A Driving Simulator Study to Evaluate the Impact of Portable Changeable Message Signs (PCMS) on Drivers' Speed Characteristics in Work Zones

Final Report
March 2014

SWZDI
Smart Work Zone Deployment Initiative

MISSOURI S&T
University of Science & Technology

Sponsored by
Smart Work Zone Deployment Initiative
(TPF-5(081))
Federal Highway Administration
(InTrans Project 06-277)

About SWZDI

Iowa, Kansas, Missouri, and Nebraska created the Midwest States Smart Work Zone Deployment Initiative (SWZDI) in 1999 and Wisconsin joined in 2001. Through this pooled-fund study, researchers investigate better ways of controlling traffic through work zones. Their goal is to improve the safety and efficiency of traffic operations and highway work.

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The mission of the Institute for Transportation (InTrans) at Iowa State University is to develop and implement innovative methods, materials, and technologies for improving transportation efficiency, safety, reliability, and sustainability while improving the learning environment of students, faculty, and staff in transportation-related fields.

The preparation of this report was financed in part through funds provided by the Iowa Department of Transportation through its "Second Revised Agreement for the Management of Research Conducted by Iowa State University for the Iowa Department of Transportation" and its amendments.

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
InTrans Project 06-277		

4. Title and Subtitle	5. Report Date
A Driving Simulator Study to Evaluate the Impact of Portable Changeable Message Signs (PCMS) on Drivers' Speed Characteristics in Work Zones	March 2014
	6. Performing Organization Code
7. Author(s)	**8. Performing Organization Report No.**
Ghulam H. Bham, Ming C. Leu, and Bharat K. Venkat, and Mojtaba Ale Mohammadi	InTrans Project 06-277
9. Performing Organization Name and Address	**10. Work Unit No. (TRAIS)**
Missouri University of Science and Technology 1401 N. Pine Street, 135 Butler Carlton Hall Rolla, MO 65409	**11. Contract or Grant No.**
12. Sponsoring Organization Name and Address	**13. Type of Report and Period Covered**
Midwest Smart Work Zone Deployment Initiative Iowa Department of Transportation 800 Lincoln Way Ames, Iowa 50010 Federal Highway Administration U.S. Department of Transportation 1200 New Jersey Avenue SE Washington, DC 20590	Final Report **14. Sponsoring Agency Code** TPF-5(081)

15. Supplementary Notes

Visit www.intrans.iastate.edu/smartwz/ for color pdfs of this and other Midwest Smart Work Zone Deployment Initiative research reports.

16. Abstract

This report analyzed the effects of portable changeable message signs (PCMS) on driver behavior in terms of speed characteristics using a driving simulator. Fifty-two participants from different age groups evaluated four messaging signs with "text and number" by driving through a virtual work zone. Driver reactions to the message signs were analyzed by examining drivers' speed before and after each PCMS. It was observed that speeds did not vary significantly for the first seven intervals (defined before and after each PCMS). Significant difference, however, was found on the eighth interval before the start of the lane closure. A 70 mph highway served as the control scenario on which the mean speed of drivers was observed to be 62.55 mph. For the first message sign (MS-1) ("Caution Work Zone Ahead: Reduce Speed Ahead") the mean speed of drivers decreased by 9.35 mph compared to the control scenario. For MS-2 ("Speed Ahead 30 mph; 2 min to end of WZ"), the mean speed reduced by 36.06 mph compared to the control scenario. For MS-3 ("Prepare to stop; 4 min to end of WZ") a decrease of 39.46 mph was observed. For MS-4 ("Prepare to stop; Stopped traffic ahead") a decrease of 48.91 mph was observed compared to the control scenario. Therefore, MS-4 showed the highest speed reduction compared to other messages. A participant survey was conducted to examine the drivers' rating of the message signs. From this subjective evaluation, MS-2 was rated as the most effective as it was specific in terms of the anticipated speed ahead indicated and hence easier for drivers to follow.

17. Key Words	18. Distribution Statement
driver behavior—driving simulator—PCMS—portable changeable message signs—temporary traffic control—virtual reality—work zone	No restrictions.

19. Security Classification (of this report)	20. Security Classification (of this page)	21. No. of Pages	22. Price
Unclassified.	Unclassified.	64	NA

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

A DRIVING SIMULATOR STUDY TO EVALUATE THE IMPACT OF PORTABLE CHANGEABLE MESSAGE SIGNS (PCMS) ON DRIVERS' SPEED CHARACTERISTICS IN WORK ZONES

Final Report
March 2014

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Sponsored by the Midwest Smart Work Zone Deployment Initiative and
the Federal Highway Administration (FHWA) Pooled Fund Study TPF-5(081):
Iowa (lead state), Iowa, Kansas, Missouri, Nebraska, Wisconsin

Preparation of this report was financed in part
through funds provided by the Iowa Department of Transportation
through its Research Management Agreement
with the Institute for Transportation
(InTrans Project 06-277)

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ACKNOWLEDGMENTS

This research was conducted under the Midwest Smart Work Zone Deployment Initiative (SWZDI) and Federal Highway Administration (FHWA) Pooled Fund Study TPF-5(081), involving the following state departments of transportation:

- Iowa (lead state)
- Kansas
- Missouri
- Nebraska
- Wisconsin

The authors gratefully acknowledge the support for this project from SWZDI, the FHWA, and the Intelligent Systems Center at the Missouri University of Science and Technology. The following people are also acknowledged: Randy Haffer, Scott Hamilton, Brian Swift, and the numerous participants of the experiment.

The authors would also like to thank Daniel Smith and Andrew Hanks from the Missouri Department of Transportation and Tracy Scriba from the FHWA for their review of this report and valuable feedback.

EXECUTIVE SUMMARY

This research project examined the effects of sequential Portable Changeable Message Signs (PCMS) on speeds of drivers in work zones. PCMS are temporary traffic control (TTC) devices, which are part of Intelligent Transportation Systems that supplement static signs to provide advance warning and real-time information to drivers. PCMS display text and number based messages for which detailed evaluation of sequentially placed PCMS has not been carried out before. This research project fills this gap using a driving simulator (DS) with both an objective analysis and a subjective survey. A work zone on I-44 in rural Missouri was replicated in a DS. The DS experiment consisted of five scenarios (0-4) in which the control scenario (scenario-0) was compared to scenarios 1-4. Each scenario evaluated a different message (message signs 1-4). These messages were used by the Missouri Department of Transportation on the I-44 work zone. The DS experiment evaluated the four message signs displayed on the PCMS by examining the effect of each on drivers' speeds while driving through the work zone.

Fifty two participants evaluated the effectiveness of the PCMS in a virtual work zone. The results showed statistically significant decrease in the speeds as a result of the message type displayed by the PCMS. Message sign-4 (MS-4) (Prepare To Stop, Stopped Traffic Ahead) saw the maximum decrease in the speeds when compared to the control scenario. Results from the drivers' survey showed that MS-2 (Speed Ahead 30 mph, YY Mins. to End of Work Zone) was the preferred message as it displayed a specific speed for the participants to follow. The 85^{th} percentile speeds in the work zone closely matched with the displayed speed for MS-2. The results from the drivers' survey reinforced the fact that PCMS were effective in reducing the speeds of the drivers. The results obtained from this study were not compared to any field data as growing evidence suggests that driving simulator measures are predictive of on-road performance. Further, it was not possible to directly compare the driving simulator results to the field data for similar driver, traffic, control and environmental conditions.

A survey of State Departments of Transportation was also conducted, which showed that text-based messages are the most commonly used message types displayed on the PCMS. The study recommends further evaluation of PCMS in terms of their effectiveness during different times of the day, weather conditions, optimal location, number and message types.

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 the posted speed limits (Horowitz et al., 2003).

Figure 1.1 Example of a PCMS

Crashes that occur in work zones can result in fatalities and serious injuries. Figure 1.2 shows the number of work zone crash fatalities in the United States between 1994 and 2010. In 2010, 87,606 crashes occurred in the US in which 37,476 people were injured in work zones. Further, 514 crashes were fatal causing 576 deaths (FHWA 2011). Though 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 and Zhao, 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).

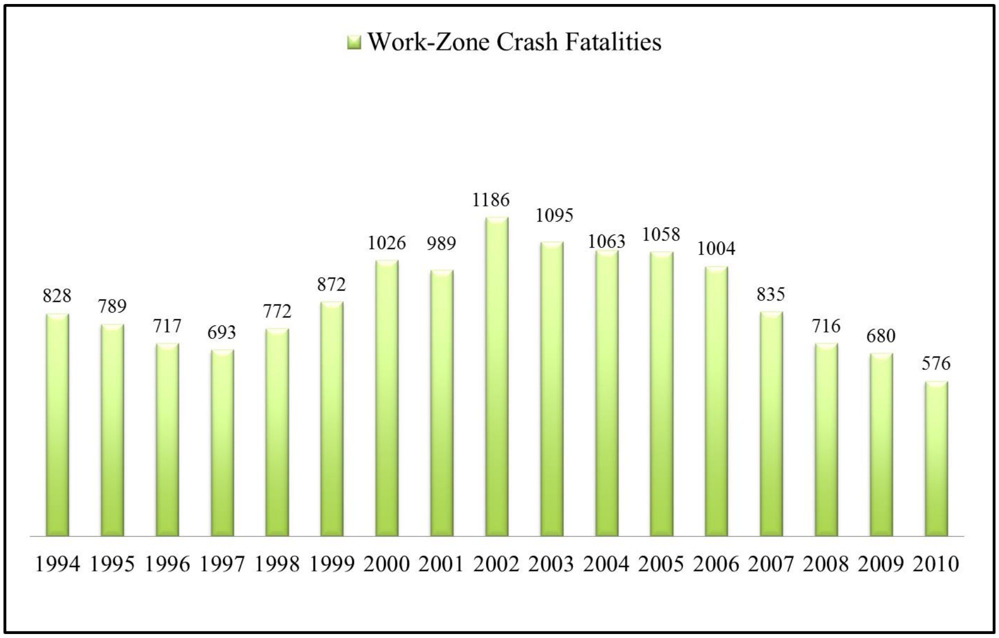

Figure 1.2 Work zone crash fatalities from 1994 to 2010 in the US

The losses in time and resources due to work zone delays are aplenty. It is estimated that work zones 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 a 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 have raised an urgent need to make work zones safer and minimize congestion and delay.

1.2. PROBLEM STATEMENT

In recent years, PCMS have been broadly deployed 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 State Departments of Transportation to provide traffic information to passengers.

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

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 of state Departments of Transportation (SDOTs) in the United States and any other agencies.
2. To examine the effectiveness of different messages displayed on the PCMS by using a driving simulator.
3. To assess the driver perception of different PCMS.

The first of the above objectives was accomplished by reviewing the literature and surveying the common practices among SDOTs 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 and Zhao, 2002; Chambless et al.; 2002). Any reduction in drivers' speed in the work zone as a result of PCMS can be helpful in reducing the frequency and severity of crashes, thereby preventing fatalities and serious injuries. This is a strong motivation for this study.

The use of a driving simulator helps researchers conduct the experiments in a controlled environment, enables reproducibility and standardization, allows easy collection of data, and annul any hazardous driving conditions. The drawbacks of performing the experiments in a driving simulator are limited physical, perceptual and behavioral fidelity. The results obtained from this study were 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 actual driver behavior. The driving simulator used in this project, however, has been tested thoroughly and validated both at the objective and subjective levels using field data. The interested reader is referred to Bham et al. (2014).

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 and after each PCMS. The same message sign (MS) was displayed on all PCMS used for a given traffic condition. The experiments performed in the driving simulator replicated the same procedure, hence a particular scenario contained the same MS displayed on the PCMS used. The MS were tested only for light traffic, as testing them under different traffic conditions would cause a confounding effect (change in driver behavior due to traffic, the MS, the drivers' compliance with the MS, etc.).

2.3. RESEARCH METHODOLOGY

Figure 2.1 presents the research methodology. Participants were recruited from different age groups and tested using a driving simulator. In addition to this, SDOTs were surveyed online. The objective evaluations conducted statistical analysis of characteristics of vehicle speeds for different message signs using data collected from the driving simulator. The subjective analysis analyzed the results from the post-experiment questionnaire (feedback survey) which participants took after completing the DS experiments. This section explains the SDOT survey, the driving simulator setup, the statistical analysis of data obtained from the simulator, and the different questionnaires (pre-screening, pre-driving and post- driving) used.

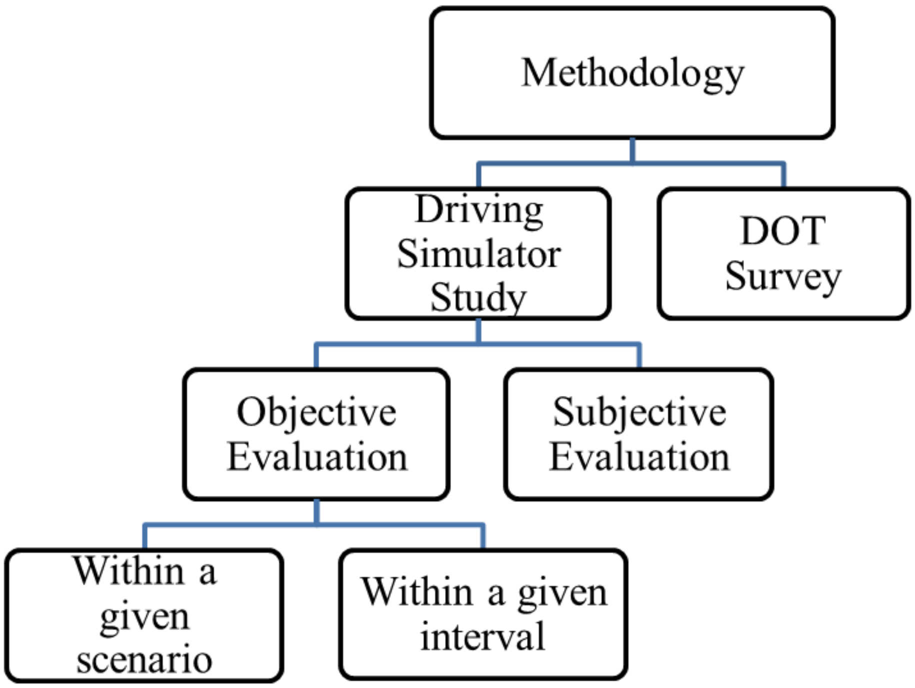

Figure 2.1 Research methodology

2.3.1. SDOT Survey

The purpose of the 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 to:

1. Analyze the conditions when PCMS were used.
2. Determine the criteria for the selection of type of message.
3. Identify the measures of effectiveness used to examine the PCMS compared to the static signs.
4. Examine 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 SDOTs in the United States responsible for PCMS implementation, its operation and evaluation. Follow-up emails were sent to maximize the comprehension of the recorded responses and to gather additional information to enhance the research.

The first objective was to review the SDOTs 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.

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

2.3.2. Driving Simulator Study

2.3.2.1. Missouri S&T driving simulator

The driving simulator (DS) at Missouri S&T is a fixed-base driving simulator with a Ford ranger pickup making up the cabin (Figure 2.2a). The DS consists of three LCD projectors a projection screen and a master computer. The pixelation on the three projectors is the same (1280 x 1024), which reduces the distortion of the ongoing simulation. The DS steering wheel (Figure 2.2b) is encompassed with force feedback to ensure realistic driving. The DS 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. 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

Figure 2.2. Driving simulator components

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 lane closure). The first PCMS was placed at mile marker 166.0; the second PCMS was placed 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 four PCMS were placed at 1.5, 2.3, 3.9, and 5.6 miles. For a given scenario, the same messages were displayed on all four PCMS. Figure 2.3 illustrates the work zone setup.

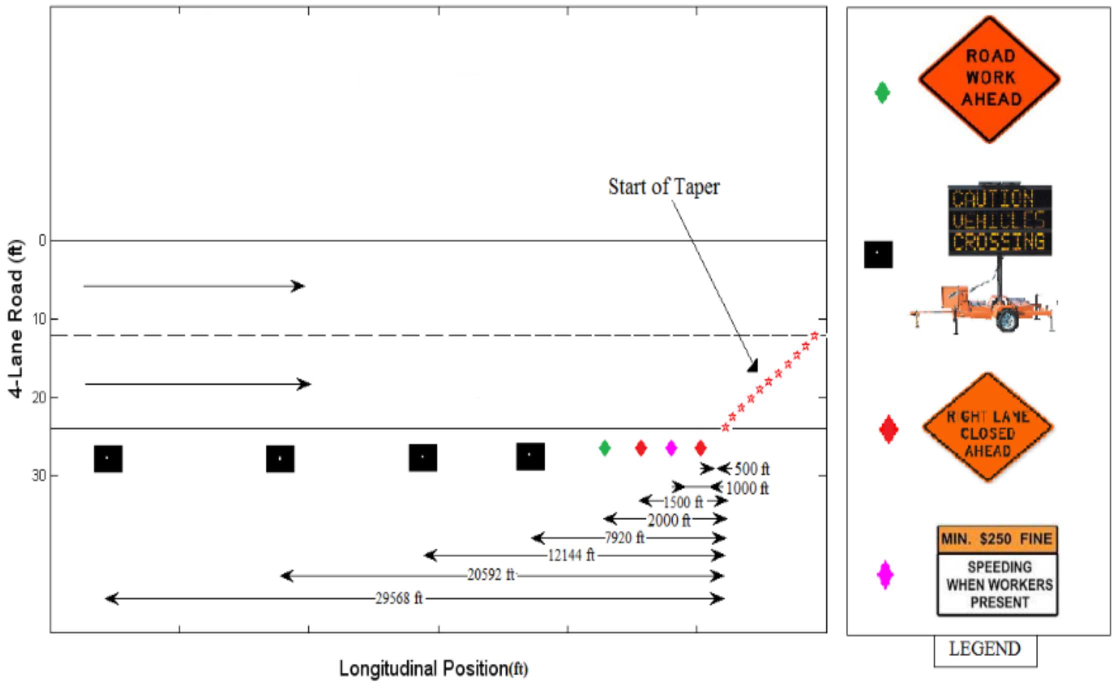

Figure 2.3 Work zone setup

Table 2.1 shows the different message signs used by the Missouri Department of Transportation. In the real world scenario; Message-sign-1 (MS-1) (used when the average speed of the vehicles is between 50-70 mph) is 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 the 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) are 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) is used for heavy traffic conditions (volume of traffic larger than 1800 vehicles/hr/lane measured at a given point).

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

Scenarios/ Message Signs	PCMS#1	PCMS#2	PCMS#3	PCMS#4
Control Scenario (No messages)	No Message Displayed	No Message Displayed	No Message Displayed	No Message Displayed
Scenario-1, Message Sign-1 (MS-1) $\overline{X}$= 50-70 mph	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) $\overline{X}$ = 20-50 mph	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) $\overline{X}$ = 5-20 mph	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) $\overline{X}$ < 5 mph	PREPARE TO STOP STOPPED TRAFFIC AHEAD	PREPARE TO STOP STOPPED TRAFFIC AHEAD	PREPARE TO STOP STOPPED TRAFFIC AHEAD	PREPARE TO STOP STOPPED TRAFFIC AHEAD

$\overline{X}$ indicates average speed of vehicles

2.3.2.3. Participant recruitment

Participants were recruited through campus emails, flyers and through the Missouri S&T's online news and information service (e-connection). The participants were either affiliated with Missouri S&T or were from surrounding areas. The prospective participants were asked to complete a pre-screening questionnaire and based on their answers were either selected or rejected for the experiment. 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 also asked. They were also asked about the validity of a driver's license issued in the United States. All the participants had encountered a PCMS before and none of them were familiar with a driving simulator.

2.3.2.4. Pre-driving and post-driving questionnaire

Prior to the start of the experiment, all of the participants who agreed to participate in the project completed two forms presented in the appendix. The pre-driving questionnaire surveyed participants regarding their driving patterns, including the vehicle they drove, number of years of driving experience, alcohol or drug consumption during the past 24 hours, etc. Only participants with a valid US driver license were 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 licenses and again were not allowed to participate in the experiment. Overall, 52 participants were selected to participate in the driving simulator experiment. 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 years old and the mean age of the female participants was 36.4 years old. From the samples, two age groups were defined, age group-1 (16-40 years) included 14 males and 12 females, whereas age group-2 (41-66 years) included 12 males and 14 females.

Each participant who completed the four scenarios was asked to complete a post driving questionnaire. The participants were asked to identify the messages they came across during the experiment and to describe each of the messages in detail. Further the participants were asked to rate the messages according to their 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.

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 adhere to all traffic laws. The working of the simulator, the control of 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 adjust to the controls. The drivers were then asked to drive through the scenarios in a random order.

2.3.2.6. Data collection methodology

Data collection included vehicle speeds 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 data at 0.1 second intervals. As a result of four PCMS in each scenario, data from eight sections (intervals) along the work zone were obtained and 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.

2.3.2.7. Data analysis methodology

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

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 in a random order. 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 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 speed of vehicles. 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.

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 also calculated by plotting the cumulative distribution of the speeds for a particular interval. The statistical significance (null hypothesis) of the independent variables (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 using the Statistical Analysis System (SAS 9.3™) software.

If the p-value in the ANOVA table was significant, pairwise comparison of least square means (LSM) for different intervals was performed. 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 equal 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 for 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:

$$HSD = Q_{k,df,\alpha}\sqrt{\frac{MS_{Error}}{n}} \tag{1}$$

where:

MS_{error}	= Mean square error (MSE) obtained from the ANOVA table.
n	= number of drivers = 52
$Q_{k,\ df,\ \alpha}$	= studentized range statistic
k	= number of intervals = 8
df	= error degrees of freedom from ANOVA table
α	= significance level = 0.05

The outputs from an ANOVA table are presented 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 freedom 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 as a product of (a-1) and (b-1), where "a" and "b" are the levels of factors A and B.
3. Sum of Squares (SS) or Treatment Sum of Squares: The sum of squares accounts for the variability in the response variable (e.g., speed) due to the application of different treatments.
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: $MS_{treatments} = SS_{treatments}/df$.
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 is less than or 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, then 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 ($p\text{-value} < \alpha$), further analysis was carried out. Our primary variables of interest were the scenario and the intervals (sub-plot factors) and their respective interactions with other variables. Figure 2.4 shows the elements in a box plot.

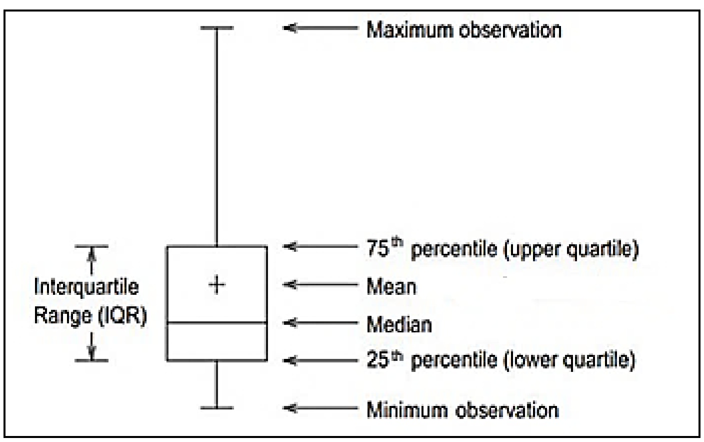

Figure 2.4 Box plot annotation

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 was unequal for a given message sign. The results were analyzed at a significance level of 0.05 (accept H_O if $p\text{-value} > 0.05$, and accept H_A if $p\text{-value} < 0.5$). The H_O and H_A for the experiment are defined below:

H_0: $\mu_1 = \mu_2 = \ldots\ldots \mu_i$

H_A: At least one μ_i (mean speed) differed from the other

where:

μ_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 factors (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 intervals with the other two factors (age, gender) were studied. Only the significant factors and their interactions are 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 were 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_0: $\mu_1 = \mu_2 = \ldots\ldots \mu_i$

H_A: At least one μ_i (mean speed) differed from the other

where

μ_i = mean speed for the i^{th} interval for the scenario (i varies from 1 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 on 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 traffic information regarding the ongoing work activities, or any incident in the work zone ahead (Levinson, 2003). PCMS, however, do not replace already existing static signs on the highway; they supplement the existing static signs specified by the Manual on Uniform Traffic Control Devices (MUTCD, 2009).

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, it is necessary to consider driver response to PCMS in order 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' opinions through a list of multiple choices or open-ended questions. In most projects, no field driving performance data were 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 can be 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) 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 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) found that the messages placed in the work activity area were effective in reducing the average speed of the cars at a point just after the PCMS but were no longer effective downstream. Richards et al. (1986) found that the PCMS could result in only modest reductions (less than 10 mph) when used alone, and the devices would lose their effectiveness if operated continuously for long periods with the same message.

Garber and Srinivasan (1998) studied the effectiveness of PCMS in controlling the vehicle speeds in a work zone and concluded that PCMS was effective when used with a radar in reducing the speed of drivers. They also stated that the complete isolation of the PCMS 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 inclined drivers to return to their original speeds after passing the signs. Huebschman et al. (2003) argued that PCMS are actually no more effective than traditional message panels (static signs) in work zone management. Firman et al. (2009) conducted field experiments for a resurfacing work zone project in Kansas, 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 et al. (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 stated 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.

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

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' responses to these messages via questionnaires.

Wardman et al. (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 models used in these studies revealed the importance of relative journey times and the precise phrasing used in 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 high correlation exists between the information provided (route choice and speed limits) on the VMS and driver response.

3.5. DRIVING SIMULATOR STUDIES

Godley et al. (2002) summarized that speed was shown to be a valid dependent variable for measuring driver responses to various scenarios in a simulated environment. Ulfarsson et al. (2002) conducted a study on the I-90 corridor to examine the effectiveness of DMS on speed reduction and traffic flow management. 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 et al. (2005) performed a study to evaluate the information provided related to traffic flow in work zones to drivers through DMS. A questionnaire was used along with a driving simulator study. The study revealed that younger drivers tend to respond and comprehend the message more quickly than older subjects. The 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 difference. Boyle and Mannering (2004) conducted experiments to examine drivers' speed characteristics under different advisory information using a driving simulator. Four conditions were evaluated: 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 for shorter distances (less than 800 ft), and nothing significant was observed for longer distances regardless of the travel-information.

Ullman et al. (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 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. In this study, quantitative data was not recorded. Hence, the actual behavior of the participants in terms of speed was not understood. Clark (2008) conducted a driving simulator study on drivers of different ages on the understanding of the VMS and concluded that though older drivers slowed down after reading the displayed messages, their responses were inaccurate and their 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 speeds. 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 the 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.

3.6. SUMMARY

From the literature review, it is clear that a few studies have investigated the impact of sequentially placed PCMS with different messages on driver behavior, especially its effect on speed. Only very few studies, however, have examined the effects in a controlled environment on driver behavior, their responses to PCMS, and the different messages displayed. Hence, this project used a DS to study the impact of PCMS on driver behavior in a controlled environment. Further, this study examined how participants reacted to multiple PCMS placed in a work zone and how they perceived the PCMS. The project also studied the speed profile of the participants before and after each PCMS placed along the highway and examined the variance in the speed of the drivers at each interval as drivers travelled through the work zone. The study also looked at the differences in speeds for the same set of drivers across the four different message types and analyzed the speed variation for different messages of the same message type. Although the effects of multiple PCMS on speed have been examined, the effect of each PCMS on speed in a multiple PCMS system has not been studied. This is the first study that examines the behavior of a driver before and after each PCMS for different age groups and gender.

4. DEPARTMENTS OF TRANSPORTATION SURVEY RESULTS

4.1. SURVEY RESULTS

The State Departments of Transportation (SDOTs) survey was developed using the Qualtrics software and conducted online. The survey was sent to all SDOTs in the United States. Thirty three SDOTs took the survey but only twenty-four completed the entire survey. The results of the survey are presented below.

4.1.1. Conception of PCMS

The SDOTs 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 stated that PCMS have been used by SDOTs for traffic control for more than two decades.

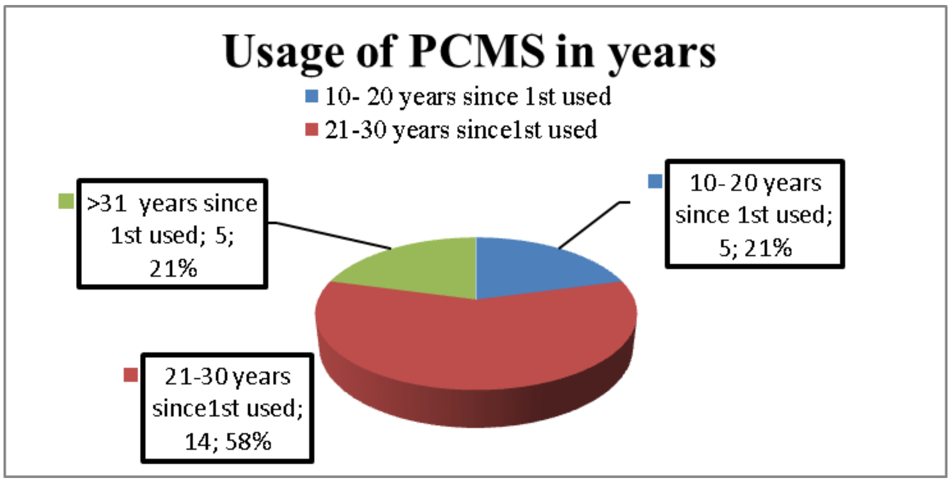

Figure 4.1 Conception of PCMS

4.1.2. Usage of PCMS by Facilities

The questionnaire inquired about the classification of highways on which PCMS have been used. The SDOTs were asked to indicate the usage of PCMS on freeways (not in work zones), freeway work zones and/or at other locations. Twenty one (88%) SDOTs responded by stating that they used PCMS on freeways and work zones. Two (8%) SDOTs use PCMS only in work zones and one (4%) uses them only on freeways. Figure 4.2 illustrates the usage of PCMS. It can be inferred that the usage of PCMS is mainly for traffic management of freeway work zones.

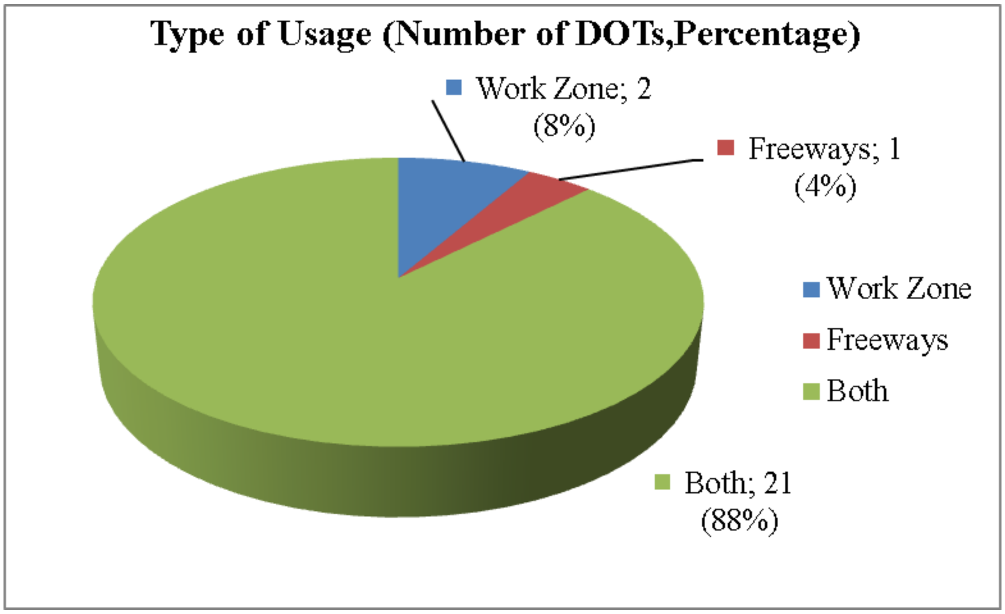

Figure 4.2 Facility usage of PCMS

4.1.3. Usage of PCMS by Purpose

Various SDOTs had different applications of PCMS.

Michigan Department of Transportation (DOT) uses PCMS as an incident management system and to provide drivers with real-time information regarding the activities in the work 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 also use it for work zone applications where general and specific information about the activities of work zones are displayed and they sometimes include travel time information.

Missouri DOT uses PCMS to provide real-time information about traffic conditions ahead. It also provides information to assist road users in making decisions prior to the point where 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.

Oklahoma DOT uses PCMS in a work zone system they call “Smart Work Zones”. A smart work zone consists of PCMS and a radar for detection of queues within the work zone. When a queue is detected, messages are displayed on PCMS to inform incoming traffic and specify a speed limit according to traffic congestion downstream. PCMS are also used for providing information about future construction activities, 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 SDOT 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, and Indiana DOTs, as well as the Arkansas Highway and Transportation Department, use the PCMS for incident management on freeways, and the display of 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 SDOT survey that PCMS are commonly used for providing drivers' with real time information regarding incident management in work zones, AMBER and weather alerts and alternate routes.

4.1.4. Message Type Displayed

The SDOTs were asked about the types 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.

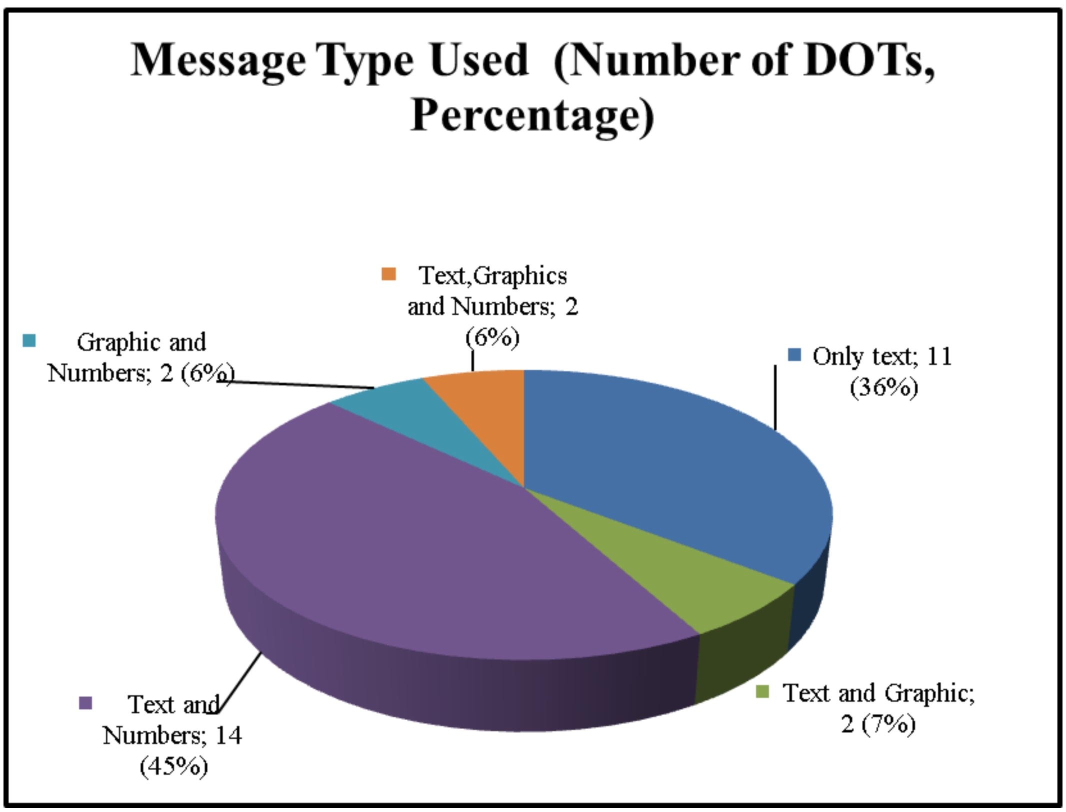

Figure 4.3 Message type used

Some agencies use more than a single type of message. The most commonly used message type is “text and numbers”; 14 (45%) of the SDOTs preferred this message type over the others. The next most commonly used message type is “only text”; 11 (36%) of the SDOTs 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. Although the survey yielded that none of the SDOTs use just graphic PCMS, the 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 “only text” and “text and numbers” message types 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, graphic 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 SDOTs were asked if they followed particular criteria when setting up the PCMS on different classes of highways.

Missouri and Michigan DOTs place a PCMS where it is visible to the driver from “at least half a mile” in both daytime and night. 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 the type of facility where 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 a 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 not to be 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 a 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 placement of the PCMS is site and condition specific. Iowa DOT does not require their PCMS to be 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, out of the twenty-four SDOTs that responded to the survey, only two DOTs, Texas and Minnesota, have carried out evaluation of PCMS. Maryland DOT have also conducted studies and the results will be available soon. They did not respond to the survey.

Minnesota DOT conducted a study to evaluate the effectiveness of early warning of PCMS. Public surveys and observed traffic behavior were used to evaluate and obtain feedback regarding its effectiveness. The qualitative data was collected by detecting slower driver speeds that were attributed to the messaging signs. This was considered proof that drivers followed PCMS. It was also stated that the speed reduction was sometimes extreme and there were instances of drivers' complaining about the same. 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 the literature review.

4.1.7. Summary of SDOT Survey

From the SDOT survey it, can be stated 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 the messages that are effective and to analyze the information displayed on the PCMS as perceived by the drivers. The SDOT survey provided minimal feedback on the measure of effectiveness used by the SDOTs or the methods used to evaluate the effectiveness of PCMS. Further, the placement (location from the work zone and its spacing) of PCMS requires further research.

5. OBJECTIVE AND SUBJECTIVE EVALUATIONS

The objective evaluations used data collected from the driving simulator and statistical analysis of characteristics of speeds for different message signs. The subjective analysis analyzed the results from the post-experiment questionnaire (feedback survey) which participants took after completing the DS experiments. These evaluations were carried out mainly to study each participant's perception about the effectiveness of the PCMS and how PCMS impacted their driving. Fifty two participants' data were extensively analyzed for both the objective and subjective analysis. The participants were divided into two age groups (levels), with the first age group ranged from 16-40 years and the second ranged from 40-66 years. Other factors considered were gender and the 1000 feet intervals before and after every PCMS. Four PCMS were placed sequentially with each displaying the same message. Four different messages were evaluated.

5.1. OBJECTIVE EVALUATION

Analysis of variance (ANOVA) was carried out to find the significant factors (main effects) and their interactions with other factors (e.g., Table 5.1). If the main effect or the interaction was found to be significant i.e., p-value was less than the given significance level, it was further analyzed. The factor "interval" and its interaction with other factors were of interest. If the interaction "interval*gender" was significant, it meant that for at least one interval the mean speeds of male and females were 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 were calculated using Tukey's method (e.g., Table 5.2). The difference in the mean speeds was compared to the HSD value. If the difference in the mean speeds for a given pair of intervals (e.g., the values in parentheses in Table 5.2) was greater than the HSD value, the mean speeds were stated to be significantly different between the two intervals. The Mean Square Error (MSE) value was 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 required to calculate the HSD along with the "Q value".

Table 5.1 Statistical 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

5.1.1. Control Scenario

No PCMS was used in the control scenario, which was modeled as a static work zone site. From Table 5.1, the results indicated a significant difference between males and females in terms of the p-value (<0.0001) for the interaction (gender * interval). Further, to analyze the effects of interaction, box plots of mean speeds of male and female participants were graphed for the different intervals. Though the interaction (gender * age) was significant, it was not analyzed further as age was not significant and did not show significant interaction with interval. The MSE from the ANOVA table was 4.22. A HSD value of 1.22 was calculated using Equation 1.

Table 5.2 illustrates the mean, standard deviation, LSM and HSD values of speeds from interval-1 to interval-8. The differences in mean speeds between the intervals are presented in parentheses below the p-values and are compared to the HSD value. If the difference in the mean speeds is lower than the HSD value, no significant difference was found between the intervals. For example, the difference in mean speed of interval-1 and interval-8 is 6.08 mph, which is greater than the HSD value of 1.22. Hence, the p-value is less than the level of 0.05 and the difference between the two mean speeds is highly significant. All of the p-values for the eighth interval are highly significant (p<0.0001) and different compared to the remaining intervals. The highway posted speed limit was 70 mph. For the eighth interval, the mean speed of the participants is 62.55 mph. This decrease in speed in addition to the PCMS is due to the start of the taper for entering the construction zone that can be observed by the drivers.

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 shows the box plot of speed between the intervals and gender representing the interaction "interval * gender". The plot indicates that the overall speed of female drivers was higher 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. Figure 5.2 presents the mean speed plot along with the 85th percentile speed of the control scenario. The 85th percentile speed remained above the speed limit of 70 mph, which indicated that 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.

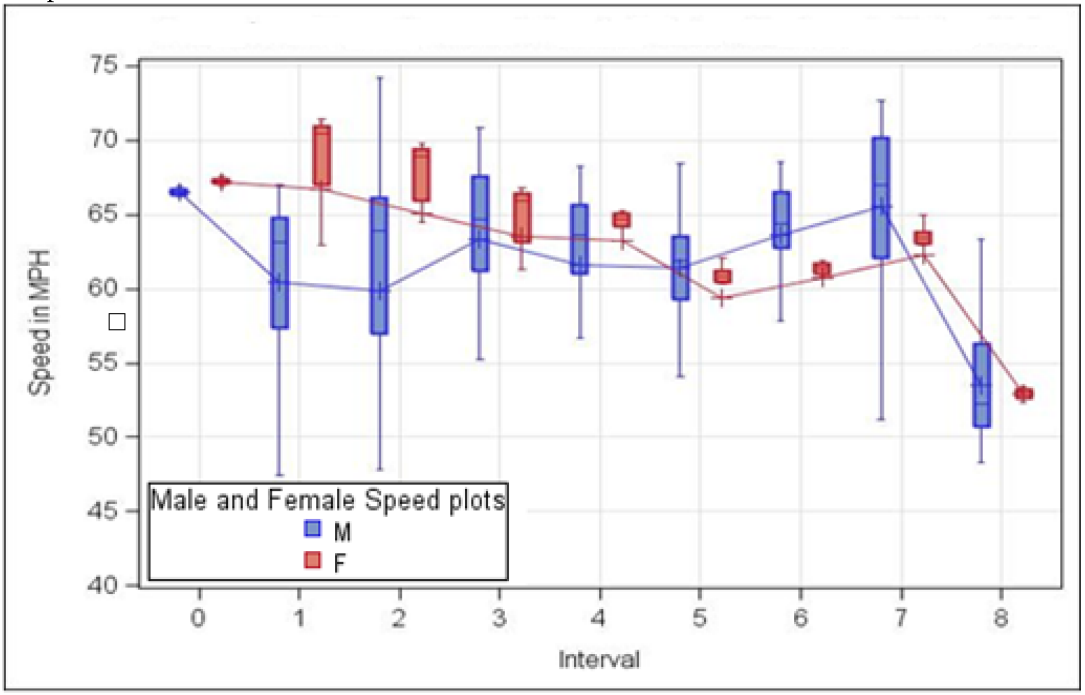

Figure 5.1 Box plot comparison for control scenario

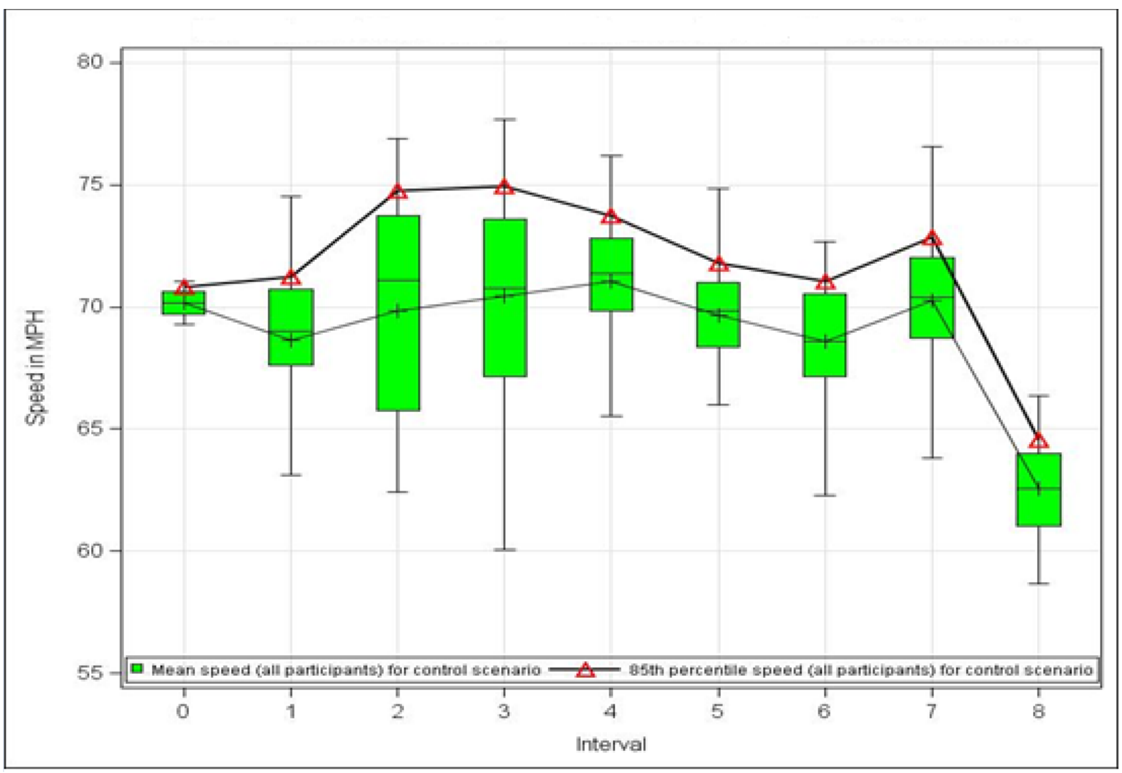

Figure 5.2 Comparison of mean speeds and 85th percentile speed for control scenario

5.1.2. Scenario-1

Scenario-1 displayed message sign-1, “CAUTION WORK ZONE AHEAD, REDUCE SPEED AHEAD”, on all of the four PCMS. This message was intended for free flowing traffic.

The results of analysis presented in Table 5.3 yielded a p-value of the interaction (gender * interval) as significant ($p < 0.0001$). Box plots of mean speeds of male and female participants were plotted for different intervals. The MSE was found to be 19.58 with an HSD value of 2.64.

Table 5.3 Statistical 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 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

Table 5.4 shows the mean, standard deviation, the LSM and HSD values of 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 overall the mean speeds of the first seven intervals do not significantly differ from each other.

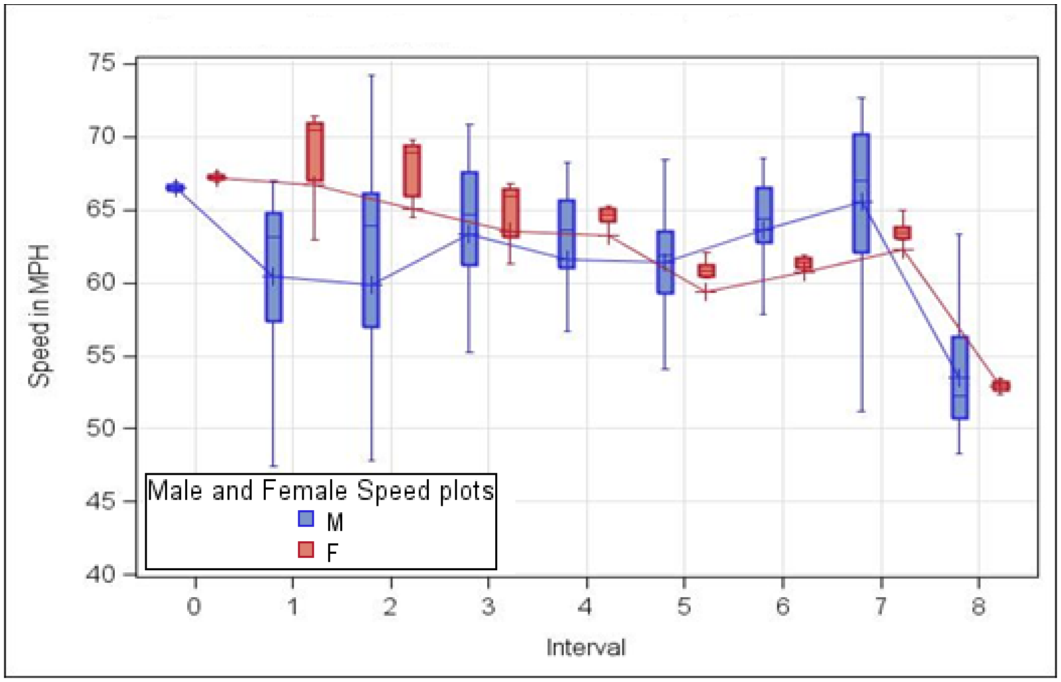

Figure 5.3 Box plot comparison for scenario-1

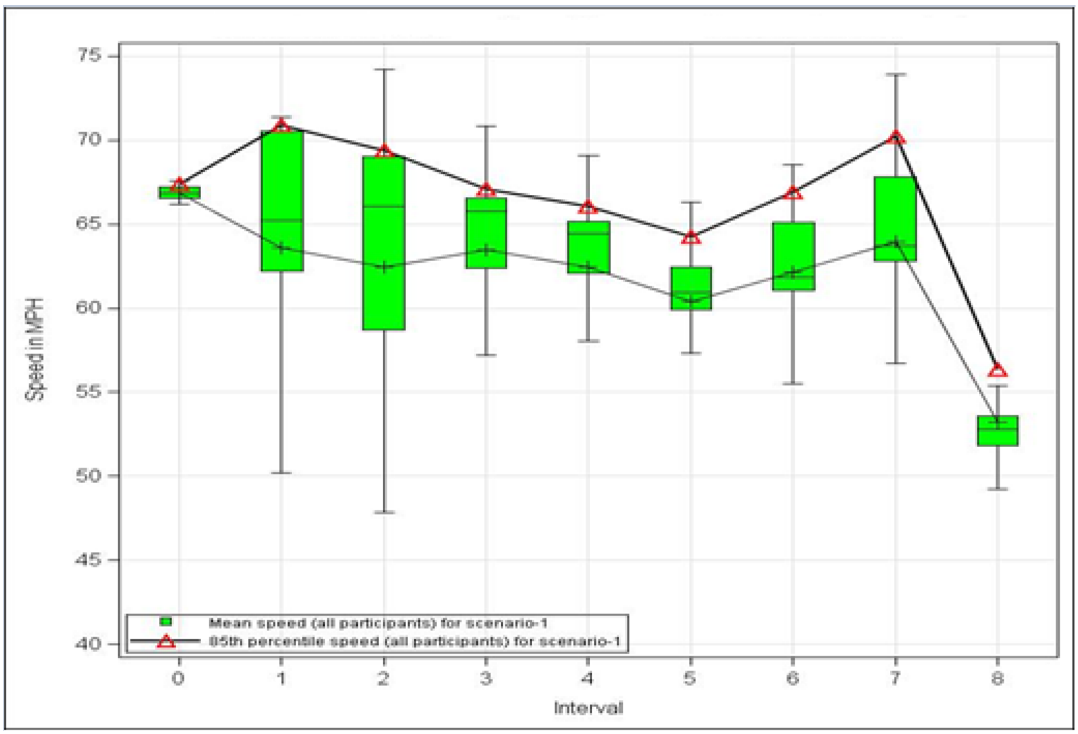

Figure 5.4 Comparison of mean speeds and 85th percentile speeds for scenario-1

Figure 5.3 shows the box plot of speed between the intervals and gender. The plot indicates that female participants initially started at higher speeds but then decreased speed after spotting the PCMS. The overall mean speeds of female participants were greater than the male participants for scenario-1. However, the box plots indicate that the variance in speed for female participants was 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 lane closure.

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

5.1.3. Scenario-2

Scenario-2 displayed message Sign-2, “SPEED AHEAD 30 MPH, XX MIN TO END OF WZ”, on all the four PCMS. The XX were replaced with either 11, 7, 4, or 2 minutes depending on the location of the PCMS in the work zone. This message had a specific speed limit displayed for the participants to follow.

Table 5.5 yielded p-values for the interaction (gender * interval) as significant (< 0.0001). Box plots of mean speeds of male and female participants were plotted for different intervals. The MSE and HSD values were found to be 30.04 and 3.29, respectively.

Table 5.5 Statistical 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 mean, standard deviation, the LSM and HSD values of mean speeds from interval-1 to interval-8 for scenario-2. From the LSM values, it can be observed that the mean speed of interval-8 is significantly different when compared to the other intervals. In this scenario, it can also be observed that the mean speeds for other intervals are significantly different from each other. High variations in the mean speeds were 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 followed the speed limit of 30 mph displayed on the messaging sign while other participants only slowed down when they were near the construction zone. 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 the different intervals versus gender. The appreciable variation in the mean speeds of male participants from interval-1 to interval-7 (before PCMS#4) can be noticed. The male participants eventually slowed down when they were closer to the lane closure i.e., the construction zone and less variation in mean speed was observed at interval-8. Less variation was observed in the female participants from interval-1 to interval-7. Female participants also slowed down when they neared the lane closure and observed the speed displayed on the PCMS. A gradual decrease in speed for both male and female participants was observed, slowing down near the lane closure. The mean speeds in the eighth interval were similar for both the male and female participants.

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

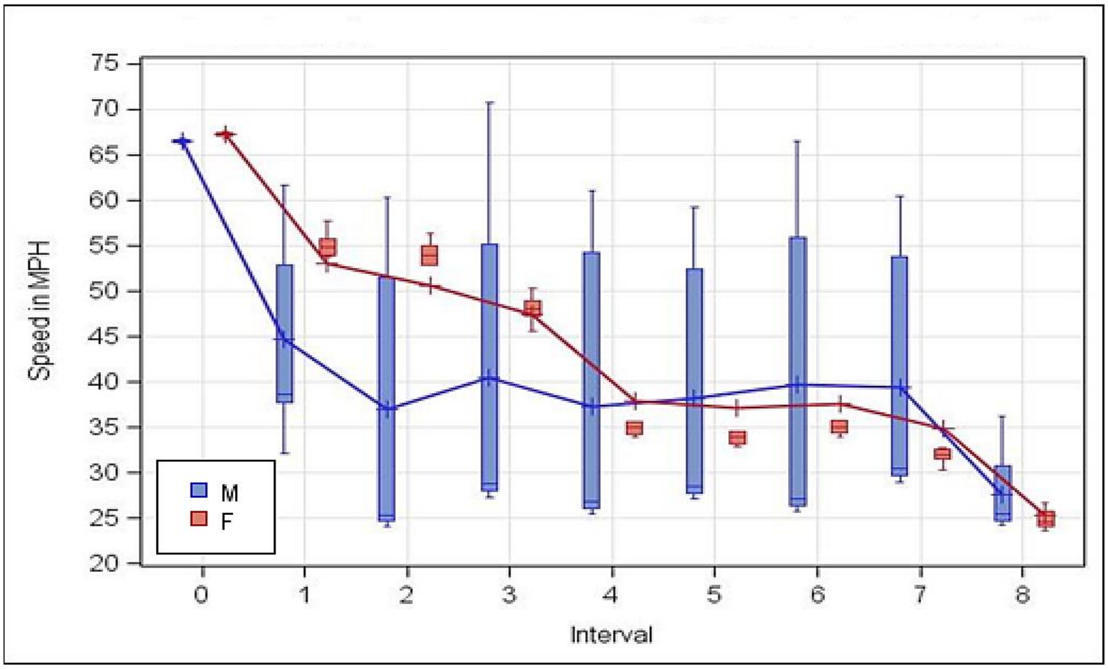

Figure 5.5 Box plot comparison for scenario-2

Figure 5.6 shows the 85th percentile speed and the mean speeds. The 85th percentile speed at interval-8 (30.67 mph) was very similar to the displayed speed on the PCMS. The mean speeds at interval-8 were less than the displayed speed, which implies that the participants complied with the PCMS.

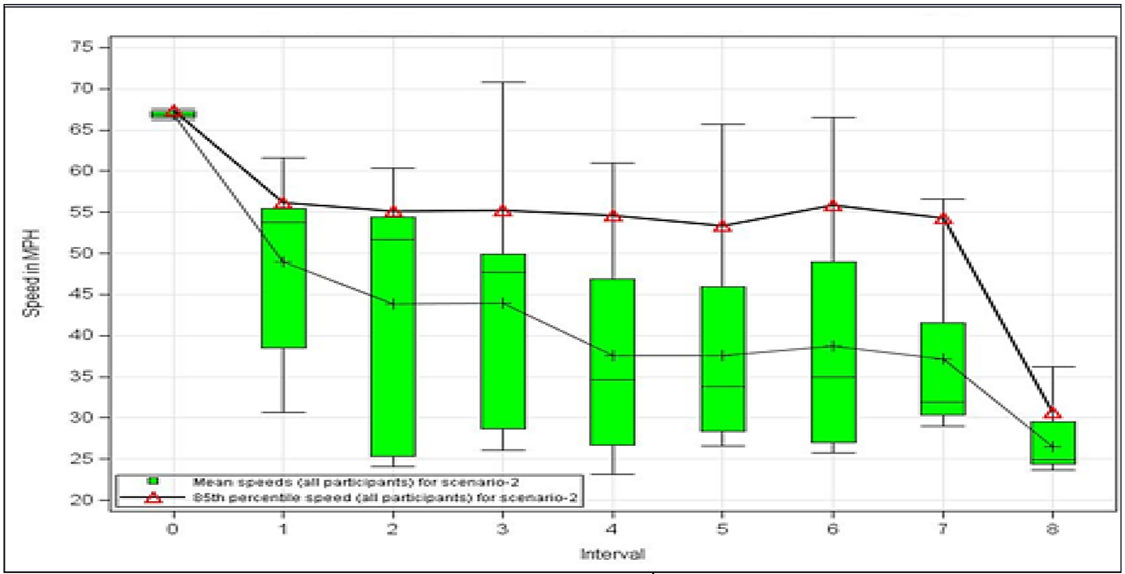

Figure 5.6 Comparison of mean speeds and 85th percentile speeds for scenario-2

5.1.4. Scenario-3

Scenario-3 displayed MS-3, "PREPARE TO STOP, YY MINS TO END OF WZ", on the four PCMS. The YY mins were replaced with either 16, 11, 7, or 4 minutes depending on the location of the PCMS in the work zone. The message displayed prepared the drivers to stop ahead. From results of statistical analysis, presented in Table 5.7, the interaction (gender * interval) was found to be significant (p<.0001). For all of the intervals, box plots of mean speeds of male and female participants were plotted. The MSE and HSD values were found to be 31.73 and 3.36, respectively. For this scenario, age was not a significant factor.

Table 5.7 Statistical 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 mean, standard deviation, and the LSM and HSD values of mean speeds from interval-1 to interval-8 for scenario-3. It is interesting to note 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 even slow down. A decrease in the mean speeds of the drivers can be observed after they sighted PCMS#1 and PCMS#2 but an increase in speed near PCMS#3 can be observed.

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

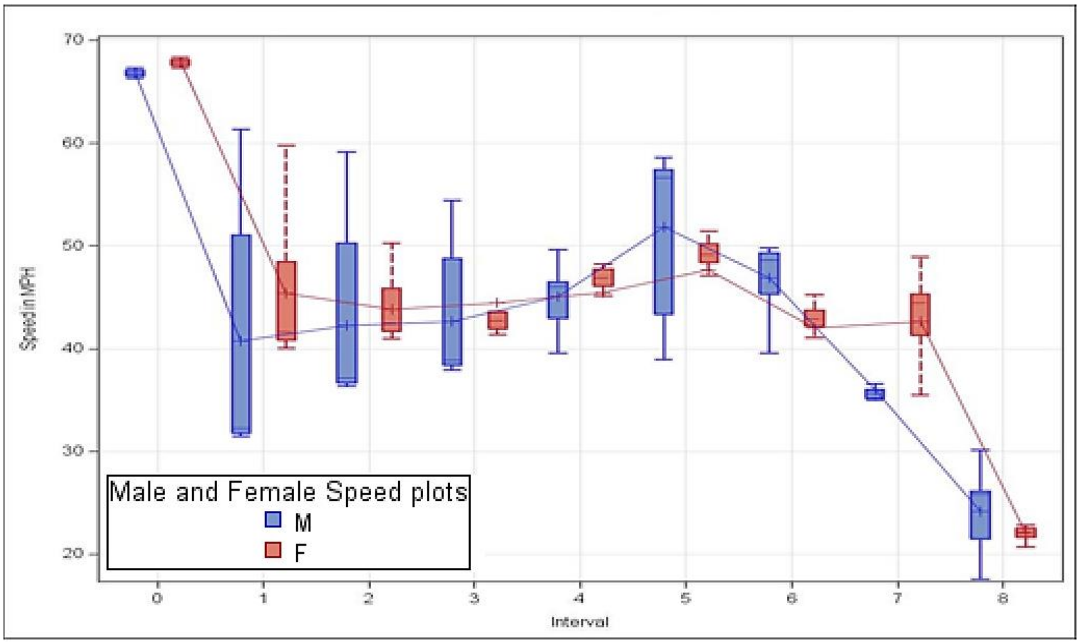

Figure 5.7 Box plot comparison-scenario-3

Figure 5.7 shows the box plot of mean speeds. An appreciable variation in the mean speeds of male participants from interval-1 to interval-5 (before PCMS#3) can be observed. Less variation of mean speeds is observed at interval-7 for male participants, which suggests that the majority of male participants slowed down before the lane closure. For female participants, as observed in the previous scenarios, less variation was found from interval-1 to interval-7, which indicates that they complied with the message. An increase in speed can be observed at interval-5 for both male and female participants. It is assumed that after observing three PCMS with the same message, drivers started not complying with the message, as a lane closure was not visible and there was no need to slow down or prepare to stop. The mean speed for the eighth interval was lower and similar for both male and female participants.

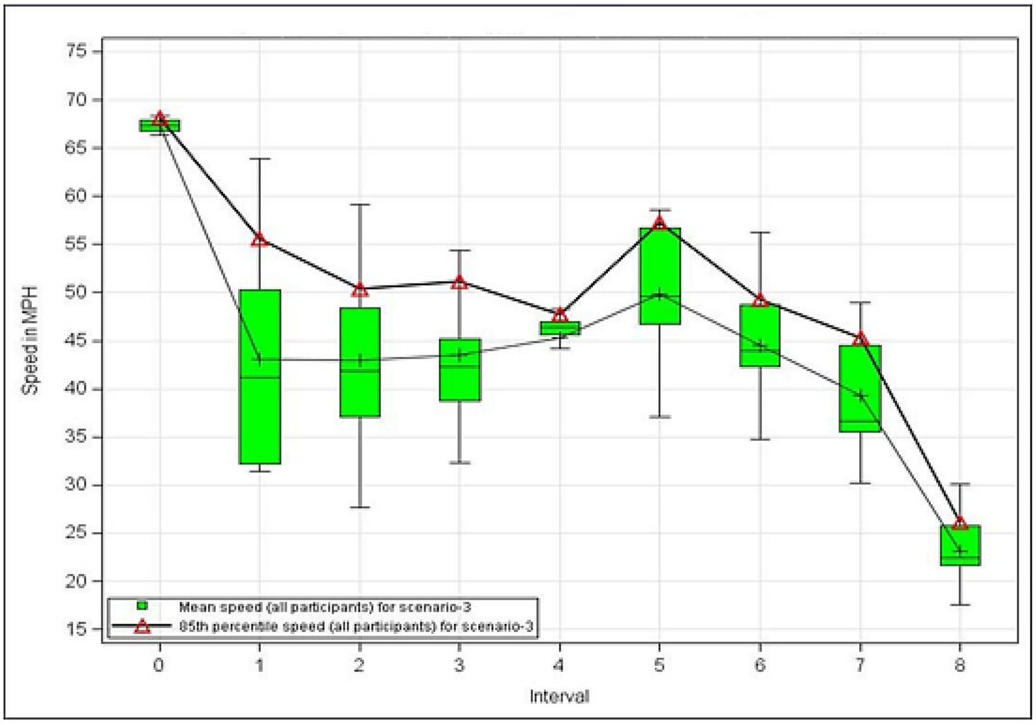

Figure 5.8 Comparison of mean speeds and 85th percentile speed for scenario-3

Figure 5.8 shows the 85th percentile speed and the mean speeds. The speed increase and then decrease indicates the pattern representative of driver behavior i.e., initially the drivers complied with the messages and the speed decreased, but after the 2nd PCMS their speed was not impacted by the message and began to increase. The drivers finally slowed down as they approached the construction zone near the 4th PCMS.

5.1.5. Scenario-4

Scenario-4 displayed MS-4, “PREPARE TO STOP, STOPPED TRAFFIC AHEAD”, on the PCMS. The message warned the drivers to stop ahead. The statistical analysis presented in Table 5.9 indicates the sub-plot factor ‘interval * gender’ as significant (< 0.0001). Hence, box plots of mean speeds of male and female participants were plotted for all of the intervals. The MSE and HSD values were found to be 10.05 and 3.36, respectively. For this scenario, age was not a significant factor.

Table 5.9 Statistical 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 with mean speeds of 36.60 and 37.77 mph, respectively show no significant difference before and after the PCMS#1, but a significant difference of mean speeds between interval-3 (41.33 mph) and interval-4 (36.11 mph) can be observed. The difference in speeds before and after PCMS#2 was 5 mph. The speed at interval-8 was 13.64 mph, which indicates that the message was clear to the participants, and they complied as a result.

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 illustrates the mean speeds for intervals versus gender. The mean speeds of male participants were slightly higher than the female participants. For interval-8, the speeds were similar for males and females.

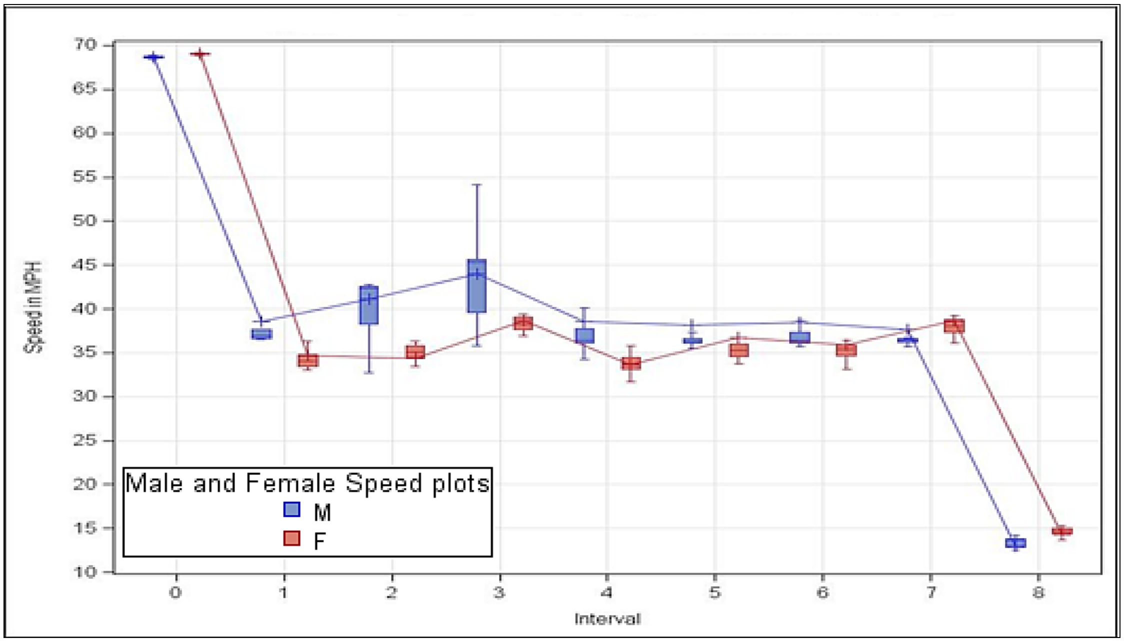

Figure 5.9 Box plot comparison for scenario-4

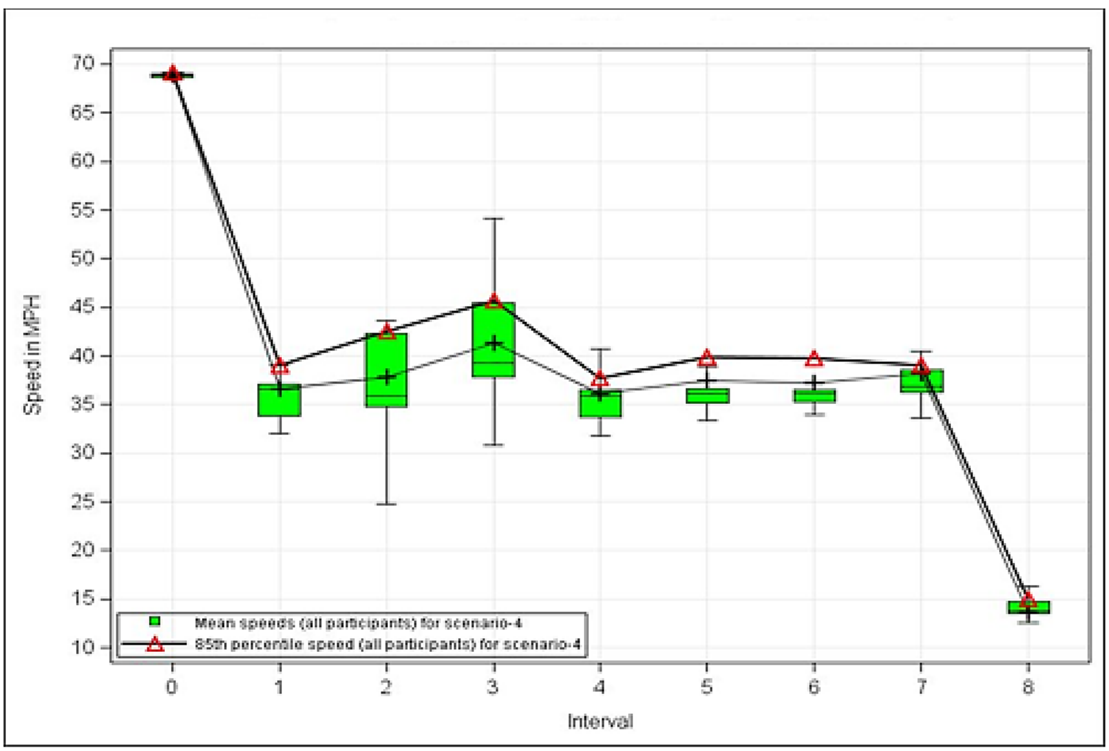

Figure 5.10 Comparison of mean speeds and 85th percentile speeds for scenario-4

Figure 5.10 illustrates the plot of the mean and 85th percentile speeds. The 85th percentile speed for the third interval is slightly higher than the other intervals, but an appreciable decrease in the speeds from interval-7 to interval-8 was observed, which indicates the overall effectiveness of the PCMS for scenario-4. This also suggests that for scenario-4, the effect of the two-phrase message decreased the speeds of the participants significantly.

5.2. DATA ANALYSIS ACROSS THE SCENARIOS

The speeds of vehicles before the start of lane closure is important and can impact work zone crashes. The speeds of drivers were therefore examined before the vehicles entered the construction zone. The interval-8 is upstream of the lane closure and the speeds were impacted by the different messages (Table 2.1) displayed on the PCMS. The speeds of vehicle were analyzed over interval-8 located within 1000 feet of the fourth PCMS for the five scenarios; the control scenario is included for comparison with other scenarios that included the PCMS.

Table 5.11 Statistical 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 Mean, Standard Deviation, and p-values for LSM and HSD: interval-8

Scenario	Mean	Standard Deviation	1	2	3	4
	Miles per hour		p-values and difference between the mean speeds (HSD = 1.51, α = 0.05)			
0 (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

The statistical analysis yielded main plot factor 'gender' and sub-plot factor 'message-sign' significant (p-value <0.0001). Table 5.11 presents the results from the ANOVA conducted for different scenarios. The significant values are marked in bold. The interaction 'gender * message-sign' was significant as well (<0.0001). Further analysis was carried out to analyze the pairwise comparison between different scenarios. Hence, LSM and HSD were calculated (Tukey's method) for comparison and to determine the significance of difference between them based on the p-value. Table 5.12 summarizes the comparison of the four message signs for interval-8. The mean speeds across the scenarios were significantly different from each other.

The highest mean speed was observed in the control scenario, which was expected, followed by scenarios 1-4. The mean speeds for scenarios 0-4 were 62.55 mph, 53.20 mph, 26.49 mph, 23.09 mph and 13.64 mph, respectively.

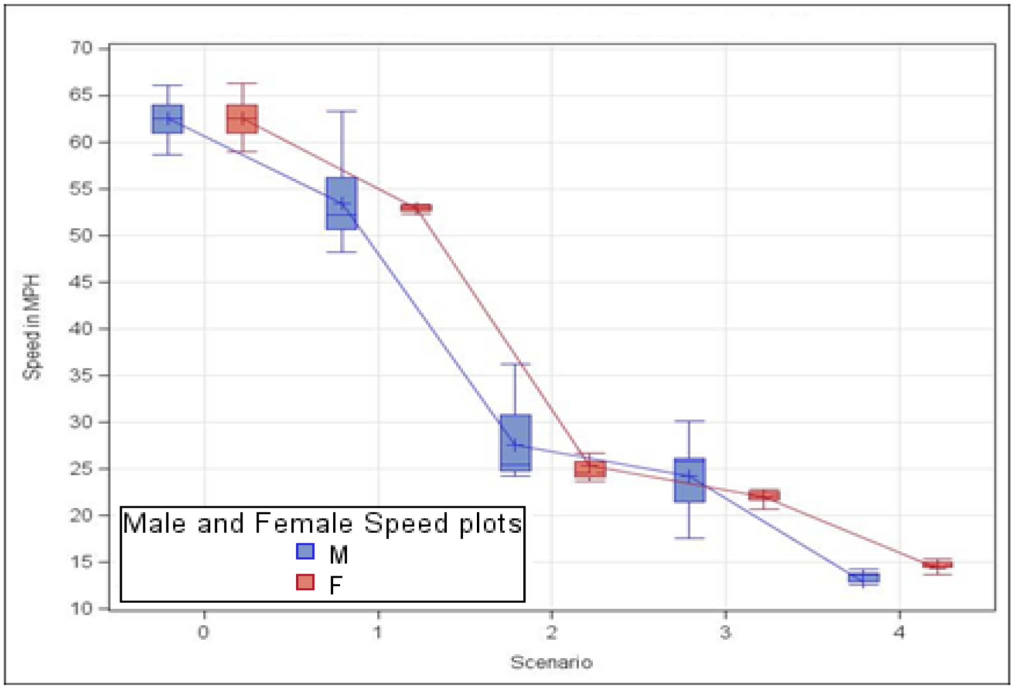

Figure 5.11 Comparison of speeds for interaction (gender*interval) - interval8

Figure 5.11 illustrates the mean speeds by gender. It can be observed that the difference in mean speeds between the genders is minimal. However, men, as indicated previously, continued to show higher variance in speeds compared to female drivers. Figure 5.12 presents the mean and 85th percentile speeds for each message as perceived by the participants. It indicates that message sign-4 resulted in the lowest speeds compared to other scenarios.

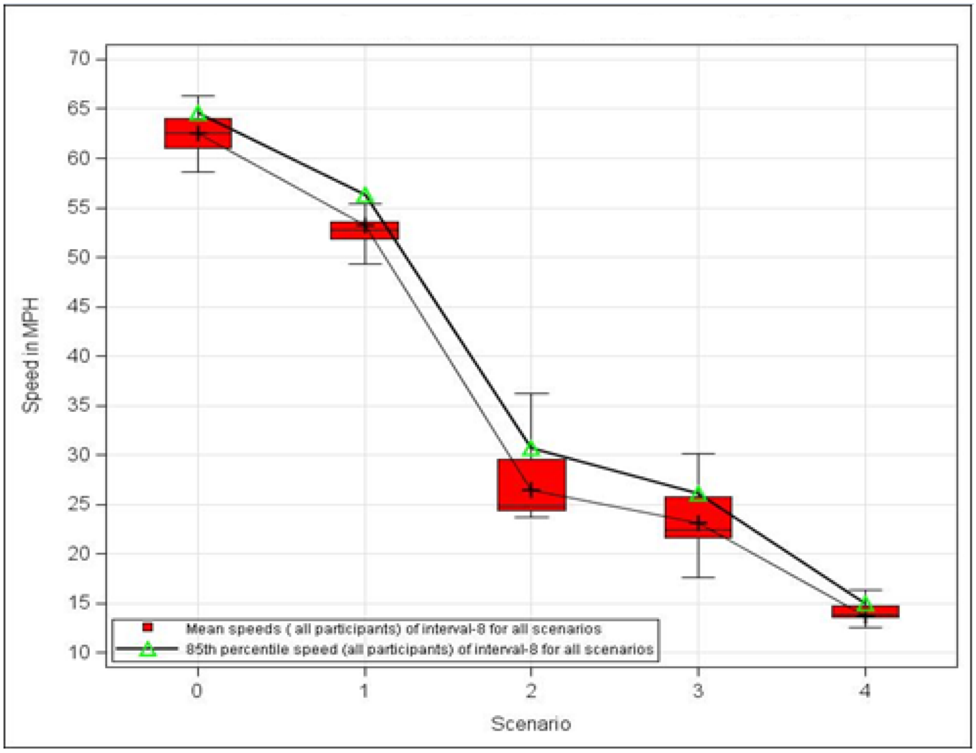

Figure 5.12 Mean speeds and 85th percentile speed for the final interval

5.3. COMPARISON OF SPEED PROFILES FOR DIFFERENT SCENARIOS

A comparison of speed profiles was performed to evaluate the driver behavior over the length of the work zone replicated in the DS. Figure 5.13 presents the speed profiles of all the scenarios. The control scenario did not see an appreciable change in speeds across the intervals. The main decrease in mean speed was observed for intervals 7 and 8.

For scenario-1, the observed mean speeds for all intervals were much lower than the control scenario and were significantly lower at interval-8. It can be deduced that MS-1 had an impact in reducing the speed of the participants. There is a slight increase in mean speeds at interval-3. This can be possibly attributed to the fact that participants expected a lane closure ahead after seeing the first PCMS but did not see it.

For scenario-2, the observed mean speeds were lower compared to the control scenario and scenario-1. Again, a slight increase of mean speeds at interval-3 can be observed, which again is assumed to be due to the participants not sighting the lane closure after the first PCMS. There is a significant decrease in the mean speed at interval-8 when compared to the control scenario and scenario-1.

For scenario-3, with a message sign “PREPARE TO STOP, YY MIN TO END OF WZ”, an appreciable decrease of speed at interval-1 can be observed. However, an increase in mean speeds is observed until interval-5. This increase in the speed may be due to participants not finding a reason to slow down when they observed the PCMS as they were farther from the end of the work zone. The mean speed began to decrease from interval-6 (after PCMS#3) as participants anticipated nearing the end of the work zone as the travel time (in minutes) decreases to reach the end of the work zone.

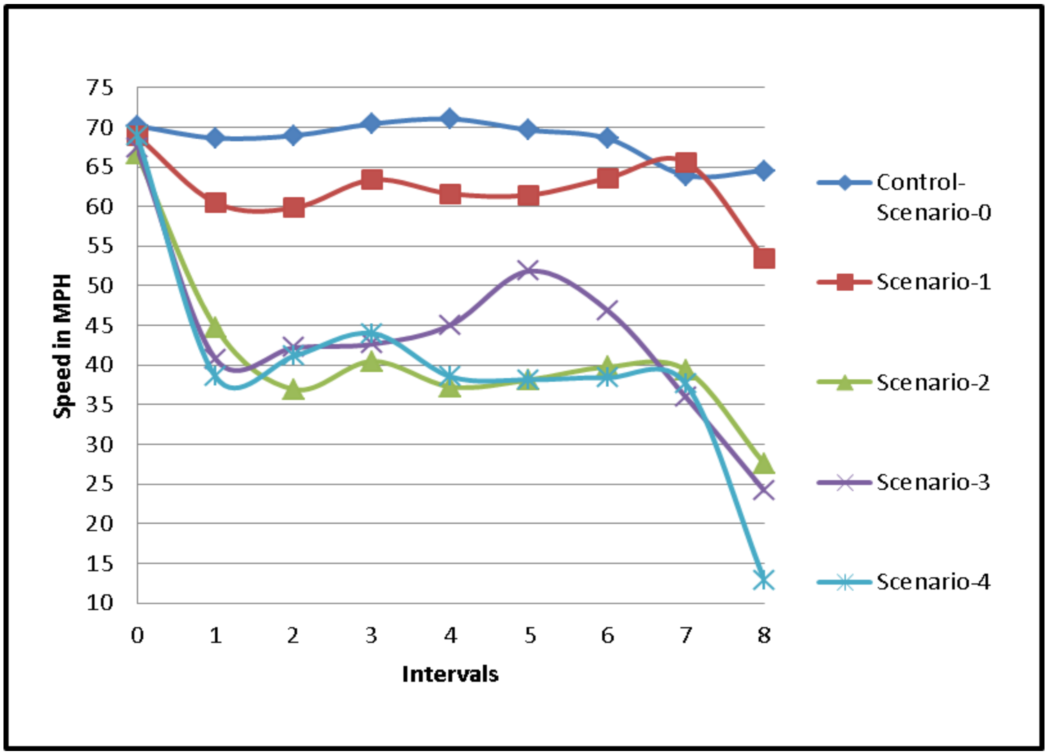

Figure 5.13 Mean speed profile: nine intervals versus scenarios 1-5

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"

Scenario-4, with a message sign "PREPARE TO STOP, STOPPED TRAFFIC AHEAD" also showed a similar trend as in scenario-2. At interval-3, an increase of speed is observed as participants did not find either "stopped traffic" or the need the stop. However, the mean speed did not change significantly from interval-4 to interval-7. The participants started to slow down as they approached the lane closure. In scenario-4, the final speed was very low and was the lowest compared to the other scenarios as the drivers' perception of stopped traffic ahead was the highest.

5.4. SUBJECTIVE SURVEY RESULTS

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

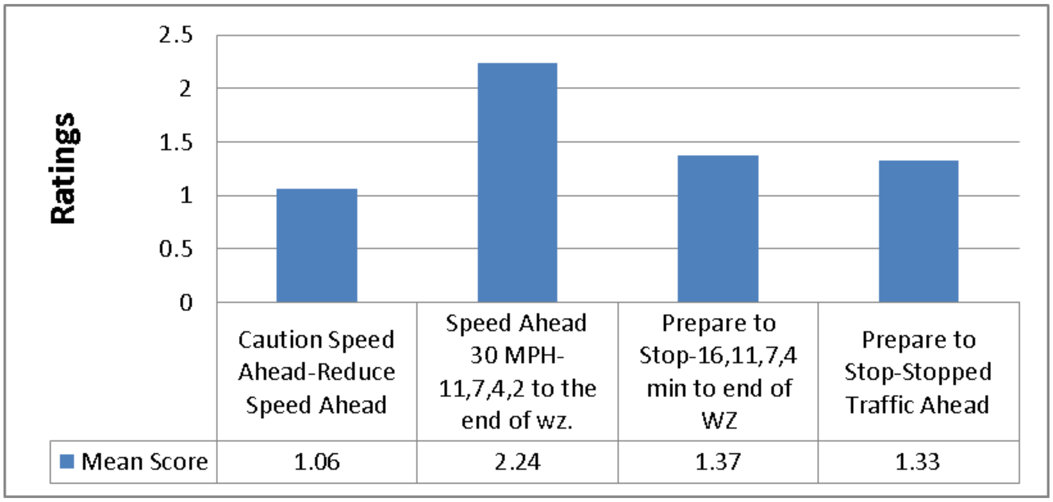

Figure 5.14 Mean ratings of message signs

The participants were asked to rate the different message signs according to their effectiveness and their ability to convey the most accurate information to the drivers. A rating of '4' was considered to be the most effective message and a rating of '1' was considered to be the least effective of the four message signs. Figure 5.14 illustrates the mean ratings of the message signs. The results indicate that MS-2 was considered to be most effective (with a mean rating of 2.24) by the participants. The two other messages (MS-3 and MS-4) had similar mean ratings suggesting that drivers did not find the information effective enough. MS-1 mainly alerted the drivers and no action was required from them. The participants preferred MS-2 in terms of a speed to follow, whereas the other three messages seemed ambiguous as specific actions were only required by drivers when the indicated conditions were observed.

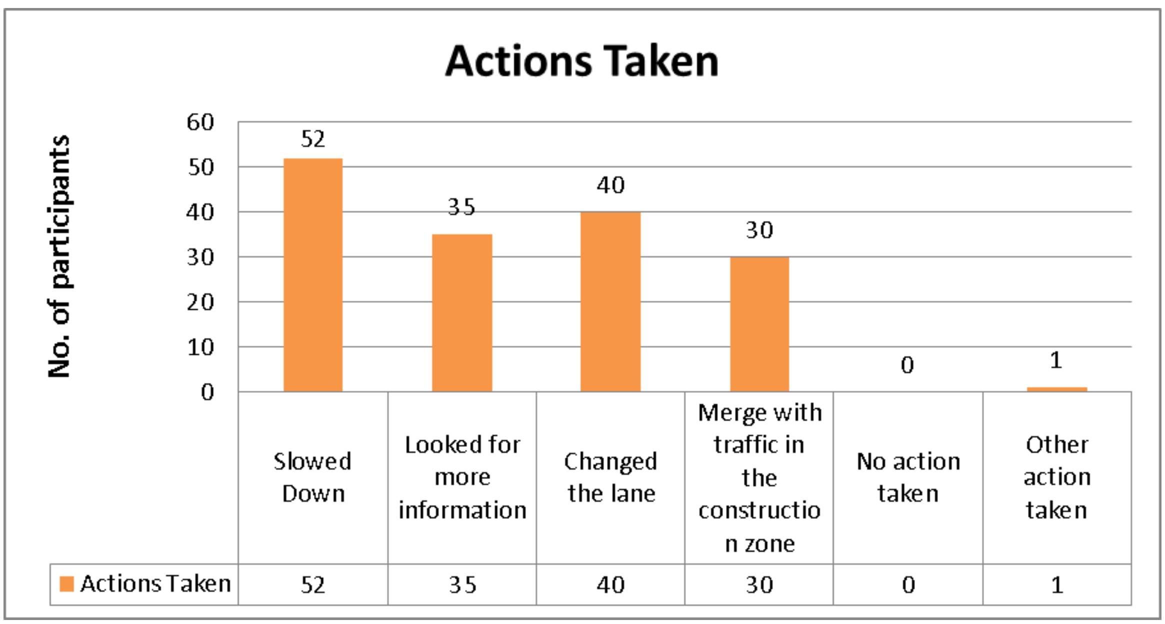

Figure 5.15 Action taken by the participants after sighting the PCMS

The participants were also asked about their actions taken after sighting, reading and comprehending the PCMS. Figure 5.15 shows the actions taken by the participants. All fifty-two (100%) participants slowed down after sighting the PCMS. This indicates that the participants complied with the PCMS. Thirty-five (67%) participants stated that they looked for more information when they sighted the message. This can be attributed to the nature of messages 1, 3 and 4. Forty (76%) participants changed the lane. This behavior can be attributed to the start of taper and the lane closure, as this occurred at the end of the experiment.

The participants were surveyed on their capability to recall the messages displayed on the PCMS. The results are presented in Figure 5.16. Thirty-seven (71%) of participants were able to recall all of the observed messages correctly. This high percentage might be attributed to the fact that participants knew beforehand what they were being tested on and paid more attention to the message signs than expected in normal driving conditions. 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 eight 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 contained the same first phrase of the two-phrase message. The participants might have perceived this as a repetition of the experiment.

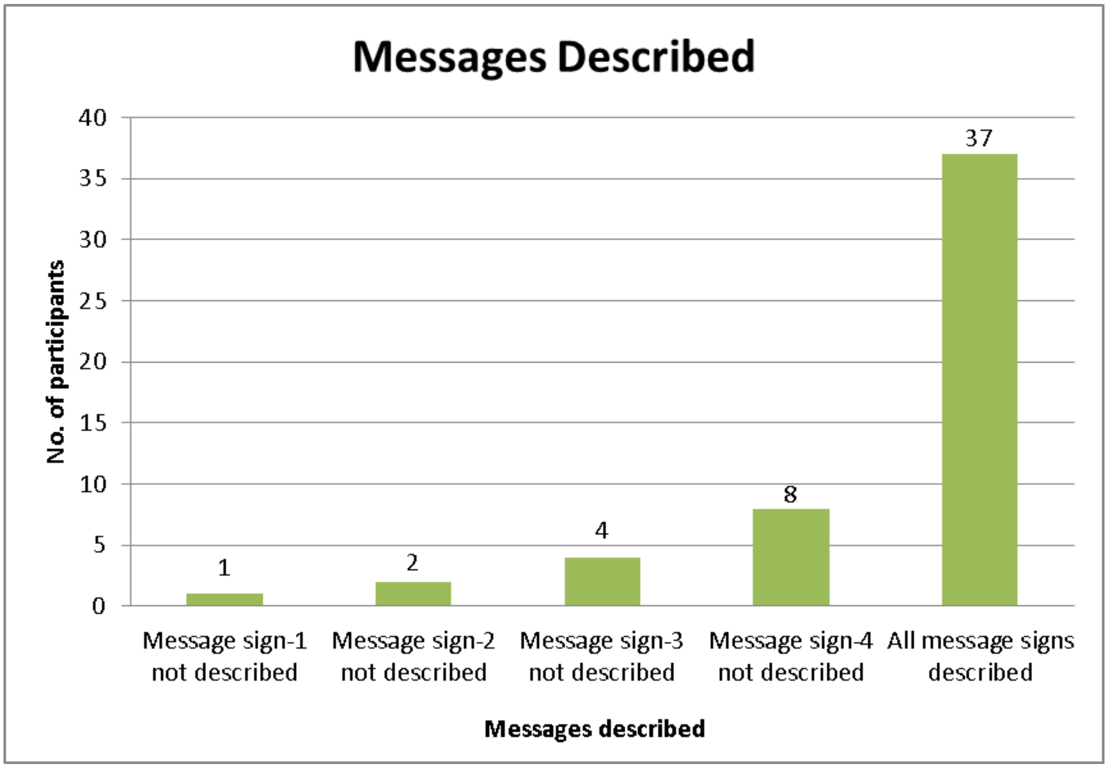

Figure 5.16 Participant's ability to recall the observed messages

5.5. SUMMARY

The statistical analysis yielded gender and interval as the main factors of significance for all the scenarios, which suggests that the messages were perceived differently by male and female participants. Age was not found to be a significant factor for any of the simulated scenarios. From the subjective evaluation it can be deduced that MS-2 (used when the average speed of vehicles is between 20-50 mph in the work zone) was the most effective, as it displayed a particular value of speed 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 very close to the displayed value of speed on the PCMS (30 mph). The mean speed for MS-2 in interval-8 was 26.47 mph, lower than the displayed speed. From the objective evaluation, the observed mean speeds were the lowest for MS-4 (to be used when the average speed of vehicles is less than 5 mph). The mean speed for MS-4 was 13.64 mph, which was higher than the average mean speeds meant for the usage of MS-4. Therefore, it can be deduced from the objective and subjective evaluations that MS-2 is the most effective message sign.

6. CONCLUSIONS AND RECOMMENDATIONS

This project conducted a subjective and objective evaluation of the effectiveness of PCMS using a driving simulator (DS). The objective evaluation used speed as the main criterion and examined the effects of different message signs on driving characteristics. The objective evaluation considered the variables of gender, age and message signs. Five scenarios were tested: a control scenario without any message and the remaining four scenarios with different (four) messages (Table 2.1). 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 drivers' speeds over 1000 ft before and after each PCMS. As a result, the participants' driving characteristics were examined over eight intervals, before and after each of the four PCMS.

From the objective evaluation, it was observed that the speeds did not vary significantly for the first seven intervals of the scenarios. However, a significant difference was found on the eighth interval after the fourth PCMS was placed before the lane closure. On a virtual highway with a 70 mph speed limit used for the control scenario, the mean speed of drivers in the eighth interval was observed as 62.55 mph. The mean speed of drivers in the eighth 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 eighth 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 eighth 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, a decrease of 39.46 mph. For scenario-4 ("Prepare to stop; Stopped traffic ahead", displayed on each of the four PCMS) the mean speed for the eighth interval was 13.64 mph, a decrease of 48.91 mph from the control scenario. This speed drop is representative of real-world conditions as this scenario represents stopped traffic ahead and drivers are expected to appreciably decrease their speeds. It can be concluded that all of the message signs reduced the speed of the participants before the start of the lane closure. 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 for the eighth interval (after the fourth PCMS) for message sign-2 (MS-2) was observed to be very close to the anticipated speed of 30 mph displayed on the PCMS. From this observation, it can be inferred that drivers followed the anticipated speed displayed on the PCMS and they reacted to the messages that only alerted them when those messages were accompanied by specific conditions such as lane closure.

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) being the most effective among all message signs. The participants preferred the usage of message sign-2 (MS-2) because it directed drivers to a certain speed value. The participants followed the message and slowed down to around 30 mph. Thus messages that are concrete requiring the driver to take an action and can be adhered to are more effective. PCMS that alert drivers and provide information such as values of travel time are not as effective. From the objective and subjective analysis, messages with a suggested value of speed, such as in MS-2, are recommended.

6.1. RECOMMENDATIONS

The suggested future research efforts based on this study include:

1. Study the impact of placement of PCMS on driver behavior and determine the best criterion for its placement, especially the effects of spacing between them;
2. Study the impact of fewer than four PCMS on driver speed characteristics;
3. Evaluate PCMS using different message signs for a given scenario; and
4. Study the effects of PCMS, during different times of the day, weather conditions, and interval lengths (before and after each PCMS) to examine any difference in the speed reduction pattern.

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APPENDIX: 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 ones.

____

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 1^{st}, 2^{nd}, 3^{rd} and the 4^{th} 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 actions 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 <u>30</u> MPH, <u>11, 7, 4, 2</u> MIN TO END OF WORK ZONE
   ☐ PREPARE TO STOP, <u>16, 11, 7, 4</u> 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 <u>30</u> MPH, <u>11, 7, 4, 2</u> MIN TO END OF WORK ZONE
   ☐ PREPARE TO STOP, <u>16, 11, 7, 4</u> 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 small	O	O	O	O	O	Text (font) size very 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: