ABSTRACT

Title of Thesis: Impact of Work Zone Signage on Driver Speeding Behavior: A Driving Simulator Study

Duwan Morris, M.S. May, 2019

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Driving in a work zone can be dangerous. To enhance and maximize safety in work zones, we must strategically address important issues such as speeding. In this study, a high fidelity driving simulator is used to evaluate the effectiveness of three different work zone signs including speed photo enforced, dynamic speed display signs (DSDS), and reduced speed limit as it relates to driver behavior. These signs were used to compare speed in a scenario where there was no sign. The simulated area for this study was (MD-295) which connects Washington D.C to Baltimore, Maryland. Signs were strategically placed informing drivers before entering the work zone. Additional signs were placed in the work zone in attempt to change driver behavior. Data was collected from 66 participants who drove approximately 264 driving simulations. The study involved four phases which included initial speed area, sign visible area, sign readable area, and post-sign area. These areas were used comparing speed, finding the effectiveness of signs in each area. The result from an ANOVA and post hoc analysis showed that the best sign of the three tested was the speed-photo-enforced sign; which cause the greatest decrease in speed. In addition, results show female participants are more successful than male participants in decreasing speed when seeing the photo-enforcement sign.

Keywords: Work Zone, Driving Simulator, Speed Study, Speed Sign

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by

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Chapter 1: Introduction

Speeding in a work zone is not only a hazard to motorists, but workers are at great risk as well. The Federal Highway Administration (FHWA) reported in 2008, accidents within work zones counted for more than 40,000 injuries and over 720 fatalities (Banerjee, Jeihani, & Moghaddam, 2018). More than 100 crew members die in work zone related crashes each year (Morris, Cooper, Ton, Plummer, & Easterlund, 2016). The total cost of work zone crashes count for billions of dollars and is steadily increasing due to congestion and traffic on our roadways (S. B. Mohan & Gautam, 2002). To stop the increase in fatalities, accidents, and work zone accident cost, improvements in work zone signage should be considered. Since ineffective signs have caused risks and increased accidents and fatalities; signs should be properly tested for effectiveness before implementation. (Reyes, Khan, & Initiative, 2008).

The literature shows that researchers have focused on evaluating the influence of a single sign on speeding behavior (Ardeshiri & Jeihani, 2014; Rahim F. Benekohal, Wang, Chitturi, Hajbabaie, & Medina, 2009; N. Garber & Srinivasan, 1998; McAvoy & Center, 2011; Morris et al., 2016). Consequently, from these studies, the effectiveness of different signs cannot be truly compared, since they are not subjected to the same conditions and study environment. This study evaluates 3 different signs: speed photo enforced sign, DSDS and a reduced speed limit sign; in a high-speed work zone on speeding behavior. Speed photo enforced signs and reduced speed limit signs are placed before the start of the work zone and in the work zone to test the effect on driver speeding behavior. Results from this study can be used by safety experts to deploy the most effective signage compelling drivers to slow down in a work zone, thereby safeguarding both the driver and work zone crews.

The objective of this thesis is to identify and test the most effective signage on driver speeding behavior in different areas of a work zone. Furthermore, this thesis validates the impact of signage on reducing driver speed. The signs that are used to test the effect on driver speeding behavior in this study are photo enforcement, DSDS and speed limit signs.

The hypothesis in this thesis is that proper signage in work zones can effectively decrease driver speed and improve work zone safety. Moreover, as drivers enter work zones, drivers will be compelled to decrease speed due to the placement of continuous signage.

Chapter 2: Literature Review

Work Zone and Crash

An important factor of accidents and fatalities in work zones has been identified as speeding by some research studies (Bai & Li, 2007; Bryden, Andrew, & Fortuniewicz, 2000; S. Dissanayake & Akepati, 2009; N. J. Garber & Zhao, 2002). In 2008, Kansas State University reported (S. Dissanayake & Akepati, 2009) 225 out of 720 cases causing fatalities across work zones were related to speeding. In the United States, nearly 15% of fatal crashes and 20% of injury crashes were associated with speeding from an additional work zone crash study that the Kansas state conducted (Li & Bai, 2009).
Furthermore, higher accident rates in work zones can be a result of larger speed variances. The relationship between travel speed and accident rates indicates that when speed differences between different vehicles increase, the accident risk increases as well (Salem, Genaidy, Wei, & Deshpande, 2006).

Work zones are highly overrepresented in terms of their impact on road safety, even though they are relatively infrequent during every day driving. 2006 data recorded over 1000 fatal crashes in work zones according to the U.S. National Highway Traffic Safety Administration (NHTSA, 2008).

The NHTSA also developed a study that found an elevated risk indicating once inside the work zone, the total crash rate was 21.5% higher than a comparable pre-work area. Council et al noticed that when crash frequencies are considered, factors of work zone duration and length are those which most systematically contribute to this increased risk. These are surely not unprecedented conclusions since previous researchers had earlier reported similar increasing collision trends as it relates to work zones (Khattak, Khattak, & Council, 2002).

Five distinct types of work zone collisions were found in an analysis by New York State researchers Mohan and Zech (S. Mohan & Zech, 2005). The New York State Department of Transportation construction projects examined the majority of incidents in work zones from 1999 to 2001 included work space intrusion, workers struck by vehicles inside work zones, flag bearers struck by vehicles, workers struck by vehicles entering/exiting work spaces, and construction equipment struck by vehicles inside work spaces. It has been no surprise that these 5 crash types accounted for nearly 86% of fatal injuries and 70% of hospitalizations experienced in work zone areas.

In a more general evaluation, Bryden and Andrew (2000) found work zone intrusion accidents accounted for 10% of all total traffic accidents and 8% of all serious injuries (Bryden et al., 2000).

Based on these findings, any effort to improve the safety buffer between drivers and the vulnerable elements of the work zone is a critical step in increasing safety. From the total reported crash data, any work zone improvements serve to enhance the safety of the overall transportation system to a significant degree. Reducing vehicle speed before and at the actual onset of a work zone presents one of the most promising means of decreasing collisions. However, this form of remediation is complicated by driver behavior patterns immediately prior to work zone entry. For example, a significant portion of drivers wait until the point of lane closure before they begin the process of merging (Rahim F. Benekohal, Orloski, & Hashmi, 1993).

This often leads to situations where drivers can be unaware of the need to, or are unable to adequately slow or stop upon entering the work zone area (Sorock, Ranney, & Lehto, 1996).

In situations where drivers change lanes so late, the associated crash risk significantly increases. Accordingly, this has led some researchers to conclude that appropriate and clear roadway markings are vital for safe work zone travel (Pietrucha, 1995).

In highly motorized countries such as the United States (US), Great Britain, and the Netherlands reported that about 1–2% of road fatalities occur in work zones (Debnath, Blackman, & Haworth, 2015). Although this is a rather low proportion of all road fatalities, crash rates appear to increase significantly during roadworks compared to pre-work periods (Debnath et al., 2015). Additionally, research has proven that work zone crashes are also more severe than other crashes (Pigman & Agent, 1990).

However, threats in work zones have typically been studied through analyses of historical crash data to identify the reasons contributing to the frequency of work zone crashes (Debnath et al., 2015) and their injury severity (Yang, Ozbay, Ozturk, & Xie, 2015).

Although a driver may have crashed because of speeding or risky driving in the work zone, a crash may not be documented as a work zone crash. The lacks of crash data limit the scope for revealing the common hazards in Australian work zones and consequently little is known about their relative contribution to crash connection. Studies utilizing crash data from other countries assists in providing valued visions into the risk of work zones. Researchers have found fairly little information about what road workers think regarding work zone and its risks.

The need for maintenance, rehabilitation, and upgrading of the existing networks is steady increasing since most of the U.S. highway infrastructure is aging. Therefore, motorist are increasingly exposed to work zone activities during travel.
Motorists encounter an active work zone for every average 100 miles driven on the national highway system (Ullman, Finley, & Ullman, 2004).

This number can be much larger in view of other work zones implemented on municipal, county, and state roads. The presence of so many work zones directly affects the safety of road users and highway workers. The latest safety statistics reported, 667 work zone fatalities occurred in the U.S. in 2009. Approximately 85 percent of those killed in work zone were motorist or passengers and the remaining 15 percent were work zone workers. In addition to these fatalities, more than 40,000 injuries resulted from motor vehicle crashes in work zones in addition to these fatalities (FHWA, 2011). FHWA, 2011. Safe driving, safer work zones: national work zone awareness week 2011. FOCUS, March 4–5.

As shown by many studies (Yang, Ozbay, Ozturk, & Yildirimoglu, 2013) compared with the normal road conditions, crash rates increase in the existence and presence of work zones. This increase can be related to the inconveniency of the work zone circumstance that disturbs continuing traffic flow and makes many traffic conflicts. Conversely, exact reasons is why more crashes occur at work zones may still not be vibrant (Venugopal & Tarko, 2000; (R. Harb, Radwan, Yan, Pande, & Abdel-Aty, 2008; Khattak et al., 2002).

In order to decrease the number of fatalities and injuries and to improve traffic operation and safety within work zones, we must completely understand of the hazard features connected to work zone crash incidence. Nevertheless, many site and state-specific factors need to be studied to better understand the causes of work zone crashes. A number of studies have accompanied work zone safety analysis. However, majority of them focused on the development of the descriptive statistics of work zone crash data to interpret the characteristics such as crash experience, consequences, temporal, and spatial distributions of crashes at work zones (Bushman, Chan, & Berthelot, 2005; Sunanda Dissanayake & Akepati, 2009; N. J. Garber & Zhao, 2002; R. Harb et al., 2008; Jin, Saito, & Eggett, 2008; Li & Bai, 2008; Müngen & Gürcanli, 2005; Salem et al., 2006; Schrock, Ullman, Cothron, Kraus, & Voigt, 2004; Yang et al., 2013).

Commonly, the literature indicated that the existence of work zones surges the probability of crash happening (Venugopal and Tarko, 2000; Khattak et al., 2002; Qi et al., 2005; Harb et al., 2008a; Ullman et al., 2008)(R. C. Harb, Essam Radwan PHD, Yan, Mohamed Abdel-Aty PHD, & Pande, 2008; Khattak et al., 2002, 2002; Qi, Srinivasan, Teng, & Baker, 2005; Venugopal & Tarko, 2000).

Also, crashes were found to unreasonably happen across different sectors of work zones. For example, the work zone activity area was the major location of crashes and rear-end collision was the main form of crash (Center et al., 2007; N. J. Garber & Zhao, 2002; Salem et al., 2006)

When comparing daytime and nighttime work zone crashes, there was no strong evidence that crash rate significantly increased at night (Daniel et al., 2000; Ullman et al., 2004a; Udoka, 2005; Ullman et al., 2008)(Daniel, Dixon, & Jared, 2000; Ullman, Finley, Bryden, Srinivasan, & Council, 2008; Ullman et al., 2004; Xing, Takahashi, & Iida, 2010; Yang et al., 2013). For example, work zone crash data resulting from police crash reports were usually subject to a number of hesitations (Daniel et al., 2000).

Pal & Sinha (1996) displayed crashes at regional work zones in Indiana and found that a normal regression model outperformed the classical NB and Poisson models. Similarly, Qi et al. (2005) constructed the truncated NB regression model and truncated Poisson regression model to analyze the rear-end crashes at work zones in New York. The truncated NB regression model was found to have better analytical power. Other than these observed models, Yang et al. (2013) used the Monte Carlo simulation approach to progress a crash rate probability distribution function that considered the intrinsic lack of work zone crash data.

Despite of model differences, factors most commonly found to significantly affect work zone CF included the length of the work zone, duration, and average daily traffic (ADT). Usually, the modeling results showed that work zone CF increased with increasing ADT, duration, and work zone length. A probable reason of why few studies explored the casual factors associated with work zone CF is the shortages of work zone data as stated in (Bourne et al., 2010; Pal & Sinha, 1996; Salem et al., 2006)

Explanatory variables such as ADT, work zone length, and duration were also found to be issue to measurement errors. For example, the occurrence of significant unfairness was found when using the estimated ADT instead of the real volume during work zone circumstances (Venugopal & Tarko, 2000).

Difficulties in explaining the length of certain work zones such as bridge works and those involving detours were recognized by some studies (Venugopal & Tarko, 2000).

Work zone and Speed

For enhanced traffic safety, study of driver behavior has fundamental significance (Reyes et al., 2008). There are diverse factors which impact the speed of vehicles while traveling through a work zone such as road geometry, warning signs and traffic control devices, speed displays and law enforcement (Noel, Dudek, Pendleton, McGee, & Sabra, 1987). In different road conditions, drivers alter their vehicle speed in response to traffic control devices and roadway geometry (Rahim F. Benekohal et al., 2009). The following is a summary of prior research on speeding behavior using different signs.

When all vehicles are travelling at or about the same speed, the safest traffic flow conditions happen; as a result, the speed variance is small. Also, the results show that the smallest increase in the upstream-to-work-zone speed variance are the safest work zones (Migletz et al., 1998).

Although temporary speed limits induce the drivers to reduce their speed, lower speed limits do not necessarily result in a lower speed variance (Hou, Edara, & Sun, 2013). More than 270 technical methods used to manage and control the speed of vehicles in road work zones. Informational measures (such as signs and flaggers), physical systems (such as rumble strips, chicanes, lane width restrictions), and enforcement (police presence, automated control) are different kind of technical methods. Some of the most operational methods are those associated with speed monitoring and variable message signs (VMSs) when the motorist is real time notified on the driving speed or on the traffic situation ahead (Nocentini & LaTorre, 2013).

To understand the effectiveness of the speed management devices on drivers' speed, advanced warning trailer, speed camera sign, speed display, variable message sign (VMS), rumble strips, automatic speed camera and police car as a speed management devices have been tested within work zones in Czech and Belgian motorways (Cocu et al., 2014).

In 2009 Bella conducted an extensive literature review which showed that driving simulation offer enough visual information to drivers which allow them to correctly perceive speed and distance (Bella, 2009a).

In the last decade numerous researches aimed at evaluating the driving behavior before and within work zones have been carried out with driving simulators (Sommers & McAvoy, 2013).

Most of these studies were focused on evaluating the effect of different speed management systems on driving behavior and the analysis of mean speeds and decelerations. For example, In 2009, Bella accompanied a study to evaluate the driver behavior near to work zones (Bella, 2009b).

Driving simulations were used on four different work zone configurations and focused on the analysis of mean speeds and mean decelerations in response to different patterns of signaling and different work zone geometry. The results showed that drivers travel at higher speeds than that indicated on the traffic sign and are not affected by the imposed speed limits. Only within the specific area the recorded mean speeds were below the limits. Not many driving simulation studies explored the effects of these speed management systems on speed variances in the work zone area (Cocu et al., 2014).

Due to demands increasing on road network, the related construction and maintenance operations denote an undesired but essential disruption to the smooth flow of transportation system operations which cause challenges to operational safety on the roadway. The fact that driver expectation of forthcoming roadway conditions is very often violated it has been among the leading concerns created by work zone interruptions to smooth traffic flow is. Such violations occur because work zones are encountered relatively occasionally. It is difficult to predict the spatial location and also the temporal duration at any one location. In result, the driver's first encounter with any specific work zone is accountable to include surprise and uncertainty together with the necessity to engage in escaping maneuvering. Driving over work zones then obviously increase the risk of crash (J. Wang, Hughes, Council, & Paniati, 1996).

As vehicle speed is a crucial factor in work zone-related collisions (Graham, Paulsen, & Glennon, 1977), some researchers have focused on developing strategies for reducing speed within and immediately prior to work zone entry.

In one such effort, Rouphail & Tiwari (1985) hat although speed generally decreases through the work zone as the intensity of construction or maintenance activities themselves increases, simply controlling overall speed across the whole work zone also serves to reduce collision frequency.

Although there are effective measures to ensure drivers maintain safe speeds within work zones themselves (Hildebrand, Wilson, & Copeland, 2005), making the transition into the work zone as safe and predictable for drivers is a practical key to work zone safety improvements. One practical method of ensuring a safe and predictable transition out of a closing travel lane is through the use of tapering configurations. These transitional, channelized, lane closings require the driver to perform a mandatory lane change as the work zone approaches.

On high-speed rural interstate highways, reduced Speeding in work zone spaces remains to be one of the main safety worries on many of our roads. Extreme speed is among the major contributing factors most often stated for work zone accidents (McGee, 1982, p. 2).

In addressing this speeding problem, many speed control approaches ranging from enforcement by patrol vehicles (R. F. Benekohal, Resende, & Orloski, 1992; Shinar & Stiebel, 1986) to radar equipped speed monitoring devices (Bloch, 1998; Patrick T. McCoy, Bonneson, & Kollbaum, 1995) and more sophisticated changeable message sign systems (N. J. Garber & Patel, 1995; N. Garber & Srinivasan, 1998; Patrick T. McCoy & Pesti, 2002) have been studied and field-tested.

One of the promising technologies established in the late 1970s that have been successfully applied both in the U.S. and abroad has been the speed monitoring display (SMD). The SMD notifies drivers of their speeds and thereby encourages them to slow down if they are traveling above the speed limit. The objective of the system is to decrease the speed of traffic and increase speed limit compliance.

Though some primary studies (Dart & Hunter, 1976) found it ineffective, the use of the SMD technology and the research directed to the evaluation of its effectiveness has grown in recent years. Most recent studies (Bloch, 1998; P. T. McCoy & Pesti, 2000; Patrick T. McCoy et al., 1995) constantly found that vehicle speeds can be reduced by SMDs. For example, a study (P. T. McCoy & Pesti, 2000) In Nebraska the effectiveness of a SMD at a work zone on I-80, found that the 85th-percentile speed, upper limit of the pace, and mean of the highest 15 percent of speeds were reduced considerably (? = 0.05) by about 5 mph, which lowered the values of these limitations to, or below, the speed limit. Nevertheless, the functioning of the speed monitoring demonstration had only been observed during a relatively short phase of time and over a relatively short length of roadway. So, the time period and the spatial extent, for which its helpfulness could be sustained, is still unknown. A comparative study of photo-radar and SMD conducted in California found that both devices significantly (i.e., by 7-8 km/h) reduced speed. They also found that complementing an SMD with police enforcement can further increase the effectiveness. Another recent study (Carlson, Fontaine, Hawkins, Murphy, & Brown, 2000) SMDs used at rural high speed temporary work zones can be expected to reduce vehicle speeds by about 5 mph. It has also been concluded that the speed reduction effect of SMDs is about 2 to 3 mph higher than that of the radar drone and speed advisory signs. But, the temporal and spatial effects of the devices were not evaluated.

In the State of Georgia, Speed limit compliance studies performed at highway construction work zones show that although drivers reduce speeds in the vicinity of active work zones, these speeds are significantly higher than the posted speed limits (C. Wang, Dixon, & Jared, 2003).

Within the work zone, Speed limit noncompliance endangers both workers and drivers. During the period between 1995 and 1997 in the State of Georgia, a total of 158 fatal crashes or about 52 fatal crashes per year occurred within highway work zones. A major percentage of these crashes occurred on rural roadways and in idle construction work zones. Traffic control devices designed at reducing speeds within Georgia work zones may help to limit both the number and severity of the crashes therein. Although enforcement of speed limits is an effective measure to reduce speeds within work zones, this strategy is limited due to its expense and extensive manpower requirements. As a result, work zone speed reduction plans should be effective without the presence of enforcement. In this study, the research team field tested selected strategies to evaluate their ability to influence drivers to reduce vehicle speeds (C. Wang et al., 2003).

Work Zone and Sign and signals

To guide driver speeding behavior in a work zone, multiple signs were used. The most common signs used to encourage driver speeding behavior are Dynamic Speed Display Signs (DSDS), VSL (variable speed limit), Portable Changeable Message Signs (PCMS), reduced speed limit signs and speed photo enforcement (Bloch, 1998; N. Garber & Srinivasan, 1998; McAvoy & Center, 2011). DSDS has been highly used and placed in work zones to encourage drivers to reduce speed. Several researchers has studied to confirm if DSDS has made and impact in safety in work zone (N. Garber & Srinivasan, 1998)(McAvoy & Center, 2011). When comparing DSDS and photo radar, both devices reduced vehicle speeds by 4 to 5 mph and encouraged drivers driving 10 miles over the speed limit to slow down (Bloch, 1998). In other driving simulation studies, VSL and DSDS were effective signs to reduce speed (McAvoy & Center, 2011). VSL alone can encourage drivers to slow down, but to maximize the effort, signs with messages similar to "SLOW DOWN" has encouraged drivers to slow down (McAvoy & Center, 2011). These messages had a greater impact at reducing speed by 2 mph more than VSL. Implementing DSDS in work zone, the speed was reduced by an average of 1.4 mph (Walter & Broughton, 2011) and in high speed work zones speeds were reduced greater than 10 mph (N. Garber & Srinivasan, 1998). An observation stated that DSDS were effective for a the moment that motorist see the sign, but after they pass it they start to increase speed again(Ardeshiri & Jeihani, 2014). Furthermore, studies has suggested that DSDS cannot maximize speed reduction alone. If you combine DSDS with another speed control devices such as photo enforce; drivers has a greater potential to slow down.

Speed photo enforcement sign is another way to encourage drivers to reduce speed in work zones. The presence of law enforcement and the installation of speed cameras has both been successful in encouraging drivers to comply with work zone speed (Rahim F. Benekohal et al., 2009; Debnath, Blackman, & Haworth, 2012; Migletz, Graham, & Harwood, 1993). A 16% reduction on the number of speeding vehicles was found due to the presence of photo-radar enforcement and speed display boards (Rahim F. Benekohal, Chitturi, Hajbabaie, Wang, & Medina, 2008). The average free flow speed was reduced in cars and trucks due to the presence of speed cameras (Rahim F. Benekohal et al., 2009). Researchers have found an interesting perspective from drivers when it comes to work zone and speed reduction. Drivers believe that when work is not being performed there should not be a requirement to reduce speed. Drivers also believe that when the work is not in the direction of their travel, speed reduction should not be required (Migletz et al., 1998; Zech, Mohan, & Dmochowski, 2005).

PCMS is a part of intelligent transportation systems. It is used as temporary traffic control (TTC) device. These are also used in the advance-warning area of a work zone to provide real-time information to drivers. These signs are also effective in work zones and help to reduce vehicle speeds (Bham & Leu, 2018; Venkat, 2014). Studies found that concise and clearly worded messages have the most impact in influencing speed. Messages with both speed and time limit were found to be the most effective on drivers in reducing overall speed (Bham & Leu, 2018). This speed reduction was a combined effort of four PCMS used in a work zone. In another study, driver behavior was investigated when through sequential PCMS (Venkat, 2014). It was found that, drivers slow down more when a specific speed limit was shown on PCMS. Sometimes drivers don't follow the messages on the PCMS as they doubt the reliability of the signs (P. McCoy & Pesti, 2002). The drivers ignore the signs and do not slow down if the location of the sign is far from the work zone (Migletz et al., 1993).

Reduced speed limit signs are another intervention which have shown varying degrees of effectiveness in past studies (Bham & Mohammadi, 2011). However, the effectiveness of reduced speed limit signs may be dependent on sight distance, geometry of the road and posted speed limits, while in some cases the effectiveness may be dependent on the work zone location (Bham & Mohammadi, 2011). Reduced speed limit signs for extended work zones which have no ongoing activity are ineffective and have the ability to turn the drivers skeptical of additional reduced speed limit signs posted in other work zones (Outcalt, 2009). Another study found that reduced speed limit signs have very little effect on speed reduction and presence of law enforcement officers was more effective when compared to such signs (Migletz et al., 1993).

The result of Czech shows a good impact of a speed camera sign with a mean speed reduction of about 4 km/h. Also, Positive effects on reducing speed were induced by VMSs in the work zone area and by presence of a police car upstream. Results from Belgian showcases shown a localized effect of the presence of automatic speed cameras, while no significant effects were logged from other devices such as speed display and transversal rumble strips installed within the advance warning and transition areas.

Domenichini, La Torre, Branzi, & Nocentini (2017) the effects of different speed limits and enforcement devices as well as the effects of various channelization devices in four different work zone crossovers was investigated in Switzerland. The results specified that the crash rate was roughly the same of that recorded in the situation without work zone, when travel directions were structurally separated from the work zone activity area by concrete barriers. The increase of the speed limit within the transition area had no significant influence on the general speed behavior. Since the evaluation of work zone safety measures by means of field tests is costly, difficult to modify, subject to environmental changes and can pose risks for safety of both test participants and researchers, driving simulators are an effective alternative research tool allowing researchers to assess a wide range of interventions that cannot be applied on site due to legislation limitations and involving reduced operation costs and safer testing conditions.

Perhaps the largest contributor to potential safety improvements in work zones is forward signaling. The forewarning of the upcoming work zone allows drivers to make lane transitions earlier and in a more controlled manner. In a study examining driver expectancies in work zones, (Pietrucha, 1995) noted that drivers who traverse a long section of road within a work zone without encountering any signs, construction, or lane closure are unlikely to enter the directed lane until an obstacle is actually encountered.

Chapter 3: Methodology

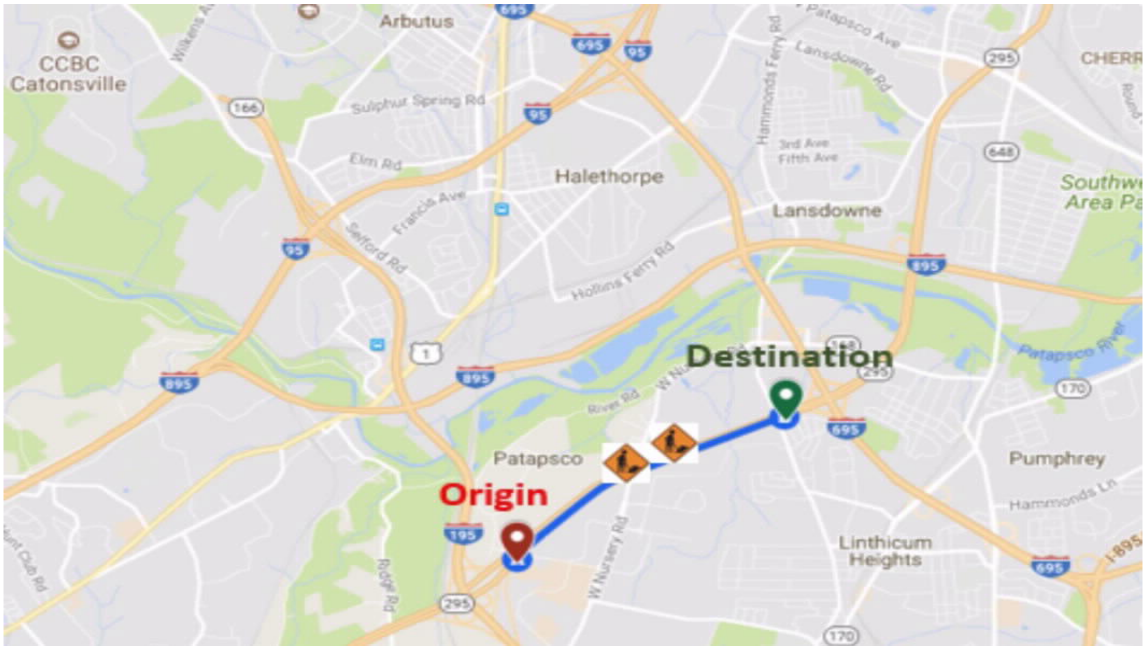
Scenario/Network Design

In this thesis, a driving simulator (Figure 1) at Morgan State University is used to examine the effect of work zone signs on speeding behavior. This thesis is a smaller portion of a larger study conducted at Morgan State University evaluating the potential effects of Dynamic Message Sign (DMS) Messages on Driver Behavior and Their Decision to Use Freeway Incident Traffic Management (FITM) Routes. The overall goal of the study was to examine the effect of DMS message content, length, type and structure on drivers' behavior. The research team's mission was to develop a framework for DMS usage based on best practices. The team used a driving simulator and survey questions to investigate potential route choice and compliance behavior. A total of 65 participants from diverse socioeconomic backgrounds and 390 simulation runs were conducted in the study. The results of the study indicate single-phase message were always preferable to two-phase messages, because motorist understand the message faster. The results also indicate that lane closure and delay information with advisory messages were found to be the most influential DMS regarding diversion. DMS with "avoid route" advice and color-coded DMS were top contributors to DMS compliance and route choice decisions.

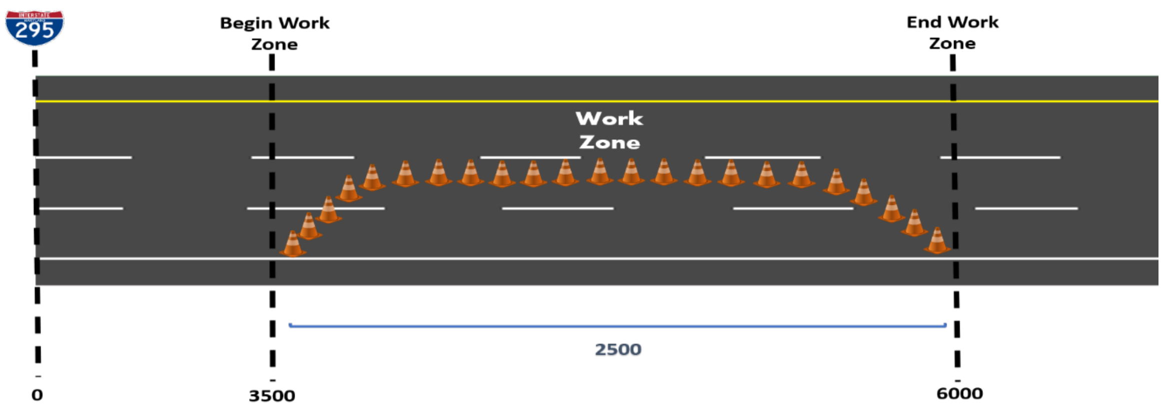
In the DMS study, there were 10 scenarios and 4 included a route with construction work zones; which this thesis talks about. The data collected from the last four scenarios of the DMS study was used to complete this work zone thesis. A simulated work zone study area was created on (MD-295) using the software, VR-Design Studio developed by FORUM8 Co. (*23*) for this thesis. In the driving simulator software, information was collected in real time such as lane-changing, acceleration, braking, steering control and speed.

Figure 1 Driving Simulator at the SABA Center, Morgan State University

MD-295 connects Baltimore, MD to Washington D.C. and has a speed limit of 55 mph. The simulation area consists of three, 12 ft lanes, while one lane was open with the other 2 lanes blocked off for construction as shown in Figure 2b.



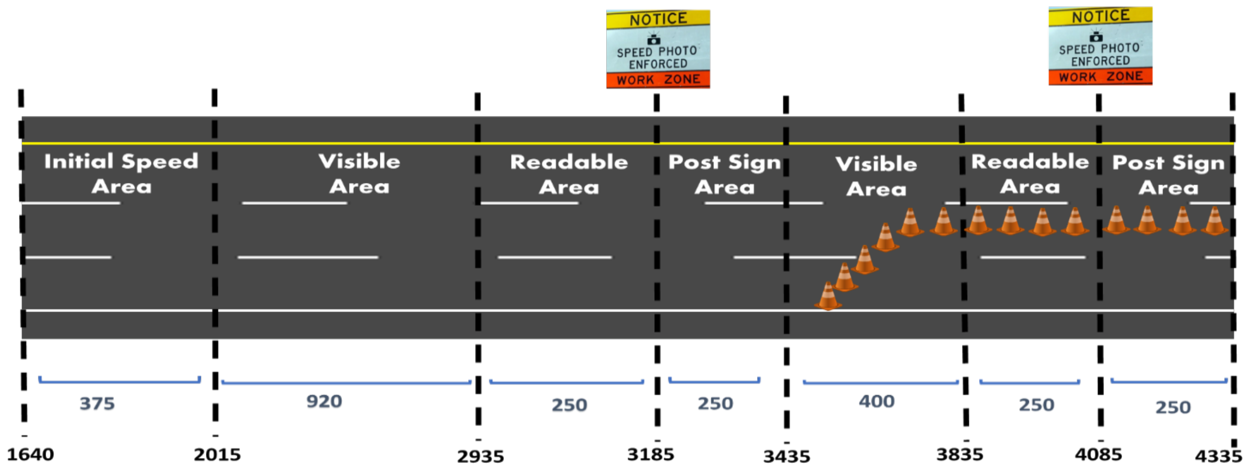
2(a) Work Zone on MD-295, Baltimore



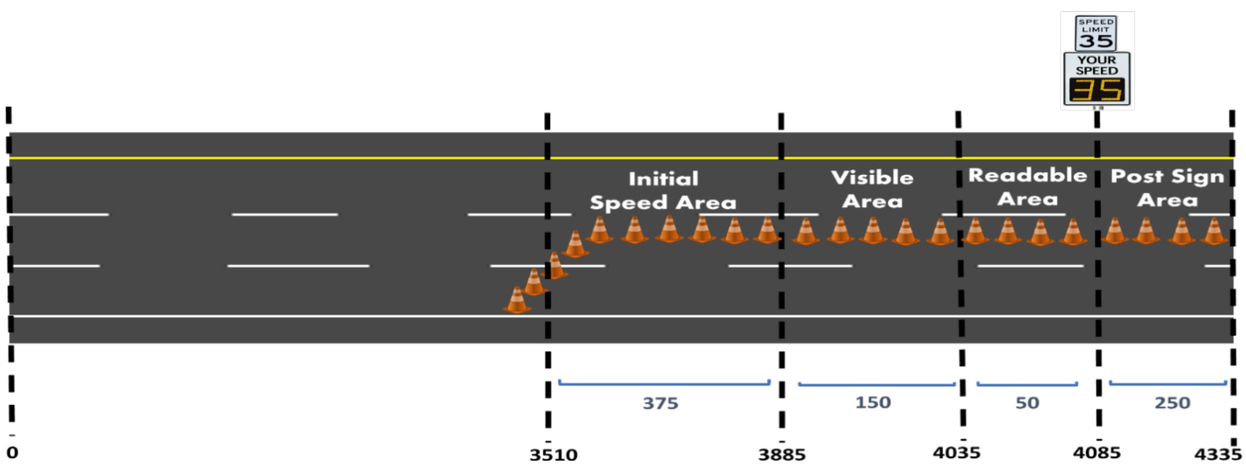
2(b) Work Zone schematic

Figure 2 The Study Corridor

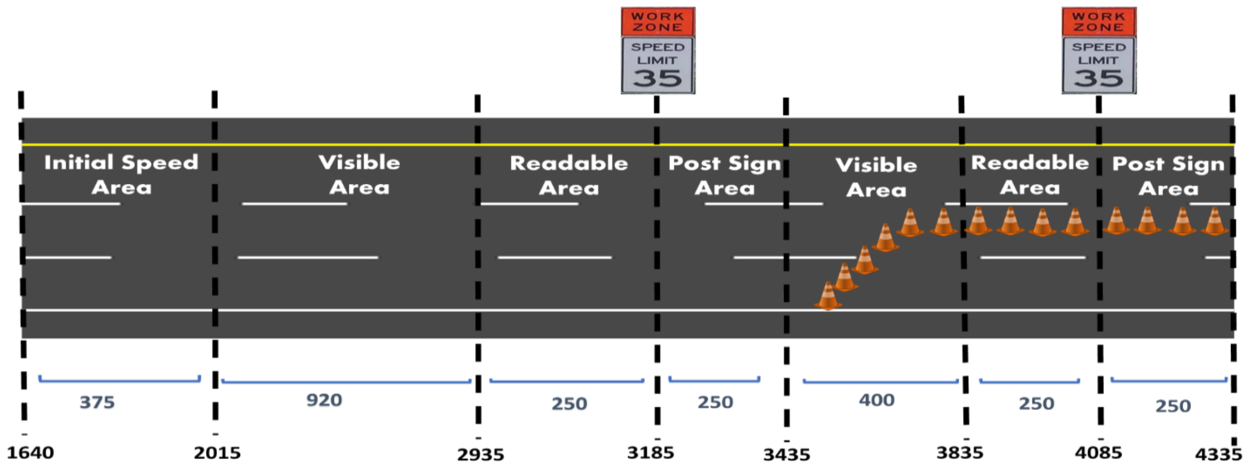
Four phases of driver speed were tested before and as they passed the signs. The initial speed area is a random distance of 375 feet before the start of the next phase. The visible area and readable area distances were measured by 3 independent people who determined the distance when the signs were clear to read. These distances from the independent people were averaged and used for calculations in the study. The post sign area distance is another random distance of 250 ft evaluating the speed immediately after driver passes the sign as shown in Figure 3.



3(a) Work Zone with speed photo enforcement signs



3(b) Work Zone with DSDS



3(c) Work Zone with reduced speed limit signs

Figure 3 Work zone signs tested in this study

To measure the impact of consecutive work zone signs on speeding, speed photo enforced signs and reduced speed limit signs were placed before the start of the work zone and in the work zone. The visible and readable area distances can change based on road geometry, size of the sign, traffic ahead, and other factors. The Manual on Uniform Traffic Control Devices (MUTCD) has a minimum standard for visibility, but the distances in the study could not replicate it due driver simulator verses reality. We were aware every person may not have the same vision, therefore we chose 3 volunteer participants to determine the distance for the different signs in the study. We were able to average the results of the three participants determining the standard distance for the signs in the study. The Highway Capacity Manual (HCM) i.e. defines light traffic as Level of Service B, which we used for the traffic in this study. Therefore, participants do not slow down due to traffic and we will be able to effectively test the influence of the signs. Two photo enforced signs as well as reduced speed limit signs were tested; before and inside the work zone.

The participants in this study were asked to drive 4 different scenarios, which tested the 3 different signs and one scenario as the control scenario without any signs. We had every participant start with the controlled scenario evaluating how they drive in real life. Also, we did not want participants anticipating where signs were in other scenarios.

SURVEY QUESTIONNAIRES

Prior to the start of each simulation session, participants were asked to complete a socio-demographic. We used this information to record information about the participants such as gender, age, level of education and annual household income. This data was used to and assessed correlations between sociodemographic and speed compliance.

Participants were asked to complete a post simulation survey after the completion of the 4 simulation sessions. In this survey which they were asked about their experience driving the driving simulator and if they had and discomfort.

STUDY DATA

Before participants were solicited for the study approval from the Institutional Review Board (IRB) was received. During the recruitment process flyer were distribution at Morgan State University (MSU), Towson University, Baltimore County and Baltimore City. Participants were paid $15 each for their participation. To ensure we collected real driving behavior, participants were informed of penalties for reckless driving. The participants were given the chance to explore and become familiar with the driving simulator before the start of the simulation session. . 66 individuals participated in over 264 simulation sessions, which involved a balance of males and females shown in table 1.

Table 1 Socio-demographic Characteristics of the Participants

Variables	**Description**	**Percentage**
Gender	Male	55%
	Female	45%
Age	18 – 25	33%
	26 – 35	39%
	36 – 45	11%
	46 – 55	10%
	56 - 65	7%
Familiarity with Study Area	Yes	53%
	Somewhat	28%
	No	13%
Education	High School or less	14%
	Associate Degree	15%
	Undergraduate student	36%
	Undergraduate degree completed	11%
	Post Graduate student	15%
	Post Graduate degree completed	9%
Household Income	< $20,000	42%
	$20,000 - $29,999	15%
	$30,000 - $49,999	23%
	> $50,000	20%

Chapter 4: Analysis and Discussion

For each of the signs tested in the work zone an ANOVA analysis was conducted to identify the differences in mean speed across the various phases. The mean speeds at different phases and ANOVA significance for each sign is shown in Table 2.

Table 2 Descriptive statistics and ANOVA of different phases by sign

Work Zone Photo Enforced Signs					
Phases	Mean (mph)	Std. Deviation	Std. Error	F	Sig.
Initial Speed Area	49.508	4.789	0.599	16.723	0.000*
Visible Area	50.221	8.731	1.091		
Readable Area	51.420	9.615	1.202		
Post Sign Area	49.947	9.657	1.207		
Visible Area (Sign II)	46.245	9.817	1.227		
Readable Area (Sign II)	41.769	11.228	1.404		
Post Sign Area (Sign II)	38.928	10.399	1.300		
Dynamic Speed Display Sign (DSDS)					
Initial Speed Area	56.158	8.908	1.105	6.841	0.000*
Visible Area	53.214	10.315	1.279		
Readable Area	49.993	11.564	1.434		
Post Sign Area	48.233	12.185	1.511		
Reduced Speed Limit (SL) 35 Signs					
Initial Speed Area	55.668	9.407	1.167	1.926	0.075
Visible Area	53.153	10.893	1.351		

Readable Area	53.083	10.033	1.244		
Post Sign Area	52.360	10.128	1.256		
Visible Area (Sign II)	51.698	10.395	1.289		
Readable Area (Sign II)	50.970	10.643	1.320		
Post Sign Area (Sign II)	50.211	10.824	1.343		
No Signs (Control Scenario)					
Work Zone	55.883	9.586	1.180	-	-

* Significant at 95% Confidence Interval

There is a statistically significant difference in mean speeds across the different phases in the presence of photo enforced work zone signs and DSDS shown in Table 2. Reduced speed limit 35 sign does not seem to cause a statistically significant change in speed. In the controlled scenario with no sign, the mean speeds in the work zone is approximately equal to that of the highway speed limit of 55 mph at MD-295. The comparison of mean speed by phase, in the presence of work zone photo enforced signs is shown in Table 3.

Table 3 Tukey's Post Hoc Analysis – Work Zone Photo Enforced Signs

Phase Comparison		**Mean Difference (I-J)**	**Sig.**
Initial Speed Area	Visible Area	-0.713	1.000
	Readable Area	-1.912	0.911
	Post Sign Area	-0.439	1.000
	Visible Area (Sign II)	3.263	0.436

	Readable Area (Sign II)	7.738*	0.000
	Post Sign Area (Sign II)	10.580*	0.000
Visible Area	Initial Speed Area	0.713	1.000
	Readable Area	-1.199	0.991
	Post Sign Area	0.274	1.000
	Visible Area (Sign II)	3.976	0.202
	Readable Area (Sign II)	8.451*	0.000
	Post Sign Area (Sign II)	11.293*	0.000
Readable Area	Initial Speed Area	1.912	0.911
	Visible Area	1.199	0.991
	Post Sign Area	1.472	0.974
	Visible Area (Sign II)	5.174*	0.031
	Readable Area (Sign II)	9.650*	0.000
	Post Sign Area (Sign II)	12.492*	0.000
Post Sign Area	Initial Speed Area	0.439	1.000
	Visible Area	-0.274	1.000
	Readable Area	-1.472	0.974
	Visible Area (Sign II)	3.702	0.280
	Readable Area (Sign II)	8.177*	0.000
	Post Sign Area (Sign II)	11.019*	0.000
Visible Area (Sign II)	Initial Speed Area	-3.263	0.436
	Visible Area	-3.976	0.202
	Readable Area	-5.174*	0.031

	Post Sign Area	-3.702	0.280
	Readable Area (Sign II)	4.476	0.101
	Post Sign Area (Sign II)	7.317*	0.000
Readable Area (Sign II)	Initial Speed Area	-7.738*	0.000
	Visible Area	-8.451*	0.000
	Readable Area	-9.650*	0.000
	Post Sign Area	-8.177*	0.000
	Visible Area (Sign II)	-4.476	0.101
	Post Sign Area (Sign II)	2.842	0.607
Post Sign Area (Sign II)	Initial Speed Area	-10.580*	0.000
	Visible Area	-11.293*	0.000
	Readable Area	-12.492*	0.000
	Post Sign Area	-11.019*	0.000
	Visible Area (Sign II)	-7.317*	0.000
	Readable Area (Sign II)	-2.842	0.607

*. The mean difference is significant at the 0.05 level.

The initial photo enforced work zone sign outside the work zone had a less impact on speed than the next photo enforced sign (Sign II) that was inside the work zone shown in table 3. The participants reduced their speed after they passed the first sign and continued to reduce their speed as they approached the 2nd sign. This gives evidence that having consecutive work zone photo enforced signs at suitable intervals (310 ft in this study) could possibly lead participants to reduce speed in work zone. The results also show that decrease in speed takes place when the sign becomes readable and after passing the sign. Approximately an 11mph speed reduction was seen from the initial speed area to after passing the 2nd sign.

The comparison of mean speed by phase in the presence of DSDS is shown in table 4. The participants reduced their speed gradually once the DSDS became visible, readable and after passing the sign as well. The total 8pmh speed reduction was found from the initial speed area to after passing the DSDS.

Table 4 Tukey's Post Hoc Analysis – DSDS

Phase Comparison		**Mean Difference (I-J)**	**Sig.**
Initial Speed Area	Visible Area	2.943	0.408
	Readable Area	6.164*	0.007
	Post Sign Area	7.924*	0.000
Visible Area	Initial Speed Area	-2.943	0.408
	Readable Area	3.221	0.327
	Post Sign Area	4.981*	0.045
Readable Area	Initial Speed Area	-6.164*	0.007
	Visible Area	-3.221	0.327
	Post Sign Area	1.760	0.790
Post Sign Area	Initial Speed Area	-7.924*	0.000
	Visible Area	-4.981*	0.045
	Readable Area	-1.760	0.790

*. The mean difference is significant at the 0.05 level.

To identify the most effective sign on the basis of reduction in overall mean speeds, an ANOVA analysis was conducted as shown in Table 5. The difference in mean speeds is statistically significant among the 3 signs.

Table 5 Descriptive statistics and ANOVA of all signs

All Signs	Mean (mph)	Std. Deviation	Std. Error	F	Sig.
Photo enforced signs	46.863	10.319	0.488	16.723	0.000*
DSDS	51.899	11.176	0.693		
Reduced SL 35 signs	52.449	10.406	0.488		

* Significant at 95% Confidence Interval

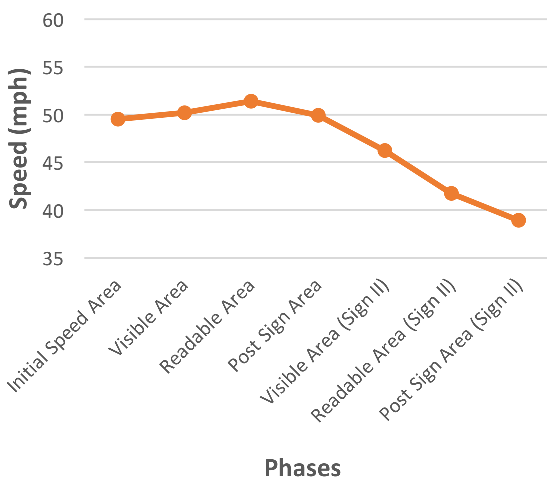
As shown in Table 6 the result of A Tukey's post hoc analysis shows that work zone photo enforced signs are the most effective work zone signs with respect to overall speed. The overall reduction in speed compared to 2nd most effective sign (DSDS) is 5 mph.

Table 6 Tukey's Post Hoc Analysis – All 3 signs

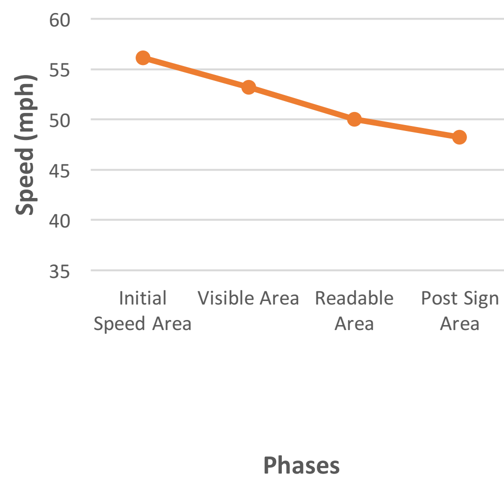
Phase Comparison		Mean Difference (I-J)	Sig.
Photo enforced signs	DSDS	-5.036*	0.000
	Reduced SL 35 signs	-5.586*	0.000
DSDS	Photo enforced signs	5.036*	0.000
	Reduced SL 35 signs	-0.549	0.781
Reduced SL 35 signs	Photo enforced signs	5.586*	0.000
	DSDS	0.549	0.781

*. The mean difference is significant at the 0.05 level.

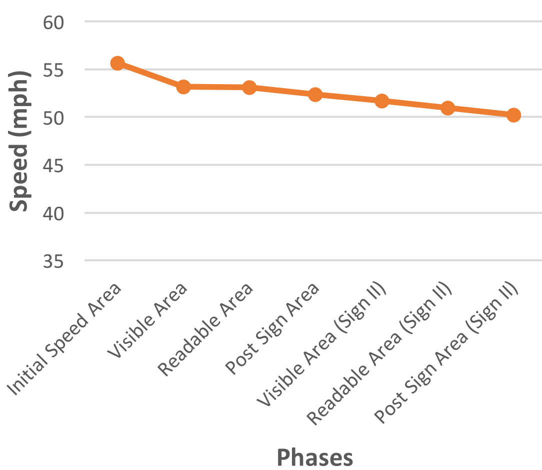
The mean speed trends are shown in Figure 4.



4 (a) Photo Enforced Sign Speed trends



4 (b) DSDS Speed trends



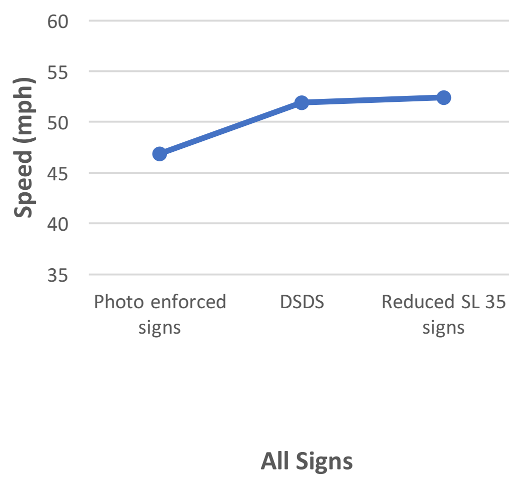


Figure 4 Mean Speed Trends

4 (c) Reduced SL 35 Speed trends

4 (d) All Sign Speed trends

A t-tests were conducted to identify the impact of sociodemographic on changes in speed. Table 7 shows the mean speeds by gender for all signs.

Table 7 Mean speeds by Gender – All signs

All Signs	Gender	Mean speeds (mph)	Std. Deviation	Std. Error
Photo enforced signs	Male	48.063	10.377	0.654
	Female	45.319	10.061	0.719
DSDS	Male	52.463	10.764	0.885
	Female	51.154	11.706	1.106
Reduced SL 35 signs	Male	52.949	10.230	0.636
	Female	51.788	10.625	0.759

An independent samples t-test was conducted to identify change in speeding behavior by gender for all signs as shown in Table 8.

Table 8 Independent Samples t-test – Gender

Signs	F	Sig.	t	df	Sig. (2-tailed)	Mean Difference
Photo enforced signs	1.727	0.189	2.814	446	0.005*	2.745
DSDS	0.517	0.473	0.935	258	0.351	1.309
Reduced SL 35 signs	0.576	0.448	1.179	453	0.239	1.161

* Significant at 95% Confidence Interval

Levene's statistics is a method used to assess if variances are equal when two or more variables are being calculated. An alpha of 0.05 is the designated limit for a test to be significant. The t-test shows that gender is significant for only photo-enforced signs in a work zone. Female participants have a tendency to slow down more compared to male participants. T-tests for other sociodemographic including age, income and education were found to be insignificant and hence were not included in the results.

A Chi-Square Test was performed to analyze the speed compliance behavior of the drivers in readable areas of the three different scenarios. The result shows that 89.1% were significantly compliant with in the photo enforcement scenario, 76.9% in DSDS and 70% speed limit scenario. Also, a Chi Square test was conducted for readable area II and the results showed a significance in scenario type with photo enforcement also being the most compliant.

Table 9 Chi-Square Analysis

		Compliance percentage	Pearson chi-square	Significance (2-sided)	Pearson correlation	Significance (1-sided)
Scenario Type	Photo Enforcement	44.70%	14.302	0.001	0.21	0.001
	DSDS	19.60%				
	SL	35.70%				
Gender	Female	44.70%	0.915	0.339	-0.053	0.339
	Male	55.30%				
Age	18 to 25	32.50%	2.46	0.652	0.087	0.652
	26 to 35	40.00%				
	36 to 45	11.40%				
	46 to 55	9.80%				
	56 to 65	6.30%				

Chapter 5: Conclusions

This study examines the impact of work zone signs including photo enforcement, DSDS and speed limit signs on driver speeding behavior by using a high-fidelity driving simulator. Some 66 participants from different socio-demographic backgrounds completed a total of 264 driving simulations. Participants were recruited by word of mouth, social media, and from colleges in the Baltimore metropolitan area. Each participant received $15 to complete the four-scenario simulation session. Participants were advised of penalties if they decided to engage in intentional reckless driving. This allowed the study to be as authentic as possible, capturing participant's normal driving behavior.

Participants drove through a light traffic (LOS B) construction work zone on MD-295 in Baltimore, MD with 2 lanes of 3 closed due to construction. Each participant was required to drive four scenarios which included a base scenario with no signs, photo enforcement sign, DSDS and speed limit sign. While the participants drove through different scenarios, the driving simulator captured their speed in various phases such as initial speed area, visible area, readable area, post sign area, visible area (Sign II), readable area (Sign II), and post sign area (Sign II).

After participants completed all 4 scenarios, they were given a post survey to complete regarding their personal experience driving the simulator. Some 98% of the participants stated on the post survey that the simulation experience felt realistic. The results from the three scenarios with different signs in comparison with no sign scenario showed that the tested signs in this study were effective and caused a reduction in speed. Furthermore, the most effective sign among the three different tested signs was speed photo-enforced. After conducting an ANOVA analysis for the three signed scenarios, speed photo enforcement sign had the lowest average mean speed of 46 mph compared to DSDS with average mean speed of 51 mph and reduce speed limit with average mean speed of 52 mph. The results indicate in the presence of speed photo enforced work zone signs, female participants have a tendency to slow down more than male participant.

One of the limitations of this study is participants used a high-fidelity driving simulator to collect the data rather than a real driving experience. Although safety is one of the benefiting factors of using the driving simulator, it can sometimes give participants a false sense of comfort. Danger and real consequences of actions were not able to occur when participants engaged in risky driving behavior. Another limitation of this study is the sample of people participating in the study. In this study, 66 people participated in the driving simulation testing our hypothesis regarding work zone speed. When using such a small sample size, it is rather difficult to argue the real intervention effect of the entire population.

After conducting analysis in a t-test, we found that females average mean speed in the presence of photo enforced was 45 mph whereas males were 48 mph. Based on the results of this study, signs especially photo enforcement are beneficial to reducing speed in work zones. Applying proper signage not only impacts speed but will improve safety in work zones. In this study, there was only one sign tested at a time identifying the impact on speed. Future studies should involve testing a combination of different signs and also include photo enforcement in work zones.

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Appendix

Pre-Questionnaire

Dear Participant,

We greatly appreciate your participation in our research to evaluate the potential effects of Dynamic Message Signs (DMS) on driver behavior. Your participation is of great importance to this study. Please fill in the appropriate choice for each question. Thank you.

1. What is your gender?

☐ Female
☐ Male

2. What is your age group?

☐ 18 to 25
☐ 26 to 35
☐ 36 to 45
☐ 46 to 55
☐ 56 to 65
☐ More than 65

3. What is your education status?

☐ High School or less
☐ Associate degree
☐ Undergraduate student
☐ Undergraduate degree
☐ Post graduate

4. Are you currently employed?

☐ No
☐ Part time
☐ Fulltime

5. What type of driving license do you have?

☐ Don't have a license
☐ Learner's Permit
☐ Permanent license for regular vehicles (class C)
☐ Permanent license for all types of vehicles (class A)

6. What is your annual household income?

☐ Less than $20K
☐ $20 to $30
☐ $30 to 50K
☐ $50 to $75K

☐$75 to $100K
☐More than $100K

7. What is your household size?

☐1
☐2
☐3
☐4 or more

8. How many cars does your household own?

☐None
☐1 car
☐2 cars
☐3 cars or more

9. What is the average annual driving mileage on your own car (in miles)?

☐Less than 8,000
☐8,001 to 15,000
☐15,001 to 30,000
☐More than 30,000

10. Are you familiar with any type of Dynamic Message Signs (DMS), like this image?

☐Yes
☐No

Please read the following before answering the next set of questions if you are not familiar with DMS:
Dynamic Message Sign (DMS) is an electronic device providing qualitative and/or quantitative information of traffic conditions and especial events to travelers. Traffic congestion, accidents, work zones, alternative routes, and expected delay represent such information.

11. How often do you see a DMS on your travel?

☐Never
☐Sometimes
☐Everyday commute

12. To what extent do you pay attention to a DMS?

- ☐ I don’t pay attention
- ☐ Usually don’t get a chance to read it
- ☐ Only in a few situations (such as an accident)
- ☐ Always read and sometimes follow
- ☐ Always read and follow

13. When you go to work/home, do you follow DMS messages?

- ☐ Do not pay attention
- ☐ Only in a few situations (such as an accident)
- ☐ Read the DMS to check if there is a change in travel time
- ☐ Always read and follow
- ☐ Not applicable to me

14. Do you feel that DMS is a useful device for providing information to travelers?

- ☐ Absolutely
- ☐ Potentially
- ☐ I don’t think so

15. Do you usually use GPS/smartphone for route guidance when you drive?

- ☐ All the time
- ☐ Most of the time
- ☐ Sometimes
- ☐ Never

16. Do you usually listen to the radio traffic information when you commute?

- ☐ All the time
- ☐ Most of the time
- ☐ Sometimes
- ☐ Never

Post questionnaire

Dear Participant,
Thanks for driving our simulator! We'd like you to share your experience with us.

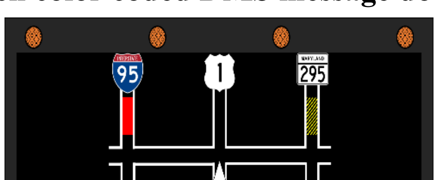
1. Please check the intensity of any symptom which applies to you now.

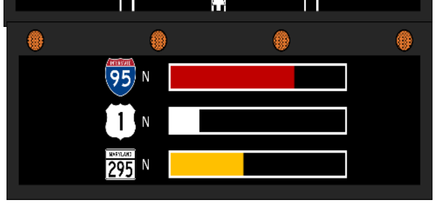
1-1- *General discomfort* ☐ No Yes (☐slight ☐ moderate ☐ severe)
1-2- *Fatigue* ☐ No Yes (☐ slight ☐ moderate ☐ severe)
1-3- *Headache* ☐ No Yes (☐ slight ☐ moderate ☐ severe)
1-4- *Eyestrain* ☐ No Yes (☐ slight ☐ moderate ☐ severe)
1-5- *Blurred vision* ☐ No Yes (☐ slight ☐ moderate ☐ severe)
1-6- *Salivation increase/decrease* ☐ No Yes (☐ slight ☐ moderate ☐ severe)
1-7- *Sweating* ☐ No Yes (☐ slight ☐ moderate ☐ severe)
1-8- *Dizziness* ☐ No Yes (☐ slight ☐ moderate ☐ severe)
1-9- *Nausea* ☐ No Yes (☐ slight ☐ moderate ☐ severe)

2. Do you think DMS is a useful device in providing information for travelers?

☐Yes
☐No

3. Which color coded DMS message do you prefer?

☐ 

☐ 

☐Do not care

4. **Will you return for another simulation run using the driving simulator?**
   - ☐ Yes
   - ☐ No