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VALIDATION OF DRIVING SIMULATOR AND DRIVER PERCEPTION OF VEHICLE MOUNTED ATTENUATOR MARKINGS IN WORK ZONES

by

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A THESIS

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ABSTRACT

This research work sought to validate the driving simulator at Missouri University of Science and Technology and to evaluate the vehicle mounted attenuator (VMA) markings for various times of day. For comprehensive validation of the driving simulator, a framework is proposed which is demonstrated using a fixed-base driving simulator. Objective and subjective evaluations were conducted, and validation of the driving simulator was performed at specific locations and along the highway. Field data were collected for a partial lane closure using a global positioning system (GPS) along the work zone and supplemented with video recordings of traffic data at specific locations in the work zone. The work zone scenario was reconstructed in a driving simulator and analyzed with 46 participants. The results of objective evaluation established the absolute and relative validity of the driving simulator. The results of subjective evaluation of the simulator indicated realistic experience by the participants.

Evaluation of four VMAs used by departments of transportation (DOTs) in work zones determined the effectiveness of specific striping patterns and color combinations. The survey of DOTs indicate that the yellow and black inverted ‘V’ pattern is the most widely used since it is the one most often provided by VMA suppliers. A driving simulator study was then conducted to evaluate each VMA for use during the day, at dusk, and at night. By driving through virtual highway work zones, 120 participants of various ages evaluated the VMA markings. Additionally, the drivers completed a detailed subjective survey. The results of the objective and subjective evaluations indicate that, overall, the red and white checkerboard pattern is most effective.

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SECTION

1. INTRODUCTION

A driving simulator is an ideal virtual reality tool for driving safety studies and driver training. The simulator can provide an environment that is both safe and replicable. By simulating vehicle motion based on the driver operation, and by providing feedback in the form of visual, motion, and audio cues to the driver, a driving simulator can give drivers the impression that they are driving an actual vehicle in the real world. It can safely measure driver reactions to dangerous and even life-threatening situations that cannot be evaluated in the real world.

1.1. CLASSIFICATION OF DRIVING SIMULATORS

Several studies have classified driving simulators. A researcher at Volvo Technological Development, Dennis Saluaar (2000) classified driving simulators as low, mid-level, or high-level. The low-level simulators are ordinary PCs equipped with a steering wheel and pedals. High-level simulators usually have huge motion base systems. Simulators between these two categories are called mid-level.

1.1.1. Low-Level Simulators. Low-Level simulators, as shown in Figure 1.1, are usually built on standard PC systems at a low cost. They have only one screen. If they have any motion system at all, it is very limited; generally, they can simulate only visual or audio conditions. They are designed for the individual home PC user and can provide the user with a standard desktop virtual reality experience. Because of their low cost and convenience, low-level simulators are the most widely used systems for home use.

FIGURE 1.1. Low-Level Driving Simulator

1.1.2. Mid-Level Simulators. Simulators on this level vary a lot in terms of performance and cost. Mid-level simulators are more advanced and thus more expensive than low-level simulators. They usually have multiple screens. Their subsystems, however, and especially their motion system, are more limited than those of high-level simulators. They are a trade-off between the low-level and high-level simulators in terms of performance and cost.

The Missouri S&T driving simulator (Figure 1.2) used for this study is a good example of a mid-level driving simulator. It is a fixed-base driving simulator consisting of a mockup passenger car, three LCD projectors, a projection screen, and three networked computers with an Ethernet connection.

FIGURE 1.2. Missouri S&T Driving Simulator

1.1.3. High-Level Simulators. High-level simulators are the most advanced and thus, the most expensive. They take millions of dollars to develop, and they provide a high-quality virtual experience. Many offer advanced features such as hydraulic motion systems and large, high-resolution displays.

The National Advanced Driving Simulator (NADS) (Figure 1.3) is the most advanced simulator available today. One such simulator costs at least $50 million (Chen et al., 2001). It has a simulation dome 24 feet in diameter and enclosing interchangeable car cabs sitting inside of the dome. This dome can accommodate various cabs, such as the Ford Taurus, Chevy Malibu, Jeep Cherokee, and Freightliner. There is a 15-channel graphic system inside the dome that covers the whole 360° field of vision. Such simulators have been used to study traffic safety, crash avoidance, and in-vehicle control technologies.

FIGURE 1.3. National Advanced Driving Simulator (NADS)

1.2. APPLICATIONS OF DRIVING SIMULATORS

A driving simulator is a useful tool for investigating and analyzing driver behavior. The advantages of using simulators over real cars are evident. A simulator permits testing of scenarios that are too dangerous to replicate in a real car, and it gives researchers full control of all the parameters for both the car and the traffic environment. Thus, tests performed using simulators are repeatable. Bella (2009) notes that driving simulators are chiefly used in the following traditional research areas:

- study of the human factors involved in driving tasks,
- assessment of the influence of alcohol on driving performance,
- study of driving performance based on driver age or weather conditions,
- design or assessment of in-vehicle systems that assist drivers with driving tasks, and
- driver training.

The availability of high-level driving simulators has expanded the use of driving simulators for multidisciplinary investigations and traffic engineering analyses.

1.3. VALIDATION OF DRIVING SIMULATOR

Driving simulators must be validated to ensure that they represent a useful research tool for studies related to driver safety. Usually, driving simulators have two levels of validity: physical and behavioral. Physical validity measures the degree to which the simulator dynamics and visual system reproduce the vehicle being simulated. The behavioral validity of a driving simulator, according to Blana (1997), is defined as the comparison of driving performance indices from a particular experiment on a real road with indices from an experiment in a driving simulator which is as close as it can be to the real environment.

Blaauw (1982) proposed two types of driving behavioral validity: absolute and relative. A driving simulator is absolutely valid if the difference between the magnitudes of critical driver performance variables such as speed, acceleration etc., observed in the driving simulator and those in the real world is statistically insignificant. A driving simulator is relatively valid if the differences with experimental conditions are in the same direction, and have a similar magnitude (Yan et al., 2008).

Many studies have evaluated the behavioral validity of driving simulators, but studies are needed using sophisticated field data collection devices like global positioning system (GPS). The research described here used GPS and video data to validate the driving simulator used by Missouri University of Science and Technology for the statistical study of driver behavior in work zones. This work relied on analysis of both a field study and driving simulator study.

1.4. VEHICLE MOUNTED ATTENUATORS (VMAS)

Crash cushions mounted on the rear of vehicles are called as vehicle mounted attenuators (VMAs). They have been used successfully for many years to reduce the severity of rear-end collisions in work zones. Figure 1.4 shows a VMA with the yellow and black inverted ‘V’ pattern. The Manual on Uniform Traffic Control Devices (MUTCD) (2009) and the American Association of State Highway and Transportation Officials (AASHTO) Roadside Design Guide (2002) both contain general guidelines for VMAs. However, neither offers recommendations for striping patterns or colors. The colors and striping patterns most commonly used is yellow or orange in an inverted ‘V’ design on a white or black background, but other options have also been used. Some states have experimented with a vertical striping or checkerboard pattern, using red and white. Figure 1.5 presents these and other striping patterns and color combinations commonly used by state departments of transportation (DOTs).

FIGURE 1.4. Vehicle Mounted Attenuator (VMA)

Lime Green and Black Inverted ‘V’ Pattern   Red and White Checkerboard Pattern

Yellow and Black Inverted ‘V’ Pattern   Orange and White Vertical Striped Pattern

FIGURE 1.5. Vehicle Mounted Attenuator (VMA) Patterns

This study evaluates driver perception of the effectiveness of various striping patterns and color combinations for VMA markings based on a DOT survey and a driving simulator study. The driving simulator study involved both objective evaluation of driver performance and drivers’ subjective evaluations of various VMA markings. Of some concern was the use of an inverted ‘V’ design when the following vehicles do not have the option of passing on both sides of the work vehicle. The impact of contrast between truck color and VMA color was also considered. The results will help state DOTs to select the most effective colors and striping patterns for VMAs**,** thereby improving safety and operations in work zones on high-speed, high-volume roadways.

1.5. THESIS OVERVIEW

This thesis validated the Missouri S&T driving simulator and evaluated four different VMA markings used in construction zones. It is organized as follows:

Paper 1 validates the driving simulator for work zone studies by comparing driver behavior in the simulator to that in the real world. Paper 2 evaluates VMA markings for work zones during daytime conditions. This study was carried out using a large sample of young drivers. Paper 3 evaluates VMA markings for work zones during daytime, dusk, and nighttime conditions

The conclusion summarizes the findings of both the driving simulator validation and the VMA marking evaluation, discusses the limitations of this work, and suggests avenues for future research.

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PAPER

1. VALIDATION OF DRIVING SIMULATOR FOR STUDY OF DRIVER BEHAVIOR IN WORK ZONES

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ABSTRACT

Objective: This study is aimed at validating a driving simulator for study of driver behavior in work zones. **Background:** Previous studies had indicated the lack of safe vantage points at critical locations as a challenge in validation of driving simulators. **Method:** For comprehensive validation of the driving simulator, a framework is proposed which is demonstrated using a fixed-base driving simulator. Objective and subjective evaluations were conducted, and validation of the driving simulator was performed at specific locations and along the highway. Field data were collected for a partial lane closure using a global positioning system (GPS) along the work zone and supplemented with video recordings of traffic data at specific locations in the work zone. The work zone scenario was reconstructed in a driving simulator and analyzed with 46 participants. The results from the simulator were compared to the field data. Qualitative and quantitative validations were performed to evaluate the validity of the driving simulator. **Results:** The qualitative evaluation results indicated that the mean speeds from the driving simulator data showed good agreement with the field video data. The quantitative evaluation established the absolute and relative validity of the driving simulator. The results of subjective evaluation of the simulator indicated realistic experience by the participants. **Conclusions:** This study has validated the driving simulator in both absolute and relative terms. **Application:** This paper has described validation framework, the application of which was demonstrated by validation of a driving simulator.

Key words: Driving Simulator, Global Positioning System (GPS), Behavioral Validity, Work Zone, Driver Behavior

1. INTRODUCTION

Work zone safety is a high priority for transportation agencies and the highway construction industry because of the growing number of work zone fatalities. Field data collection is complex and at times hazardous because it involves taking measurements under uncontrolled environmental, weather and traffic conditions. A driving simulator provides an innovative and safe way to conduct work zone studies. To demonstrate the use of driving simulators as an effective tool for research on driver behavior, a large amount of research has been carried out, including the effect of traffic-control devices (TCDs), the influence of drugs, alcohol, hypo-vigilance, and fatigue on driving performance, driver distraction, etc. (Arnedt et al. 1999; Godley et al. 2002; Bella 2005a; Fairclough and Graham 2005; Bham et al. 2009) has been studied.

Driving simulator studies have advantages over field testing as they allow the study of driving situations that may not be replicable in field tests for a wide range of scenarios. Driving simulator studies also permit the collection of various types of data.

Additionally, subjects can be tested in a laboratory under safe conditions and their reactions can be observed using multiple TCDs without exposing the researchers to unsafe road conditions.

A driving simulator, however, must be validated before it can be used as a research tool. Driving simulators can be validated at the absolute and relative behavioral levels (Blaauw, 1982). Behavioral validation can be performed by comparison of performance indices from a driving simulator experiment with indices from the real environment. The present study discusses both absolute and relative behavioral validity of a driving simulator.

A driving simulator is absolutely valid if the difference between the magnitudes of critical driver performance variables such as speed, acceleration etc., observed in the driving simulator and those in the real world is statistically insignificant. A driving simulator is relatively valid if the differences with experimental conditions are in the same direction, and have a similar magnitude (Yan et al., 2008).

Validation of driving simulators has been carried out in many studies. Vehicles' speeds were used for validation in a study by Godley et al. (2002). Tornros (1998) also used speeds for validation to study the driver behavior in a simulated tunnel. The driving simulator were shown to be behaviorally invalid in absolute terms but valid in relative terms. The relative and absolute validation of a driving simulator was also carried out using statistical tests based on speed data collected on a two-lane rural roadway (Bella, 2008). Kaptein et al. (1996) found the driving simulator to be valid in absolute terms for route choice; however, it was only relatively valid for speed and lateral control behavior.

It was concluded that a moving base and perhaps a higher image resolution would increase the validity of a driving simulator.

Among the many studies on the behavioral validity of driving simulators, none has used field measurement devices over the driving length of the study. Most studies have focused on validity at specific locations of the highway.

The present paper describes a framework that can be used for systematic validation of driving a simulator, including the use of a global positioning system (GPS) for validation of a driving simulator to overcome the issue of availability of safe vantage points. The application of the proposed framework is demonstrated by examining a fixed-base driving simulator for a work zone study.

2. VALIDATION FRAMEWORK

The proposed driving simulator validation framework categorizes the validation process into objective and subjective evaluations. The objective evaluation is divided into qualitative and quantitative validations. It further distinguishes the process into validation at specific locations and along the highway. Behavioral validation, including both relative and absolute validations, can be performed at the specific locations and along the highway. Subjective evaluation is performed by surveying participants to rate the simulator components and the simulated scenario.

The validity of the driving simulator in the Advanced Simulation and Virtual Reality Laboratory at the Missouri University of Science and Technology was performed qualitatively and quantitatively for a work zone based on comparison with field data. The field data were collected using a GPS at sub-second time intervals along the highway and by video cameras at specific locations. First, the qualitative validation is proposed for comparison of driver behavior in the driving simulator with driver behavior in the real world. This validation was carried out to determine if the results should be further validated quantitatively or any improvements should be made to the simulator. The quantitative validation was performed by statistically comparing the driving simulator data with the data collected at specific locations along the highway and along the highway. Data at specific locations can be collected using fixed video cameras for traffic flow characteristics such as traffic volume, headways, vehicle speeds, etc. Data along the highway can be collected using GPS or aerial photography such as with a helicopter, a balloon or a tall building. Various examples of data collection using these techniques can be found in the literature (Smith, 1985). In the quantitative validation, both absolute and relative validations can be performed. Subjectively evaluation can also be performed to capture participants' experience in the driving simulator. The subjective validation can provide a basis to determine if the simulator components and the driving experience through the scenario were realistic.

The use of GPS as described in this study to evaluate the validity of the simulator along the highway serves two purposes. First, it can be used to collect data at locations where continuous data cannot be collected using other devices. Second, it can be used to collect detailed data along the highway at short time intervals. A GPS is capable of collecting accurate data such as location (latitude, longitude, and elevation), speed, and distance traveled for driver behavior related studies.

3. METHODOLOGY

This section describes the field data collection process, details of the driving simulator study, and discusses analysis of the data to validate the driving simulator.

3.1. Field Data Collection

Work zone data were collected on I-44 West Bound near Doolittle, Missouri, between Exits 184 and 179. The mile markers indicated the highway location, which decreased towards Exit 179. I-44 near Doolittle is a rural four-lane divided highway with a wide median. The work zone was about 2 miles long, from mile marker 181.6 (start of temporary signs) to 179.4 (end of work area). The left lane was closed and the lane closure was one-mile long with tubular markers on the lane marking. The advance warning area was 1.2 miles, and signs were placed on both sides of the highway. The work zone speed limit was 60 mph, 10 mph below the normal posted speed limit. The horizontal alignment was mostly on a tangent along the advance warning area and the work area. However, upstream of the advance warning area had two horizontal curve on an uphill with a climbing lane.

Placement of work zone traffic signs and the data collection points in the work zone are shown in Table 1, and Figure 1 presents the locations and the data collection methods used. Video data were recorded using high definition (HD) video cameras from an outer road between 12 and 3 PM in the advance warning area, from the overpass in the work area, and work zone termination area. The traffic conditions varied from congested queued to free flow conditions during the three hours.

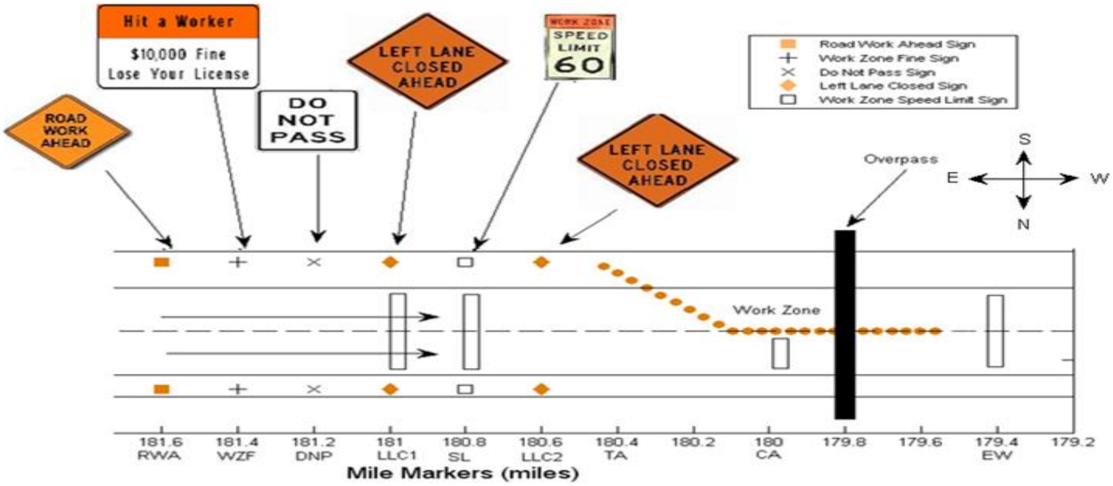
Table 1. Data Collection Locations using GPS, Video Camera and Driving Simulator

Locations	Description	Mile Marker	Data Collection		
			GPS	Video	Driving Simulator
FW	upstream of work zone	183.4	Y	Y	Y
RWA	‘Road Work Ahead’ sign	181.6	Y	-	Y
WZF	‘$1000 Fine’ sign	181.4	Y	-	Y
DNP	‘Do Not Pass’ sign	181.2	Y	-	Y
LLC1	‘Left Lane Closed’ sign	181.0	Y	Y	Y
SL	work zone speed limit sign	180.8	Y	Y	Y
LLC2	‘Left Lane Closed’ sign	180.6	Y	-	Y
TA	start of taper area	180.4	Y	-	Y
CA	construction activity area	180.0	Y	Y	Y
EW	end of lane closure	179.4	-	Y	Y

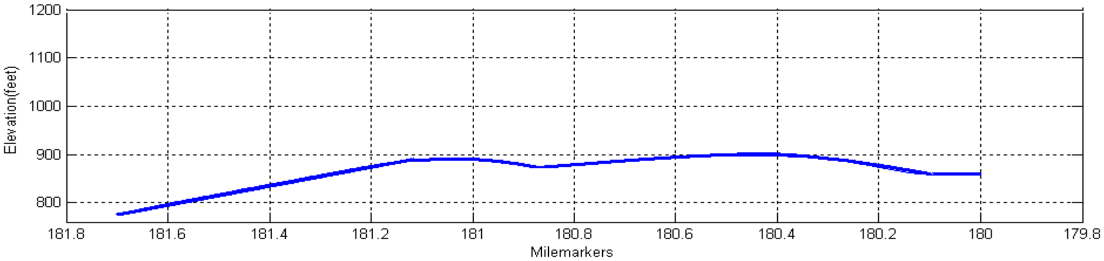
‘Y’ indicates data collected at that location
‘-’ indicates data not collected at that location

Vehicle speeds were obtained using vehicle recognition software from the recorded videos. The software was calibrated for each site before the data were extracted. To validate the data extraction, laser speed guns were used at each site, and the vehicle speeds were compared with the speeds obtained from the software. Laser speed guns have an estimated accuracy of ±1 mph (Laser Technology Inc., 2010). The video data was then processed to extract the speed of free flowing passenger cars. Vehicles were assumed to be free flowing when their time headway was more than 5 seconds (Bella, 2005).

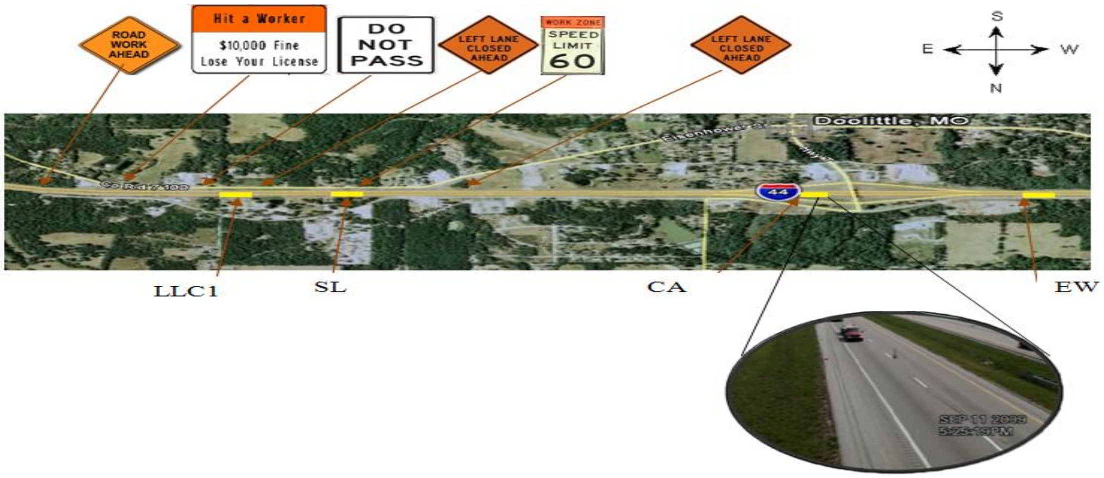
The GPS data were collected autonomously at 10 Hertz using Omnistar HP service for accuracy, as the GPS equipped vehicle traveled repeatedly on I-44 WB. The accuracy of the data using the HP service is estimated to be 0.33 feet horizontal and 0.5 feet vertical (Trimble, 2010). The GPS collected data at locations where the video data could not be collected (e.g., at the ‘Road Work Ahead’ sign) as it was not accessible from the outer road.



(a) Work Zone Configuration, Video Data Collection Points and Location of Traffic Control Devices



(b) Elevation profile



(c) Aerial View of I-44 WB and Location of Signs, Camera View of Data Collection Site

Figure 1. Field Data Collection

3.2. Driving Simulator Study

3.2.1. Missouri S&T Driving Simulator. The driving simulator is a fixed-base Ford Ranger pick-up truck equipped with different sensors to measure steering operation, speed, acceleration/deceleration, braking, etc. It is connected to three LCD projectors, and three networked computers with Ethernet connections. The computer that processes the motion of the vehicle was defined as the master and two other computers as the slaves. The projection screen has an arc angle of 54.6°, an arc width of 25 feet, and a height of 6.6 feet. The field of view is around 120°.

The resolution of the visual scene generated by the master is 1024×768 pixels, the slaves are 800×1200 pixels, and the refresh rate is 30 to 60 Hertz depending on the scene complexity. The driving simulator is also equipped with a system that replicates the sound of an engine. A more detailed description of the system structure, projection system, and the data acquisition process can be found in Wang et al. (2006).

3.2.2. Scenario Construction. The GPS data collected were used to construct the work zone scenario, including work zone setup, placement of signs, the road geometry including the horizontal alignment, the vertical profile, the roadside elements of the work zone activity area and the advance warning section. The upstream section of the work zone consisted of a tangent to allow the drivers to reach the freeway speed and then a section of 0.4 miles reproducing the road geometry at location FW. The section between FW and RWA in the real world was not simulated because of the sharp horizontal curves and the uphill grade as they cannot be realistically simulated with a fixed-base driving simulator. This highway section also has a climbing lane (not simulated) between MM 182.4 and 182.0 for heavy vehicles. The advance warning signs were placed at exact locations corresponding to the actual locations, photographed using a digital single-lens reflex 12 megapixels camera. Figure 2 compares the prominent scenarios of the driving simulator with those of the real world.

Figure 2. Comparison of Driving Simulator Scenarios (left) and Real World Captured Using a Video Camera (right)

3.2.3. Participants. Potential participants were screened with the use of a questionnaire and were selected only if they met the following requirements: in possession of a valid US driver license, no health problems that would affect their driving, did not suffer from motion sickness, no prior experience of driving in a simulator, and no prior knowledge of the research project. The selected participants had normal or corrected-to-normal vision and did not report any form of color deficiency.

Forty-six participants, mostly Missouri S&T students and staff ranging in ages from 19 to 53 years, took part in the experiment. The mean age was 25.3 years and the standard deviation was 7.9 years. Out of the 46 participants, sixteen (35%) were females, five had been driving for more than 15 years, 23 had been driving between 5 and 15 years, and 18 had been driving between 1 and 5 years.

3.2.4. Experiment. All participants completed a survey before and after the driving simulator experiment. The pre-experiment questionnaire evaluated the participants on alertness and eligibility by inquiring about alcohol and drug use during the last 24 hours. Participants were first given a brief introduction to the driving simulator experiment and advised to adhere to traffic laws as they would in real work zone traffic conditions. The participants were also told that they could quit the experiment at any time in case of any discomfort. To familiarize them with the simulator, the environment, and the instructions, participants were instructed to drive through a trial environment. Each participant drove through the constructed work zone scenario after the trial run. Driver behavior data were collected by the various sensors at every 0.1 seconds.

3.2.5. Post-Experiment Questionnaire. Each participant completed a post-experiment questionnaire, which evaluated the driving simulator based on the participants' experience. The participants rated the simulator components compared to their real-world experience on a scale of 1 to 7 (Likert, 1932), with 1 indicating unrealistic and 7 indicating very realistic conditions. The participants were asked to rate the driving simulator's components and the driving simulator's environment.

3.3. Data Analysis

The qualitative and the quantitative validations, as mentioned earlier, were performed at specific locations and along the highway. The qualitative and quantitative validations were performed with the data collected using the video cameras and the GPS, and compared with data from the driving simulator. The qualitative validation was performed by graphical comparisons of the real world data with the driving simulator data, whereas the quantitative validation was performed by conducting statistical and error tests. The statistical tests also evaluated the absolute validity of the driving simulator. This sub-section describes the statistical and the error tests carried out.

3.3.1. Validation at Specific Locations. Parametric tests such as the t-test assume that the data are normally distributed. A test of normality was, therefore, conducted to ensure the data were normally distributed. For absolute validity, the mean speeds from the driving simulator and the video data were compared using the t-test, which at each location was dependent on the equality of variance. The equality of variance was verified to ensure that the appropriate statistical test was carried out.

A normality test, which is the Shapiro-Wilk test (Shapiro and Wilk, 1965), was conducted at each location in the driving simulator and in the field study to test the hypothesis that the data were normally distributed. The test was conducted at 0.05 level of significance. The test compared the sample distribution of the speeds obtained in the simulator with the video data against the normal distribution and a p-value was obtained. If the p-value for each location was less than or equal to 0.05, the hypothesis would be rejected.

The mean speeds from the video data collected at specific locations were compared using the t-test with the mean speeds of the participants in the driving simulator at the same locations. The null hypothesis (H_0) was $MS_R – MS_S = 0$, and the alternative hypothesis (H_1) was $MS_R – MS_S \neq 0$, where MS_R equals the mean speed of vehicles at a location in video recording, MS_S equals the mean speed of participants at a location from the driving simulator data.

The t-test assumes equal variance for the two samples compared. To validate this assumption an F-test was conducted at each location. The F-ratio is the ratio of the two variances of the samples (the larger of the two variances is used as the numerator). The critical values of F-ratios were obtained from the F-distribution with degrees of freedom (DF) defined later in this section. For a location, the null hypothesis (H_0) and alternative hypothesis (H_1) were:

$$H_0:\ s_R^2 = s_S^2,\quad \text{reject } H_0 \text{ when F-ratio} > \text{F-value}_{critical} \tag{1}$$

$$H_1:\ s_R^2 \neq s_S^2,\quad \text{accept } H_1 \text{ when F-ratio} > \text{F-value}_{critical} \tag{2}$$

where:

s_R^2 = variance of sample speeds from video data at a location, and

s_S^2 = variance of sample speeds from the driving simulator at a location.

The confidence interval (CI) of the difference of the means was computed to determine the upper and lower limits of the difference. For the null hypothesis to be accepted, the difference of the means should fall inside the confidence interval. The CI for the difference in the mean speeds (MS_R - MS_S = 0) for each location with equal variance was determined as:

$$CI = (MS_R - MS_S) \pm t_C * S^2_{RS}\sqrt{\frac{1}{n_R}+\frac{1}{n_S}} \tag{3}$$

where:

n_R = number of vehicles at a location in video recording

n_S = number of vehicles at a location in driving simulator

t_c = critical t-value

S_{RS} = estimate of standard deviation at a location

S_{RS} in the above equation was calculated as:

$$S_{RS} = \sqrt{\frac{(n_R - 1)s^2_R + (n_S - 1)s^2_S}{n_R + n_S - 2}} \tag{4}$$

The value of t_c was obtained from the table for t-distribution corresponding to the degrees of freedom (DF) at 0.05 level of significance. The degrees of freedom for a location with equal variance was obtained as:

$$DF = n_R + n_S - 2 \tag{5}$$

The CI for each location with unequal variance was determined as:

$$CI = (MS_R - MS_S) \pm t_C\sqrt{\frac{s^2_R}{n_R}+\frac{s^2_S}{n_S}} \tag{6}$$

The value of t_c was obtained at 0.05 level of significance from the table for t-distribution corresponding to the degrees of freedom estimated as (Satterthwaite, 1946):

$$\mathrm{DF}=\frac{\left(\frac{s^2{}_R}{n_R}+\frac{s^2{}_S}{n_S}\right)^2}{\left[\frac{s^2{}_R/n_R{}^{2}}{n_R-1}+\frac{s^2{}_S/n_S{}^{2}}{n_S-1}\right]} \tag{7}$$

To measure the effectiveness of the t-test in determining the deviation from the null hypothesis, a power analysis was carried out by determining the probability (β) of a Type II error (i.e., accepting a false null hypothesis). The value (1-β) represents the probability that a null hypothesis will be rejected when it is false. The probability β of a Type II error depends on Δ, the absolute difference between the sample means, the driving simulator and field speeds. For this study, Δ was defined as the maximum acceptable difference between the mean speeds of the driving simulator and those from the field data. Five percent difference in the mean speeds was considered to be the maximum acceptable difference, beyond which the absolute validity of the driving simulator would be rejected. To obtain probability (β), the value of the t-statistic (t_β) for locations with equal variance was computed as:

$$t_\beta=\left(t_C * S^2{}_{RS}\sqrt{\frac{1}{n_R}+\frac{1}{n_S}}-\Delta\right)*\frac{1}{S^2{}_{RS}\sqrt{\frac{1}{n_R}+\frac{1}{n_S}}} \tag{8}$$

For locations with unequal variance, t_β was calculated as:

$$t_\beta=\left(t_C * \sqrt{\frac{s^2{}_R}{n_R}+\frac{s^2{}_S}{n_S}}-\Delta\right)*\frac{1}{\sqrt{\frac{s^2{}_R}{n_R}+\frac{s^2{}_S}{n_S}}} \tag{9}$$

The probability (β) was then obtained from the table for t-distribution corresponding to the degrees of freedom and the value of t_β.

Further, the percentage deviation, D, between the mean speeds from the simulator and that from the video data was calculated as:

$$D = (MS_S – MS_R)/MS_R *100 \tag{10}$$

3.3.2. Validation along the Roadway. To compare the speed profiles from the driving simulator with those of the GPS, error tests were conducted. These tests were conducted as they do not impose any restriction or require assumptions about the data set. Most statistical tests require assumptions of normality and the data to be mutually independent. The normality test cannot be performed accurately for a small sample size as was the case with the GPS data. Hence, error tests were found to be appropriate for comparison of driving simulator data and the GPS data. The error tests were used to quantitatively measure the closeness of results from the simulator compared to the field data. One such error test is the Theil’s inequality coefficient and its components which divide the errors into clearly understandable differences between the simulation results and the field data. These errors tests have been commonly used in validation of microscopic traffic simulation models, e.g. (Bham and Benekohal, 2004) and financial econometrics, e.g. (Pindyck and Rubinfeld, 1998).

The statistic called Theil’s inequality coefficient is defined as (Bham and Benekohal, 2004):

$$U= \frac{\sqrt{\frac{1}{N}\sum_{i=1}^{N}(MS_{Si}- MS_{Gi})^2}}{\sqrt{\frac{1}{N}\sum_{i=1}^{N}(MS_{Si})^2} +\sqrt{\frac{1}{N}\sum_{i=1}^{N}(MS_{Gi})^2}} \tag{11}$$

where MS_{Si} = mean speed for segment ‘i’.

In the above equation, the simulation model is a perfect file when U equals zero, i.e., $MS_{Si} = MS_{Gi}$ for all ‘i’. If U = 1, then the simulation model is completely different from the real system. Theil’s inequality coefficient can be decomposed into smaller errors, which provides a useful means of breaking up the total error. These smaller errors represent specific type of errors in the model. The errors were evaluated based on the following proportions (Bham and Benekohal, 2004):

$$U_M = \frac{(\mu_S - \mu_G)^2}{\sqrt{\frac{1}{N}\sum_{i=1}^{N}(MS_{Si}-MS_{Gi})^2}} \tag{12}$$

$$U_S = \frac{(S_S - S_G)^2}{\sqrt{\frac{1}{N}\sum_{i=1}^{N}(MS_{Si}-MS_{Gi})^2}} \tag{13}$$

$$U_C = \frac{2(1-\rho)S_S S_G}{\sqrt{\frac{1}{N}\sum_{i=1}^{N}(MS_{Si}-MS_{Gi})^2}} \tag{14}$$

where:

μ_S = average of the mean speeds at all locations from driving simulator

μ_G = average of the mean speeds at all locations from GPS data

S_S = standard deviation of the mean speeds in simulator

S_G = standard deviation of the mean speeds from GPS data

ρ = correlation coefficient

ρ can be calculated as:

$$\rho = \frac{\frac{1}{N}\sum_{i=1}^{N}(MS_{Si} - \mu_S)\,(MS_{Gn} - \mu_G)}{\sqrt{\frac{1}{N}\sum_{i=1}^{N}(MS_{Si})^2} + \sqrt{\frac{1}{N}\sum_{i=1}^{N}(MS_{Gi})^2}} \tag{15}$$

The proportions U_M, U_S, and U_C are called the bias, the variance and the covariance proportions of U, respectively. They are useful as a means of breaking down the differences in the mean speeds from the simulator and the GPS into its characteristic sources. U_M is an indication of systematic error, since it measures the extent to which the mean values of the simulated and GPS data deviate from each other. A large value of U_M would mean that a systematic bias was present and the mean speeds were different from the driving simulator and the GPS. A high value of U_S would mean that the GPS data varied considerably while the simulator data showed little variation, or vice versa. U_C measures nonsystematic errors, i.e., it represents the remaining errors after deviations from mean speeds have been accounted. For any value of $U > 0$, the ideal profiles of speeds from the driving simulator and the GPS over the three sources of errors are $U_M = 0$, $U_S = 0$, and $U_C = 1$ (Pindyck and Rubinfeld, 1998).

For use in the error tests, the speeds observed using the GPS over the roadway from MM 181.6 to MM 180.0 were compared with those observed from the driving simulator. This comparison was carried out by calculating the mean speeds for every 500 feet for every run. The driving simulator and the GPS data consisted of speeds captured at every 0.1 seconds. The mean speeds over each highway section for each run, was determined as presented below.

The mean speed, S_{Xin}, at every section 'i' for n^{th} run with 'm' speed measurements captured at every 0.1 seconds, presented in Figure 3, was determined as:

$$S_{Xin} = \frac{(y_m - y_{m-1}) + ...(y_2 - y_1)}{(t_m - t_{m-1}) + ...(t_2 - t_1)} \tag{16}$$

where:

X = 'S' for driving simulator, 'G' for GPS

y_m = distance coordinate at m^{th} point

t_m = time coordinate at m^{th} point

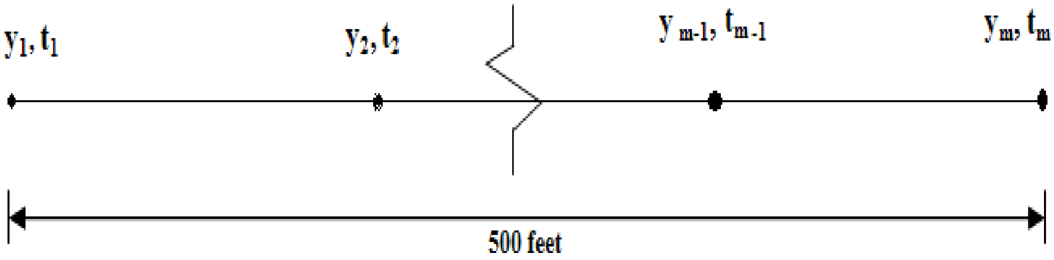


Figure 3. Calculation of Mean Speed at a Section

Since the time intervals between data points were equal, for simplicity the mean speed can be rewritten and computed as:

$$S_{Xin} = \frac{s_1 + ...+ s_m}{m} \tag{17}$$

where:

s_m = speed obtained at a point from the GPS or driving simulator at the m^{th} point

The mean speed (MS_{Xi}) for 'n' runs over section 'i' was determined as the arithmetic mean of S_{xi}.

4. OBJECTIVE EVALUATION

The objective evaluation of the driving simulator was performed in terms of both qualitative and quantitative validations. The qualitative validation compared the driver behaviors from the driving simulator with those obtained from the field study. The quantitative validation involved the absolute and the relative validations by statistical comparison of the mean speeds obtained from the driving simulator with those from the video data at specific locations along the roadway.

4.1. Qualitative Validation

As quantitative validation is detailed and time consuming, this study introduces qualitative validation as a first step before more detailed testing is carried out. The qualitative validation evaluates if the quantitative validation should be carried out or improvements in the driving simulator are required. Qualitative validation requires graphical comparison of results from the results of the driving simulator and the real world. It is, therefore, proposed that GPS data be collected in the real world for comparison with the driving simulator data. GPS data also provides the capability to validate along the highway rather than mainly at specific locations. Data collected at specific locations can supplement the GPS data collected for more detailed validation.

Qualitative validation was carried out to test if the driver behavior in the simulator was similar to the real world. Figure 4 shows the comparison of speeds obtained from the video data, the GPS data and the driving simulator. It was observed that the speeds of the drivers did not depend on the elevation of the section but was influenced by the advance warning signs, the taper area and the construction area of the work zone.

It was found that the driver behavior was similar at specific locations along the roadway in the real world captured by the video recording and in the driving simulator. In both cases, the speeds of the drivers decreased from the location at the left lane closed sign (LLC1) to the location at the end of the work zone (EW). Thus, further evaluation was carried out to validate the driving simulator quantitatively with the video data.

Additionally, the driver behavior was qualitatively validated along the entire roadway in the simulator and in the real world by comparing the simulator data and the GPS data. The comparison of the speed profiles from the GPS study and the driving simulator study seems to point to the reliability in the results from the simulator. Out of the 18 sections along the roadway shown in Figure 4, the driver behavior in the simulator and that from the GPS seems to be similar at 17 sections. The speeds of the drivers decreased from the RWA to the DNP in both the GPS and the driving simulator data. In both cases, the mean speeds of the drivers increased from the DNP to the LLC1. As the drivers approached the LLC2, the mean speed measured by the GPS and driving simulator decreased. Five hundred feet after the speed limit sign (SL) the driver behavior in the simulator was different from that in the real world because there was significant speed reduction in the driving simulator. This reduction in speed can be attributed to the slowing down of drivers to reduce their speed after noticing the reduced speed limit sign. Additionally, the lack of motion base in driving simulator lowers the perception of the speed to which the drivers were trying to reduce. The drivers increased their speed from LLC2 till they noticed the construction zone (1000 feet before the CA) and then decreased as they approached the CA. Thus, good correspondence was noted between the driver behavior in the simulator data and the field data (GPS) which indicated the relative validity of the driving simulator. Thus, further evaluation was carried out to statistically test the absolute and relative validities of the driving simulator.

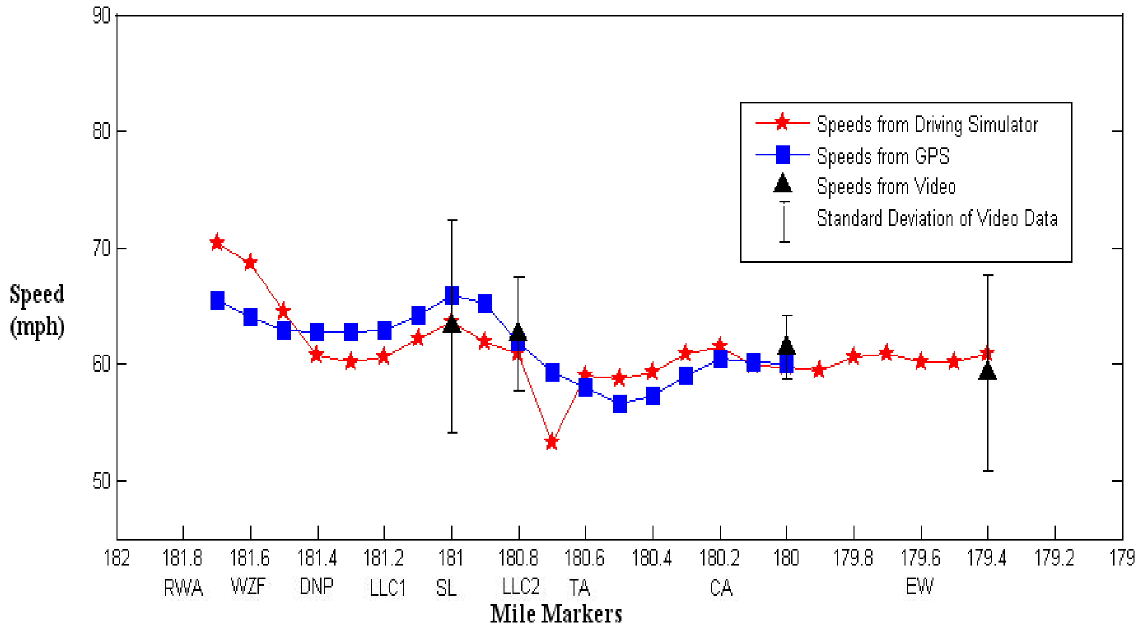


Figure 4. Comparison of speeds from Video Recording, GPS, and Driving Simulator

4.2. Quantitative Validation

The qualitative validation indicated a good correspondence in the driver behavior in the real world and in the driving simulator at specific locations and also along the entire roadway. Thus, quantitative validation was carried out to evaluate the absolute and relative validities of the driving simulator.

4.2.1. At Specific Locations. The mean speeds from the video recording were compared with those from the driving simulator at the following locations: i) upstream of the work zone (FW), ii) left lane closed sign (LLC1), iii) ‘60 mph’ speed limit sign (SL), iv) inside the construction zone (CA), and the end of the work zone (EW). Table 2 shows the means and the standard deviations of speeds from the video data (MS_R) and those from the simulator (MS_S) at the five locations. The comparison of the mean speeds from the field data with those from the simulator demonstrates the relative validity of the simulation. The difference between the mean speeds ($MS_S – MS_R$) ranged from -1.5 mph (at the speed limit sign SL) to 1.8 mph (at the freeway location FW). For the locations SL and the CA, the mean speeds were 1.5 mph and 0.9 mph lower for the simulator compared to the field study.

Table 2. Results of Field Study and Driving Simulator Study

Locations	Video Data				Driving Simulator Data			$MS_S – MS_R$	D
	Number of Vehicles (n_R)	Mean Speed (MS_R)	Standard Deviation (S_R)	Shapiro-Wilk	Mean Speed (MS_S)	Standard Deviation (S_S)	Shapiro-Wilk		
		(mph)		(p-value)	(mph)		(p-value)	(mph)	(%)
FW	41	68.5	8.9	0.18	70.3	5.4	0.18	1.8	2.6
LLC1	66	63.2	9.1	0.39	63.8	7.0	0.62	0.6	0.9
SL	59	62.5	4.9	0.13	61.0	5.0	0.18	-1.5	-2.4
CA	16	61.5	2.7	0.17	60.6	5.6	0.16	-0.9	-1.5
EW	85	59.3	8.4	0.13	60.5	3.3	0.78	1.2	2.0

Number of participants in the driving simulator study (n_S) = 46

On the freeway upstream of the work zone (FW), the percentage deviation equaled 2.6% which indicated that the drivers drove at higher speeds in the simulator. This value shows that the speeds recorded in the simulator were higher for the less demanding location, perhaps due to lower risk of crashes in the simulator than in the real world. This finding was consistent with those of the study conducted to validate the use of a driving simulator for a two-lane rural road (Bella, 2008). At the location of the speed limit sign, the deviation was -2.4%, indicating that the speeds recorded in the simulator were lower for the locations where the drivers had to make relatively complex maneuvers. This finding was consistent with the validation of a driving simulator for a crossover work zone (Bella, 2005). Bella also found that the speeds were lower in the simulator than in the real world at the speed limit sign in the advance warning area. Thus, the speeds were higher in the simulator when the drivers accelerate on the freeway whereas they were lower when the drivers decelerate in the work zone.

From Table 2, the standard deviation was found to be higher in the real world than in the driving simulator at FW, EW, and the LLC1 locations. This indicated larger variations in the speeds of drivers in the real world compared to the driving simulator when they were not reducing their speeds. It must be kept in mind that driving in the simulator is not affected by other vehicles. The standard deviation at the location CA was higher in the driving simulator compared to the real world. This indicated lowest variation in speeds from the field data as very limited data were available from this location because of congested traffic flow, i.e. most vehicles were not free flowing.

A Shapiro-Wilk test was carried out on the video data and the driving simulator data collected at five locations and the results are presented in Table 2. The test revealed that the data were approximately normally distributed, i.e., the p-values were greater than 0.05 and it fitted a Gaussian distribution at the five locations in the field and also in the driving simulator. Figure 5 shows the distribution of speeds at LLC1.

Table 3 shows the results of F-test, t-test and power analysis for each location. The results of F-test indicate that the null hypothesis was accepted, that is, the variance of the speeds in the driving simulator and in the field was equal at the SL location. Since the variance was unequal at four locations as evidenced from Table 3, the field observations and the simulator results were compared at each location using tests that does not assume equality of variance. The t-test indicated that the difference in the mean speeds lies within the confidence interval. Thus, the null hypothesis was accepted at a 5% level of significance at the five locations, and there was no significant difference between the mean speeds in the driving simulator and those in the real world. Therefore, the absolute validity of the driving simulator was obtained. Also, the relative validity of the driving simulator was obtained since the speeds were not statistically different and varied in the same direction in the video data and in the driving simulator data.

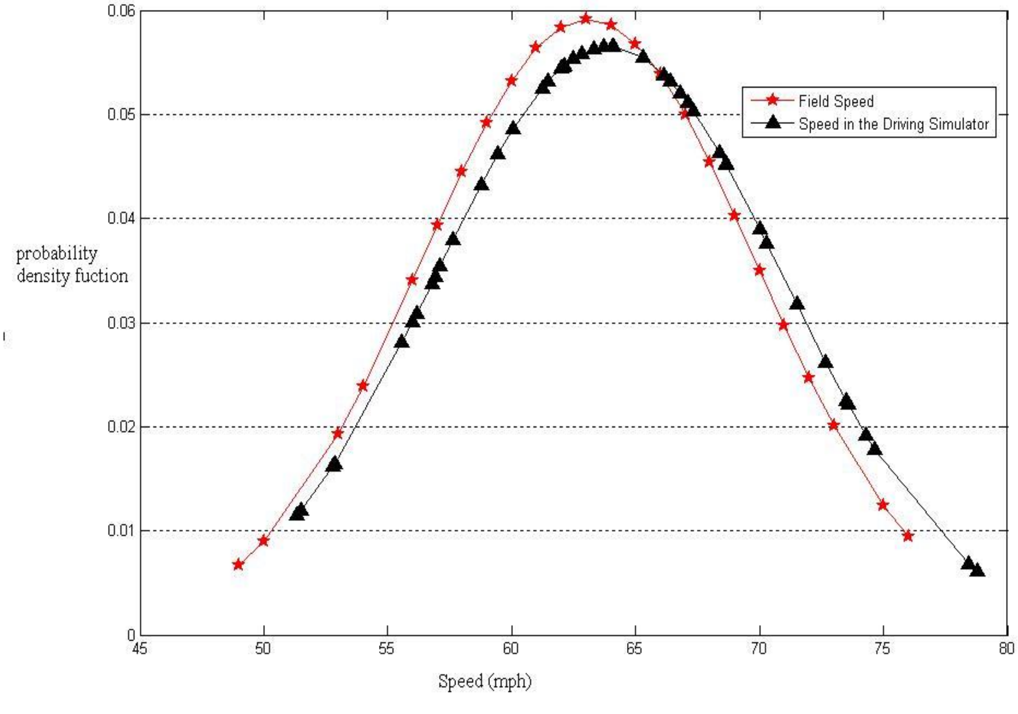


Figure 5. Distribution of Speeds Observed from the Video data and from the Driving Simulator Data at LLC1

The power of the t-test ranged from 68% upstream of the work zone (FW) to 93% at the location of the speed limit sign (SL). These values indicate a very low probability that a false null hypothesis will be accepted by mistake. In other words, the power analysis indicated a low probability of type II error in the work zone advance warning area and in the construction activity area. The possibility of such errors was higher at the freeway location.

Table 3. F-Test, t-Test and Power Analysis: Field data versus Driving Simulator data

Locations	F-test			t-test				
	F-ratio	F-critical	Result (H_0)	t_C	DF*	CI^	Power (1- β)	Result (H_0)
FW	2.71	1.65	Rejected	1.67	64	±2.68	0.68	Accepted
LLC1	1.69	1.59	Rejected	1.66	109	±2.55	0.93	Accepted
SL	1.04	1.69	Accepted	1.66	103	±1.64	0.93	Accepted
CA	4.13	2.13	Rejected	1.67	53	±0.97	0.89	Accepted
EW	6.48	1.56	Rejected	1.65	120	±1.69	0.89	Accepted

*DF = Degrees of freedom for the t-test
^CI = Confidence Interval

Thus, the results of the statistical analysis indicate that the driving simulator experiments were valid, both relatively and absolutely, at all the locations and confirm that the driving simulator yields speeds similar to those observed in the real world and the differences in the mean speeds were insignificant. The lower speeds in the simulator at the location of a complex maneuver may reflect the lack of motion cues that influence driver behavior in the real world.

4.2.2. Along the Roadway. Since qualitative validation indicated similar driver behavior in both the driving simulator and the field captured by the GPS, the quantitative validation was carried out using error tests to evaluate the absolute and relative validity of the driving simulator along the simulated roadway. As stated in the previous section, the error tests were conducted for the mean speeds calculated at every 500 feet from the driving simulator and the GPS. The Theil inequality coefficient ($U = 0.022$) indicated that the driving simulator was perfect in predicting the driver behavior in real world.

As described previously, the Theil inequality coefficient was further decomposed into three proportions: bias, variance, and covariance. The bias proportion ($U_M = 0$) indicated that the mean speed from the simulator was the same as the real world i.e., there was no systematic errors. This indicated the absolute validity of the simulator along the entire roadway. This was also indicated by the t-tests conducted at specific locations. The variance proportion ($U_S = 0.13$) was not significant or troubling but the dispersion in the speeds were experienced in the real world and in the driving simulator. The small sample of the GPS data might be one of the reasons for the small difference in the degree of variability. The covariance proportion ($U_C = 0.87$) was high, demonstrating that the speeds in the driving simulator significantly co-varied with the real world. Thus, the relative validity of the driving simulator was obtained along the roadway. The small nonsystematic error indicated by the covariance proportion is less worrisome and can be reduced by decreasing the variance proportion.

Thus from the error tests, the absolute and relative validity of the driving simulator was also obtained by comparing the speeds from the driving simulator along the entire roadway with those obtained by the GPS from the real world. With the larger sample size from the GPS and improvements to the driving simulator, the variance proportion and covariance proportions are expected to approach 0 and 1, respectively.

5. SUBJECTIVE EVALUATION

A post-experiment survey of participants evaluated the driving simulator based on their driving experience. The participants completed a questionnaire that surveyed them to rate the realism of various driving simulator components and the various aspects of the simulated driving scenario. The components included the brake pedal, steering wheel, and gas pedal whereas the aspects of the driving scenario included the surrounding terrain along the road, the simulated road geometry constructed using the GPS data, and the drivers' feeling of the simulated vehicle. For each criterion, participants rated the driving simulator on a scale of 1 to 7, with 1 indicating unrealistic and 7 very realistic. The mean ratings for each criterion were calculated by determining the arithmetic mean. Table 4 shows these ratings calculated for each criterion.

Table 4. Results of Subjective Evaluation

	Simulator Components			Driving Scenario		
	Brake Pedal	Steering Wheel	Gas Pedal	Surrounding Terrain	Road Geometry	Feel of driving
Mean Rating	5.0	**5.8**	5.3	5.5	**5.9**	5.2

The results show that the participants were comfortable with the driving simulator as they rated the various components and characteristics to be realistic. All of the values were much higher than the neutral value of 4. The steering wheel was rated highest among the driving simulator components. Among the various aspects of the driving scenario, road geometry was rated highest indicating that the use of GPS to construct the road scenario effectively replicates the real world.

6. CONCLUSIONS AND RECOMMENDATIONS

This paper presents the framework for objective and subjective evaluations of a driving simulator. Validation was divided into quantitative and qualitative validations, which were performed along the roadway and at specific locations where additional data were collected. The validation of the driving simulator was performed by comparing the vehicle speeds from a real work zone with those from the simulator.

The qualitative comparison indicated that the driver behavior was similar in the driving simulator and in the real world at specific locations and also along the entire roadway. Since the qualitative validation indicated good correspondence in the driver behavior, the quantitative validation was performed. The quantitative validation was carried out using statistical tests to evaluate absolute and relative validity at specific locations. For the quantitative validation at specific locations, the absolute and relative validity of the driving simulator were analyzed at five locations and t-tests were conducted. From these tests it was concluded that the field speeds and the driving simulator speeds were essentially the same. Therefore, the driving simulator was validated absolutely and relatively at these locations.

From the error tests, the bias proportion showed that the mean speed of the GPS data and that of the simulator data were the same. This indicated the absolute validity of the driving simulator along the entire roadway. The high value of covariance proportion also demonstrated the relative validity of the driving simulator. The subjective evaluation of the driving simulator showed that the participants rated the driving simulator realistic in both the simulator components (for braking, acceleration, and steering) and the driving scenarios (surrounding terrain, road geometry, and feel of driving). Road geometry was rated most realistic, indicating that the use of GPS to reconstruct the road in a simulator was effective and provided realistic experience.

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2. YOUNG DRIVER'S EVALUATION OF VEHICLE MOUNTED ATTENUATOR MARKINGS IN WORK ZONES USING A DRIVING SIMULATOR

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ABSTRACT

This paper evaluates the effectiveness of four vehicle mounted attenuator (VMA) striping patterns and color combinations used by the Departments of Transportation (DOTs) in work zones. A driving simulator was used to evaluate the perception of seventy-three young participants who drove through virtual highway work zones. Lane change distance (LCD) was used to analyze their reaction to the VMA markings during the daytime. An analysis of variance (ANOVA) test was performed to determine the significant variables affecting the LCD. A pairwise least-square means test was performed to determine the difference between the LCDs of the markings. A subjective evaluation was also carried out in which the participants ranked the markings based on different criteria. The participants were also surveyed on the features of the individual markings and their most preferred pattern. The results of the objective and subjective evaluation were consistent, and they suggested that overall the red and white checkerboard pattern was the most effective and preferred among the four markings. A DOT survey conducted in conjunction with this study indicated that the yellow and black

inverted ‘V’ pattern was widely used in the United States as it was provided by most VMA suppliers.

Key words: vehicle mounted attenuator (VMA), driving simulator, work zone, driver behavior, traffic control devices (TCD)

1. INTRODUCTION

Work zone safety is a high priority for transportation agencies and the highway construction industry because of increasing work zone fatalities. The number of such fatalities grew in the United States by nearly 45% between 1997 and 2006, from 693 to 1004 (NWZSIC, 2010). Additionally, younger drivers between the ages of 18 and 35 were involved in 56% of all fatal crashes for 2008. Similarly, younger drivers were involved in 58% of all fatal work zone crashes (FARS, 2010). Missouri reported 163 fatalities between 2005 and 2007 for all ages (Crash Data, 2007) in work zones. It is imperative that highway safety be improved with an objective of reducing the number of fatalities and severe injuries. Safety improvements can generally adopt one of two approaches. The first approach focuses on protecting vehicle occupants in the event of a crash. The second approach focuses on preventing crashes. This present paper addresses the second approach.

Crash cushions mounted on the rear of vehicles are called vehicle mounted attenuators (VMAs). They have been used successfully for many years to reduce the severity of rear-end collisions in work zones. The Manual on Uniform Traffic Control Devices (2003) and the American Association of State Highway and Transportation

Officials (AASHTO) Roadside Design Guide (2002) both contain general guidelines for VMAs. However, neither publication includes recommendations for striping patterns and/or colors for these devices. The predominant color combinations used by the United States Departments of Transportation (DOTs) are yellow and black, orange and white, red and white, and lime green and black in an inverted ‘V’, striped or checkerboard design, but other options have also been used. Some states have experimented with a vertical striping or checkerboard patterns in red and white. Figure 1 shows four striping patterns and color combinations used by DOTs in the United States.

(a) Lime Green and Black Inverted ‘V’ Pattern

(b) Red and White Checkerboard Pattern

(c)Yellow and Black Inverted ‘V’ Pattern

(d) Orange and White Vertical Stripes Pattern

FIGURE 1. Vehicle Mounted Attenuator Markings

This study evaluated the driver perception of the effectiveness of four striping patterns and color combinations for VMAs, as shown in Figure 1, using both objective evaluation and a subjective survey. Of particular concern was the use of an inverted ‘V’ design when the following vehicles do not have the option of passing on either side of the work vehicle. The importance of contrast with the VMA truck color was also an issue of interest. The results of this study can help state DOTs to select the most effective color and striping patterns for VMAs**,** thereby improving safety and operations in work zones on high-speed, high-volume roadways. As part of this study, a survey questionnaire of state DOTs evaluated their use and policies regarding VMAs. The results of this survey are also presented in the paper.

Driver perception and behavior can be evaluated by field studies or using a driving simulator. Field data collection is expensive and can test only a limited number of TCDs. Driving simulator studies, however, permit the study of hazardous driving situations that cannot be safely replicated during field tests. Such studies are also efficient and inexpensive, facilitating the collection of a wide range of data. They are repeatable, and they permit easy and safe replication of numerous scenarios to evaluate subjects' reaction to multiple TCDs.

2. LITERATURE REVIEW

Construction and maintenance work on streets and highways is dangerous, especially on high-speed highways. The safety of construction operations has received much attention over the past several years. Efforts to improve safety have increased substantially, particularly in the wake of a fatal accident in Washington D.C. in 1975 (Mackay and John, 1995). However, roadway fatalities have reduced but crash frequency has continued to increase, probably due to an increase in highway construction activities. Preventing crashes and reducing the severity of crashes require anticipation of driver reactions to specific situations.

Research by Humphrey and Sullivan (1991) on the effectiveness of VMAs indicated that these devices save about $23,000 per crash and reduce damage to the maintenance vehicle. The study indicated that injury rates were higher for maintenance vehicles not equipped with VMAs. Additionally, it demonstrated that the cost of crashes is considerably higher when no VMAs were used.

A field study carried out on VMA best practices in New Zealand (Smith, Edwards, O'Neil, and Goluchowski, 2006) reported that positioning an advance warning system 1312 feet from a VMA during daytime conditions performed better than other practices, resulting in 27.7% fewer drivers reacting in the last 984 feet and at least 25.4% fewer drivers reacting in the last 700 feet. The setup of VMA with the advance warning system fitted with strobe lights, and a message board with words stating 'Left Lane Closed' achieved mean recognition distance of 1494 feet during the daytime conditions. Another study (Steele and Vavrik, 2009) around lane closures with an aim to improve the safety of moving lane closures found that 94.4% of drivers moved out of the closed lane at least 500 feet before the start of the taper at a rural test site compared to 86.8% for an urban area.

Many studies on work zones have compared the use of different colors. Kamyab and Storm (2001) used a fluorescent yellow-green background with an orange sign and found that this improved the contrast between the sign and the orange DOT truck. They conducted a driver survey on the visibility of the sign with and without the fluorescent background. The report presented the differences in terms of traffic volume with and without the fluorescence background. Another study by Atchley (2006), however, suggested that fluorescent traffic signs had no advantage over non-fluorescent signs.

The literature reviewed offered no specific guidelines for selecting color or striping patterns for use with VMAs. The present research is a first major step toward determining the best VMA patterns for use in construction zones.

3. METHODOLOGY

Participants were tested in a driving simulator to evaluate their perception and behavior objectively, and were surveyed subjectively. A survey of state DOTs evaluated their use and policy regarding VMAs. This section describes the details of DOT survey, the driving simulator experimental setup, the statistical data analysis conducted to evaluate the driver behavior, and the details of the questionnaires used.

3.1. DOT Survey

Fifty state DOTs were contacted and requested to complete the VMA survey on-line. The survey was carried out for six weeks between February and March of 2008 and 30 states responded. The survey comprised of five parts: 1) General information related to VMAs, 2) Policy pertaining to VMA usage, 3) VMA striping patterns and colors in use, 4) VMA evaluation and effectiveness, and 5) VMA crash data. The results of the web survey are summarized in the next section.

3.2. Driving Simulator Study

3.2.1. Missouri S & T Driving Simulator

A fixed-base driving simulator for this study uses a Ford Ranger pick-up truck, three LCD projectors, a projection screen, and three networked computers. The computer that processes the motion of the vehicle is defined as the master; the other two computers are defined as slaves. The vehicle is equipped with a speedometer and other standard components. Different types of sensors are used to measure the steering operation, vehicle position and speed, acceleration/deceleration, and braking. The screen has an arc angle of 54.6°, an arc width of 25 feet and a height of 6.6 feet. The field of view is around 120°.

The resolution of the visual scene generated by the master is 1024×768 pixels, and that for the slaves is 800×1200 pixels; the refresh rate is 30 to 60 Hertz depending on the scene complexity. The system is also equipped with a system that replicates the sound of an engine. Wang et al. (2006) provided a more detailed description of the system structure, projection system, and the data acquisition process.

3.2.2. Work Zone Setup and Configuration

A virtual work zone scenario was developed to resemble a 4-lane rural divided highway with a median and four consecutive work zones. The highway was approximately eight miles long with the first work zone setup at 1.5 miles and each work zone was 0.5 miles long and 1.5 miles apart. Figure 2 shows the setup of traffic control devices, two VMAs and a construction vehicle on the closed lane. The colors and patterns of the four VMAs changed randomly for the participants for the four work zones. The two VMAs within a single work zone were kept identical.

A virtual work zone environment was created for the simulation according to MUTCD (2003) specifications for a partial lane closure on a divided highway. These guidelines specify sign spacings, taper lengths, and optional buffer length channelizer spacings for various speed limits, sign heights, and work zone lengths. Various signs were set up to replicate a construction zone on a freeway. The first 1.5 miles of the freeway had a speed limit of 70 mph, indicated by a regulatory speed limit sign at the beginning of the section. Traffic signs were placed along the right side of the roadway 500 feet apart, as shown in Figure 2, starting with ‘Road Work Ahead’ warning sign located 1.5 miles before the beginning of the work zone. The four remaining signs were placed in the following order: ‘Speed Limit 45 mph’, ‘Right Lane Closed Ahead,’ ‘Speed Limit 45 mph,’ and ‘Right Lane Closed Ahead’. The construction zone was 1300 feet long with barriers on the lane marking. The construction zone consisted of a shadow vehicle with a VMA, a work vehicle with a VMA, and a construction vehicle. These vehicles were separated by a distance of 550 feet from the center of the vehicle.

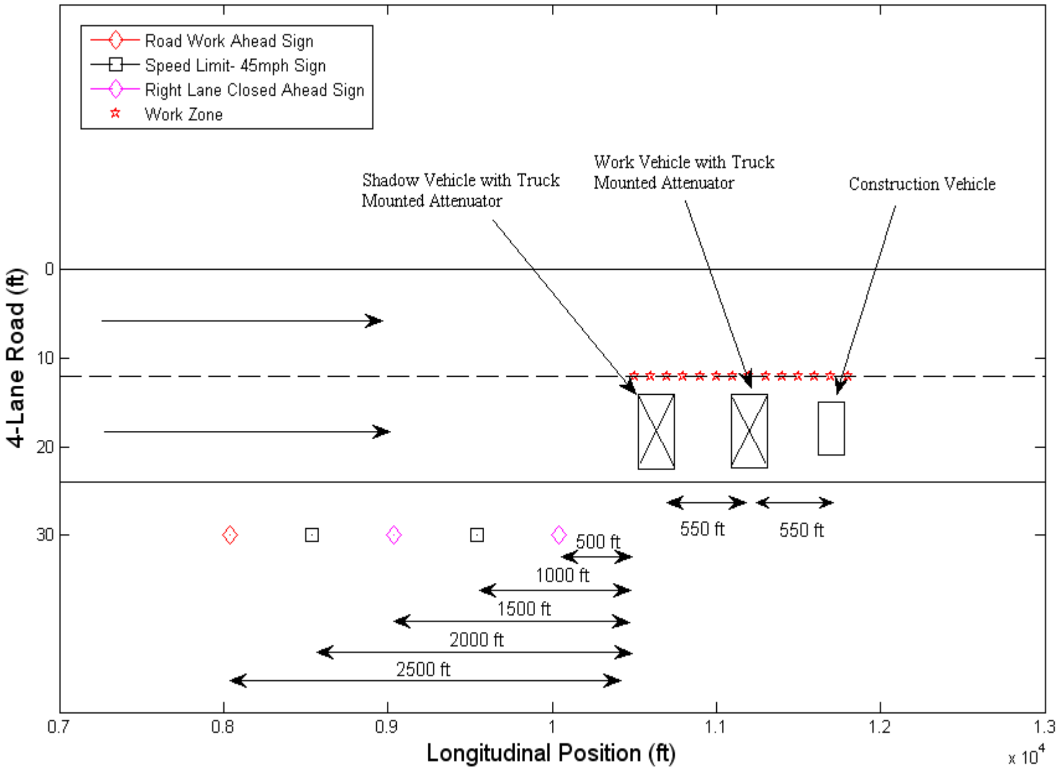


FIGURE 2. Work Zone Configuration

3.2.3. Participants

Prior to scheduling the experiment, the subjects were screened using a questionnaire to inquire if they had a US driver's license, no health problems that would affect driving, and they do not suffer from motion sickness. Seventy-three drivers met the requirements and participated in the experiment. Participants were mostly students, some staff and faculty from Missouri S&T and residents of Rolla, Missouri. The drivers were between the ages of 18 and 35 years with an average age of 22.2 years and a standard deviation of 2.34 years. Twenty three participants were female and 50 were male. Of the 73 participants, one had been driving for more than 15 years, 49 had been driving between 5 and 15 years, and 23 had been driving between 1 and 5 years. All participants had previously encountered VMAs in highway work zones.

3.2.4. Pre- and Post-Experiment Questionnaires

The participants were surveyed before the start and after the end of the driving simulator experiment. The pre-experiment questionnaire inquired about health issues specifically that could affect their driving in a simulator, and consumption of alcohol/drug use during the last 24 hours. This was carried out to ensure that drivers were alert and eligible for participation in the experiment on the day of the experiment. All participants had normal or corrected-to-normal vision and no one reported color deficiency. The participants were also checked for validity of the US driving license and anyone found with an invalid license was turned away from the experiment.

After the driving simulator experiment, each participant was asked to complete a post-experiment questionnaire. This questionnaire served as the subjective evaluation of the VMA patterns based on the participant’s experience with the driving simulator. The participants were asked to rank (1 highest and 4 lowest) the four patterns based on the following criteria: i) visibility, ii) alerting drivers to work zone, iii) capturing driver’s attention, and iv) color contrast with the VMA vehicle. Visibility was used as a criterion for evaluation of the VMAs because it is important with regard to specific environmental conditions such as weather and times of the day. A pattern that is easily visible from a distance would alert the driver to construction activity downstream, thus reducing the risk of a crash. The pattern that captures the most attention of the drivers would cause drivers to notice a work zone and change lanes before approaching the VMA.

Alerting drivers to work zones and contrasting the VMA pattern with the VMA vehicle were also used as criteria. The participants were also asked to rank features of individual patterns. This was carried out for participants to indicate their preferences for each pattern based on pattern design, color combination, and color contrast using a scale of 1 to 3, with 1 indicating most liked and 3 indicating least liked. The participants were also asked which pattern they preferred and how they interpreted the meaning of features of the patterns.

3.2.5. Experiment

The participants were first given a brief introduction to the driving simulator and advised to adhere to traffic laws and drive as they would in normal traffic conditions. To familiarize the participants with the driving simulator, the environment, and the instructions, participants first drove through a trial scenario similar to that used in the experiment. Typically, each participant first drove for several minutes during the trial run and then drove through the experimental scenario with the four construction zones. The VMA patterns appeared in random order. Driver behavior data was collected by various sensors for every 0.1 seconds.

3.2.6. Data Analysis

The drivers' acceleration/deceleration, speed, position and steering angle were the main variables measured during the driving simulator experiment for use with the objective evaluation. From vehicle positions, the distances from the point of lane change on the closed lane to the VMA were obtained. This distance, called the lane change distance (LCD), was used as the criterion for determining the effectiveness of a VMA pattern. LCD was measured from the point where the driver began to steer continuously out of the right lane (closed lane) and towards the left lane, achieving the maximum steering angle. The drivers were assumed to respond to the appearance of the VMA pattern. This measure was selected because most DOTs that responded to the survey had used it along with crash data to determine the effectiveness of VMAs in work zones. Further, Bham et al. (2009) found that the speed reduction identification distance, i.e. the distance from the VMA at which the driver starts decelerating, should not be used to evaluate VMA patterns because drivers reduce their speed in response to advance warning signs.

The experiment was conducted such that each participant was exposed to the different VMA markings in a single run, with the markings in random order. Therefore, the appropriate statistical design for this experiment was a split-plot, with each participant represented as a main-plot and the four work zones as a sub-plot. Gender was used as the main-plot factor (independent variable) and the pattern was used as the sub-plot factor. The analysis of variance (ANOVA) was carried out to test the statistical significance of gender and VMA patterns on the mean LCD. The test was conducted using the Statistical Analysis System (SAS, 2008) software package. The statistical significance of the independent variables (factors) was determined at the 0.05 significance.

The ANOVA results showed a significant difference among the LCDs, therefore, pairwise comparisons of least-square means (LSM) between patterns were performed in SAS using the LSMEANS command. LSM are predicted values, based on the model fitted across the values of a categorical effect where other model factors are held constant by setting them to the least-square estimate of their means. If the experiment is a balanced one, where each combination of factors (i.e., independent variables) were replicated an equal number of times, least-square means will be the same as regular sample means. In this experiment, however, we did not have equal samples within factor combinations and therefore the use of least-square means is warranted.

The LSM test was conducted by employing the Tukey-Kramer adjustment, which uses the approximation described by Kramer (1956). It was used to accommodate the unbalanced data and provide good control of the Type 1 error rate. To further analyze the data, a Kolmogorov-Smirnov (KS) test was also conducted using SAS to ascertain if there is a statistically significant difference between the lane change frequency distributions. The KS procedure tests the null hypothesis of any significant difference between the LCD cumulative distributions for the four VMA patterns by looking at the difference at the point of maximum separation between the distributions. This is in contrast to the ANOVA based test described earlier, which looked at the differences between the means. A significant difference between the cumulative frequency distributions for two patterns would imply that the lane change behavior of drivers was different between the patterns. Straightforward use of the KS test on the distribution of participant's LCD would reduce the power of the test because of the heterogeneity of driving styles as that would add to the "noise" in the data. The effect of an individual participant's driving style was eliminated by calculating the dependent variable as the difference between the pattern LCD for a participant and the average LCD of that participant for the four patterns. This distance was used instead of the actual LCD of the patterns for the KS test. The KS test was conducted at 0.05 level of significance.

To supplement the objective evaluation, all participants completed a post-experiment questionnaire for subjective evaluation of the VMA markings. The subjective evaluation served as an opinion poll of the participants regarding the four patterns in contrast to measuring the effect of the patterns on their actual driving behavior. The results of the subjective evaluation should be carefully interpreted as they present the perception of the drivers. Participants ranked the four VMAs based on each criterion, as described above, on a scale of 1 to 4, with 1 indicating excellent, 2 good, 3 average, and 4 poor. The mean rank of a pattern for a criterion was calculated by summing up the ranks given to a pattern and dividing the sum by the total number of participants, thereby calculating the arithmetic mean. The mean of the ranks for each pattern was compared against each other.

A statistical test was also carried out to find the significance of pattern preference by the participants. It should be noted here that the participants ranked the four patterns according to a criterion. Thus, the data for an individual participant provided information on their first, second, third and the last choice. Further, the ranks for each pattern were correlated within each individual. The statistical model that was used to analyze this data can be explained as follows. First, a participant selected his/her first choice (rank = 1, the highest). Then, among the rest, the next best choice was selected (rank = 2) and so on. The resulting model is sometimes referred to as the exploded logit model, a discussion of which can be found in Allison and Christakis (1994). The likelihood function obtained for this model is exactly the same as the likelihood one would obtain for the stratified Cox regression analysis and thus can be estimated using the PHREG procedure in SAS (2008). In this, context, the PHREG procedure estimates the parameters of the model and provides risk ratios of proportions, which are the odds of a pattern to be ranked 1 (best) under a particular criterion when compared against a base pattern. For analysis of results, the yellow and black inverted V pattern was used as the base pattern and the risk ratios for the rest of the patterns with respect to it were estimated.

4. ANALYSIS AND DISCUSSION OF RESULTS

4.1. DOT Survey Results

This section summarizes the responses from 30 state DOTs. The results of the survey are presented in different categories below.

4.1.1. VMA Policy

The DOTs were inquired about the policy of VMA usage in work zones. Twenty-two states (76%) reported the use of VMAs in work zones because it is a transportation agency policy; one state, Delaware, reported its use because of state law; five states (17%), Rhode Island, Minnesota, Wisconsin, Hawaii, and Massachusetts, use VMAs in work zones independent of transportation agency policy or state law. All DOTs, except Minnesota, reported the use of VMAs in work zones. Two states did not respond to this question.

4.1.2. VMA Striping Patterns and Colors

The DOTs were asked about the different color combinations used with the VMAs. The survey result is shown in Figure 3(a). Twenty five states indicated the use of yellow and black for VMAs. Washington D.C. uses all four VMA markings. California uses three color combinations; yellow-black, orange-white, and red-white. Kansas uses yellow-black and orange-white, and Texas uses yellow-black and red-white color combinations. New York does not use any of the four patterns presented in Figure 1; it uses a yellow-blue color combination. Figure 3(a) graphically presents the DOT's use of different VMA patterns.

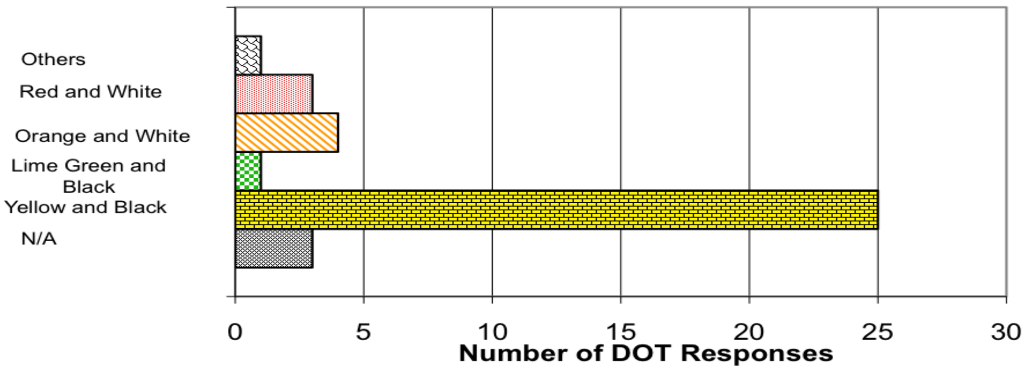
The DOTs were also inquired about the type of VMA patterns in use. Twenty-seven agencies indicated they use inverted 'V' pattern for VMA stripes. California indicated use of a stripe pattern from the lower left corner to the upper right corner. When DOTs were asked about the basis for the selection of VMA colors and patterns, out of the 27 state agencies, eight use the VMA patterns and colors provided by VMA suppliers and 11 use these colors and patterns to conform to MUTCD guidelines for work zones, warning colors, and object markers. Kansas uses an inverted 'V' pattern similar to a Type III barricade. Delaware and Oregon use yellow and black to make the device stand out from orange and white construction equipment. New York uses yellow and blue to match the colors of their trucks. Texas and New York use an inverted ‘V’ pattern to indicate that vehicles can pass on either side of the truck.

4.1.3. VMA Evaluation and Effectiveness

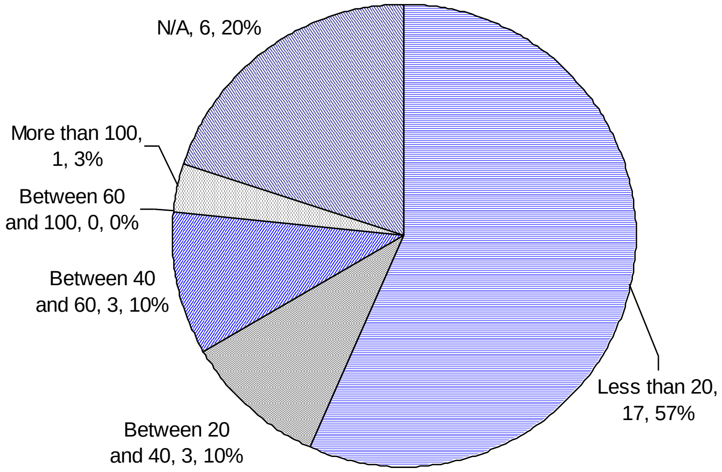
The agencies were asked if they had tested the patterns and colors used with the VMAs. Only Texas indicated that they had evaluated various colors and striping patterns for VMAs. They found that red and white inverted ‘V’ pattern was most appropriate for their fleet. Also, the DOTs were asked about the conditions during which the VMAs were used. Six agencies use VMAs in both daytime and nighttime conditions, whereas three agencies use them only during the day. Only two agencies, West Virginia and California, use VMAs during day and nighttimes, and misty/foggy conditions.

The DOTs were also asked if they had evaluated the effectiveness of VMAs in work zones. Washington, Wisconsin, and Hawaii indicated they had used crash data and LCD to determine the effectiveness of using VMAs in work zones. Nine agencies only used crash data as a measure of effectiveness. Rhode Island, Texas, Indiana, and Washington had used the following measures of effectiveness:

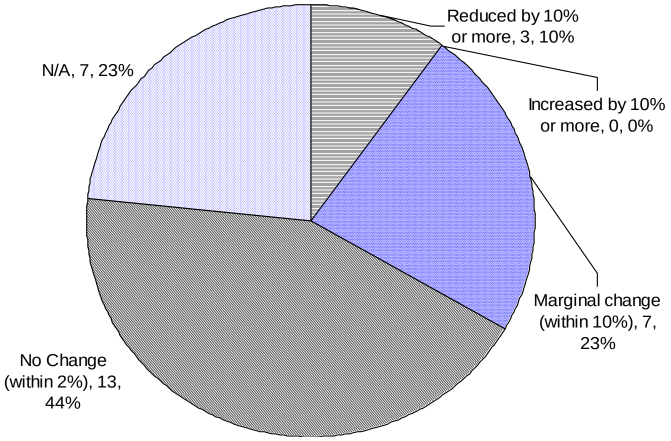
- visibility of VMAs (determined through surveys or the use of videos during which changes in driver behavior were observed),
- work zone operation and proximity to traffic,
- workers survival rate after car or truck impacts, and visual assessment under various light conditions.



(a) Use of different color combinations by DOTs



(b) Vehicle crashes with VMAs over the last three years based on 30 responses (crash frequency, number of DOT responses, percentage of DOT responses)



(c) Effect of VMA on number of crashes in work zones over the last three years based on 30 responses (Change in crashes by percentage, number of DOT responses, percentage of DOT responses)

FIGURE 3. DOT Survey Results

None of the DOTs reported conducting a detailed study to evaluate the effectiveness of VMA striping patterns or color combinations.

4.1.4. VMA Crash Data

Figure 3(b) presents the results of the survey about work zones crash frequency and severity with the VMAs during the last three years. Seventeen agencies (57%) reported fewer than 20 vehicles had crashed into VMAs and three agencies (10%) reported that 20 to 40 vehicles had crashed into VMAs. Three agencies (10%) reported that 40 to 60 vehicles had crashed into VMAs, and Colorado reported more than 100 vehicles had crashed into VMAs. No agencies reported vehicle crashes numbering between 60 and 100.

Figure 3(c) summarizes the responses about the effect of VMA usage on the number of crashes in work zones. The DOTs reported a reduction in number of crashes in work zones when VMAs were used compared to the crashes without use of VMAs. Seven agencies (23%) noticed a marginal reduction (less than 10%), and three agencies (10%) noticed a 10% reduction in the number of crashes in work zones when VMAs were used. Thirteen agencies (44%) noticed almost no change (less than 2%) in the number of crashes in work zones. Most of the agencies indicated that less than 5% crashes involving VMAs were severe.

4.2. Driving Simulator Study

4.2.1. Objective Evaluation

Using split-plot ANOVA, the data was analyzed to determine if pattern, gender and the interaction of pattern with gender (pattern*gender) had an effect on the mean LCD. The outputs of the ANOVA were the p-value and $F_{i,j}$ ratio. The statistical analysis indicated that the variable 'pattern' ($p = 0.0002$; $F_{3,275} = 6.88$) was statistically significant, whereas the variable 'gender' ($p = 0.8147$; $F_{1,71} = 0.06$) and the interaction between pattern and gender (gender*pattern) ($p = 0.4028$; $F_{3,275} = 0.98$) were statistically insignificant. This indicates that the preference of the patterns was the same for both males and females. Thus, further analysis disregarded the effect of gender.

Since the pattern had a significant effect on the LCD, the mean and standard deviation of LCD were determined for each pattern and Table 1 summarizes these results. On the average, the drivers changed lanes farthest from the work zone when the red and white pattern (1085 feet) and the orange and white pattern (1071 feet) were used on the VMA. When the lime green and black pattern was used, the drivers changed lanes on an average of 952 feet from the work zone. The LCD for the yellow and black pattern (931 feet) was the lowest.

The LSM test, whose results are given in Table 1, was conducted to determine the differences among the LCDs of the patterns. The mean LCDs of the red and white checkerboard pattern and the orange and white vertical striped pattern were found to be significantly higher than the lime green and black pattern and the yellow and black pattern. Significant difference was not found between the mean LCDs of the red and white checkerboard pattern and the orange and white vertical striped pattern. Also, the mean LCDs of the lime green and black pattern and the yellow and black pattern were not statistically different.

TABLE 1. LCD Mean, Standard Deviation and p-Values of Least Square Means Test

Patterns LCD (Mean, Standard Deviation) feet	p-values			
	Yellow and black	Lime green	Orange and white	Red and white
Red and white (**1085**, 399)	**0.0026**	**0.0120**	0.9904	**-**
Orange and white (**1071**,403)	**0.0066**	**0.0275**	-	0.9904
Lime green (952, 326)	0.9639	-	**0.0275**	**0.0120**
Yellow and black (931,337)	-	0.9639	**0.0066**	**0.0026**

Patterns: Red and white = red & white checkerboard; Orange and white = orange & white vertical striped; Lime green = lime green & black inverted 'V', Yellow and black = yellow & black inverted 'V';
Bold indicate statistically significant at 0.05 level of significance
"-"= not applicable

The effectiveness of the patterns was also evaluated based on the frequency of LCDs at various distances from the VMA. Specifically, the cumulative frequency of lane changes at intervals of 50 feet from the VMA was investigated, as shown in Figure 4. The vertical bars indicate the frequencies of lane changes at different distances from the VMA vehicle. The curves indicate the cumulative frequencies of lane changes at different distances. For the red and white pattern and the orange and white pattern, the drivers moved out of the closed lane earlier compared to the other two patterns. The separation between these curves signifies the difference in driver perception of the patterns.

It can also be observed that most drivers (95.6%) moved out of the closed lane at least 500 feet before the VMA with the yellow and black inverted 'V' pattern. This result is similar to that of the field study (Steele and Vavrik, 2009) in which 94.4% drivers vacated the closed lane at least 500 feet from the VMA with the yellow and black inverted ‘V’ pattern at a rural test site. This indicates similarities in the results of the driving simulator and the field data.

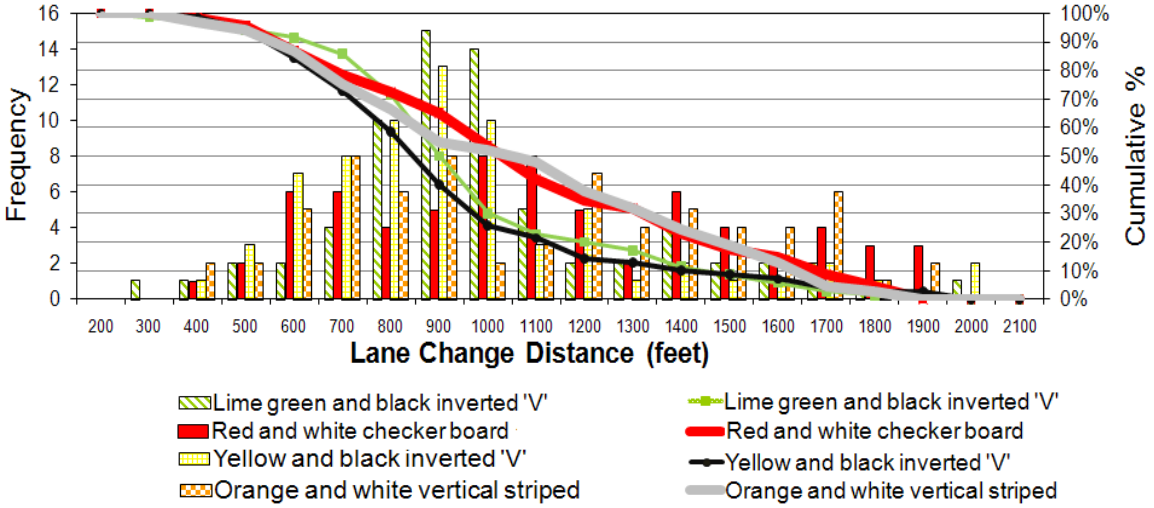


FIGURE 4. Lane Change Distance Frequency and Cumulative Frequency Curves for Different Patterns

The KS test for the LCD distributions of the red and white pattern with the lime green and black pattern ($p = 0.0048$) and with the yellow and black pattern ($p = 0.0007$) indicated that the distributions were not identical, the differences were statistically significant, and the red and white pattern indicated higher cumulative frequency of lane changes at the point of maximum separation between the distributions. The test for the cumulative frequency distribution of the orange and white vertical striped pattern with the lime green and black inverted ‘V’ pattern ($p = 0.0083$) and with the yellow and black inverted ‘V’ pattern ($p = 0.0014$) also showed a significant difference in the cumulative frequency of lane changes at the point of maximum separation between the distributions. Therefore, the perceptions of drivers in response to the red and white checkerboard pattern and the orange and white vertical striped pattern were statistically significant compared to the lime green and black and the yellow and black inverted ‘V’ patterns.

The driving simulator experiment demonstrated that when LCD is used as the criterion, which is very important to avoid crashes with the VMA, the red and white checkerboard pattern and the orange and white vertical striped pattern were most effective, whereas the yellow and black inverted ‘V’ pattern was the least effective.

4.2.2. Subjective Evaluation

The mean ranks of the patterns based on the four criteria are presented in Table 2. To statistically test the participants’ preferences of the patterns, PHREG analysis was carried out with the yellow and black pattern as the base pattern. The yellow and black pattern was used as the base pattern because it is the most widely used pattern in work zones, especially in Missouri. Table 3 presents the results of the PHREG analysis. The risk ratio from the analysis indicated the preferences of the participants for the patterns when compared to the yellow and black pattern. The risk ratio for the yellow and black pattern equaled 1.00. The patterns with values more than 1.00 were more preferred than the yellow and black pattern. The patterns with risk ratios below 1.00 were less preferred than the yellow and black pattern.

From the mean ranks in Table 2, the participants ranked the red and white checkerboard pattern to be more visible (2.23), capturing more attention of drivers (2.15), and contrasting better with the VMA truck (2.08) compared to the other patterns. For the alerting drivers to work zones criterion, the yellow and black pattern had the lowest mean rank (2.01) while the red and white checkerboard pattern had the highest mean rank

(2.95). This indicated that the yellow and black pattern is most effective in alerting drivers to work zones; probably because it is the most commonly used pattern in work zones.

TABLE 2. Mean Ranks for the VMA Patterns

Patterns/Criteria	Visibility	Alert drivers to work zones	Capture attention of drivers	Color contrast*
Red and white	**2.23**	<u>2.95</u>	**2.15**	**2.08**
Orange and white	<u>2.67</u>	2.44	<u>2.64</u>	2.75
Lime green	2.55	2.60	2.58	2.34
Yellow and black	2.55	**2.01**	2.63	<u>2.82</u>

Patterns: Red and white = red & white checkerboard; Orange and white = orange & white vertical striped; Lime green = lime green & black inverted 'V', Yellow and black = yellow & black inverted 'V';
Bold: Lowest mean value for the column, Underlined: Highest mean value for the column (Rank 1 = highest, Rank 4 = lowest)
Color Contrast with the VMA vehicle

The risk ratios from the statistical analysis reported in Table 3 shows the odds of selecting a given VMA pattern as the preferred pattern over the yellow and black base pattern. For example, the risk ratio of 1.873 for the red and white pattern given under the color contrast column indicated that the odds of the participants selecting the red and white checkerboard pattern as the best was 87.3% higher than the selection odds for the base pattern. Clearly the red and white pattern was preferred over the other patterns for color contrast (risk ratio of 1.873 compared to 1.001, 1.439, and 1.0). This result was statistically significant based on the p-value reported in Table 3. For the alerting drivers to the work zones criterion, none of the patterns had a risk ratio that indicated that they were preferred over the yellow and black pattern, with lime green and black pattern having a risk ratio of 0.557, while the red and white pattern having the least risk ratio of 0.428. Both ratios were less than 1.0 indicating that the base pattern was preferred, and the p-values for both patterns indicated that this preference was statistically significant. The fact that the red and white pattern was least preferred for this criterion might be because drivers have seldom been exposed to the red and white color pattern.

In a recent meeting, a MoDOT official explained that the red and white checkerboard pattern will be implemented in work zones even though it is least able to alert drivers and the results are expected to improve as drivers become familiar with the pattern. From the mean ranks in Table 2, participants showed the least preference for the yellow and black pattern (2.82) under the color contrast criterion with the VMA background, probably because Missouri DOT VMA vehicles are yellowish orange in color. Similar result was observed for the orange and white pattern.

TABLE 3. Risk Ratios and p-Values for the VMA Patterns

Patterns/Characteristics	Visibility	Alert drivers to work zones	Capture attention of drivers	Color contrast*
Red and white	1.310^ (0.1996)~	0.428 **(<.0001)**	1.487 (0.0601)	1.873 **(0.0031)**
Orange and white	0.9018 (0.6178)	0.668 (0.0549)	0.960 (0.8433)	1.001 (0.9961)
Lime green	0.993 (0.9726)	0.557 **(0.0063)**	1.033 (0.8737)	1.439 **(**0.0784)
Yellow and black	1.000 (-)	1.000 (-)	1.000 (-)	1.000 (-)

Patterns: Red and white = red & white checkerboard; Orange and white = orange & white vertical striped; Lime green = lime green & black inverted 'V', Yellow and black = yellow & black inverted 'V';
'-' indicates p-value not available for base pattern,
Bold font indicates statistically significant at 0.05 level
** Color Contrast with the VMA vehicle*

When the participants were asked which pattern was most preferred, 27 drivers (36.98%) preferred the red and white checkerboard pattern, 19 (26.02%) preferred the lime green and black inverted 'V' pattern, 15 (20.5%) preferred the yellow and black inverted ‘V’ pattern, and 12 (16.4%) preferred the orange and white vertical stripes pattern. Thus, the red and white checkerboard pattern was found to be the most preferred pattern among the four.

Table 4 presents the mean ranks when the drivers were surveyed about the different features of each pattern. This part of the subjective survey was different compared to the mean ranks presented in Table 2 in which the four patterns were ranked. Table 4 presents the mean ranks of the features of each pattern. This was carried out mainly to identify the features that are distinct for each VMA marking. Table 4 indicates that the drivers preferred the inverted ‘V’ pattern design for the lime green and black pattern and the yellow and black pattern. For the lime green and black pattern, the least liked feature was the color combination. Color contrast was most liked for the red and white checkerboard pattern and least liked for the yellow and black inverted ‘V’ pattern. For the orange and white striped pattern, the color combination was the most liked feature and color contrast was the least liked feature.

TABLE 4. Mean Ranks of the Features for the VMA Patterns

Features \ Patterns	Red and white	Orange and white	Lime green	Yellow and black
Pattern Design	2.07	2.01	**1.81**	**1.89**
Color Combination	<u>2.11</u>	**1.95**	<u>2.18</u>	1.91
Color Contrast*	**1.82**	<u>2.04</u>	2.01	<u>2.21</u>

Patterns: Red and white = red & white checkerboard; Orange and white = orange & white vertical striped; Lime green = lime green & black inverted ‘V’, Yellow and black = yellow & black inverted ‘V’; Bold: Lowest mean value for the column, Underlined: Highest mean value for the column (Rank 1 = highest, Rank 3 = lowest)

**Color Contrast between the different colors of the pattern*

The post-experiment survey yielded some interesting results. Based on discussions with representatives of Missouri DOT, the inverted ‘V’ pattern was considered an effective sign for drivers to change lanes in a specific direction and to move out of the closed lane. Further, the checkerboard pattern was expected to indicate clearly a lane closure without indicating the direction of lane change. However, when participants were surveyed regarding the information provided by the inverted 'V' pattern, 57 (78%) did not perceive that the inverted 'V' design signifies the direction of lane change, and only 16 (22%) perceived that it signifies a lane change either to the left or to the right. Regarding the checkerboard pattern, 41 (56%) participants stated that it indicates a need to reduce speed, 16 (22%) stated that it indicates a need to stop, and an equal number stated that it conveys no message.

5. CONCLUSIONS AND RECOMMENDATIONS

This paper presents the results of a survey of state DOTs and a driving simulator study to evaluate the perception of younger drivers for striping patterns and color combinations for VMAs used in work zones during the daytime. Out of the 30 state agencies that responded to the survey, it was found that 22 (77%) use VMAs in work zones to meet the requirements of transportation agency policy and one agency uses VMAs to meet the requirements of state law. The yellow and black inverted 'V' pattern was most commonly used by DOTs as it is provided by the VMA suppliers.

The driving simulator study evaluated the VMA markings using objective and subjective evaluation criteria. The objective evaluation used LCD as the criterion. It can be inferred from the LCDs that the red and white checkerboard pattern and the orange and white vertical stripes pattern were more effective compared to the two other patterns evaluated. The results of the subjective evaluation indicated that the red and white checkerboard pattern was ranked highest for visibility, color contrast, and capturing the attention of drivers. The participants regarded the yellow and black inverted ‘V’ pattern as highly effective in alerting drivers to a work zone.

Thus, out of the four VMA patterns evaluated, the red and white checkerboard was found to be more effective and preferred overall than the other patterns. Further evaluations are being conducted with older drivers and during dusk and nighttime conditions. VMA patterns should also be evaluated based on differences in heights, flashing patterns of arrows and beacons, and use in different work zone configurations. Further, crash data should be used to evaluate the effectiveness of VMAs.

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3. A DRIVING SIMULATOR STUDY:

EVALUATION OF VEHICLE MOUNTED ATTENUATOR MARKINGS IN WORK ZONES DURING DIFFERENT TIMES OF THE DAY

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ABSTRACT

This paper presents a study of driver perceptions using a driving simulator carried out on the effectiveness of four markings, which vary in striping patterns and color combinations, used at the rear of vehicle mounted attenuators (VMAs) in work zones during daytime, dusk and nighttime. One hundred and twenty participants from different age groups took part in the evaluation of VMA markings by driving through virtual highway work zones. During this experiment, driver reaction to VMA markings was determined based on their lane change distance (LCD). Additionally, the drivers were surveyed using a detailed subjective survey. Analysis of variance (ANOVA) was performed to determine the significant variables affecting the LCD. For each time of day, a pair wise least-square means test was conducted to calculate the difference in LCD between the markings. A Kolmogorov-Smirnov test was carried out to evaluate the significance of differences between the LCD frequency distributions of the markings. For the subjective evaluation, the markings were ranked by participants indicating their preferences using four different criteria for each time of day. The participants were also surveyed on the features of the individual markings and for the most preferred marking. The results of the objective and subjective evaluations indicated that, overall, the red and white checkerboard pattern was most effective.

Key words: vehicle mounted attenuator (VMA), driving simulator, virtual reality, work zone, driver behavior, traffic control device (TCD), state department of transportation

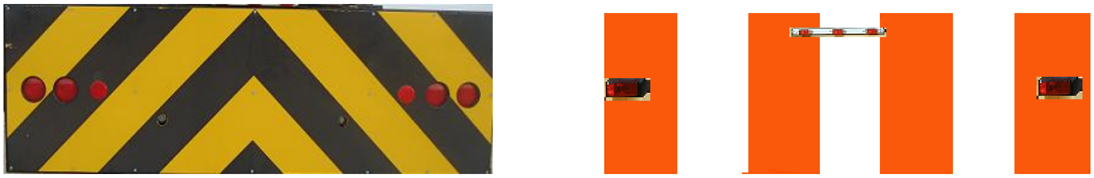
1. INTRODUCTION

Work zone safety is a high priority for transportation agencies and the highway construction industry because of the high frequency of work zone fatalities. The number of such fatalities grew in the United States by nearly 45% between 1997 and 2006, from 693 to 1004 (NWZSIC, 2010). The safety of construction operations has received much attention over the past several years. As crash frequency continues to increase, mostly due to increase in highway construction activities, preventing crashes and reducing the severity of crashes require anticipation of driver reactions to specific situations, which is addressed in this paper.

Vehicle mounted attenuators (VMAs) are crash cushions mounted at the rear of vehicles and can reduce the severity of rear-end collisions with construction vehicles in work zones. Humphrey and Sullivan (1991) studied the effectiveness of VMAs and indicated that these devices save about $23,000 per crash and reduce damage to the construction vehicle. The study also showed that injury rates were higher when construction vehicles were not equipped with VMAs. Safety improvements generally can adopt one of two approaches. The first approach focuses on protecting vehicle occupants in the event of a crash whereas the second approach focuses on preventing crashes. The present study addresses the second approach.

The Manual on Uniform Traffic Control Devices (MUTCD) (2003) and the American Association of State Highway and Transportation Officials (AASHTO) Roadside Design Guide (2002) both contain general guidelines for VMAs. Neither publication, however, includes recommendations for striping patterns and/or colors for these devices. The predominant color combinations used by the state Departments of Transportation (DOTs) are yellow and black, orange and white, red and white, and lime green and black in an inverted ‘V’, striped or checkerboard design. Figure 1 shows striping patterns and color combinations mainly used by the DOTs in the United States.

(a) Lime Green and Black Inverted ‘V’ Pattern (b) Red and White Checkerboard Pattern



(c)Yellow and Black Inverted ‘V’ Pattern (d) Orange and White Vertical Stripes Pattern

FIGURE 1. Vehicle Mounted Attenuator Patterns

This study evaluates the driver perception of the effectiveness of various striping patterns and color combinations for VMAs. Of particular concern is the use of an inverted ‘V’ design when the following vehicles do not have the option of passing on either side of the work vehicle. The importance of contrast with the truck/vehicle color is also of interest. The results of this study can help state DOTs to select the most effective VMA color combination and striping pattern**,** thereby contributing to the improvement of safety and operations in work zones on high-speed, high-volume roadways.

Driver perception and behavior can be evaluated by field studies, traffic modeling and simulation, and using a driving simulator. Popular microscopic traffic simulation models do not incorporate driver perceptions such as vision, hearing, driver sight identification distance and cannot be used to evaluate the colors and patterns of traffic control devices (TCDs). Field data collection can test a limited number of TCDs. Driving simulator studies, however, permit the study of hazardous driving situations that cannot be safely replicated during field tests. Such studies can be efficient and facilitate the collection of a wide range of data. They are also repeatable, and permit easy and safe replication of numerous scenarios to evaluate subjects' reaction to multiple TCDs.

A field study carried out on VMAs in New Zealand (Smith, Edwards, O'Neil, and Goluchowski, 2006) reported that flashing strobe lights provided enhanced capabilities over rotating beacons, with at least 11.3% of drivers reacting at distances larger than 984 feet during nighttime. Under day and night conditions, a wide retro-reflective tape around the edges of the arrow board significantly improved drivers' average recognition distance of the VMA by at least 125 feet. Also, the recognition distance increased at night when the traffic volumes were lower (i.e. approximately 400 vehicles/hour) as compared to recognition distance during the day with higher traffic volumes (i.e. approximately 880 vehicles/hour). The drivers were not observing the far-distance ahead probably because they were more focused on monitoring the activities of other drivers who may be a potential risk to them.

Another field study on driver behavior (Steele and Vavrik, 2009), aimed at improving the safety of moving lane closures found that 94.4% of drivers moved out of the closed lane at more than 500 feet before the start of the taper for a rural test site compared to 86.8% for an urban area. The percentage of vehicles that reached the VMA vehicle within 500 feet was 4.8% and 12.2% for rural and urban areas, respectively.

Studies have also compared the use of different colors. Kamyab and Storm (2001) used a fluorescent yellow-green background with an orange sign and found that this showed an improvement in the contrast between the sign and the orange DOT truck. They conducted a driver survey on the visibility of the sign with and without the fluorescent background. Traffic volumes were measured and data analysis revealed significant decrease in traffic volume within 100 feet for the lane where the truck was present when the fluorescent yellow-green background was used with the sign. Another study by Atchley (2006), however, suggested that fluorescent traffic signs have no advantage over non-fluorescent signs.

The literature reviewed did not offer specific guidelines for selecting VMA color combinations or striping patterns. The present research is a first step towards determining effective VMA markings for use in construction zones for different times of the day with drivers from different age groups.

2. METHODOLOGY

A driving simulator was used to evaluate driver perceptions and behavior objectively as well as subjectively. This section presents the driving simulator experimental setup, the statistical data analysis to evaluate the objective and subjective data and the details of the questionnaires used.

2.1. Missouri S&T Driving Simulator

A fixed-base driving simulator used for this study comprised of a passenger car, three LCD projectors, a projection screen, and three networked computers with Ethernet connection. The computer that processes the vehicle movements was defined as the master; the other two computers were defined as slaves. The passenger car is a Ford Ranger pick-up truck with a speedometer, and different types of optical sensors are used to measure the steering operation, vehicle position, speed, acceleration/deceleration, and braking. The screen has an arc angle of 54.6°, an arc width of 25 feet and a height of 6.6 feet. The field of view is around 120°.

The resolution of the visual scene generated by the master was 1024×768 pixels, and that for the slaves was 800×1200 pixels; the refresh rate was 30 to 60 Hertz depending on the scene complexity. The system was also equipped to reproduce engine sound. A more detailed description of the system structure, projection system, and the data acquisition process can be found in Wang et al. (2006).

2.2. Work Zone Setup and Configuration

Work zone scenarios for daytime, dusk and nighttime were developed which replicated a 4-lane rural divided highway. Each scenario included four consecutive work zones on a highway with different VMA markings. The highway was approximately eight miles long; first work zone was setup after 1.5 miles, each work zone was 0.5 miles long and 1.5 miles apart. Figure 2 shows a work zone setup with traffic control devices, two VMA vehicles (with the same markings), and a construction vehicle on the closed lane. The four VMA markings varied randomly for the participants driving on the virtual highway with work zones.

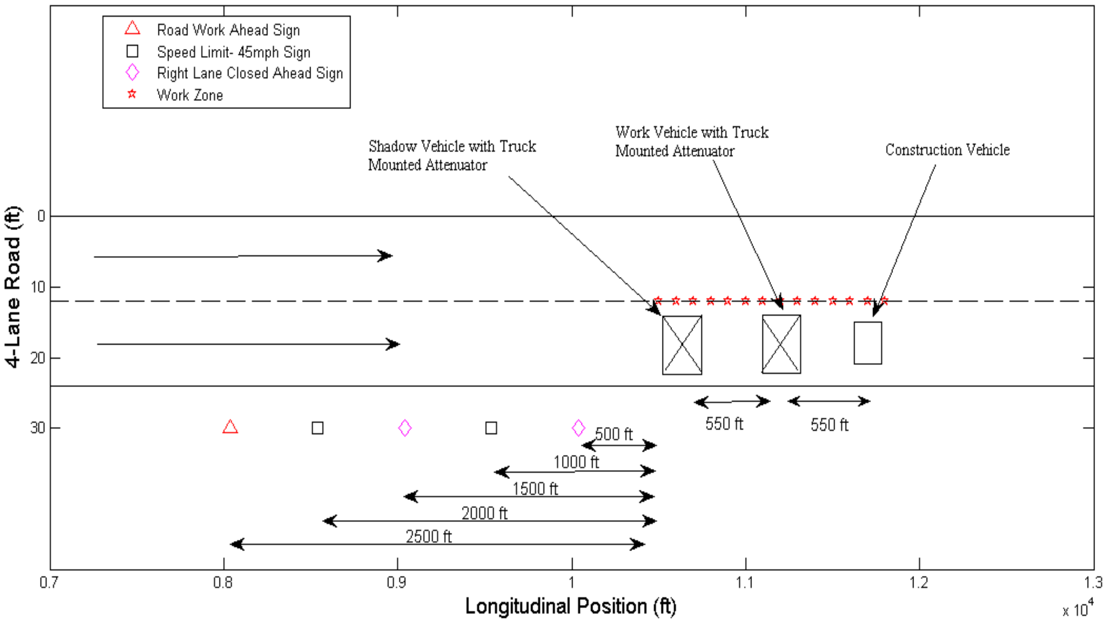


FIGURE 2. Work Zone Configuration

The virtual work zone environment created for the experiment was set up according to MUTCD (2003) and Missouri DOT specifications for a partial lane closure on a divided highway. These guidelines specified sign spacings, taper lengths, and optional buffer length channelizer spacings for various speed limits, sign heights, and work zone lengths. To replicate a real environment, traffic control devices such as cones, barriers, and traffic signs were placed on the highway. The first 1.5 miles of the freeway had a speed limit of 70 mph indicated by a regulatory speed limit sign at the beginning of the section. Additional traffic signs were placed along the right side of the roadway 500 feet apart, as shown in Figure 2, starting with ‘Road Work Ahead’ warning sign located 1.5 miles at the start of the work zone. The four remaining signs were placed in the following order: speed limit sign ‘45 mph’, ‘Right Lane Closed Ahead,’ another speed limit sign ‘45 mph,’ and then ‘Right Lane Closed Ahead’ again. Each construction zone was 1300 feet in long with barriers on the lane markings. The construction zone consisted of a shadow vehicle with a VMA, a work vehicle with a VMA, and a construction vehicle. These vehicles were separated by a distance of 550 feet.

2.3. Participants

Participants in this study were students, staff and faculty from Missouri S&T, and residents of Rolla, Missouri. One hundred and twenty people were selected to participate in the experiment. Three age categories were selected for this study: younger aged group was 18 to 34 years (sample size (S) = 70, mean (M) = 21.8 years, standard deviation (SD) = 2.0 years), middle aged group was 35 to 64 years (S = 30, M = 45.3, SD = 7.6), and older aged group 65 years and up (S = 20, M = 73.3, SD = 6.8). The gender split was approximately 50/50 for all age groups. Prior to scheduling the experiment, the participants were screened using a questionnaire to inquire if they have a US driver’s license, any health issues that would affect driving, and they do not suffer from motion sickness. All participants had normal or corrected-to-normal vision and none of them reported any form of color deficiency. Most surveyed met the requirements and participated in the experiment. Of the 120 participants, 51 had been driving for more than 15 years, 49 had been driving between 5 and 15 years, and 20 had been driving between 1 and 5 years. All participants had previously encountered VMAs in highway work zones.

2.4. Experiment

Before the start of the experiment, the participants were checked if they were carrying a valid US driving license with them. Participants who were found without a valid US license were turned away from the experiment. The participants were first given a brief introduction to the driving simulator and advised to adhere to traffic laws and to drive as they would in normal traffic conditions. The participants were also notified that they could quit the experiment at any time in case of motion sickness or discomfort. To familiarize the participants with the driving simulator, the environment, and the instructions, the participants first drove through a trial scenario similar to that used in the experiment. Typically, each participant first drove for several minutes during the trial run. After the trial run, each subject drove through the three scenarios: daytime, dusk and nighttime in random order. Also, the four work zones with different VMA patterns appeared in random order and were equally distributed within each scenario. Driver behavior data was collected by various sensors of the driving simulator for every 0.1 seconds.

The markings used in the present study did not incorporate retro-reflective properties. During a visit to Missouri DOT’s maintenance facility, it was observed that the yellow and black inverted ‘V’ pattern did not have retro-reflective properties whereas the red and white checkered board pattern newly bought by the DOT had retro-reflective markings.

2.5. Pre- and Post-Experiment Questionnaires

All participants were surveyed before and after the driving simulator experiment. The pre-experiment questionnaire inquired about any health issues and consumption of alcohol/drug use during the last 24 hours of the experiment. This was carried out to ensure that drivers were alert and eligible for participation on the day of the experiment.

After the driving simulator experiment, each participant was asked to complete a post-experiment questionnaire. The questionnaire served as the subjective evaluation of the VMA patterns based on the participant's experience with the driving simulator. The participants were asked to rank the four patterns based on the following criteria: i) visibility, ii) alerting drivers to work zones, iii) capturing the attention of drivers, and iv) color contrast with the VMA vehicle, by different times of the day. Visibility was used as a criterion for evaluation of the VMAs because it is important with regard to specific conditions such as times of the day and the environment. A VMA pattern that is visible from a distance would alert the drivers to construction activity downstream, thus reducing the risk of a crash. The pattern that captures the attention of the drivers would cause them to notice a work zone and change lanes before approaching the VMA. Alerting drivers to work zones and contrast with the VMA background were used as criteria to make conclusions about the best possible color combinations that contrast with the construction equipment.

The participants were also asked to rank features of individual striping patterns they liked the most. This was carried out to indicate their preference for each marking based on pattern design, color combination, and color contrast using a scale of 1 to 3, with 1 indicating most liked and 3 indicating least liked. The participants were also asked to indicate their overall preference of a pattern and how they interpreted the meaning of some of the features of the markings.

2.6. Data Analysis

The drivers' acceleration/deceleration, speed, position and steering angle were the main variables measured during the driving simulator experiment, for use in the objective evaluation. From vehicle positions, the distances from the point of lane change to the VMA on the closed lane were obtained. This distance, called the lane change distance (LCD), was used as a criterion for determining the effectiveness of the VMA patterns. The LCD was measured from the point where the driver began to steer continuously out of the right lane towards the left lane, achieving the maximum steering angle. The drivers were assumed to be responding to the appearance of the VMA pattern in the construction zone. LCD was selected because most DOTs that responded to a survey (Bham et al., 2009) conducted as part of this study, indicated its use to determine the effectiveness of VMAs in work zones. The details of the state DOT survey and the results have been presented elsewhere (Bham et al., 2009) and thus are not repeated here. Further, the study (Bham et al., 2009) found that the speed-reduction identification distance, i.e. the distance from the VMA at which the drivers start decelerating, should not be used to evaluate VMA patterns because drivers reduce their speed in response to advance warning signs.

The driving simulator experiment was set up such that each participant drove through the three scenarios: daytime, dusk and nighttime in random order. During each scenario the drivers were exposed to the four VMA markings in random order as well. The appropriate statistical design for this experiment was a split-split-plot, with each participant represented as a main-plot with gender and age group playing the role of main-plot factors, the time-of-day acting as the sub-plot factor and the four markings as the sub-sub-plot factor. The aggregate data was unbalanced because the numbers of participants tested for each marking and time-of-day combination were different. This was caused by drivers who did not complete the experiment as they had to leave and the result of data loss due to human error.

Analysis of variance (ANOVA) was carried out to test the statistical significance of gender, age groups, time-of-day, VMA markings, and their interactions on the mean LCD. The test was conducted using the Statistical Analysis System (SAS, 2008) software package. The statistical significance (null hypothesis) of independent variables (factor) or the interactions of two or more variables on the mean LCD was rejected if the p-value was less than or equal to the chosen significance level of 0.05. Because of the unbalanced data, the expected mean squares for the error terms (three error terms in a split-split-plot setup: the main-plot error, the sub-plot error, and the sub-sub-plot error) and those for the corresponding treatment effects did not match exactly under the null hypothesis. As a result of this, each test was carried out manually by computing the error terms for each test based on the estimates of the three variance components associated with the main-plot, sub-plot and sub-sub-plot error terms. The error terms were constructed such that under the null hypothesis the tested effect is zero, the expected mean squares of the tested effect and the corresponding error terms are equal.

Pairwise comparisons of least-square means (LSM) between patterns for each time of day were performed in SAS software. LSM are predicted values, based on the model fitted, across values of a categorical effect where other model factors are held constant by setting them to the least square estimate of their mean. If the experiment is balanced where each combination of factors (i.e., independent variables) is replicated an equal number of times, least square means will be the same as regular sample means. In this experiment, however, equal samples were not available within the factor combinations, therefore, sample means were not unbiased estimates of the true population means associated with the treatment combinations and the use of the least-square means was warranted. The least-square means test was conducted by employing the Tukey-Kramer adjustment, which uses the approximation described by Kramer (1956). It was used to accommodate the unbalanced data and provide good control of the Type 1 error rate.

To further analyze the data, a Kolmogorov-Smirnov (KS) test was also conducted for each time of day to ascertain statistically significant difference between the lane-change cumulative frequency distributions for the four VMA patterns. The KS procedure tests the null hypothesis of no significant difference between the LCD cumulative distributions for the four VMA markings by looking at the difference at the point of maximum separation between the distribution curves. This is in contrast to the ANOVA based test described earlier, which looked at the differences between the means. A significant difference between the frequency distributions for any two markings for a given time of day would imply that the lane-change behavior of drivers was different between these markings. Straightforward use of the KS test on the LCD distribution of participants would reduce the power of the test because of the heterogeneity of participants' driving styles and would add to the "noise" in the data. The effect of an individual participant's driving style was eliminated by calculating the dependent variable as the difference between the marking LCD for a participant and the average LCD of that participant for the four markings. This distance was used instead of the actual LCD of the marking for the KS test. The KS test was conducted at 0.05 level of significance.

To supplement the objective evaluation, all participants completed a post-experiment questionnaire for subjective evaluation of the VMA markings. The subjective evaluation served as an opinion poll of the participants regarding the four markings in contrast with measuring the effect of the marking on the actual driving behavior. The results of the subjective evaluation should be carefully interpreted as they represent the perception of the drivers. The analysis of the subjective evaluation was carried out for each time of day as it was found from the objective evaluation that the subjects reacted differently to the patterns at different times of the day. Thus, the mean rank for a particular pattern was calculated by taking the arithmetic mean of the ranks for each time of the day and for each criterion.

A statistical test was also carried out to find the significance of participants' preference of the markings. It should be noted here that the participants did not choose a preferred marking from among the four but ranked them according to a criterion. Thus, the data from an individual provides information on his/her ranked preference as the first, second, third and the last choice. Further, the ranks for each marking were correlated for an individual. The statistical model that was used to analyze this data can be explained as: first, a participant selected his/her the first choice (rank = 1, the highest rank). Then, among the rest, the next best choice was selected (rank = 2) and so on. The resulting model is sometimes referred to as the exploded logit model, a discussion of which can be found in Allison and Christakis (1994). The likelihood function obtained for this model is exactly the same as the likelihood one would obtain for the stratified Cox regression analysis and thus can be estimated using the PHREG procedure in SAS (2008). In this context, the PHREG procedure estimates the parameters of the model and provides risk ratios of proportions, which are the odds of a marking to be ranked 1 (best) under a particular criterion when compared against a base marking. For analysis of results, the yellow and black inverted ‘V’ pattern was used as the base pattern and the risk ratios for the rest of the markings with respect to it were estimated.

3. ANALYSIS OF RESULTS

3.1. Objective Evaluation

Table 1 presents the results of the split-split-plot ANOVA test. The analysis indicated that the variables: Gender, Age group, and the interaction term Time-of-day*Pattern were statistically significant. Age group and Gender showed no significant interaction with other variables or with each other. Their effects on the LCD were, therefore, not evaluated individually. The time-of-day and pattern were evaluated individually because they had significant interaction in their effects on the LCD.

The data showed that the average LCD for the older age group for all the markings and times of the day, 1058 feet and this was greater than the LCD of the younger age group drivers, 854 feet, and the middle age group drivers, 847 feet. This shows that the older drivers moved out of the closed lane much earlier than the younger and the middle age drivers. The difference in LCD clearly indicates that older drivers were risk averse and perhaps less prone to colliding with the VMA.

TABLE 1. Statistical Results: Main Effects and Interactions

Source	DFNUM#	DFDEN^	F-ratio	Prob > F
Gender	1	114	4.30	**0.0403**
Age group	2	114	6.44	**0.0022**
Gender*Age group	2	114	0.47	0.6233
Time of day	2	220	105.12	**<0.0001**
Gender*Time of day	2	220	0.59	0.5516
Time of day*Age group	4	220	1.48	0.2070
Gender*Time of day*Age group	4	220	2.40	0.0507
Pattern	3	982	14.59	**<0.0001**
Gender*Pattern	3	982	1.77	0.1516
Age group*Pattern	6	982	1.55	0.1595
Gender*Age group*Pattern	6	982	0.70	0.6473
Time of day*Pattern	6	982	3.18	**0.0043**
Gender*Time of day*Pattern	6	982	0.72	0.6343
Time of day*Age group*Pattern	12	982	0.74	0.7144
Gender*Time of day*Age group*Pattern	12	982	0.73	0.7199

 # DFNUM = (Number of different groups – 1)

^DFDEN = (Total sample size) – (Number of different groups)

The interaction between Age group and Pattern was not significant, indicating that the order of effectiveness of the markings was similar in all the age groups. It was also found that the mean LCD for male drivers (848 feet) averaged over all times of the day was shorter than that for female drivers (924 feet). Clearly, female drivers moved out of the closed lane earlier than the male drivers, suggesting that the male drivers were aggressive and more prone to risk taking compared to female drivers. The order of effectiveness of the markings was similar in males and females as the interaction between Gender and Pattern was not significant. The interaction term Gender*Time-of-day*Age-group was found to be very close to being statistically significant (p-value = 0.0507) as seen in Table 1. Since this interaction does not involve Pattern, the primary variable of interest, further investigation of this possibility was not carried out. It should be noted, however, that the nighttime mean LCDs for a combination of Gender and Age group were less than the LCD during the dusk and daytime.

TABLE 2. LCD: Mean, Standard Deviation and p-Values for Least Square Means

Times of Day	Patterns	Mean	Standard Deviation	Yellow and black	Lime green	Orange and white
		feet		p-values		
Daytime	Red and white	**1147**	443	**<0.0001**	**0.0011**	0.9971
	Orange and white	**1110**	438	**0.0011**	**0.0493**	-
	Lime green	991	326	0.9977	-	**0.0493**
	Yellow and black	954	346	-	0.9977	**0.0011**
Dusk	Red and white	**1157**	471	**0.0002**	0.1157	0.8499
	Orange and white	1093	459	0.1275	0.9872	-
	Lime green	1047	369	0.8610	-	0.9872
	Yellow and black	983	413	-	0.8610	0.1275
Nighttime	Red and white	636	207	1.0000	1.0000	1.0000
	Orange and white	649	210	0.9976	1.0000	-
	Lime green	658	231	0.9877	-	1.0000
	Yellow and black	611	161	-	0.9877	0.9976

“-” = not applicable

Patterns: Lime green = lime green & black inverted ‘V’, Orange and white = orange & white vertical striped,

Red and white = red & white checkerboard, Yellow and black = yellow & black inverted ‘V’

Bold values indicate statistically significant at 0.05 level of significance

The significance of the Time-of-day*Pattern interaction suggests that the way subjects responded to each of the markings changed according to the time of the day. Therefore, comparison of markings with respect to their mean LCDs was conducted separately for each time of day. Table 2 summarizes the mean and standard deviation of LCD for the four markings for each time of the day. Further statistical analysis was conducted to find which markings were significantly different from the others within each time-of-day category. A KS test was also performed to determine if there was a significant difference between the frequency distribution of the LCD associated with each of the markings. The results below are categorized by time of day so they are easier to comprehend.

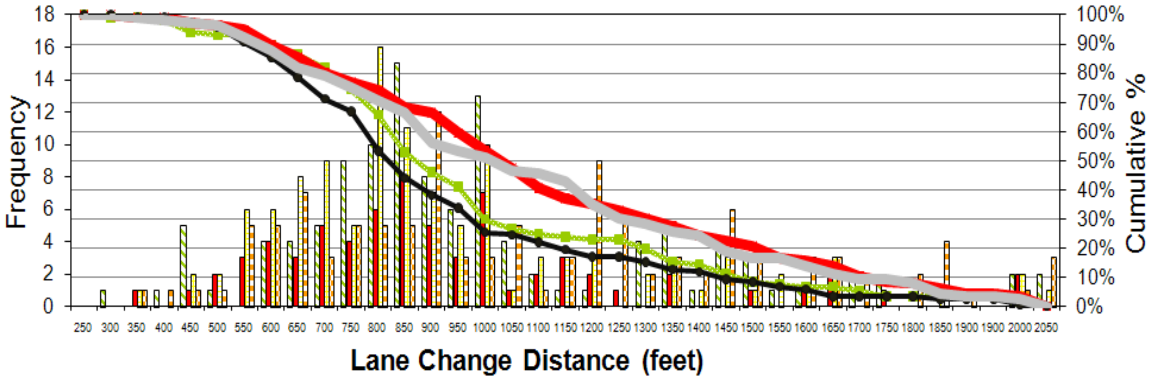
3.1.1. Daytime Conditions

From Table 2, for daytime conditions, on average, drivers changed the lane farthest from the work zone when the red and white pattern, 1147 feet, and the orange and white pattern, 1110 feet, were used on the VMA. For the lime green and black pattern, drivers changed lanes on an average of 991 feet from the VMA. The mean LCD of 954 feet for the yellow and black pattern was the lowest.

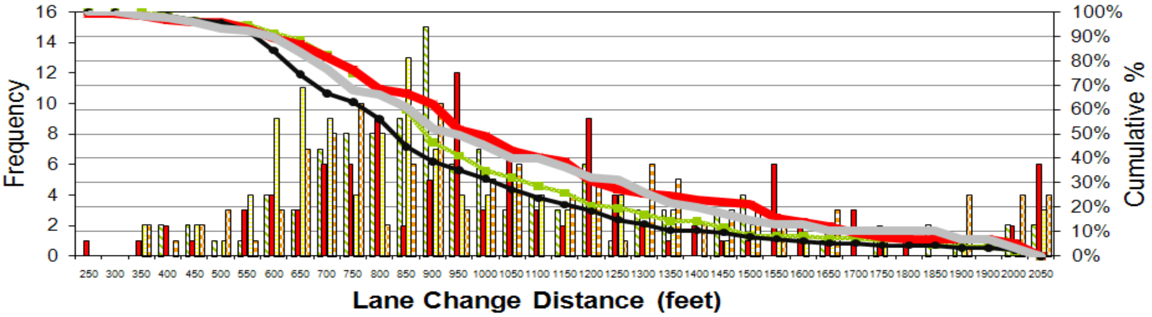
As stated earlier, the differences between the mean LCD of markings during different times of the day were tested for significance using the least square means. The mean LCD of the red and white pattern was found to be significantly higher than that of the lime green and black pattern and the yellow and black pattern. Similarly, the mean LCD of the orange and white pattern was also significantly greater than that of the lime green and black pattern and the yellow and black pattern. The difference between the mean LCD of the red and white pattern and the orange and white pattern was not found to be statistically significant. Similarly, the difference in mean LCD between the lime green and black pattern and the yellow and black pattern was not significantly different. Thus, the mean LCDs for the red and white checkerboard and the orange and white vertical striped patterns were significantly larger than those of the other patterns for daytime.

The effectiveness of the markings was also evaluated based on the cumulative lane change frequency, represented by curves in Figure 3, at intervals of 50 feet from the VMA. An interval of 50 feet was reasonably long to evaluate the difference in the frequency distributions. Figure 3 also indicates the observed frequency and percentage of drivers changing lanes at various distances from the VMA. Most drivers, 95.6%, moved out of the closed lane at least 500 feet from the VMA when the yellow and black inverted 'V' pattern was used. This result is similar to that of a field study (Steele and Vavrik, 2009) in which 94.4% drivers changed their lane at least 500 feet from the VMA with the yellow and black inverted 'V' pattern used at a rural test site in Illinois. This indicates similarities in the results from the driving simulator and from the field data.

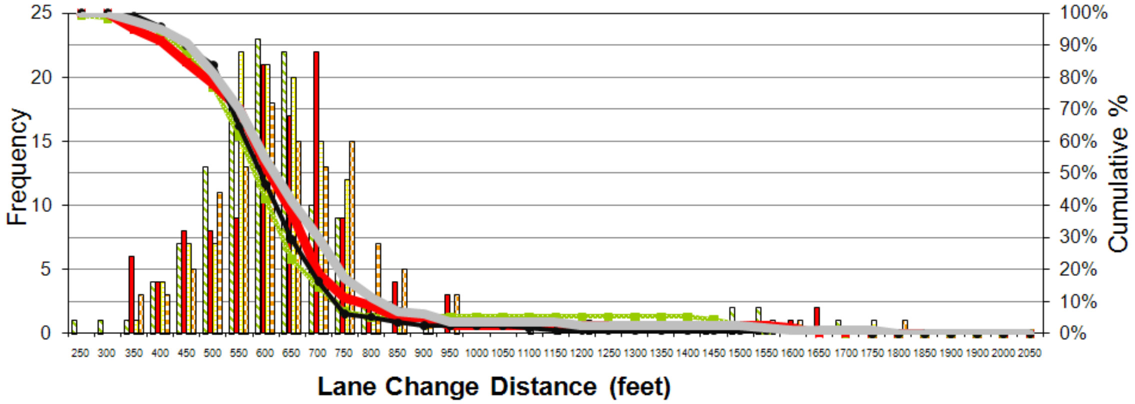
The KS test for the LCD distributions of the red and white pattern with the lime green and black pattern ($p < 0.0001$) and with the yellow and black pattern ($p < 0.0001$) indicated that these distributions were not identical and the differences were statistically significant at the point of maximum separation. Table 3 presents the results of the KS test. In these cases, the red and white checkerboard pattern had higher cumulative frequency of lane changes at the point of maximum vertical separation between the distributions. The test of the cumulative frequency distributions of the orange and white vertical striped pattern with the lime green and black inverted 'V' pattern ($p < 0.0001$), and with the yellow and black inverted 'V' pattern ($p < 0.0001$) also showed a statistically significant difference. This indicates that the driver perceptions in response to the red and white checkerboard pattern and the orange and white vertical striped pattern were significantly better compared to the lime green and black and the yellow and black inverted 'V' patterns.



(a) Daytime



(b) Dusk



(c) Nighttime

FIGURE 3. Lane Change Distance Frequency Histogram and Cumulative Frequency Curves for Different Times of the Day

3.1.2. Dusk Conditions

From Table 2, for dusk conditions, the mean LCDs showed the same trend observed for daytime conditions. The results of the LSM test indicated that there was no significant difference between the mean LCDs of the patterns except that the mean LCD of the red and white checkered board pattern was significantly (p = 0.002) greater than the mean LCD of the yellow and black inverted 'V' pattern.

TABLE 3. Kolmogorov-Smirnov Test Results

Times of Day	Patterns	Yellow and black	Lime green	Orange and white
		p-values		
Daytime	Red and white	**<.0001**	**<.0001**	0.8824
	Orange and white	**<.0001**	**<.0001**	-
	Lime green	0.2961	-	-
	Yellow and black	-		
Dusk	Red and white	**<.0001**	**0.0209**	0.4600
	Orange and white	**<.0001**	0.2867	-
	Lime green	**0.0209**	-	-
	Yellow and black	-		
Nighttime	Red and white	0.7905	0.0674	0.2281
	Orange and white	**0.0476**	**0.0010**	-
	Lime green	0.1726	-	-
	Yellow and black	-		

"-" = not applicable

Patterns: Lime green = lime green & black inverted 'V', Orange and white = orange & white vertical striped, Red and white = red & white checkerboard, Yellow and black = yellow & black inverted 'V'

Bold values indicate statistically significant at 0.05 level of significance

From Figure 3(b), it can be observed that most of the drivers recognized the construction zone from a distance of more than 400 feet. This can be attributed to better color contrast with the surroundings during dusk conditions. The KS test, Table 3, for the LCD distributions of the red and white pattern with the lime green and black pattern (p = 0.0209) and with the yellow and black pattern (p < 0.0001) indicated that the distributions were not identical at the point of maximum separation. For these cases, the red and white checkerboard pattern had a higher cumulative frequency of lane changes at the point of maximum vertical separation. The test of cumulative frequency distributions of the yellow and black inverted ‘V’ pattern with respect to the lime green and black inverted ‘V’ pattern ($p = 0.0209$) and to the orange and white vertical striped pattern ($p < 0.0001$) also showed a significant difference with a lower cumulative frequency of lane changes for the yellow and black inverted ‘V’ pattern at the point of maximum separation. Therefore, driver perception in response to the red and white checkerboard pattern, the orange and white vertical striped pattern, and the lime green and black inverted ‘V’ pattern was better compared to the yellow and black inverted ‘V’ pattern.

3.1.3. Nighttime Conditions

It can be observed from Table 2 that the mean LCDs for the four markings were very similar. No significant difference between the mean LCDs for the four markings was observed.

3.2. Subjective Evaluation

The participant’s preferences indicated by mean ranks of the markings based on the four criteria are presented in Table 4. To statistically test these preferences, statistical analysis was carried out with the yellow and black pattern as the base pattern. The yellow and black pattern was used because it is the most widely used pattern in work zones especially in Missouri. Table 5 presents the results of the statistical analysis. The risk ratio indicated the participants’ preferences of the markings when compared to the yellow and black pattern. The risk ratio for the yellow and black pattern equaled 1.0. The markings with values more than 1.0 were preferred over the yellow and black pattern. Conversely, the markings with risk ratios below 1.0 were less preferred than the yellow and black pattern.

3.2.1. Daytime Conditions

From the mean ranks in Table 4, the participants ranked the red and white checkerboard pattern to be more visible (2.14), captured the attention of drivers (2.09), and contrasted better with the VMA vehicle (1.96) in comparison to the other markings. For the alerting drivers to work zones criterion, the yellow and black pattern had the lowest mean rank (1.98), which indicated that participants found it highly effective. The red and white checkerboard pattern had the highest mean rank (2.87), ranking it as the least effective in alerting drivers to work zones. The risk ratios from the statistical analysis reported in Table 5 shows the odds of selecting a given VMA pattern as the preferred pattern over the yellow and black base pattern. For example, the risk ratio of 1.563 for the red and white pattern in the visibility column indicates that the odds of the participants selecting the red and white checkerboard pattern as the best was 56.3% higher than the selection odds for the base pattern.

Clearly the red and white pattern was preferred over other patterns for visibility (risk ratios of 1.563 compared to 1.162, 0.776, and 1.0), capturing the attention (risk ratios of 1.663 compared to 1.040, 0.898, and 1.0), and contrast with the VMA vehicle background (risk ratios of 2.490 compared to 1.470, 1.199, and 1.0). All of these results were statistically significant based on the p-values provided in Table 5. For the alerting the drivers to the work zones criterion, none of the patterns had a risk ratio indicating preference over the yellow and black pattern. The orange and white pattern had a risk ratio of 0.630 while the red and white pattern had a risk ratio of 0.439. Both ratios were less than one depicting that the base pattern was preferred, and the p-values indicated that this preference was statistically significant. The orange and white pattern had the second highest risk ratio for all criteria but it was only statistically significant for the alerting drivers to work zones criterion. Participants showed the least preference for the yellow and black pattern under the color contrast (with the VMA background) criterion.

TABLE 4. Mean Subjective Ranks

Patterns/Criterion	Visibility	Alerting drivers to work zones	Capturing attention of drivers	Color contrast*
DAYTIME				
Red and white	**2.14**	2.87	**2.09**	**1.96**
Orange and white	2.46	2.46	2.58	2.51
Lime green	2.79	2.69	2.67	2.63
Yellow and black	2.61	**1.98**	2.66	2.90
DUSK				
Red and white	**2.36**	2.68	**2.15**	**1.97**
Orange and white	2.53	2.52	2.61	2.49
Lime green	2.59	2.7	2.63	2.64
Yellow and black	2.52	**2.10**	2.62	2.90
NIGHTTIME				
Red and white	**2.08**	2.76	**1.98**	**1.92**
Orange and white	2.34	2.53	2.46	2.32
Lime green	2.75	2.68	2.74	2.87
Yellow and black	2.82	**2.02**	2.82	2.9

**Color contrast with the VMA vehicle*

Patterns: Lime green = lime green and black inverted 'V', Orange and white = orange and white vertical stripes, Red and white = red and white checkerboard, Yellow and black = yellow and black inverted 'V'

Ranks: 1- highest, 4-lowest

Bold: Lowest mean value for the column, Underlined: Highest mean value for the column

3.2.2. Dusk Conditions

From Table 4, it can be observed that the red and white checkerboard pattern was more visible (2.36), captured more attention of drivers (2.15), and contrasted better with the VMA vehicle (1.97) in comparison to the other patterns. The risk ratios from the statistical analysis reported in Table 5 showed that the red and white pattern was preferred over other patterns in capturing the attention of drivers (risk ratios of 1.459 compared to 0.929, 0.875 and 1.0) and color contrast (risk ratios of 2.475 compared to 1.490, 1.242 and 1.0). All of these results were statistically significant based on the p-values reported in Table 5. The risk ratio of 1.459 for the red and white pattern in capturing attention of drivers indicated that the odds of the participants selecting the red and white checkerboard pattern as the best was 45.9% higher than the selection odds for the base pattern. Similarly, the risk ratio of 2.475 for the red and white pattern for the color contrast criterion indicated that the odds of the participants selecting the red and white checkerboard pattern as the best was 147.5% higher than the selection odds for the base pattern. For the alerting drivers to work zones criterion, none of the patterns had a risk ratio that indicated that they were preferred over the yellow and black pattern. The orange and white pattern had a risk ratio of 0.621, while the red and white pattern had a risk ratio of 0.529. Both ratios were less than one depicting that the base pattern was preferred, and the p-values indicated that this preference was statistically significant. The orange and white pattern had the second highest risk ratio for the criteria of alerting drivers to work zones (0.621) and color contrast (1.490) and the p-values indicated that this preference was statistically significant. Participants showed the least preference for the yellow and black pattern under the color contrast criterion.

3.2.3. Nighttime Conditions

Similar to the daytime and dusk conditions, from Table 4, the red and white checkerboard pattern was more visible, captured more attention of drivers, and contrasted better with the VMA background in comparison to the other patterns. The yellow and black pattern again had the lowest mean rank for alerting drivers to work zones and the red and white pattern had the highest mean rank. The risk ratios from the statistical analysis in Table 5 showed that the red and white pattern was preferred over the other patterns for visibility (risk ratios of 2.121 compared to 1.561, 1.017 and 1.0), capturing the attention of drivers (risk ratios of 2.325 compared to 1.440, 1.025 and 1.0) and color contrast (risk ratios of 2.828 compared to 1.931, 1.013 and 1.0). All of these data were statistically significant based on the p-values reported in Table 5. For the alerting drivers to work zones criterion, none of the patterns had a risk ratio that indicated that they were preferred over the yellow and black pattern. The orange and white pattern had a risk ratio of 0.590, while the red and white pattern had a risk ratio of 0.490. Both ratios were less than one indicating that the base pattern was preferred, and the p-values indicated that this preference was statistically significant.

From Table 4, the orange and white pattern had the second highest mean rank for all the criteria. The statistical analysis from Table 5 indicated that the orange and white pattern had the second highest risk ratio for visibility (1.561), capturing attention of drivers (1.440), alerting drivers to work zones (0.590), and color contrast with the VMA background (1.931). The p-values indicated that this preference was statistically significant. Participants showed the least preference for the yellow and black pattern under the criteria of color contrast with the VMA background, visibility and capturing the attention.

TABLE 5. Risk Ratios and p-Values of VMA Patterns

Patterns/Criterion	Visibility	Alerting drivers to work zone	Capturing attention of drivers	Color contrast*
DAYTIME				
Red and white	1.563□ (**0.0063**)∆	0.439 (<**0.0001**)	1.663 (**0.0018**)	2.490 (<**0.0001**)
Orange and white	1.162 (0.3539)	0.630 (**0.0048**)	1.040 (0.8080)	1.470 (0.0178)
Lime green	0.776 (0.1194)	0.477 (<.**0001**)	0.898 (0.4992)	1.199 (0.2667)
Yellow and black	1.000 (-)	1.000 (-)	1.000 (-)	1.000 (-)
DUSK				
Red and white	1.060 (0.7150)	0.529 (**0.0001**)	1.459 (**0.0189**)	2.475 **(<0.0001)**
Orange and white	0.856 (0.3357)	0.621 (**0.0033**)	0.929 (0.6479)	1.490 (**0.0155**)
Lime green	0.824 (0.2155)	0.542 (**0.0001**)	0.875 (0.3987)	1.242 (0.1754)
Yellow and black	1.000 (-)	1.000 (-)	1.000 (-)	1.000 (-)
NIGHTTIME				
Red and white	2.121 (<**.0001**)	0.490 (<**0.0001**)	2.325 (<**0.0001**)	2.828 (<**0.0001**)
Orange and white	1.561 (**0.0077**)	0.590 (**0.0013**)	1.440 (**0.0281**)	1.931 (<**0.0001**)
Lime green	1.017 (0.9166)	0.509 (<**0.0001**)	1.025 (0.8758)	1.013 (0.9378)
Yellow and black	1.000 (-)	1.000 (-)	1.000 (-)	1.000 (-)

** Color contrast with the VMA vehicle*

□ Risk ratio

∆ p-value

'-' = p-value not available for base pattern

Patterns: Lime green = lime green and black inverted 'V', Orange and white = orange and white vertical stripes;

Red and white = red and white checkerboard, Yellow and black = yellow and black inverted 'V',

Ranks: 1- highest, 4-lowest; Bold values indicate statistically significant at 0.05 level of significance

The subjective evaluation indicated that the yellow and black inverted ‘V’ pattern was most preferred by the participants for alerting drivers to work zones, perhaps because it is the pattern most commonly used in work zones. The yellow and black pattern and the orange and white pattern, which was consistently ranked second behind the yellow and black pattern, are the colors commonly used in work zones in Missouri. The red and white checkerboard pattern was ranked the least effective probably because drivers have seldom been exposed to this pattern in work zones in Missouri. In a recent meeting, a MoDOT official explained that the red and white checkerboard pattern will be implemented in work zones even though it ranks low in this criterion, and the results are expected to improve as drivers become familiar with the pattern.

To evaluate the overall driver perceptions about the patterns, the color contrast and their combination, the participants were surveyed on the features of each pattern and their preferences about the markings in general. Table 6 presents the results of the survey. Color combination was the most liked feature for the orange and white vertical striped pattern, while color contrast was the most liked for the red and white checkerboard pattern. Color contrast for the yellow and black inverted ‘V’ pattern was the least liked feature. Pattern design was the most liked feature for the lime green and black pattern, while it was the least liked feature for the orange and white pattern and the red and white checkerboard pattern. Note that the mean ranks in Table 6 represent general rankings of the features, not specific to any particular time of the day.

When the subjects were surveyed for the most effective VMA pattern overall, out of the 120 participants surveyed, 40 drivers (33.3%) preferred the red and white checkerboard pattern, 30 (25%) preferred the lime green and black inverted ‘V’ pattern, 29 (24.17%) preferred the yellow and black inverted ‘V’ pattern, and 21 (17.8%) preferred the orange and white vertical striped pattern. Thus, the preference of the red and white checkerboard pattern by most of the participants in this evaluation is consistent with the other subjective evaluation data provided in Table 4 and discussed above.

TABLE 6. Mean Ranks for Features of the Patterns

Features \ Patterns	Red and white	Orange and white	Lime green	Yellow and black
Pattern Design	<u>2.19</u>	<u>2.18</u>	**1.89**	**1.90**
Color Combination	2.00	**1.86**	<u>2.14</u>	**1.90**
Color Contrast*	**1.82**	1.96	1.97	<u>2.21</u>

**Color contrast between different colors of the pattern*

Patterns: Lime green = lime green and black inverted ‘v’, Orange and white = orange and white vertical stripes,
Red and white = red and white checkerboard, Yellow and black = yellow and black inverted ‘v’,
Ranks: 1- highest, 3-lowest
Bold: Lowest mean value for the column, Underlined: Highest mean value for the column

The post-experiment survey in conjunction with the driving simulator study as described revealed interesting results. In initial discussion with MoDOT before the driving simulator study, it was conjectured that the inverted ‘V’ design would provide the direction of lane change and suggest the driver to move out of the closed lane. It was further conjectured that the checkerboard pattern would indicate that the lane is closed without indicating the direction of lane change. When the subjects were surveyed regarding the information provided by the inverted ‘V’ pattern, 98 (81.7%) subjects did not perceive that the inverted ‘V’ design signifies the direction of lane change , 1 (.001%) subject perceived the pattern signifies lane change to the left and 21 (17.5%) perceived that it signifies lane change in either left or right directions. Regarding the checkerboard pattern, 65 (54.2%) subjects stated that it indicates reduction in speed, 29 (24.2%) stated that it indicates coming to a stop, and 26 (21.7%) stated that it does not signify any message.

4. CONCLUSIONS AND RECOMMENDATIONS

The paper presents the results of a study carried out using a driving simulator to evaluate the driver perception of four markings with different striping patterns and color combinations for VMAs used in work zones during daytime, dusk and nighttime for drivers of age 18 and above. The study evaluated the VMA markings using both objective and subjective criteria. The objective evaluation used LCD as the criterion and the variables: gender, age group, time-of-day and pattern. When tested during the daytime for the mean LCDs, the red and white checkerboard pattern and the orange and white vertical striped pattern were found to be more effective compared to the two other patterns evaluated. For the dusk condition, the test indicated that the yellow and black inverted ‘V’ pattern was significantly less effective than the other three patterns. The mean LCD of the red and white checkerboard pattern was the largest; however, the differences between the LCD of this pattern and the LCDs of the orange and white vertical striped pattern and of the lime green and black inverted ‘V’ pattern were not statistically significant. For the nighttime condition, no significant differences in the mean LCDs of the patterns were observed. The KS test results were fairly consistent with these results based on LCD frequency distributions of the patterns.

In terms of subjective evaluation, the data for daytime, dusk and nighttime conditions indicated that the participants’ preferred the red and white checkerboard pattern over the other three patterns for the criteria of visibility, capturing attention of drivers, and color contrast with the VMA background. The participants preferred the yellow and black inverted ‘V’ pattern over other patterns in alerting drivers to work zones, a criterion for which they ranked the red and white checkerboard pattern lowest. This response might be attributed to the fact that the red and white checkerboard pattern is not commonly used in work zones compared to the yellow and black pattern. When surveyed in terms of overall effectiveness among the various markings, the red and white checkerboard pattern was regarded as the most preferred pattern.

From the overall objective and subjective results, it can be inferred that the red and white checkerboard pattern is the most effective pattern for use on VMAs in work zones. VMA patterns should also be evaluated based on differences in heights, flashing patterns of arrows and beacons, and their use in different work zone configurations. It is also suggested that the findings of this study be further investigated in other states before recommendations are made to the Federal Highway Administration to update the guidelines for VMA markings.

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SECTION

3. CONCLUSIONS

This work presents the framework for objective and subjective evaluations of a driving simulator. Validation was divided into quantitative and qualitative validations, which were performed along the roadway and at specific locations where additional data were collected. The validation of the driving simulator was performed by comparing the vehicle speeds from a real work zone with those from the simulator.

The qualitative comparison indicated that the driver behavior was similar in the driving simulator and in the real world at specific locations and also along the entire roadway. Since the qualitative validation indicated good correspondence in the driver behavior, the quantitative validation was performed. The quantitative validation was carried out using statistical tests to evaluate absolute and relative validity at specific locations. For the quantitative validation at specific locations, the absolute and relative validity of the driving simulator were analyzed at five locations and t-tests were conducted. From these tests it was concluded that the field speeds and the driving simulator speeds were essentially the same. Therefore, the driving simulator was validated absolutely and relatively at these locations.

From the error tests, the bias proportion showed that the mean speed of the GPS data and that of the simulator data were the same. This indicated the absolute validity of the driving simulator along the entire roadway. The high value of covariance proportion also demonstrated the relative validity of the driving simulator. The subjective evaluation of the driving simulator showed that the participants rated the driving simulator realistic in both the simulator components (for braking, acceleration, and steering) and the driving scenarios (surrounding terrain, road geometry, and feel of driving). Road geometry was rated most realistic, indicating that the use of GPS to reconstruct the road in a simulator was effective and provided realistic experience.

This work also evaluated VMA markings for daytime, dusk, and nighttime driving conditions using both objective and subjective criteria. The objective evaluation used LCD as the criterion and considered four variables: gender, age group, time of day, and pattern. During daytime, when tested for the mean LCDs, the red and white checkerboard pattern and the orange and white vertical striped pattern were found to be more effective than the other two patterns evaluated. At dusk, the yellow and black inverted ‘V’ pattern was significantly less effective than the other three patterns. The mean LCD of the red and white checkerboard pattern was the largest; however, the differences between the LCD of this pattern and that of the orange and white vertical striped pattern and the lime green and black inverted ‘V’ pattern were not statistically significant. At night, no significant differences were observed in the mean LCDs of the patterns. The Kolmogorov-Smirnov (KS) test results were fairly consistent with the mean LCD results based on LCD frequency distributions of the patterns.

Subjective evaluation indicated that, for daytime, dusk, and nighttime conditions, participants preferred the red and white checkerboard pattern over the other three patterns based on its visibility, its ability to capture the attention of drivers, and its color contrast with the VMA background. The participants preferred the yellow and black inverted ‘V’ pattern over other patterns for alerting drivers to work zones, a criterion for which they ranked the red and white checkerboard pattern lowest. Their preference may be attributable to the fact that the red and white checkerboard pattern is not used in work zones as often as the yellow and black pattern. In terms of the overall effectiveness of the various markings, participants preferred the red and white checkerboard pattern.

Based on the objective and subjective results overall, the red and white checkerboard pattern is the most effective for VMAs in work zones. VMA patterns should also be evaluated based on differences in height, flashing patterns of arrows and beacons, and use in a variety of work zone configurations. The findings of this study be tested in other states before recommendations are made to the Federal Highway Administration to update the guidelines for VMA markings.

APPENDIX A.

INSTRUCTIONS FOR DRIVING SIMULATOR

INSTRUCTIONS FOR S & T DRIVING SIMULATOR

1. Configuring the hardware

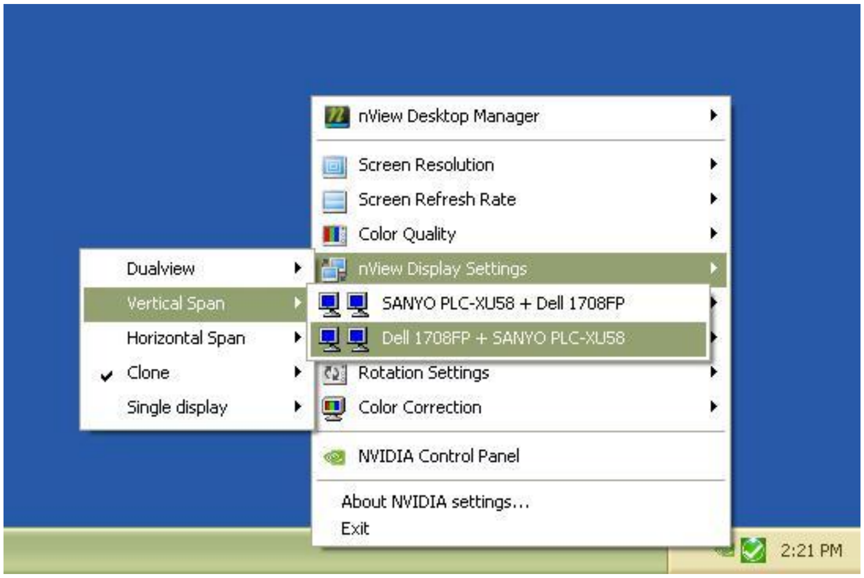
<u>Step 1: Power the computer system</u>

- Facing the screen, the projectors from left to right are Projector1, Projector2, and Projector3; the LCD display monitors for rear mirrors from left to right are mirror1 and mirror2.
- Facing the computer, the computer names for the computers from left to right are carsim1, carsim2, and carsim3.
- Projector 1, 2 and 3 are corresponding to computer carsim1, carsim2 and carsim3.
- Carsim1 and carsim3 are the slave computers and carsim2 is the master computer.

Turn on all the computers and projectors

<u>Step 2: Connect the display system</u>

- Each computer has a graphics card which has two output ports.
- Plug the input cable of each projector to its corresponding computer's graphic card. (Projector1 to carsim1, projector2 to carsim2, and projector3 to carsim3)
- Adjust the display settings of carsim1: a) Icon tray -> NIVIDIA Settings -> nView display settings -> **Vertical span** -> Dell 1708FP +SANYO PLC-XU58; b) Icon tray -> NIVIDIA Settings -> Screen Resolution -> 800x1200



- Adjust the display settings of carsim3 same as carsim1.
- Adjust the display settings of carsim2: a) Icon tray -> NIVIDIA Settings -> nView display settings -> **Clone** -> Dell 1708FP +SANYO PLC-XU58; b) Icon tray -> NIVIDIA Settings -> Screen Resolution -> 1024x768.
- Disconnect the desktop monitor's input cable from carsim1's graphic card, then connect the mirror1's input cable to carsim1's graphic card.
- Disconnect the desktop monitor's input cable from carsim3's graphic card, then connect the mirror2's input cable to carsim3's graphic card.
- Turn on the LCD display monitors

Step 3: Configure the network

- There are two ways to setup the network.
- Normally directly connect three computers to the MST network. They should be able to automatically acquire IP addresses. No more configurations are needed.

- If the above way cannot work out, then try the other way:
    a. Connect the three computers to the same hub and disconnect the hub from the outside network.
    b. Turn off the firewalls of all the computers (Norton firewall or Windows firewall).
    c. Set the IP address for each computer manually as the following instruction:

	Carsim1	Carsim2	Carsim3
IP	131.151.8.162	131.151.8.178	131.151.8.144
Subnet mask	255.255.255.0	255.255.255.0	255.255.255.0
Gateway	192.169.1.2	192.169.1.2	192.169.1.2

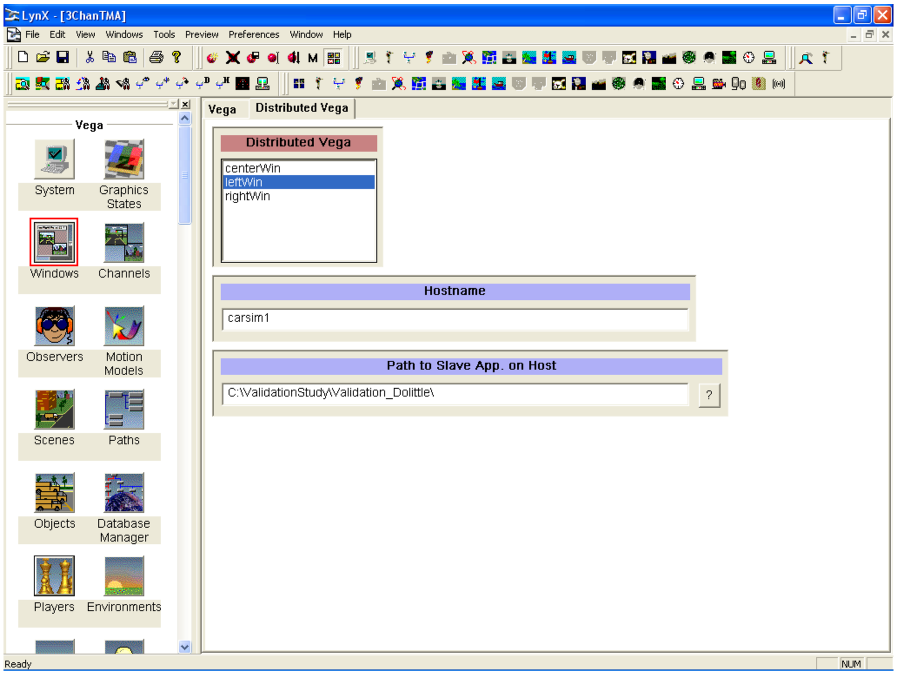
<u>Step 4: Connect the control circuit</u>

- The sensor data acquisition circuit should be connected to the master computer carsim2 by USB port “COM1”.
- The Immersion Arcade Wheel Electronics is connected to master computer carsim2 by USB port.
- Make sure the power inputs for above two circuits are off before running the program.
- The speedometer control circuit is the commercial National Instruments card PCI 6601 plugged directly into the main board of carsim2.

Configuring the software

Step 5: Configure the Vega file

- The program folder contains a Vega configuration file with the extension name of adf. It is used to configure and construct the virtual scenario, including setup of 3D model objects, observers, projection transformation, display channel and windows, and synchronization of different display consoles, etc.
- Open 3chan.adf file with Lynx. Select windows panel -> Tab Distributed Vega. Select “leftWin”, then enter “carsim1” for the hostname and “C:\ValidationStudy\Validation_Dolittle\” for the path to the slave app. After finishing, select “rightWin”, enter “carsim3” for the hostname and “C:\ValidationStudy\Validation_Dolittle\” for the path to the slave app.



Distributed Vega

centerWin
leftWin
rightWin

Hostname

carsim1

Path to Slave App. on Host

C:\ValidationStudy\Validation_Dolittle\

<u>Step 6: load the program folder</u>

- Copy the program folder "C:\ValidationStudy\Validation_Dolittle\" to slave computers carsim1 and carsim3 under the path "C:\ValidationStudy". This is based on the path we entered in the last step.

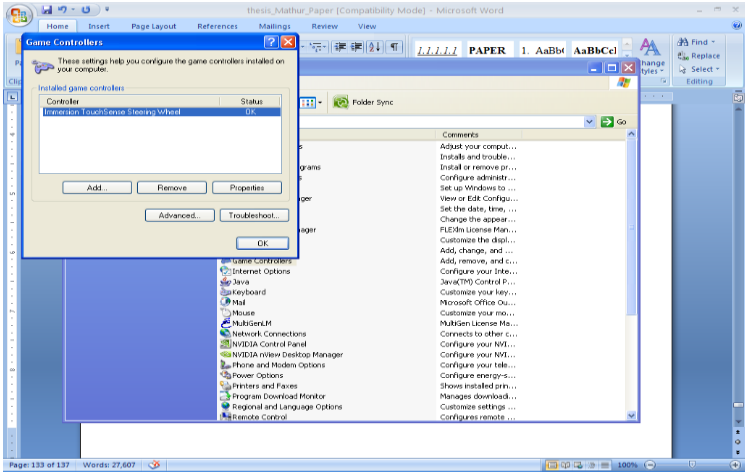
3. Running the simulator

<u>Step 7: Start the slave trigging program on the slave computer</u>

- In carsim1 Start->run->enter "vgslaveservice –m"
- Do the same thing for carsim3

<u>Step 8: Power the Immersion Arcade Wheel circuit</u>

- The power of the Immersion Arcade Wheel circuit should be turned on before starting the simulator.
- Once the power is turned on, check the "game controllers" in the "control panel". If "Immersion TouchSense Steering Wheel" appears, it will be ok. Otherwise, turn off the power and turn it on again, until the above text appears.



These settings help you configure the game controllers installed on your computer.

Installed game controllers

Controller	Status
Immersion TouchSense Steering Wheel	OK

	Comments
s	Adjust your comput...
	Installs and trouble...
grams	Install or remove pr...
s	Configure administr...
	Set up Windows to ...
ger	View or Edit Configu...
	Set the date, time, ...
	Change the appear...
ager	FLEXlm License Man...
	Customize the displ...
	Add, change, and ...
Game Controllers	Add, remove, and c...
Internet Options	Configure your Inte...
Java	Java(TM) Control P...
Keyboard	Customize your key...
Mail	Microsoft Office Ou...
Mouse	Customize your mo...
MultiGenLM	MultiGen License Ma...
Network Connections	Connects to other c...
NVIDIA Control Panel	Configure your NVI...
NVIDIA nView Desktop Manager	Configure your NVI...
Phone and Modem Options	Configure your tele...
Power Options	Configure energy-s...
Printers and Faxes	Shows installed prin...
Program Download Monitor	Manages downloadi...
Regional and Language Options	Customize settings ...
Remote Control	Configures remote ...

Step 9: Place the steering wheel at the center (home) position

Step 10: Start the program

- In the master computer, run the application file “main.exe” in the program folder.
- If there is a popup window from the firewall software for connection permission, choose “unblock”.
- Wait until all the graphics appear.

Step 11: Turn on the power of speedometer and sensor data acquiring circuit

4. Ending the simulator

Step 12: End the program

- Press “ESC” on the keyboard of carsim2. Wait until all the graphics disappear. It will take a moment.

Step 13: Turn off the power

- Power off the sensor data acquiring circuit
- Power off the Immersion Arcade Wheel Electronics
- Power off the speedometer

Step 14: Change back display settings

- If you want to use the desktop monitor of the slave computers again, make sure you change the display setting as the master computer (clone), then reconnect the monitor cable. After the monitor works, you can power the projectors off.

Note: Normally steps 1, 3, 4, 5, and 6 are only required to setup at the first time. There should be no need to repeat these steps each time running the simulator.

APPENDIX B.

ARCHITECTURE OF DRIVING SIMULATOR

1. Software Architecture

The software is the key module of the simulator. It works like the brain of the simulator. The functions of the software contain reading the sensor input, computing the vehicle state, driving the mechanical part (speedometer, motor, projectors, etc), updating graphics and sound, and recording useful data. In other words, the software is used to coordinate every part or aspect of the system to work together as a driving simulator.

So far, according to the current functions fulfilled, the software is divided into several modules: vehicle model, speedometer display control, graphics rendering, and haptic rendering. Each module is required to take responsibility of a certain task.

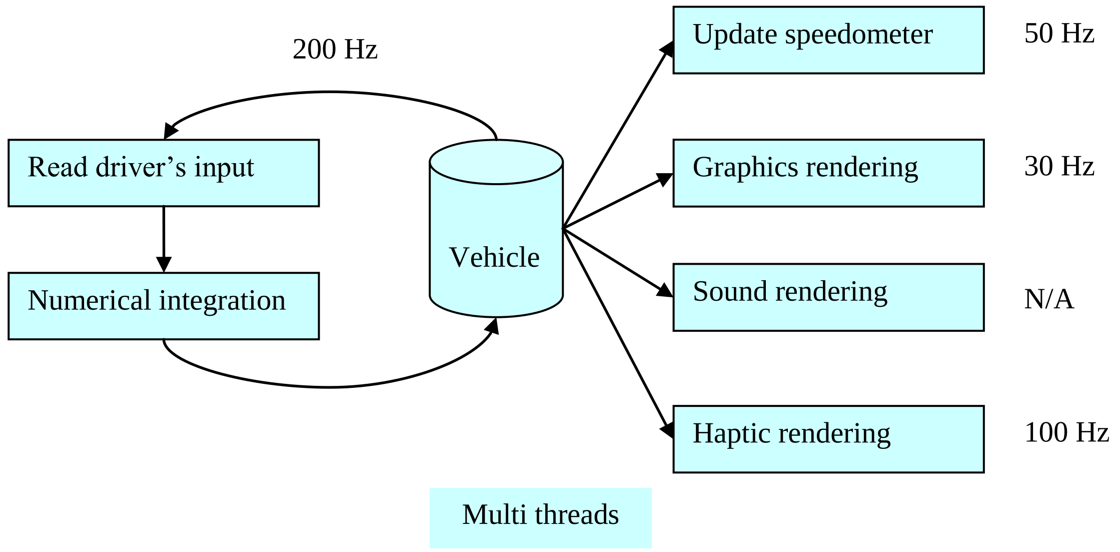


Figure. 1. Multi-thread architecture

These modules are included in figure 1. It is not difficult to observe that all the modules are interlinked with the "vehicle state". The vehicle model module will be able to update the "vehicle state", while other modules are required to use the "vehicle state". Except the "vehicle state", there are no other connections between any two modules. Therefore each module is able to run in an independent thread.

According to this trait, the software should be designed in a multi-thread structure. Each module will be allocated an independent thread. The "vehicle state" shared by different threads is defined as global variables. Communications between threads are through these global variables.

Vehicle model module

From the driver's input and the previous vehicle state, compute the new vehicle state.

- ***Read driver's input***

The driver's input includes steering angle, gas pedal and brake pedal. These input values are read from USB port. The update_driver_input() in Vehicle Model.cpp performs this function of taking driver's input. The steering angle is in radian, and its resolution is PI/4000 rad. The gas and brake values are normalized in the range from 0 to 1. The resolution for gas value is 1/8; the resolution for brake value is 1/4.

- ***Compute the engine torque***

The engine torque is determined by an engine torque curve, engine speed and gas pedal position. The torque curve of the **Corvette V8 engine** with a maximum RPM of about 6000 is used. A fourth-order polynomial model is employed to capture the relation between the engine torque and engine speed. The actual torque that the engine delivers depends on the throttle position and is a fraction of this maximum between 0 and 1. The engine torque is updated in update_engine_torque() in Vehicle Model.cpp.

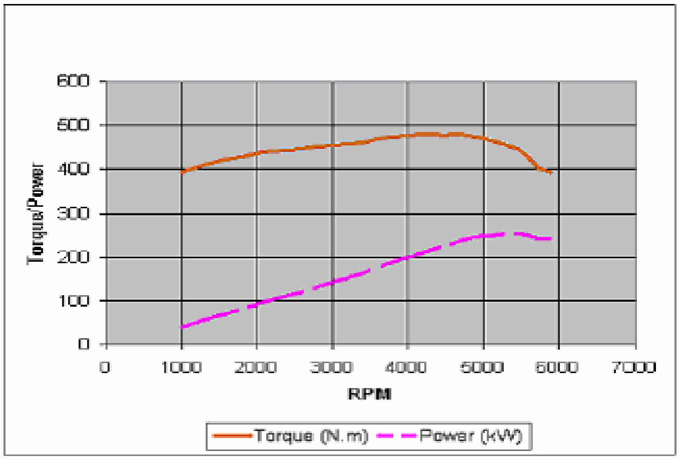


Figure. 2 Corvette V8 engine torque curve [1]

$$T_{\max} = -1.9465 \cdot rpm^4 + 22.004 \cdot rpm^3 - 90.5314 \cdot rpm^2 + 188.1051 \cdot rpm + 272.1317 \qquad (1)$$

$$T_{engine} = fgas \cdot T_{\max} \qquad (2)$$

-rpm: engine speed

-fgas: gas pedal position

- ***Compute longitudinal force***

Several force components contribute to the longitudinal force: engine force, brake force, weight force due to the hill, rolling resistance and wind resistance. This functionality is implemented in update_force() in Vehicle Model.cpp. Equations for computing these forces are:

$$F_{engine} = (k * xd * xg * T_{engine})/wheelRadius \qquad \textit{(3)}$$

$$F_{brake} = (fbrake * BRAKE\_T)/wheelRadius \qquad \textit{(4)}$$

$$F_{hill} = m * G * \sin(pitch) \qquad \textit{(5)}$$

$$F_{Drag} = DRAG * VLong * VLong \qquad \textit{(6)}$$

$$F_{Roll} = ROLL * VLong \qquad (7)$$

-k: efficiency (0.7)

-xd: differential ratio (3.6)

-xg: gear ratio (2.4, 1.46, 1.0, 0.67, -2.0)

-wheelRadius: wheel radius (0.3 m)

-fbrake: brake position (between 0 and 1)

-BRAKE_T: maximum brake torque (3000 Nm)

-m: vehicle weight (1300 kg)

-G: gravity acceleration

- ***Compute vehicle state***

Assume there is no slip angle in the front wheel when cornering; the vehicle therefore follows a curve path with the radian center of point O as showing in figure 4. This functionality is carried out in update_vehicle_state() of Vehicle Model.cpp. Then we have:

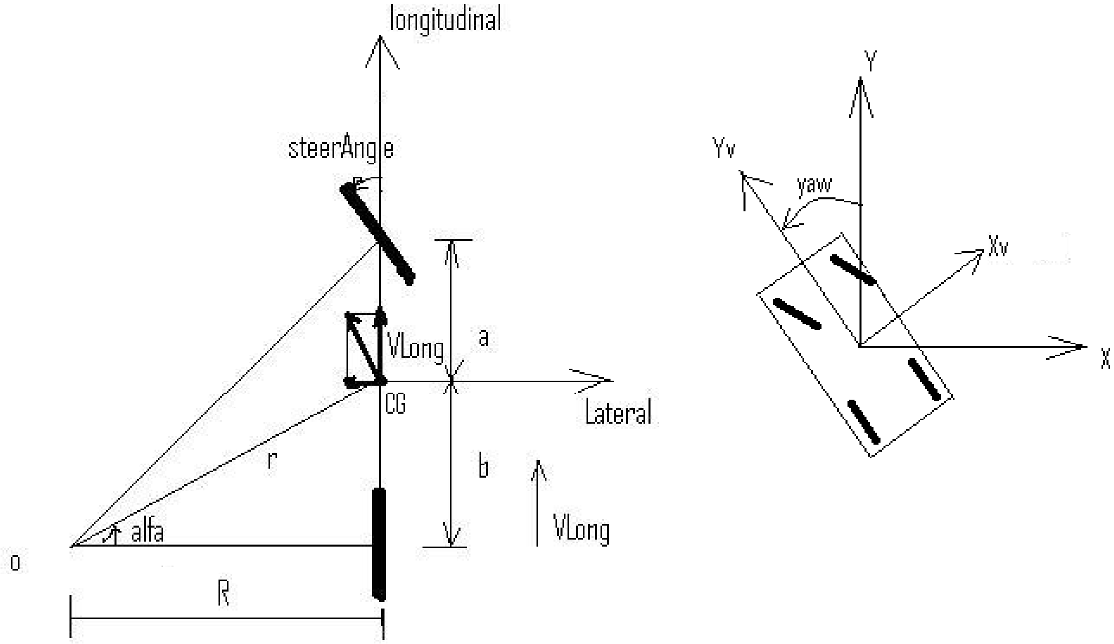


Figure 3. Vehicle state computation

Along = ((FEngine – Fbrake – Fhill – Fdrag –Froll)/m

*VLong = VLong + Along*delta_t*

R = (a+b)/tan(steerAngle)

yawRate = VLong/R

*deltaYaw = yawRate*delta_t*

beta = alfa + deltaYaw

*ULong = r*sin(beta) – b*

*ULateral = r*cos(beta) – R*

*wx = wx + ULateral*cos(-yaw) + ULong*sin(-yaw)*

*wy = wy - ULateral*sin(-yaw) + ULong*cos(-yaw)*

yaw = yaw + deltaYaw

-ALong: longitudinal acceleration

-delta_t: time interval

-yawRate: yaw velocity

-alfa, R, a, b, r: see figure 4

-beta: alfa + deltaYaw

-ULong: longitudinal displacement along Yv direction

-ULateral: lateral displacement along Xv direction

-wx: x coordinate along X direction

-wy: y coordinate along Y direction

-steerAngle: steering angle

-CG: center of mass

Haptic rendering module

Based on the current steering wheel angle, angular velocity and angular acceleration, control the motor to generate corresponding torque applied on the steering wheel. This functionality is carried out in Steering_Haptic fuction of Global.cpp

The feedback torque on the steering wheel consists of stiffness torque and damping torque.

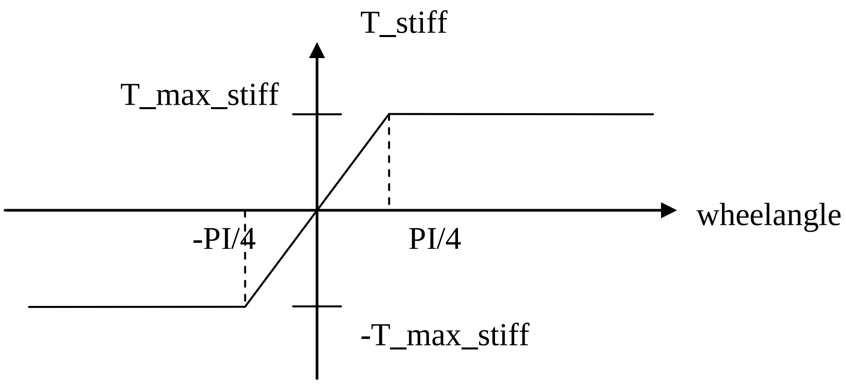
The stiffness torque is computed from steering wheel angle:

$T_{stiff} = T_{\max\_stiff} * wheelangle/(PI/4)$ if –PI/4<wheelangle<PI/4

$T_{stiff} = T_{\max\_stiff}$ if wheelangle>PI/4

$T_{stiff} = -T_{\max\_stiff}$ if wheelangle<-PI/4

Where $T_{\max\_stiff} = 3000$



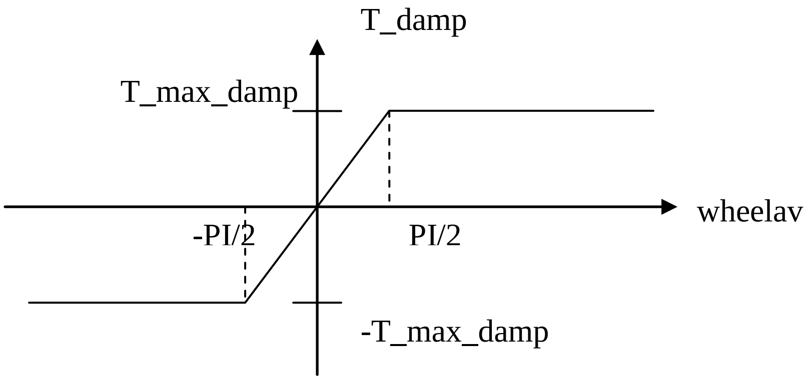
The damping torque is computed from steering wheel angular velocity (wheelav):

$T_{damp} = T_{\max\_damp} * wheelav/(PI/4)$ if –PI/2<wheelav<PI/2

$T_{damp} = T_{\max\_damp}$ if wheelav>PI/2

$T_{damp} = -T_{\max\_damp}$ if wheelav<-PI/2

Where $T_{\max\_damp} = 1600$



The flowchart of the vehicle model module is:

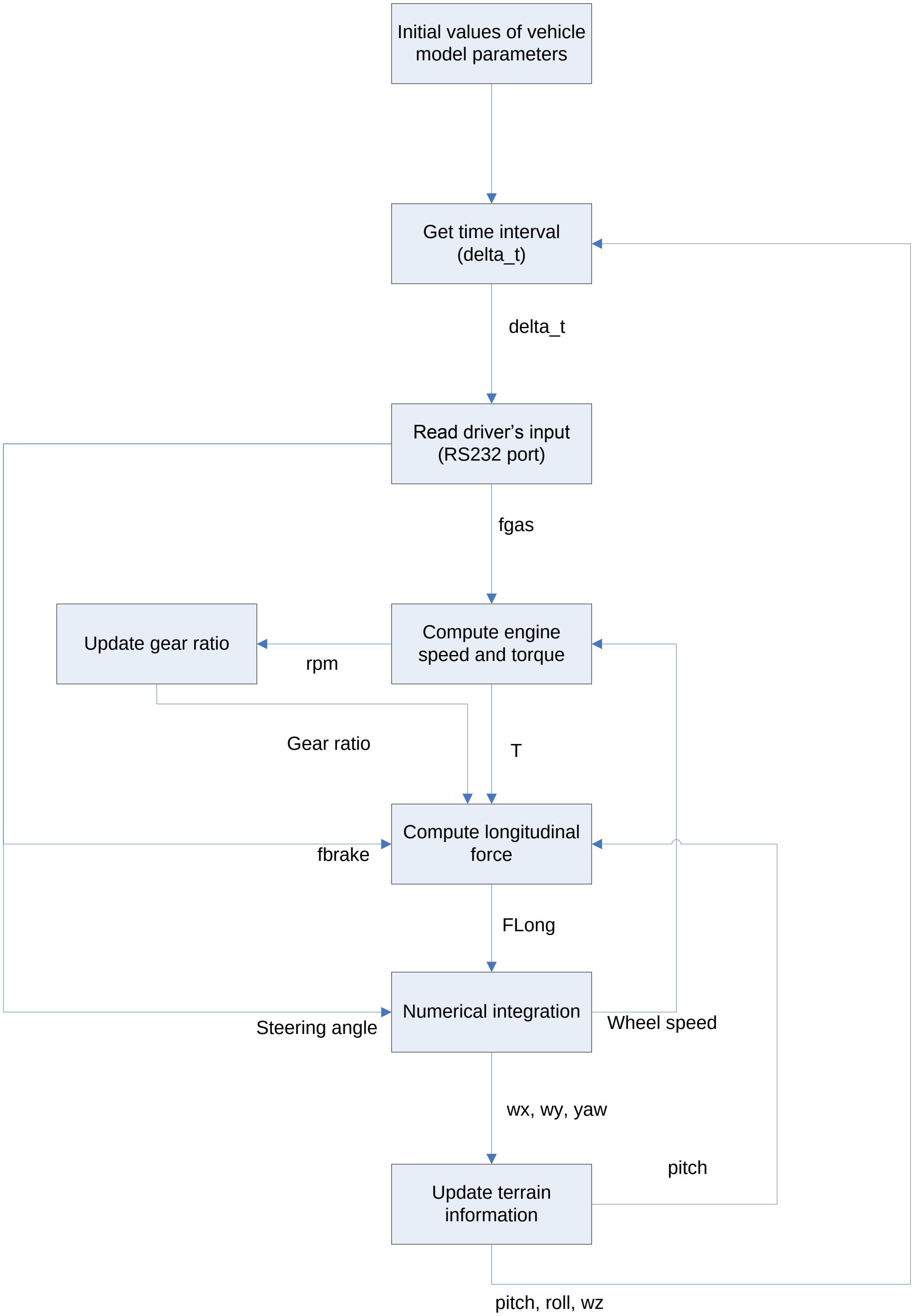


Figure 4. Flowchart of vehicle model computation

2. Software implementation by C++, Vega, and Creator

The software consists of C++ code files, Vega files and model files.

C++ file

The code files are all written by C++ and vega API, they are including:

- Main.cpp (basic.cpp)
    - Define the main thread of the program (main function), which is also used as the graphics rendering thread.
    - Multi-thread initialization
    - Read Vega file and Vega configuration
    - Master/slave synchronization.
- Com.h & com.cpp
    - Define the manipulation functions of USB port
    - Port open function
    - Port read function
    - Port write function
    - Port close function
- Global.h & global.cpp
    - Define global variables
    - Define vehicle numerical integration thread
    - Define speedometer control thread
    - Define haptic rendering thread
- Vehicle Model.h & Vehicle Model.cpp

  - Define the vehicle model, including dimension, weight, motion model, engine performance, transmission, and functions of how operate the model, etc.

<u>Vega file</u>

- The Vega file which has the extension name of ".adf" is edited by "lynx". The file is used to configure and construct the virtual scenario, including setup of 3d model objects, observers, projection transformation, display channel and windows, and synchronization of different display consoles, etc.
- The Vega file is read by the program using Vega API function in "main.cpp" file, so that the program is able to use and manipulate all the objects that configured in the Vega file.

<u>Model file</u>

- The model file represents both the geometry and the texture of the object model. There are two types of model files. One is with the extension of ".flt" while the other is with the extension of ".fst". Both types of model files are generated by the software "creator 2.5.1"
- A flt file should be used together with the texture image file it refers
- A fst file already contains the texture image data in the file when created, so it can be used without the texture image file it referred.
- The model file is referred by the Vega file.

VITA

Durga Raj Mathur was born in Andhra Pradesh, India. He received his primary and secondary education in Andhra Pradesh, India. He received his Bachelor of Engineering in Mechanical Engineering from Osmania University, India in May 2006. Since January 2008, he began to pursue his Master degree in Mechanical Engineering at the Missouri University of Science and Technology as a Graduate Research Assistant. He received his Master degree in May 2010.