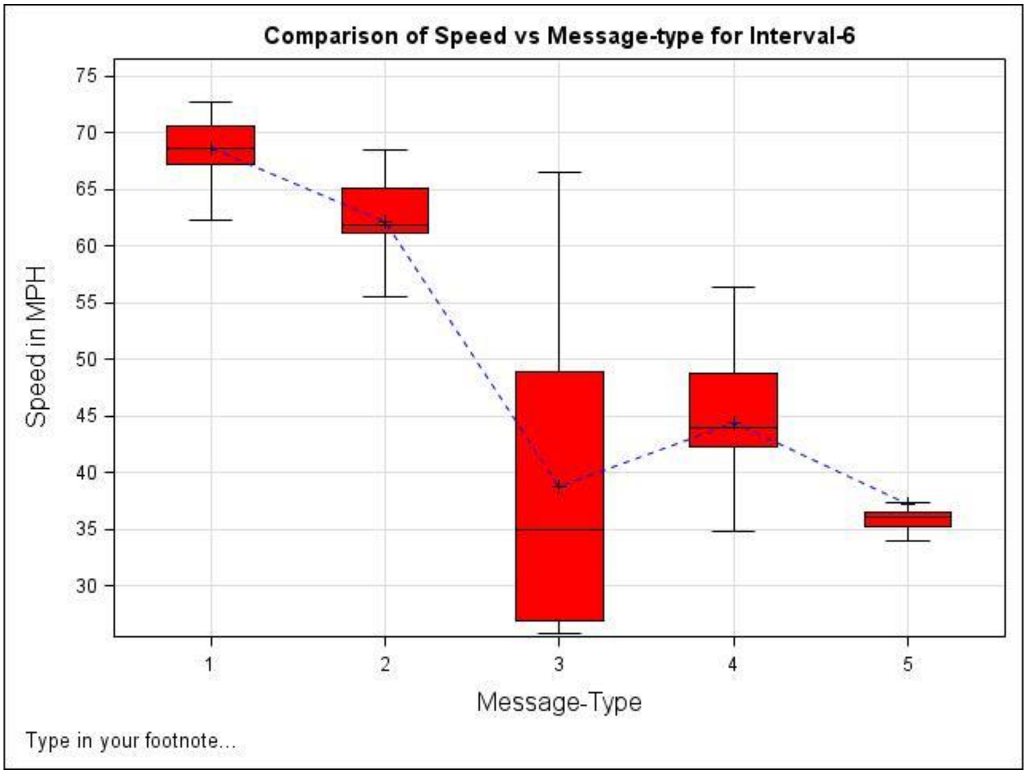


Comparison of Mean speeds for interval5 across various scenario

6. Interval-6

Source	Degrees of Freedom	Type III SS	Mean Square	F-ratio	Prob > F
Gender	1	316.21362	316.21362	6.81	0.0098
Age	1	15.57657	15.57657	0.34	0.5632
Gender*Age	1	6.15251	6.15251	0.13	0.7163
Message-Type	**4**	**41481.89561**	**10370.47390**	**223.33**	**<.0001**
Gender*Message-Type	4	289.12418	72.28104	1.56	0.1876
Age*Message-Type	4	48.69546	12.17386	0.26	0.9019
Gender*Age*Message-Type	4	36.34864	9.08716	0.20	0.9404

ANOVA table for Interval6 across various scenarios.

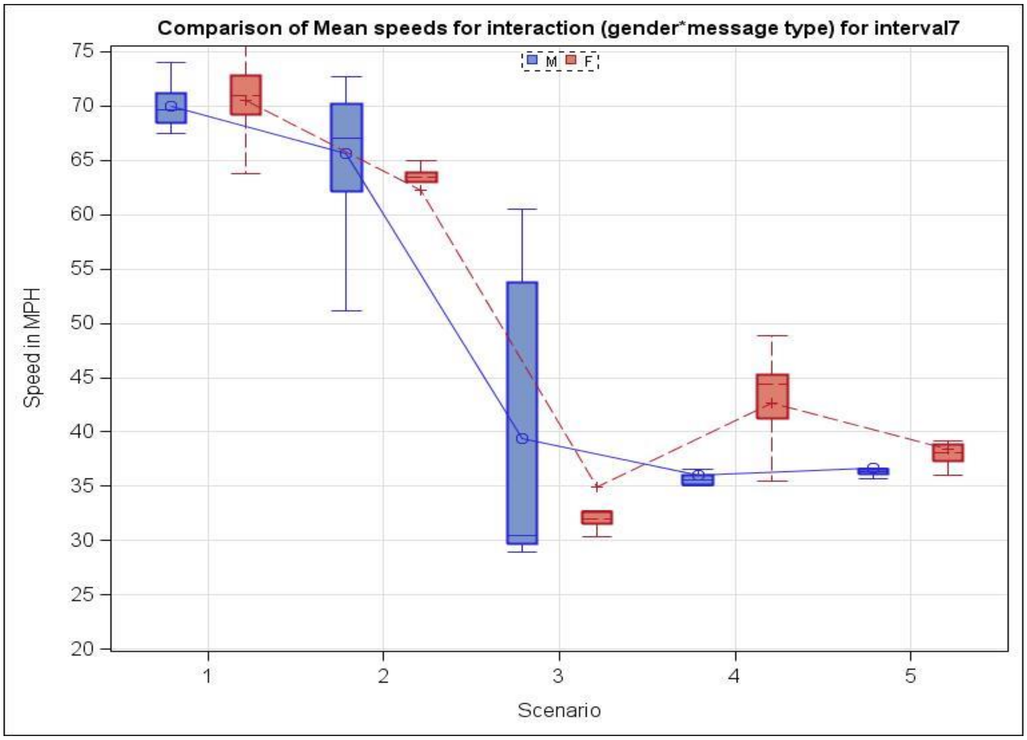


Comparison of Mean speeds for interval 6 across various scenario

7. Interval-7

Source	Degrees of Freedom	Type III SS	Mean Square	F-ratio	Prob > F
Gender	1	1.58784	1.58784	0.04	0.8470
Age	1	18.36273	18.36273	0.43	0.5119
Gender*Age	1	12.25628	12.25628	0.29	0.5920
Message-Type	**4**	**52949.70291**	**13237.42573**	**311.22**	**<.0001**
Gender*Message-Type	**4**	**1065.14710**	**266.28677**	**6.26**	**<.0001**
Age*Message-Type	4	68.44524	17.11131	0.40	0.8068
Gender*Age*Message-Type	4	73.56687	18.39172	0.43	0.7851

ANOVA table for Interval-7 across various scenarios.



Comparison of Mean speeds for gender*scenario interaction

APPENDIX C.

INSTRUCTIONS FOR S&T DRIVING SIMULATOR

1. HARDWARE SETTINGS

Step 1: Powering the Simulator.

- Facing the simulator, the projectors left to right are Projector1 (id=1), Projector2 (id=2) and Projector3 (id=3).
- The name of the master computer is fordsimdev.
- Projector 1, 2 and 3 should be connected to video cards of the master computer.
- Make sure all the projectors are turned on and the master computer is turned on too.

Step2: Configuring the Projectors.

- Open catalyst control center icon to configure the projectors.
- Adjust the display settings so that the three projectors and the desktop of the master computer have the same resolution.
- Open Catalyst Control Center: (a) Click on AMD Eyefinity Multi-Display.

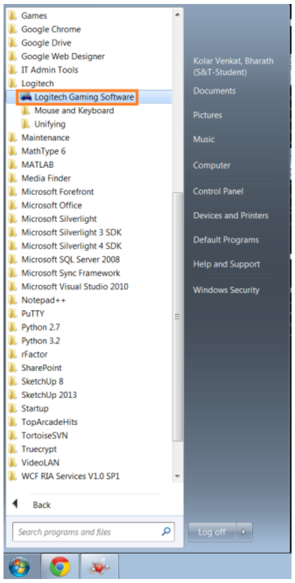
  (b) Select a layout for display, for the simulation purpose select the 4x1 (4 horizontal displays setting). (c) Select the 3 projectors and the desktop to create a layout display.
- Select the resolution to be 1280*1024 on all the four screens.

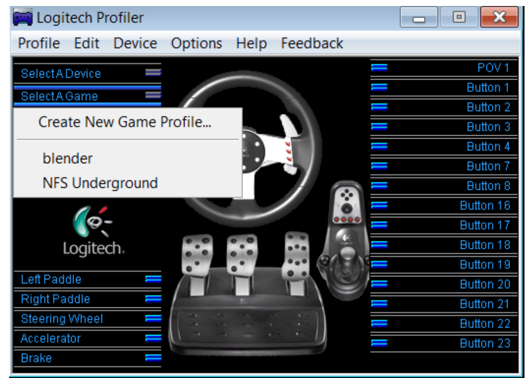
Step3: Configuring the arduino

- Connect the arduino port to one of the USB port of the master computer.
- To switch on the arduino, upload the program from the arduino software.
- Next open the python IDLE module, and open the program adwrite. This will upload the program to configure the arduino as a speedometer and receive and display the speed.
- This has to be done before the start of the simulation.

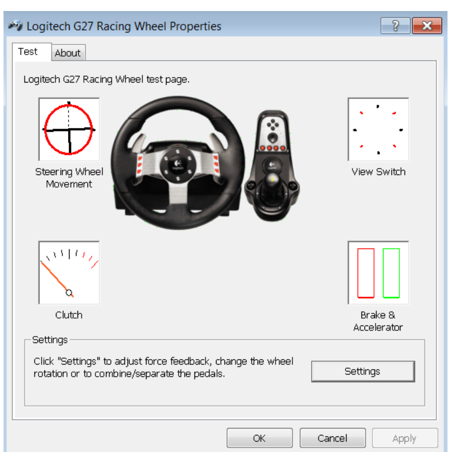
Step4: Configuring the Steering Wheel.

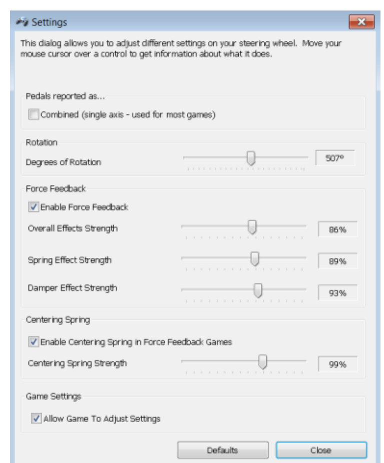
- Programs → Logitech-G27 gaming profiler→ Click on Select a Game → and choose Blender as your default game engine.





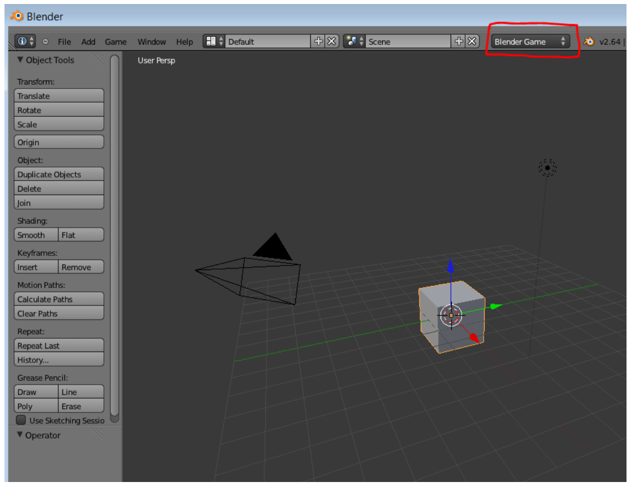
- Start→Devices and Printers→G 27 Racing wheel →Right Click→ Game controller settiings→Settings→ And apply the settings below.



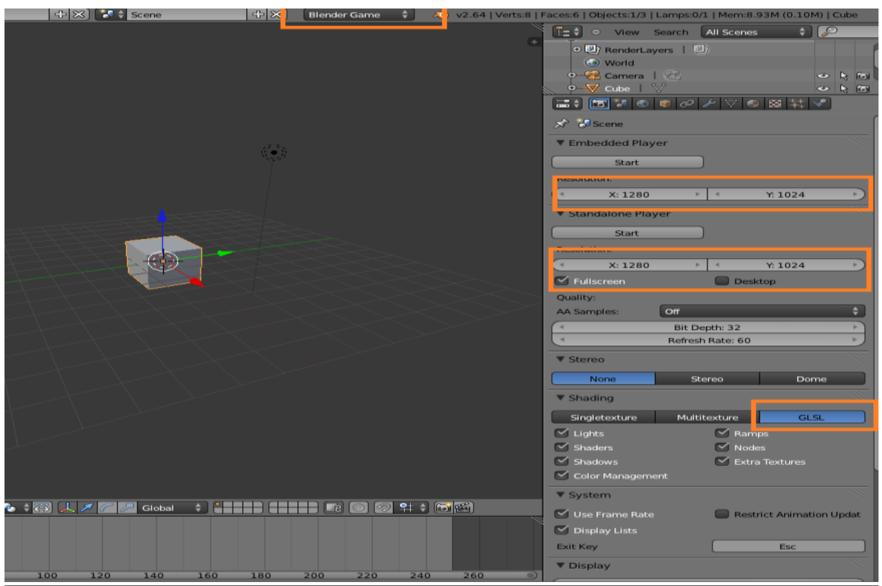


Step5: Configuring Blender

- Start→ Open Blender→ Change the default setting into Blender game.



- Change the resolution of the embedded player into 1280x1024. And change the shading mode to GLSL.



- After these initial settings are completed, select the scenario and with the mouse cursor in the 3D window press “P” for the game to begin.

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VITA

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