Work Zone Speed Reduction Utilizing Dynamic Speed Signs

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ABSTRACT

A simulator study was used in this research to determine speed compliance based upon dynamic speed design and presence. The scenarios designed for this research simulated driving through a highway work zone with a right lane closure. Each participant drove through a control scenario and four experimental scenarios subdivided into five areas for data collection. The four experimental scenarios included dynamic speed signs in place of the regulatory speed limit sign as follows: (1) Steady 'SLOW DOWN 45', (2) Flashing 'SLOW DOWN 45', (3) Steady 'SPEED LIMIT 45' and (4) Steady 'SPEED LIMIT 65'. The five areas included the following: (1) Before the first work zone sign, (2) Between the first work zone sign and the dynamic speed sign, (3) Between the dynamic speed sign and the lane closure, (4) Between the lane closure and the end of the work zone, and (5) After the work zone.

Comparisons were made of the measures of effectiveness (speed, lane position, acceleration, deceleration, gap, time to collision, latency of visual detection, average fixation durations and the proportion of target fixations) to assess compliance with the speed limit and changes in driver behavior. When using dynamic message signs stating 'SLOW DOWN 45', participants maintained the speed limit prior to entering the work zone and through the work zone as compared to scenarios using regulatory signs or dynamic message signs displaying the speed limit. The dynamic message signs did not create unsafe driving conditions based upon the analysis of the other measures of effectiveness studied.

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1.0 INTRODUCTION

According to a recently released report by the National Highway Traffic Safety Administration (NHTSA), speeding is one of the major contributing factors to traffic crashes. In the 2005 and 2008 *Traffic Safety Facts*, it was reported that excessive speed was the contributing factor in 30 and 31 percent of all traffic crashes, respectively [1,2]. Unfortunately, while traffic crashes have been declining, speed, as a contributing factor to crashes, has been trending positively. When considering the economic impact of these speed-related crashes on society, the most recent NHTSA figures estimate an annual cost of $40.4 billion [2]. Across the nation, speeding related crashes claimed 11,767 lives in 2008, while Ohio speeding related crashes claimed 269 lives [2].

These fatal crashes are not restricted to adverse environmental or roadway conditions. In 2008, 29 percent of speed-related fatal crashes occurred on dry roads while 35 percent occurred on wet roadways [2]. Fatal crash data indicates an increase in fatalities on interstates and highways and a decrease in fatalities on local arterials and rural roadways between 1992 and 1998. However, data presented in the NHTSA report *Analysis of Speed-Related Fatal Motor Vehicle Crashes*, published in 2005 indicated fatalities on local and collector roadways has increased significantly since 2000 [3]. The 2008 NHTSA *Traffic Safety Facts* reported that nearly 88 percent of the speeding-related fatal crashes occurred on roadways other than interstates [2]. When considering the fatal crashes by gender and age, drivers 15-24 years old are the most likely to be involved in a speeding-related fatal crash, with males being involved more often than females [2]. Studies have also determined that crash severity can be substantially reduced with adherence to posted speed limits [4].

Speed control on roadways where nearly 88 percent of all fatal speed-related crashes occur resides with the jurisdiction of local city and or county law enforcement agencies [3]. While enforcement has been determined to be the most responsive method of improving speed limit adherence, local agencies do not have adequate staff or budget to conduct speed enforcement in addition to their other public safety responsibilities resulting in unenforced speed limits along local roadways. Combining the increase in speed-related fatal crashes on local and collector roadways with restrictive law enforcement agencies budgets and staff, there is an ever present need for effective, low-cost, speed mitigation measures. Based upon the increase in speed-related crashes on non-interstate roadways and the limits on active enforcement, efforts must be made to increase passive enforcement, or self-enforcement of posted speed limits.

Several passive enforcement traffic calming alternatives have been found to be effective on local roadways. These include but are not limited to: Chicanes, Speed Humps, Speed Tables, Lane Narrowing, and Traffic Circles. Each of these methods have been found effective at reducing the travel speed; however, they are not always feasible due to existing roadway conditions nor are applicable for high speed or high volume roadways. The cost of the design and installation of these traffic calming measures may also limit the ability of local municipalities to implement these options effectively for local roads. Other methods, including increasing the reflectivity of speed limit sign sheeting and pavement markings have been used; however, the desired speed reductions are not realized [4].

Another passive enforcement speed reduction tool is dynamic speed signs (DSS). These signs can be trailer mounted or permanently mounted to telephone or light poles and use laser detectors to measure the speed of approaching vehicles. The sign displays the approaching vehicle's speed to the driver in addition to the posted speed limit. Studies have determined that DSS, when used in relation to construction work zones, can reduce the traveled speed of vehicles by as much as five miles per hour [6, 7]. Similar results were found when these devices were used near speed limit transition locations. These studies reported speed reductions of six to eight miles per hour [4, 5, 8]. Speed trailers have also been used by law enforcement agencies instead of active enforcement. Unfortunately, even though proving effective over a short-time period, the cost and placement options for these trailers are also restrictive. Research has been performed to determine the long-term effects of the DSS, as well as the impact on vehicular speed after the signs have been removed [4, 8]. The research indicated that the long-term impact of the DSS signs were slightly less than the immediate speed reductions; however, after a year, the reductions were still statistically and practically significant. Immediately after the removal of the DSS, traveled speeds returned to similar levels prior to the installation [4, 5, 8]. Research has also been performed to determine the effectiveness of these signs prior to school zones with similar results.

Additional research has been performed with respect to the use of DSS as permanent traffic calming measures on arterial and collector roads with constant speed limits. A before and after study performed by Chang et al. along a corridor in King County, Washington found a speed decrease of 1.19 - 2.21 miles per hour at three of four DSS installation locations seven and 22 months after the installation [5]. One site had a 0.51 mile per hour speed increase after the installation of the DSS. The researchers attributed this increase to the sign's proximity to the presence of a school speed zone where speed limit compliance was not a prior concern. The data collected at three of the sites indicates that adherence to the posted speed limit immediately after the DSS install was sustained for 22 months. These results indicate that the permanent use of DSS as a speed reduction measure may be effective [5].

The Ohio University Department of Civil Engineering evaluated the effectiveness of Dynamic Speed Signs as a speed reduction measure by analyzing both driver behavior and performance in a controlled environment. During the evaluation, three different configurations and messages were examined to determine the most effective Dynamic Speed Sign. The study was conducted through the use of a driving simulator to monitor driver performance and a eye-tracking system to monitor driver behavior. The result of this study provides concepts that can be utilized in the development of Variable Speed Signs for interstates and highways during recurring or nonrecurring congestion in order to limit queuing and poor levels of service.

2.0 OBJECTIVES

The objective of this research is to determine driver performance and behavioral changes as a result of the presence of various dynamic speed signs during work zone roadway conditions. The following outlines the tasks which were performed to complete the research objectives:

1. A comprehensive review of existing literature relating to the use of dynamic speed signs as a vehicle speed reduction technique and variable speed signs for congestion mitigation was conducted.
2. A controlled laboratory experiments to quantify driving performance and behavior of a representative focus group using a high-fidelity driving simulator was conducted to determine the impact of the dynamic speed sign design.
3. Perform statistical analysis to determine the effectiveness of the dynamic speed signs as a measure of speed reduction.
4. Prepare a final report of the findings of this study including recommendations for or against the use of dynamic speed signs for various conditions.

3.0 SIMULATOR STUDY DESIGN

A simulator study was used in this research to determine speed compliance based upon dynamic speed design and presence. A simulator study allowed the research team the ability to conduct trial runs with a large sample population with various sign placement and design configurations in a relatively short time period, in a safe, controlled environment.

The simulator that was used for this study was obtained through a National Science Foundation Grant and is located in Ohio University's Safety and Human Factors Facility. The DriveSafety Research Simulator is a high-fidelity driving simulator that is fully integrated with a full-width Ford Focus automobile driver and passenger compartment. The simulator includes a Q-Motion platform that provides inertial cues representing acceleration and deceleration with longitudinal travel up to five inches and a pitch range of 2.5 degrees The simulator includes several standard data collection measurements and allows for up to 25 additional user defined measurements. All of the data collection measurements are collected approximately every 0.03 seconds. A photograph of the simulator is shown in Figure 1.

Figure 1. Research Simulator with Eye-Tracking System

In addition to the driving simulator, an eye-tracking system is also available through the Safety and Human Factors Facility. The Seeing Machines faceLAB system is an innovative, remote and non-contact eye and face tracking system that monitors gaze direction, eye closure, facial gestures and head position for laboratory and field applications. The faceLAB system is able to work with all eye types, in light and dark environments, and with subjects wearing sunglasses, contact lenses and most eye-glasses. The faceLAB system provides seamless integration with the driving simulator. The data analysis software automatically correlates eye fixation data from the eye and face cameras to the dynamic simulation approximately every 0.03 seconds corresponding to the simulator data collection. The data is synchronized and stored in a database or spreadsheet format. A photograph of the eye-tracking software is shown in Figure 2.

Figure 2. Eye-Tracking Software

The scenarios designed for this research simulated driving through a highway work zone with a right lane closure. The highway environment which was modeled in each simulation was a six lane two-way highway with a grass median. Five different simulations were designed to test different sign configurations and messages which were separated by non-work zone driving sections of approximately one mile in length to allow the participants to return to their normal driving habits. The control scenario was designed so that drivers would interact with the typical group of work zone warning signs that could be expected on a similar road in Ohio as specified by the Ohio Manual for Uniform Traffic Control Devices (OMUTCD). All sign messages, spacing, and lateral locations followed the OMUTCD regulations. In this scenario the following signs were used; 'ROAD WORK AHEAD 1 MILE', 'RIGHT LANE CLOSED AHEAD', 'REDUCED SPEED LIMIT AHEAD', the symbolic right lane merge to the left sign, 'SPEED LIMIT 45' and at the end of the work zone 'END ROAD WORK'. Signs were placed beginning one mile prior to the work zone and were spaced at 650 feet and 1300 feet. The ambient traffic in this scenario was allowed to drive at a normal speed in a 65 miles per hour speed zone and at the point of the lane closure the vehicles would slow to a stop and allow vehicles to merge. Then after the merge was completed traffic was allowed to accelerate to the work zone speed limit of 45 miles per hour.

The remaining scenarios were the experimental environments with dynamic speed sign messages. All of the signs in the experimental scenarios replicated the control scenario with the exception of the 'SPEED LIMIT 45' sign. This sign was replaced with the dynamic speed sign which was placed between the 'ROAD WORK AHEAD 1 MILE' sign and the 'RIGHT LANE

CLOSED AHEAD' sign at approximately 3600 feet prior to the start of the work zone taper. In the experimental scenario 1 and 2 the dynamic speed sign message was 'SLOW DOWN' and the speed displayed was '45 MPH'. In experimental scenario 1 this message was displayed constantly. In the experimental scenario 2 the message displayed and flashed once a second. Experimental scenario 3 used the same sign arrangement as the first and second scenarios except that the message on the dynamic speed sign was 'SPEED LIMIT' and the speed which was displayed was '45 MPH'. The message and speed on the dynamic sign was displayed constantly. In the final simulation, experimental scenario 4, the dynamic speed sign displayed 'SPEED LIMIT' and the speed limit was set to '65 MPH'. The speed limit and message were displayed constantly.

3.1. Simulator Experiment Procedure

A detailed test procedure was developed with standard instructions for each participant of the simulator experiment. In a pre-test survey, the participants were able to comment on their driving experiences in terms of roadway congestion and their daily driving habits. The pre-test survey was also used to obtain demographic information regarding the participants in order to determine if the focus group consisted of a representative sample of motorists. The participant was first orientated to the simulator and the location of the controls followed by adaptation scenarios to acquaint them with the simulator vehicle motion and response rates. Participants were all exposed to the control scenario first. To reduce the bias associated with the experiment, participants were equally exposed to one of two congested scenarios followed by the two non-congested scenarios and ending with the second congested scenario. Upon completion of the simulator scenarios, the participants completed a post-survey form with questions focused at determining their assessment of the dynamic speed signs, anticipated compliance with the sign and measures to reduce congestion.

3.2. Simulator Focus Group

Participants for the simulator experiment were primarily recruited at Ohio University from the introduction to psychology college course, courses offered in the Russ College of Engineering and Technology and by flyers posted on and near campus. The psychology course is required for many of the undergraduate majors offered at Ohio University and provided a wide demographic.

In order to generalize the data and results of the simulator experiment, comparisons were made between the sample population used in the simulator experiment and the population in Ohio. The populations were compared using the chi-square goodness of fit test by calculating the expected number of participants by age group or gender based upon the population of licensed drivers in Ohio. The focus group for the simulator experiment consisted of 39 individuals with a gender breakdown of 92 percent male and 8 percent female. The age group breakdown was 18 percent from the age group 16 to 20, 79 percent from the age group 21 to 25 and 3 percent from the age group 26 to 35. While the ages and genders did not represent the Ohio driver population, the sample does represent the most hazardous gender and age groups, in terms of crashes. Male drivers have a higher crash rate than females. Similarly, the age groups of 16 to 20 and 21 to 25 have higher crash rates than all age groups; however, the age group of 65 and older tends to have a similar crash rate. Therefore, the focus group utilized will exhibit more aggressive tendencies, unsafe driving habits and less experience resulting in lower than expected driver performance.

Due to the participation of human subjects in this research, federal regulations required a review and approval for the proposed research methodology by an Institutional Review Board (IRB) for Human Subjects. An application for expedited approval for the simulator experiment was submitted and approved by the IRB in the Office of Research Compliance at Ohio University.

4.0 DATA COLLECTION

The purpose of the simulator experiment was to observe and quantify participant performance and behavior. As the vast majority of the information drivers receive in obtained visually from which drivers make decisions and adjust their driving behavior accordingly, the ability of a driver to perceive and react to certain stimuli was analyzed utilizing typical traffic engineering parameters as well as eye gaze parameters. The measures of effectiveness included the following:

- Speed
- Lane Placement
- Acceleration
- Deceleration

- Gap
- Time to Collision
- Latency of Visual Detection
- Average Fixation Duration
- Proportion of Target Fixations

Comparisons were made of the measures of effectiveness to assess compliance with the speed limit and changes in driver behavior. All of the measures of effectiveness were compared among the simulator scenarios. The simulator data for driver performance were also examined for five specific areas. The five areas included the following: (1) Before the first work zone sign, (2) Between the first work zone sign and the dynamic speed sign, (3) Between the dynamic speed sign and the lane closure, (4) Between the lane closure and the end of the work zone, and (5) After the work zone. A description of sample size determination and each measure of effectiveness is provided in the following sections.

4.1. Sample Size

In order to determine the number of participants required to assure a statistically valid representative sample, the following formula, which controls for Type I and Type II errors was utilized:

$$n = \frac{(Z_\beta - Z_{\alpha/2})^2 \times \sigma^2}{\varepsilon^2}$$

Where:

Z_β= critical value corresponding to a given value of β in the upper tail of the standard normal distribution, 0.842
Z_α= critical value corresponding to a given value of $\alpha/2$ in the lower and upper tail of the standard normal distribution, ± 1.96
σ = standard deviation of the difference
ε = detectable difference in the means

When considering detectable differences in mean speed, a review of past simulator studies conducted was examined to determine reasonable assumptions for this research. Previous simulator studies completed utilizing the same equipment yielded mean speed standard deviations of approximately four and mean lane position standard deviations of 0.3. In reviewing past research, the detectable difference in speed were set between two and three miles per hour. Using a standard deviation for speed of four and a detectable difference of two and three, the resulting required sample size was 31 and 13, respectively. In addition to speed, lane position is another critical safety measure. Assuming sample sizes of either 13 or 31, the detectable difference in lane position would be 0.76 and 0.5 feet, respectively. For lane placement, accuracies of 0.5 feet would be preferable for a half lane width of six feet. Based upon these preliminary calculations, the targeted sample size required to maintain an alpha of 0.05 and a beta of 0.20 with the assumed standard deviations and detectable differences was 31 participants.

4.2. Speed

Speed data was used as an indicator of perceived risk associated with a given roadway configuration and scenario. The speed for each participant was recorded at a rate of 60 Hertz, or approximately every 0.034 seconds for the five areas of the control scenario and the experimental scenario. The mean speed and standard deviation for all the participants was calculated for each area by scenario and are provided in Table 1 along with the minimum and maximum values.

4.3. Lane Placement

Lane placement or position of a vehicle was quantified in order to assess the ability of the participant to maintain a consistent lane position. The lateral placement for each participant of the simulator experiment was determined for each area and scenario. The lane offset for each participant was recorded similar to that of the speed, approximately every 0.034 seconds along the length of the simulation scenarios. The lane offset is recorded in feet within the current travel lane in which the participant is driving based upon the centerline of the vehicle. The lane offset is recorded as a positive number if the participant is traveling to the right of the center of the lane and a negative number if they are left of the center of the lane. As each lane was 12 feet in width, the lane offset could be recorded as a ± six feet. The mean lane position and standard deviation for each participant was calculated for each area by scenario and are provided in Table 2 along with the minimum and maximum values.

Table 1. Speed Data Summary

Area	Scenario	Mean (mph)	Standard Deviation	Minimum (mph)	Maximum (mph)
1	Control	63.87	2.87	50.90	68.55
	Exp. 1	63.79	3.35	56.77	70.25
	Exp. 2	63.33	4.33	48.78	69.37
	Exp. 3	66.44	4.22	50.77	76.77
	Exp. 4	67.48	2.89	62.07	76.27
2	Control	56.48	3.04	47.17	63.54
	Exp. 1	61.57	8.28	26.90	69.06
	Exp. 2	62.37	6.06	36.57	69.98
	Exp. 3	64.02	5.14	50.14	75.97
	Exp. 4	65.77	5.59	45.84	73.49
3	Control	N/A	N/A	N/A	N/A
	Exp. 1	30.86	6.62	21.18	50.04
	Exp. 2	31.86	5.69	21.38	46.99
	Exp. 3	50.50	3.86	46.00	63.72
	Exp. 4	65.68	4.12	45.79	72.59
4	Control	45.55	1.63	38.79	47.61
	Exp. 1	44.89	1.72	36.83	51.11
	Exp. 2	44.73	1.86	37.97	50.53
	Exp. 3	46.89	8.28	0.00	63.68
	Exp. 4	62.64	11.00	0.00	71.70
5	Control	60.26	5.00	45.79	66.28
	Exp. 1	59.84	5.20	43.65	66.11
	Exp. 2	58.51	8.54	19.82	65.95
	Exp. 3	57.41	12.23	0.00	67.44
	Exp. 4	63.04	11.75	0.00	70.87

Table 2. Lane Placement Data Summary

Area	Scenario	Mean (feet)	Standard Deviation	Minimum (feet)	Maximum (feet)
1	Control	-0.39	0.50	-1.18	1.15
	Exp. 1	-.63	0.55	-1.41	0.49
	Exp. 2	-0.63	0.48	-1.67	0.23
	Exp. 3	-0.64	0.75	-1.74	1.12
	Exp. 4	-0.74	0.58	-1.77	1.15
2	Control	-0.56	0.50	-1.64	0.52
	Exp. 1	-0.61	0.65	-1.90	0.62
	Exp. 2	-0.52	0.75	-1.97	1.38
	Exp. 3	-0.58	0.67	-1.61	0.95
	Exp. 4	-0.75	0.56	-1.77	0.56
3	Control	N/A	N/A	N/A	N/A
	Exp. 1	-0.85	0.53	-1.77	0.33
	Exp. 2	-0.82	0.77	-1.94	2.13
	Exp. 3	-0.84	0.59	-1.94	0.62
	Exp. 4	-0.75	0.46	-1.61	0.33
4	Control	-1.05	0.53	-2.20	0.16
	Exp. 1	-1.18	0.57	-2.36	0.03
	Exp. 2	-1.13	0.82	-2.89	2.49
	Exp. 3	-1.10	0.64	-2.23	0.26
	Exp. 4	-1.13	0.70	-2.30	0.85
5	Control	-0.78	0.44	-1.57	0.26
	Exp. 1	-0.98	0.55	-1.97	0.20
	Exp. 2	-0.92	0.57	-2.20	0.49
	Exp. 3	-0.91	0.61	-2.10	0.43
	Exp. 4	-0.89	0.69	-2.20	1.02

4.4. Acceleration and Deceleration

Acceleration and deceleration data was used as an indication of the participant's reaction time and attention span while traveling through a given scenario. The acceleration and braking for each participant was recorded at a rate of 60 Hertz, or approximately every 0.034 seconds. The acceleration was recorded as a normalized accelerator value with a range between 0.00 and 1.00. A value of 0.00 indicated that the accelerator pedal was not being depressed and a value of 1.00 indicated that the accelerator pedal was at maximum depression. Similarly, the braking data was recorded as a normalized braking value with a range from 0.00 to 1.00. The same descriptions apply for the braking data; expect the pedal evaluated is the braking pedal. The mean acceleration and deceleration as well as standard deviation for all the participants were calculated for each area by scenario and are provided in Table 3 along with the maximum values. Minimum values were consistently collected at 0.00 for the deceleration and therefore are not shown in the table.

Table 3. Acceleration and Deceleration Data Summary

		Acceleration				Deceleration		
Area	**Scenario**	**Mean**	**Standard Deviation**	**Minimum**	**Maximum**	**Mean**	**Standard Deviation**	**Maximum**
1	Control	0.18	0.03	0.13	0.23	0.00	0.00	0.00
	Exp. 1	0.19	0.04	0.07	0.26	0.002	0.004	0.02
	Exp. 2	0.18	0.03	0.12	0.28	0.001	0.003	0.01
	Exp. 3	0.19	0.04	0.09	0.32	0.00	0.00	0.00
	Exp. 4	0.19	0.02	0.15	0.25	0.00	0.00	0.00
2	Control	0.13	0.03	0.10	0.26	0.01	0.007	0.03
	Exp. 1	0.14	0.06	0.01	0.31	0.002	0.01	0.06
	Exp. 2	0.14	0.06	0.06	0.31	0.001	0.003	0.02
	Exp. 3	0.13	0.06	0.01	0.31	0.005	0.01	0.04
	Exp. 4	0.18	0.05	0.08	0.27	0.00	0.00	0.00
3	Control	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Exp. 1	0.06	0.02	0.03	0.16	0.01	0.008	0.03
	Exp. 2	0.06	0.02	0.03	0.15	0.01	0.009	0.04
	Exp. 3	0.11	0.03	0.07	0.23	0.004	0.006	0.02
	Exp. 4	0.18	0.03	0.10	0.26	0.0003	0.002	0.01
4	Control	0.12	0.03	0.10	0.29	0.0003	0.002	0.01
	Exp. 1	0.12	0.03	0.11	0.25	0.00	0.00	0.00
	Exp. 2	0.12	0.02	0.11	0.22	0.001	0.006	0.03
	Exp. 3	0.11	0.02	0.00	0.17	0.00	0.00	0.00
	Exp. 4	0.18	0.03	0.00	0.23	0.00	0.00	0.00
5	Control	0.25	0.07	0.05	0.35	0.001	0.005	0.03
	Exp. 1	0.26	0.07	0.08	0.37	0.003	0.015	0.09
	Exp. 2	0.24	0.07	0.03	0.38	0.004	0.02	0.08
	Exp. 3	0.24	0.07	0.00	0.37	0.008	0.03	0.16
	Exp. 4	0.18	0.05	0.00	0.28	0.002	0.01	0.06

4.5. Gap

Vehicle gap or the distance in tame from the participant's front bumper to the rear bumper of the vehicle ahead was utilized to quantify safe following distances indicating the presence of tailgating (an indication of aggressive driving) which increases the probability of rear-end collisions. It is widely accepted that safe following distances are in the range between two and three seconds. The gap for each participant was recorded at a rate of 60 hertz. The mean gap and standard deviation for all the participants were calculated for each area by scenario and are provided in Table 4 along with minimum and maximum values.

Table 4. Gap Data Summary

Area	Scenario	Mean (seconds)	Standard Deviation	Minimum (seconds)	Maximum (seconds)
1	Control	0.94	1.65	0.00	6.03
	Exp. 1	2.59	1.22	0.00	4.94
	Exp. 2	2.90	1.20	0.00	5.30
	Exp. 3	3.39	1.67	0.00	7.44
	Exp. 4	2.90	2.27	0.00	7.12
2	Control	2.30	1.50	0.60	6.27
	Exp. 1	2.75	1.46	0.92	7.39
	Exp. 2	3.36	1.64	1.01	7.27
	Exp. 3	2.76	1.56	0.00	6.80
	Exp. 4	3.44	2.50	0.00	8.66
3	Control	N/A	N/A	N/A	N/A
	Exp. 1	3.27	1.23	1.09	6.12
	Exp. 2	3.53	1.37	1.20	6.44
	Exp. 3	3.21	1.95	0.46	8.89
	Exp. 4	4.30	1.94	1.03	7.72
4	Control	1.59	0.86	0.55	5.06
	Exp. 1	0.87	0.95	0.76	4.35
	Exp. 2	1.79	0.85	0.70	4.23
	Exp. 3	3.03	2.37	0.00	8.81
	Exp. 4	3.41	1.72	0.00	7.33
5	Control	3.21	1.66	0.73	7.62
	Exp. 1	3.06	1.67	0.71	7.22
	Exp. 2	2.62	1.63	0.00	7.22
	Exp. 3	3.46	2.29	0.00	10.21
	Exp. 4	2.51	2.32	0.00	7.81

4.6. Time to Collision

While crashes are commonly utilized to assess roadway safety, traffic crashes are rare events. In work zone situations, the temporary nature of the work zones and the short duration of the project or exposure compound the rarity. In order to overcome inadequate crash sample sizes for statistical analysis, traffic conflicts are commonly utilized. A traffic conflict is an evasive maneuver by a vehicle to avoid a collision with another vehicle or a fixed object. Traffic conflicts can be measured in terms of the time in seconds to a collision with the vehicle ahead if both vehicles maintained their present speed and direction. The time to collision was recorded at a rate of 60 hertz for each participant. The mean time to collision and standard deviation for all the participants were calculated for each area by scenario and are provided in Table 5 along with maximum values. Minimum values were all recorded at 0.00 and therefore have not been shown.

Table 5. Time to Collision Data Summary

Area	Scenario	Mean (seconds)	Standard Deviation	Maximum (seconds)
1	Control	84.50	60.23	228.38
	Exp. 1	108.97	148.40	877.40
	Exp. 2	124.03	113.27	591.00
	Exp. 3	278.05	1277.01	8038.76
	Exp. 4	176.75	306.50	1494.29
2	Control	99.31	78.03	449.07
	Exp. 1	145.88	217.45	975.67
	Exp. 2	261.82	416.05	1783.92
	Exp. 3	135.67	143.36	739.48
	Exp. 4	133.93	203.37	873.98
3	Control	N/A	N/A	N/A
	Exp. 1	78.29	32.58	184.56
	Exp. 2	82.76	43.06	191.57
	Exp. 3	184.36	192.92	756.99
	Exp. 4	246.92	291.77	1141.37
4	Control	181.91	115.66	641.56
	Exp. 1	166.02	90.32	457.35
	Exp. 2	168.77	93.95	526.19
	Exp. 3	273.52	289.42	1297.29
	Exp. 4	194.03	227.65	1261.66
5	Control	176.52	263.88	1591.83
	Exp. 1	248.77	358.60	1440.95
	Exp. 2	232.51	574.74	3034.39
	Exp. 3	278.59	756.46	4674.06
	Exp. 4	146.47	219.08	952.04

4.7. Latency Fixation

The latency of visual detection for this research is the time differential between the first appearance of the dynamic speed sign and the participant's fixation on the dynamic speed sign. Faster detection time allow drivers to perceive and react to the object thereby reducing the crash likelihood. The latency of visual detection was recorded using the eye-tracking system at a rate of 60 hertz and was measured in seconds. The mean latency fixation and standard deviation for all the participants were calculated for each scenario and are provided in Table 6 along with the maximum values. Minimum values were all recorded at 0.00 and therefore have not been shown.

Table 6. Latency Fixation Data Summary

Scenario	Mean (seconds)	Standard Deviation	Maximum (seconds)
Exp. 1	2.08	2.80	11.03
Exp. 2	1.80	2.38	10.72
Exp. 3	1.54	1.88	9.88
Exp. 4	1.23	1.28	5.07

4.8. Average Fixation Duration

Average fixation durations provide insight into safe driving habits. Previous research has indicated that mean fixation durations of 1.6 to 2.0 seconds are indicative of safe driving habits. However, high distributions with low mean fixations are considered unsafe as the driver is unable to cognitively acquire adequate information. The average fixation duration was considered as a stable eye position of at least 100 milliseconds focusing on the dynamic speed sign and measured in seconds. The average fixation duration was recorded at a rate of 60 hertz using the eye-tracking system. The average fixation duration and standard deviation for each scenario are provided in Table 7 along with the maximum values. Minimum values were all recorded at 0.00 and therefore have not been shown.

Table 7. Average Fixation Duration Data Summary

Scenario	Mean (seconds)	Standard Deviation	Maximum (seconds)
Exp. 1	0.51	0.41	1.70
Exp. 2	0.65	0.54	1.85
Exp. 3	0.65	0.45	2.18
Exp. 4	0.54	0.46	2.15

4.9. Proportion of Target Fixations

The proportion of target fixations is the proportion of time the participant spent fixating on the dynamic speed sign divided by the total time fixating on the virtual world. Higher percentages of time when the driver is focused away from the roadway or the field of interest indicate poor visual attention skills leading to a higher likelihood of a crash. The proportion of target fixations was recorded using the eye-tracking system at a rate of 60 hertz and is measured as a decimal percentage. The mean proportion of target fixations and standard deviation for all participants were calculated for each scenario by area and are provided in Table 8 along with the maximum values. Minimum values were all recorded at 0.00 and therefore have not been shown.

Table 8. Proportion of Target Fixations Data Summary

Scenario	Mean	Standard Deviation	Maximum
Exp. 1	0.10	0.09	0.32
Exp. 2	0.11	0.08	0.32
Exp. 3	0.12	0.09	0.46
Exp. 4	0.11	0.10	0.46

5.0 STATISTICAL METHODOLOGY

The statistical significance of the various dynamic speed sign configurations on driver performance and behavior was determined through examinations of the measures of effectiveness. The statistical analysis performed for the measures of effectiveness included those for normality, homogeneous variances and a one-way analysis of variance (ANOVA). The following sections outline each of the statistical analyses referenced above.

5.1. Normality

The data distributions were examined objectively for normality through a review of the z-scores for skewness and kurtosis. The skewness and kurtosis factors of a distribution numerically describe the divergence from normality where the factors are equal to zero. As the normal distribution cannot be described by one distribution with a particularly mean and standard deviation, the skewness and kurtosis factors must be converted to z-scores representing the standard normal distribution. The z-score for each factor was determined by dividing the factor by the standard error of the factor. The z-score is then compared to the absolute value of 1.96 or the z-score for a 95 percent level of confidence.

5.2. Homogeneity of Variances

Equality among group variances must be verified to maintain power and robustness for various statistical tests. To test the equality, the Levene's test and the F-max test were utilized. Levene's test examined variances for several groups without compromising power, unlike the F Max test which utilized multiple tests to determine similar results. The Levene test statistic is:

$$W = \frac{(N - k)}{(k-1)} \frac{\sum_{i=1}^{k} N_i (\bar{Z}_{i.} - \bar{Z}_{..})^2}{\sum_{i=1}^{k} \sum_{j=1}^{N_i} (Z_{ij} - \bar{Z}_{i.})^2}$$

Where,

N = the sample size
k = the number of groups tested
$Z_{ij} = \left| Y_{ij} - \bar{Y}_{i.} \right|$

The F Max test is simply the ratio of the two variances of the samples where the larger of the two variances is utilized in the numerator. The test statistic for the F Max test is:

$$F = \frac{s_1^2}{s_2^2}$$

The critical values for the Levene's test and the F Max test were based upon the F-distribution and were determined by the number of degrees of freedom as well as a 95 percent level of confidence or alpha equal to 0.05. The Levene's test F-calculated value was also based upon the number of groups tested. If the F-calculated exceeded the F-critical, the assumption of homogeneity failed. Levene's test allowed slight deviations from normality in order for various statistical tests to retain power and robustness. If the differences in the variances were found statistically significant with the Levene's test, Box suggested utilizing the ratio calculation of the F Max Test to determine if the differences in variances were significant. If the ratio was calculated less than the square root of three or 1.73, then the threat to the robustness would be considered mitigated.

5.3. Analysis of Variance (ANOVA)

In order to compare several means simultaneously, a one-way analysis of variance (ANOVA) was utilized to determine if the means were similar. Although a Student's t-test could have been conducted on the same data, several iterations of the t-test would be required in order to compare all possible scenarios. However, the Type I error rate is greater when multiple t-tests are conducted and can be calculated as follows:

$$\text{Type I Error Rate} = 1 - (1 - \alpha)^c$$

Where:

α= the level of confidence for each t-test
C = the number of independent t-tests

The ANOVA determines the level of confidence based upon the number of dependent variable categories that are being compared. The one-way ANOVA required the comparison of one independent variable, for example, scenario, with several categories of the dependent variable, such as mean speed. The assumptions for the ANOVA are similar to those for the Student's t-test. The data must be continuous, independent, follow the normal distribution and have equal variances. Violations of these assumptions impact the results of the test; however, the robustness of the ANOVA varies from the Student's t-test. For instance, the ANOVA is considered a very robust test even with the violation of normality, unless the variances and sample sizes are unequal. To perform the ANOVA, an F-statistic is calculated which is equal to the mean squares between the groups divided by the mean squares within the groups. If F-calculated was greater than the F-critical obtained in available statistical tables, the difference in the means was statistically significant. When conducting the ANOVA test, the Levene's test for equal variances was performed simultaneously. When the Levene's test indicated that the variances were equal, the ANOVA calculated F-statistic was reported. If the variances were determined not to be equal, the Welch's modification to the ANOVA was conducted and the calculated F value based upon an asymptotically distribution was reported. The equations used to perform this test are as follows:

$$SS_T = \sum_{k=1}^{K}\sum_{i=1}^{n_k} X_{ik}^2 - \frac{T^2}{N}$$

Where:

SS_T = Total sum of squares
$\sum_{k=1}^{K}\sum_{i=1}^{n_k} X_{ik}^2$ = squared scores summed across all individuals and groups
K = Number of groups

n = Number of observations
T = sum of scores summed across all observations and groups
N = total number of scores

$$SS_B = \sum_{k=1}^{K} \frac{T_k^2}{n_k} - \frac{T^2}{N}$$

Where:

SS_B = Sum of squares between-groups
T_k= sum of observations for k^{th} group

$$SS_W = \sum_{k=1}^{K}\sum_{i=1}^{n_k} X_{ik}^2 - \sum_{k=1}^{k} \frac{T_k^2}{n_k}$$

Where:

SS_W = Sum of squares within-groups

$$MS_B = \frac{SS_B}{K - 1}$$

$$MS_W = \frac{SS_W}{N - K}$$

$$F_{calc} = \frac{MS_B}{MS_W}$$

Where:

MS_B = Mean sum of squares between-groups
MS_W = Mean sum of squares within-groups

When statistically significant results are obtained in the ANOVA, the only conclusion that can be drawn from the test is that differences exist between the means. However, the determination of which two means are in fact not equal cannot be concluded. Therefore, in order to solve this issue, post-hoc tests can be utilized to assist in specific comparisons among groups. There are numerous post-hoc tests that have been established for various assumptions or violation of assumptions. Most of the post-hoc tests have been shown in past statistical research to withstand small deviations from normality. If the variances and the sample sizes are not equal, the Games-Howell test is the most appropriate post hoc test.

5.4. Practical Significance

The statistical tests performed in this research indicated whether the differences in comparisons made were statistically significant. However, a comparison being significantly statistically different indicates only that the probability of the difference between the experimental data and the expected values computed from a given statistical distribution occurring due to chance is less than the significance level, in this research alpha equaled 0.05. Statistical significance is based on the standard error of the sample which can be controlled by sample sized. Large sample sizes lower the standard error and will correspondingly lower the threshold for considering differences to be significant. Conversely, a small sample size can cause a large difference between groups to be statistically insignificant when in reality the difference may be practically significant.

One method provided to consider the practical significance of a result is through the calculation of the effect size. By definition the effect size is the degree to which a phenomenon exists. In this research, the phenomenon would be the diamond grade sheeting caused statistically significant differences in lane placement and traveled speed within work zones when compared to the high intensity sheeting. The effect size calculated is a measure of the number of standard deviations the difference between the groups is from the null hypothesis. The effect size was calculated as follows:

$$r = \sqrt{\frac{SS_B}{SS_T}}$$

Where:

r = effect size
SS_B = sun of squares between groups
SS_T = total sum of squares

Based on standards presented by Cohen, the practical significance, or actual difference of the comparisons made, is as follows:

r = 0.20	Small Effect
r = 0.50	Medium Effect
r = 0.80	Large Effect

6.0 RESULTS

The purpose of the simulator experiment was to determine driver performance and behavior including speed compliance based upon dynamic speed design and presence. Driver performance and behavior was collected through the simulator and eye-tracking system. The measures of effectiveness included the following: speed, lane position, acceleration, deceleration, gap, time to collision, latency of visual detection, average fixation durations and the proportion of target fixations. Each participant drove through a control scenario and four experimental scenarios subdivided into five areas for data collection. The four experimental scenarios included dynamic speed signs in place of the regulatory speed limit sign as follows: (1) Steady 'SLOW DOWN 45', (2) Flashing 'SLOW DOWN 45', (3) Steady 'SPEED LIMIT 45' and (4) Steady 'SPEED LIMIT 65'. The five areas included the following: (1) Before the first work zone sign, (2) Between the first work zone sign and the dynamic speed sign, (3) Between the dynamic speed sign and the lane closure, (4) Between the lane closure and the end of the work zone, and (5) After the work zone. Comparisons were made of the measures of effectiveness for each area and scenario using an ANOVA with a level of confidence of 95 percent. As expected, the measures of effectiveness were similar for the area before the first work zone sign and after the work zone due to the typical layout of the work zones in the scenarios. It was expected that before or after the dynamic speed signs and in the work zone, drivers would exhibit changes in performance and behavior. The data was found to deviate from normality and when the threat to the robustness of the test was threatened due to the lack of homogeneous variances, the Welch's modification to the ANOVA was utilized to determine statistical significance. The following sections detail the results of the statistical analysis for each measure of effectiveness.

6.1. Focus Group

The participants obtained from convenience and purposive sampling procedures for the driving simulator experiment totaled 39 individuals generally representing the most hazardous age group and gender (Males between the ages of 16 and 25). In a pre-test questionnaire, the participants commented on their driving experiences in terms of roadway congestion and their daily driving habits. In regards to their driving behavior when approaching roadway congestion, 28 percent of the participants acknowledged exhibiting aggressive behavior in the past when encountering roadway congestion. Over 56 percent of the participants believe roadway congestion in work zones is caused by roadway factors such as lane reductions and lower speed limits. However, in non-work zones nearly 60 percent of the participants believe roadway congestion is caused by drivers related to distracted driving and careless driving leading to crashes. The post-test survey aimed at determining the participant's assessment of the dynamic speed signs, anticipated compliance and recommendations of measures to reduce congestion. 13 percent of the participants felt the dynamic speed sign should be larger in size, which would indicate that an oversized speed sign is not adequate to deliver information to drivers. Ten percent of the participants also felt the information provided was lacking and that more information on the traffic flow ahead should be provided. Participants generally identified the purpose of the dynamic speed sign as a speed reduction measure prior to the work zone as well as the ability to alter the speed limit based upon the presence of workers in the work zone.

6.2. Speed

The analysis of speed data was used as an indication of a motorist's perceived risk of traveling through a specific area of the roadway given various conditions. Significant differences were found for the speed data particularly for the areas between the dynamic speed sign and the end of the work zone (Areas 3 and 4). The scenarios utilizing the dynamic speed signs stating 'SLOW DOWN 45', either flashing or constant, were similar and yielded lower speeds by more than 18 miles per hour than the dynamic speed sign stating the speed limit as 45 miles per hour. The scenario with a posted speed limit of 65 miles per hour was significantly different from the other three experimental scenarios; however, the speeds did not differ from the speed limit of 65 miles per hour. The analysis for Area 4 did not produce significant results between the two experimental scenarios with the 'SLOW DOWN' message and the posted speed limit; however, there was approximately a two mile per hour lower speed for the 'SLOW DOWN' scenarios. The analysis indicates the effect size was large producing a significant practical difference as well as statistical difference. The results of the analysis are shown in Table 9.

Table 9. Speed Data Statistical Results for Area 3

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	p-value	Effect Size
Between Groups	94789.83	4	23697.47	0.00	0.96
Within Groups	4105.21	190	21.61		
Total	98895.04	194			

6.3. Lane Placement

Lane placement data was collected for to assess the ability of the participant to maintain a constant lane position. Based upon the ANOVA analysis, the lane position of the participants was statistically similar for each of the four experimental scenarios. This indicated that the message on the dynamic speed sign or its presence did not impact driver behavior.

6.4. Acceleration and Deceleration

Acceleration and ceceleration data was used as an indication of the participant's reaction time and attention span while driving through the scenarios. Based upon the ANOVA analysis, the acceleration and deceleration differed among the three experimental scenarios with speed limits of 45 miles per hour and the experimental scenario with a speed limit of 65 miles per hour, as expected. Area 3 produced statistically significant results between the 'SLOW DOWN' experimental scenarios and the posted speed limit scenario for both the acceleration and deceleration.

6.5. Gap

The analysis of gap data was used as to quantify safe traveling distances through a specific area of the roadway given various conditions. Significant differences were found for the gap data for the area between the lane closure and the end of the work zone (Area 4). The scenarios utilizing the dynamic speed signs stating 'SLOW DOWN' with a speed listed at 45 miles per hour, either flashing or constant, were similar and yielded lower gaps by more than 1.5 seconds than the dynamic speed sign stating the speed limit as 45 miles per hour which yielded a gap of approximately three seconds. The analysis indicates the effect size was small producing a limited practical difference. The results of the analysis are shown in Table 10.

Table 10. Gap Data Statistical Results for Area 4

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	p-value	Effect Size
Between Groups	106.14	4	26.535	0.00	0.20
Within Groups	416.32	190	2.19		
Total	522.46	194			

6.6. Time to Collision

The analysis of time to collision data was used as a surrogate for crash data to determine the risk associated with a particular scenario. Significant differences were found for the time to collision data for the area between the dynamic speed sign and the lane closure (Area 3). The scenarios utilizing the dynamic speed signs stating 'SLOW DOWN' with a speed listed at 45 miles per hour, either flashing or constant, were similar and yielded smaller times to collisions by more than half the seconds than the dynamic speed sign stating the speed limit as 45 miles per hour. The scenario with a posted speed limit of 65 miles per hour was significantly different from the other three experimental scenarios. The analysis indicates the effect size was small producing a limited practical difference. The results of the analysis are shown in Table 11.

Table 11. Time to Collision Data Statistical Results for Area 3

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	p-value	Effect Size
Between Groups	1472815.561	4	368203.89	0.00	0.24
Within Groups	4760050.87	190	25052.90		
Total	6232866.43	194			

6.7. Latency of Visual Detection

The latency of visual detection examined the time differential between the presence of the dynamic speed sign and the participant's fixation on the sign. The four experimental scenarios included different messages on the dynamic speed sign including one scenario with a flashing message. The ANOVA did not indicate a statistical difference between the four experimental scenarios. However, the latency of visual detection for the 'SLOW DOWN' messages was longer than the posted speed limit messages.

6.8. Average Fixation Duration

Average fixation durations determine if the driver is cognitively aware of the message of the dynamic speed sign. While the ANOVA did not indicate a statistical difference between the four experimental scenarios, the mean fixation durations indicate that the participants focuses on the dynamic speed signs for a very short period of time. Previous research has stated that mean fixation durations of 1.6 to 2.0 seconds are necessary for a driver to cognitively understand a message; however, the participants of the study were focused on the dynamic speed sign for less than one second. This could be due to the common nature of similar signs along roadways and the message is clear to drivers without cognitive processing.

6.9. Proportion of Target Fixations

The proportion of target fixations on the dynamic speeds signs was used to determine what percentage of time the participant was focused on the dynamic speed sign and not along the roadway. The ANOVA analysis indicated there was not a difference between the experimental scenarios. In general, the participants viewed the dynamic speed signs for ten percent of the time while approaching the sign and 90 percent of the time on the roadway ahead. This is indicative of safe driving habits.

7.0 CONCLUSIONS

The objective of this research was to determine driver performance and behavioral changes as a result of the presence of various dynamic speed signs. A simulator study was used in this research to determine speed compliance based upon the presence of dynamic speed signs and to assess if the dynamic speed signs were distracting to drivers thereby potentially creating unsafe driving conditions.

Typical measures to notify drivers of speed limits or the reduction of such through work zones has been the use of regulatory speed limit signs with advanced warning signs notifying drivers of the upcoming reduction. However, speed compliance has been known to be a concern through work zones.

Based upon the results of the simulator study, alternatives to traditional speed limit signs seem to improve speed compliance. When using dynamic message signs stating ‘SLOW DOWN 45’, participants maintained the speed limit prior to entering the work zone and through the work zone as compared to scenarios using regulatory signs or dynamic message signs displaying the speed limit. The dynamic message signs did not create unsafe driving conditions based upon the analysis of the other measures of effectiveness studied.

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