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DEVELOPMENT OF VARIABLE MESSAGE SINGS STRATEGIES FOR TRAFFIC MANAGEMENT AT WORK ZONES

BY

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ABSTRACT

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Title: Development of Variable Message Sings Strategies for Traffic Management at Work Zones

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Work zones are defined as road sections of which different activities such as road construction or maintenance take place. In most work zones, road alignments are different than the pre-work periods. Therefore, speed limits at work zones are temporary and lower than the speeds upstream the work zone. Work zones are considered as hazardous locations for drivers since crash rate and severity are high at these locations. This driving simulator study aimed to investigate the safety impact of innovative variable message signs (VMSs) based system at work zones. Seventy volunteers holding a valid Qatari driving license participated in this study. The proposed system (i.e. VMS scenario) was compared to a control scenario which was designed based on the Qatar Work Zone Traffic Management Guide (QWZTMG). The control scenario contains six static signs. Each sign in the control scenario was replaced with an innovative VMS of which two signs were animation-based. Each participant was tested for the two scenarios in two different situations. The first situation was to drive on the left lane, while the second situation was driving on the second lane. Results showed that VMS scenario motivated drivers to reduce their traveling speeds earlier compared to the control scenario. Moreover, compared with the control scenario, the VMS scenario significantly reduced drivers' traveling speed by 6.3 and 11.1 kph for the first and second situations respectively. Lane position results showed that drivers in the VMS scenario initiated lane changing maneuvers 150 m earlier than the control scenario. Furthermore, drivers in the VMS scenario were motivated to keep larger headways with the merging vehicle. In conclusion, the proposed VMS system has shown high potential in improving traffic safety at work zones.

DEDICATION

This thesis is dedicated to my mother who has always filled us with her love and to my father for his continuous support to all of us.

I also dedicate this thesis to my beloved brother and sisters.

Finally, I dedicate my thesis to my cousin Dr. Saba Dhiaa who passed away and left a void in our lives which will never be filled again.

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LIST OF ABBREVIATIONS

APTS	Advance Public Transportation Systems
ATIS	Advanced Traveler Information Systems
ATMS	Advance Traffic Management Systems
AVCS	Advance Vehicle Control Systems
CLM	Conventional Lane Merge
CMSs	Changeable Message Signs
DLM	Dynamic Lane Merge
DMSs	Dynamic Message Signs
FHWA	Federal Highway Administration
FOV	Field of View
GRIP	Graphical Route Information Panels
ITS	Intelligent Transportation Systems
JLM	Joint Lane Merge
MUTCD	Manual on Uniform Traffic Control Devices
PVMSs	Portable Variable Message Signs

QTTSC	Qatar Transportation and Traffic Safety Center
QWZTMG	Qatar Work Zone Traffic Management Guide
TTC	Temporary Traffic Control
VMSs	Variable Message Signs
VSL	Variable Speed Limit

CHAPTER 1: INTRODUCTION

1.1 Overview

1.1.1 Safety at work zones

Work zones are road sections under different activities such as construction, maintenance or development (FHWA, 2003; Hang et al., 2018; Weng et al., 2015). The presence of these activities could be because of the aging process of road networks or the need to increase the capacity of the road network by adding additional lane (Vignali et al., 2019; Yang et al., 2015). Work zones are considered hazardous locations for both drivers and road workers working in the activity area. Therefore, the safety at work zone has become a high priority research area (Weng and Meng, 2011; Osman et al., 2016; Qi et al., 2013; Bai et al., 2010). For drivers, the main reason that work zones are considered unsafe is because their expectation about the road is disrupted (Vignali et al., 2019). The purpose of work zone is to ensure that all road users and road workers are within a safe environment. For traffic agencies and engineers, their objective is to ensure that drivers are being guided efficiently and safely throughout all work zone components (Ishak et al., 2012). The environment at work zones is more complex than normal road sections which require drivers to oppose more workload to complete the process of passing the work zone safely (Hang et al., 2018). The complex situation comes from the high number of signs posted at work zones, lane channelization or mandatory lane changing maneuvers (Domenichini et al., 2017; Moradpour & Long, 2019).

1.1.2 Work zone components

According to the Manual on Uniform Traffic Control Devices (MUTCD, 2009), work zones should have 4 sections: advance warning area, transition area (i.e. taper), works area and termination area. Other manuals have 3 sections, while some manuals have 5 sections.

The first section of a work zone is the advance warning area. In this section, drivers are informed that they are approaching a work zone and given an initial indication about the upcoming activities. The advance warning area could have a single warning sign or a series of signs. Signs should properly be placed on the highway of which drivers can easily recognize the given information and act accordingly. Temporary speed limits are usually deployed in this area.

The second area is the transition area where drivers are redirected from the normal path to enter the work zone activity area. This is done through different traffic control devices such as portable variable message signs (PVMSs) and flashing arrows.

The third area is the work activity area of which the construction, maintenance and other activities take place. The last area is the termination area where drivers exit the work zone, the traffic is diverted back to its normal path and the temporary speed limits are removed.

1.1.3 Crash statistics at work zones

It was illustrated by several studies that crash rate increases at work zone (Khattak et al., 2002; Moradpour & Long, 2019). Rouphail et al. (1988) found that crash rate at long-term work zones increased by 88% compared to the before-period crash rate. Another study by Hall and Lorenze (1989) investigated work zone crashes for a three-year period, found that with the presence of work zones, crash rate has increased by 26%. Khattak et al. (2002) found that crash rate during work zone period increased by 21.5% compared to the pre-work period.

Crashes which take place at work zones are more severe than crashes at normal road sections (Pigman and Agent, 1990). According to National Highway Traffic Safety Administration (NHTSA), (2017), work zone fatalities in the U.S. considering only drivers and passengers increased from 652 fatalities in 2016 to 658 in 2017. On average, there are about 700 work zone road traffic fatalities and 24,000 injury crashes every year in the U.S. (Radwan et al., 2011). In Netherlands, approximately 2% of all road fatalities are happening because of the presence of work zones (SWOV, 2010). Furthermore, about 50 fatalities and 750 injuries every year are resulted from road crashes in the presence of work zones in Australian roads (RTA, 2008). For workers, one of the main factors for their fatalities at work zones is when a driver loses control over the vehicle causing it to break into the construction site. Vehicle intrusion account for about 50% of worker fatalities (CDC, 2016). In general, the State of Qatar has a high rate of road traffic crashes which is mainly caused by aggressive driving behavior (Timmermans et al., 2019a; Hussain et al., 2019a). Although a huge number of studies have been done focusing on motorists' and workers' safety at work zone, all these statistics show that there is a need to deeply investigate the contributing factors for traffic related crashes occurring at work zones and whether the current countermeasures implemented at work zones are sufficient or not.

1.1.4 Contributing factors

Speeding has been identified as one of the main factors for road crashes occurring at work zones (Daniel et al., 2000; Domenichini et al., 2017; Debnath et al., 2015; Nnaji et al., 2019; Austroads, 2009). Speed limits at work zones are temporary with lower limits than the speed limit of the road section upstream the work zone area. Several studies have found that drivers usually do not adapt and travel faster than the temporary speed limits at work zones (Debnath et al., 2012; Vignali et al., 2019; Finley, 2011; Paolo & Sar, 2012). A survey study by Steinbakk et al. (2017) found that drivers usually prefer to drive with high speeds at work zones when they do not notice any roadwork activity. A recent study by Debnath et al. (2014), stated that drivers travelled with higher speeds than the temporary speed limit at all work zone sections, with a difference of 20 kph in some cases. Another study by Benekohal et al. (1992) found that drivers drove over the speed limit by 16 kph at the work activity area. Statistics show that speeding was a factor in 42% of the total work zone crashes in Texas (Texas Crash Data, 2001). In many cases, speeding can lead to fatal crashes causing loss of lives. In California, out of the 65 fatal crashes which occurred at work zones, speeding was involved in 32 crashes (U.S. Department of Transportation, 2017). Moreover, speeding was the main reason for 7% of fatal crashes in Georgia, 25% of fatal crashes in Kansas and 23 fatalities out of 632 crashes which occurred in New Zealand work zones between 2003 and 2007 (Bai & Li, 2011; Daniel et al., 2000).

Another contributing factor which play a significant role in traffic related crashes at work zones is the speed variance (Daniel et al., 2000; Ishak et al., 2012; Austroads, 2009). When entering a work zone area, some drivers do not follow the temporary speed limit while others do. This will cause a difference in the traveling speed between drivers along work zone sections. Studies indicate that crash rate is associated with the increase in speed variance between vehicles (Quddus, 2013) and higher speed variance may lead to higher crash rate (Domenichini et al., 2017). The safest traffic flow condition is when the speed variance is small meaning that all drivers are travelling approximately with the same speed (Domenichini et al., 2017; Migletz et al 1993).

At many work zones, a lane closure (either left or right lane) is required in order to facilitate work activities and provide safety for workers (Weng et al., 2015). Lane closures are hazardous situations for drivers because they have to perform mandatory lane changing maneuvers which sometimes increases drivers' dangerous maneuvers (Moradpour & Long, 2019). Hwang and Park (2005) stated that driver's behavior when performing a lane changing maneuver is complex because it includes three stages, the need of changing the driving lane, the possibility to change the driving lane, and the trajectory of the lane changing maneuver.

For the whole lane changing process, Hang et al. (2018) divided the process into three consecutive phases. The first phase is called the perception phase where drivers observe the work zone sign and generate the intention for the lane changing maneuver. The next phase is the preparation phase of which drivers keep their current driving speed, or they accelerate/decelerate to adjust their driving speed. The last phase is called the action phase of which the driver has to perform the lane changing maneuver which starts when the driver turns the steering wheel until the driver merge to the open lane. According to Li et al. (2015), the lane changing maneuver is completed when the vehicle's front side is at 90^{o} perpendicular to the open lane.

In terms of steering maneuvers that drivers perform, Van Winsum et al. (1999) divided the process into three phases, the first phase is when drivers turns the steering wheel to the maximum angle, the second phase is to turn back the wheel to the neutral position, and the third phase is to turn the wheel to the maximum angle in the opposite direction until the vehicle's position is on the merged lane. Improper lane changing maneuvers could lead to conflicts causing injuries for both drivers and workers (Domenichini et al., 2017; Weng et al., 2015). The total duration to complete a lane changing maneuver which was reported was different for different studies. According to (Li et al., 2015; Weng et al., 2015), 5-6 s is required to completely change the driving lane. Other studies found that lane changing maneuvers could take up to 13 s depending on traffic condition such as traffic density and lane changing direction (Toledo & Zohar, 2007), and demographic factor such as gender and age (Hetrick, 1997). It was reported by several studies that rear-end crashes are the most common crashes occurring at work zones (La Torre et al., 2017; Ullman et al., 2008; Campbell et al., 2012; Nicholas J.

Garber & Zhao, 2002). In particular, rear-end crashes are more frequent in advance warning and merging areas (Weng et al., 2015; Srinivasan et al., 2007; Nicholas J. Garber & Zhao, 2002). It was suggested that in order to reduce rear-end crashes which improves traffic safety of work zones, early lane merging strategies should be implemented (Ishak et al., 2012; Weng et al., 2015).

1.2 Objectives

The main objective of this driving simulator study is to investigate the safety impacts of a series of innovative VMSs at work zones. The proposed system will be compared with the untreated scenario (i.e. control scenario), which is designed according to the Qatar Work Zone Traffic Management Guide (QWZTMG). The first objective is to evaluate drivers' speed behavior at work zone's advanced warning area. Secondly, to study the impact of the proposed system on lane changing maneuvers for the left lane drivers. The third objective is to find if the proposed system affects space headways between the second lane drivers and a merging vehicle.

1.3 Thesis structure

An overview about work zone safety, components, crash statistics and the contributing factor for crashes at work zone were demonstrated in the first part of this thesis. Then, a literature review about variable message signs (VMSs), speed reduction and lane changing strategies are reported. After that, the methodology in terms of apparatus, participants, scenario design and how the analysis was carried out are illustrated in the methodology chapter. Later, results of speed, ACC/DEC, lane changing, and spacing are illustrated and discussed. Lastly, conclusion and recommendation are stated in the last chapter. An illustration about the thesis structure is shown in Figure 1.

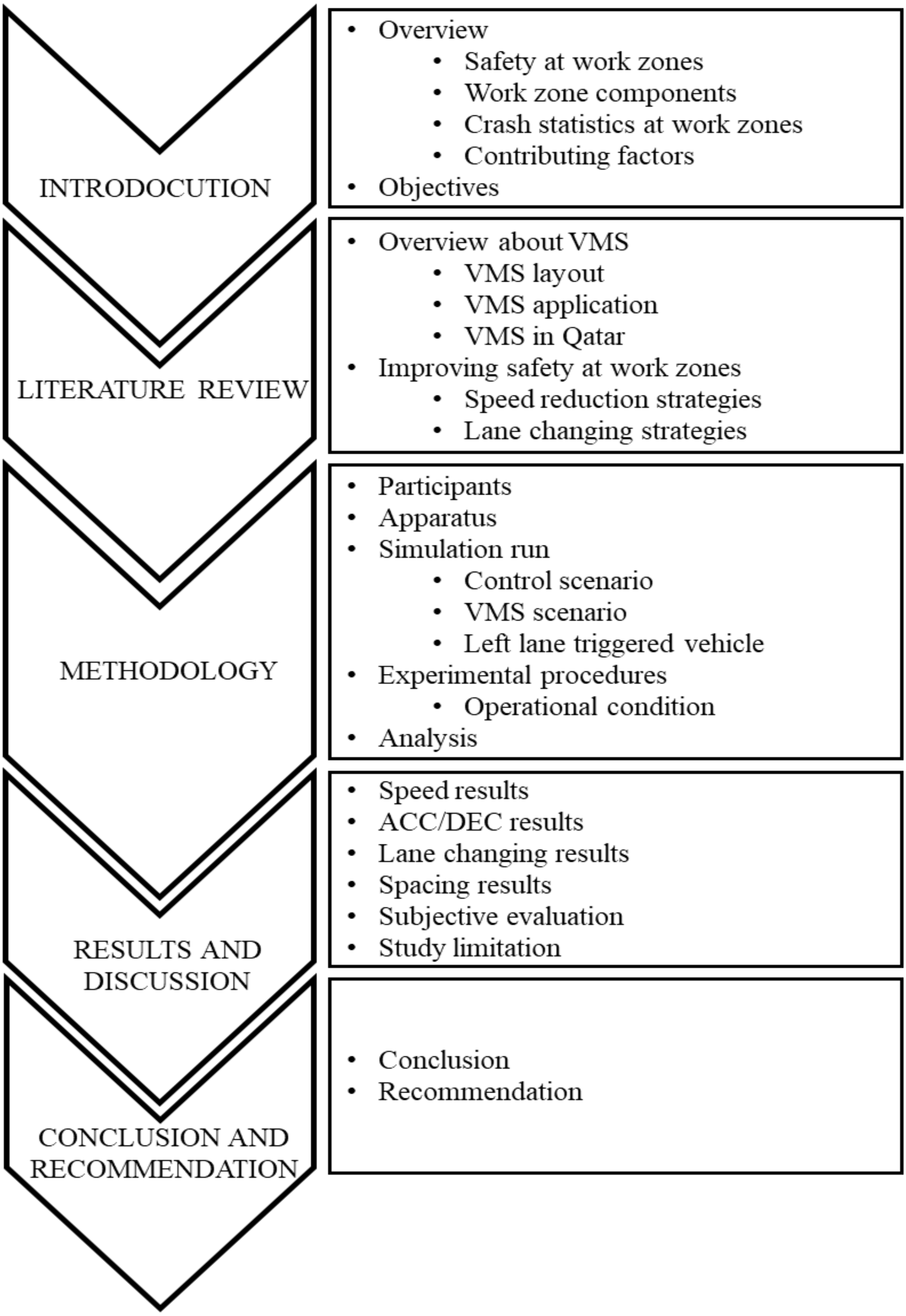


Figure 1. Illustration about thesis structure.

CHAPTER 2: LITERATURE REVIEW

2.1 Overview about VMS

In recent years, the applications of Intelligent Transportation Systems (ITS) has become popular and important tools to improve road safety and management, in many countries. ITS can be categorized into several different parts, which are Advanced Traveler Information Systems (ATIS), Advanced Traffic Management Systems (ATMS), Advance Vehicle Control Systems (AVCS) and Advance Public Transportation Systems (APTS) and

The main objective of ATIS is to use real-time traffic information to assist drivers in route guidance, reducing traffic congestion and increasing the efficiency of roads (Ma et al., 2014). ATIS uses different tools such as Graphical Route Information Panels (GRIP) (Reinolsmann et al., 2019a) and Variable Message Signs (VMSs) to disseminate different types of messages, which can be changed, and turn on/off when required. VMS is also known as Changeable Message Sign (CMS), Dynamic Message Sign (DMS), and Traffic Information Sign (Ma et al., 2014; Ronchi et al., 2016). According to the European Committee for Standardization (2005), VMS is defined as a sign that displays one or more number of messages that can be turned on/off when required. Another definition for VMS is that it is an electronic panel, which is programmable and capable of displaying different messages (Ronchi et al., 2016). Regarding the structural design, VMS can be a full-span overhead (i.e. gantry), overhead cantilever, a roadside VMS or portable variable message sign (PVMS). A PVMS is an innovative temporary traffic control (TTC) device able to display different messages to inform and warn drivers of unusual situations. The message displayed on the VMS can be controlled from a remote-control station or on site at the VMS location (Lai, 2010). VMSs are mainly used in four main categories, which are congestion, road works, incidents and dynamic traffic management. In addition to improving traffic safety, VMSs can also reduce the traffic on urban roads (Er-hui et al., 2013). Some of the advantages of VMSs are to provide drivers with information about specific incident with the effects of this incident and a recommendation of using an alternative route. Incidents can be either expected such as roadworks or unexpected such as crashes (Poulopoulou & Spyropoulou, 2019).

In general, drivers usually follow the instructions provided on the VMS panels (Erke et al., 2007). A survey study conducted by Edara et al. (2012) in Missouri State in the U.S.A found that 94% of the drivers who participated in the survey said that they would follow the information displayed on the VMS. Another survey study in Wisconsin State found that 70% of participated drivers would change their route according to the information given on the VMS (Ran et al., 2004). Moreover, the study found that drivers responded that VMSs are useful when displaying weather condition and traffic condition. In Oslo, a field study conducted by Erke et al. (2007) found a compliance of which 20% of drivers abided with the information provided on the VMS and changed their route according to the displayed message. To convey the required message properly and to increase the acceptance rates, the design of VMS message and its content plays an important role (Zhao et al., 2019). VMS require higher attention demand by drivers compared to fixed signs (Anttila et al., 2000). The time that the message is displayed is crucial to maintain smooth traffic flow and avoid unnecessary hazards on the roads (Roca et al., 2018). There are different factors, which can affect driver's performance such as the sequence of the displayed message, any visual obstructions that could prevent drivers from seeing the sign and the message content that is displayed (Xuan & Kanafani, 2014). Depending on the technology of the VMS panel, the display of animation is possible which can lead to high flexibility in content being displayed (Wang et al., 2006). The new technologies, which are used in VMSs including dynamic features such as the use animations, scrolling and flashing, have led to higher flexibility in using VMSs in terms of the displayed information (Wang et al., 2006).

According to Castro and Horberry (2004), the effectiveness of traffic signs is dependent on four processes: the sign detection (i.e. visible and conspicuous), sign readability (i.e. placed at an adequate distance with enough time for drivers to read it), sign comprehension (i.e. precise and unambiguous) and sign induced action. If the sign is properly designed and placed, the success of these processes is granted.

2.1.1 VMS layout

There are different factors of the layout, which can affect the effectiveness of the VMS. Panel size in addition to the font size can affect the understandability of the VMS. Moreover, the viewing angle of the panel and the height are also important factor. Some other factors include the background color, font color, the sequence of displaying the messages and message format (Lai, 2010).

In terms of the message content, VMS can be divided into three main categories which are; VMS that contains characters only (i.e. text message), VMS that display graphical information only and VMS that displays a combination of text and graphical messages (Ma et al., 2014). Since VMS can display a limited message size (Ma et al., 2016), a typical layout of VMS should include parts on the panel to show written text and pictograms (Roca et al., 2018). The text message could be up to three lines with 12 to 18 characters for each line and a space to display one or two pictograms. Nuttal et al. (1998) concluded that text messages require longer reading distance and they impose higher attention demand compared to the other types of messages. For example, in London, warning VMS can display up to four lines with 15 character for each line. The first line is used to display the incident location. The second line is used to display the cause of the incident while the third and fourth lines are used to give recommendation about what to do or what to expect (Chatterjee et al., 2002). The order of message lines can be changed for different situations (see Figure 2).

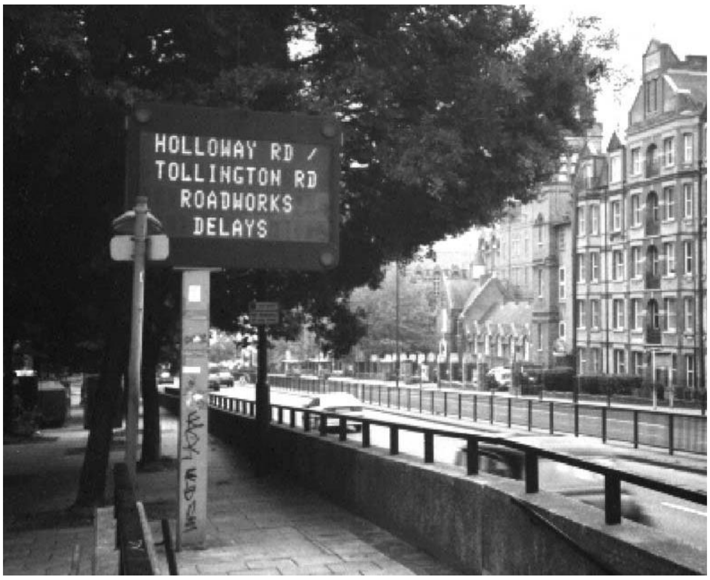


Figure 2. Warning VMS in London (Chatterjee et al., 2002).

Federal Highway Administration (FHWA) (2009) recommends that all words in text message be in capital letters with appropriate size. As the number of colors increase within the message it becomes more complex and therefore, could distract drivers from the driving task (Sanders and McCormick, 1993). The use of colors in the text-based and graphical VMS are different. For example, for a graphical VMS that shows the congestion level on a certain road, a green color indicates roads with lower congestions, while a red color indicates that the road is congested.

The message contents of the VMS can be displayed in more than one phase, in case the content itself is long. According to Dutta et al. (2004) a monolingual two-phase message which contain up to four words per phase should be repeated when the driver is approaching the VMS. In addition, 0.5 seconds duration for each word should be provided to ensure that drivers are able to read the full message. However, in case of roads with high-posted speed limits, these kind of VMS with more than one phase and only text messages would not be appropriate, as drivers would miss most of the information. Another study concluded that drivers responded faster for a double line monolingual one-phase message than the two- or three-lines message (Lai, 2010). In addition, a two-color scheme got better results than one- and three-color scheme in terms of the time drivers took to respond. A combination of double line message with two-color scheme showed the fastest response time by participants (Lai, 2010).

In some counties, the message contents of the VMS are displayed in two different languages (i.e. bilingual VMS). The State of Qatar is characterized by heterogenous population with different nationalities and cultural backgrounds (Timmermans et al., 2019b; C. P. M. Timmermans et al., 2020). In the State of Qatar, messages are usually displayed in English and Arabic languages. There are two different approaches to display a bilingual VMS. The first approach suggests to display both languages in one phase but in different lines. However, the second approach suggests that both languages should be displayed in two different phases. To make a bilingual VMS easier for drivers, for both approaches, it is recommended that the languages are displayed in different colors or different fonts (Jamson et al., 2005). In their study, drivers reacted faster for two-line message compared to four lines message (Jamson et al., 2005). Main Roads Western Australia (2015) manual suggests one-phase message with three lines. When two phase-message is used, two lines of text is enough.

The change from one phase to another should be a complete blanking of one phase and the generation of the second phase. When it comes to the difference between text-based and graphical messages, Huang & Bai (2018) stated that graphical messages have advantages over text messages for different reasons. Firstly, they are more legible compared to text with less exposure duration. Secondly, graphical messages can be recognized easier for adverse viewing condition. Thirdly, they can be understood faster by drivers when driving. Finally, they are easier for drivers who have some difficulties in reading.

2.1.2 VMS application

According to FHWA (2009), VMSs can be used for different applications including but not limited to the following; travel time, speed control, destination guidance, traffic regulations, warning situations, priced and managed lanes, ramp/lane and roadway control, control at crossing situation, special event applications, warning of adverse weather condition, route diversion and incident management.

Wang & Cao (2005) investigated the display format of PVMS for different situation in a driving simulation study. Results showed that participants took less time to respond to one-phase message than a two-phase message. Moreover, single line messages were better than two- or three-lines messages. Huang & Bai (2018) studied graphic-aided PVMSs at work zones. The results supported other studies which indicate that adding graphic to text message can improve the effectiveness of the sign.

A field study by Rämä & Kulmala (2000) investigated a warning VMS for slippery road condition (see Figure 3). The results showed that the warning message helped in reducing the means speed by 1-2 kph. Another field study investigated the effectiveness of VMS in rerouting traffic by showing a closed section of the road and recommending drivers to take an alternative route (Erke et al., 2007). Almost all drivers changed their route and did not drive until the closed section and about every fifth driver who changed the route followed the recommended route. The results showed a high compliance rate with the VMS message.

Figure 3. Slippery road condition sign (Rämä & Kulmala, 2000).

Chatterjee & McDonald (2004) studied the effectiveness of disseminating dynamic traffic information through VMSs in Europe. Results focused on four pillars of traffic information which are incident messages, route guidance information, travel time information and continuous information. The results showed that VMSs are effective in rerouting traffic when displaying the occurrence of an incident in a specific road. VMSs were also effective when advising drivers to take certain route other than the one they know. Moreover, travel time information signs were effective in making route changes. Finally, displaying continuous information regarding traffic condition for a major route increases the usage of that route by drivers when there are no traffic problems displayed. Tarry and Graham (1995) reported that there were 27% to 40%

compliance when an accident message is displayed and recommending in using another route.

2.1.3 VMS in Qatar

In Qatar, VMSs have been deployed in a large amount covering majority of the roads. Most of the VMSs in Qatar are structured with either gantry or cantilever. Moreover, at the entrance of tunnels, overhead VMSs are used. The message content is written in both Arabic and English, in case the sign is based on text. Both languages are covered in either one-phase or two-phase signs. Monolingual signs (with a single language e.g. English or Arabic) are not used in Qatar.

Lane availability VMS (as shown in Figure 4a) are used in three different colors. Green color arrow is used to show that the lane is available. Amber color diagonal arrow is used to inform drivers to change their lane. The red color is used as a cross mark to show that this lane is closed, and drivers are not allowed to use this lane.

For work zones, PVMSs are used for the advance notification of the start of the work zone (see Figure 4b). These PVMSs can show different message such as “REDUCE YOU SPEED”, “NEW ROAD LAYOUT AHEAD” or “ROAD WORK AHEAD” as shown in Figure 4b. Moreover, gantry VMSs can be used also to show a warning message of the upcoming work zone along together with the available lanes which drivers can use (as shown in Figure 4a). Furthermore, the manual does not specify a certain message to be displayed of the PVMS. The manual gives flexibility of what message that can be used as long as it provides targeted messages to assist the safe management of traffic through the work zone. Therefore, messages that are displayed on PVMSs in Qatar are different from one work zone to another.

a) Gantry VMS b) PVMS

Figure 4. Example of VMSs showing the upcoming work zone in Qatar

2.2 Improving safety at work zones

2.2.1 Speed reduction strategies

In general, VMSs have been introduced as an effective tool in reducing drivers' traveling speed at work zones (Wang et al., 2003; Strawderman et al., 2013; N. J. Garber & Patel, 1995; Zech et al., 2008).

N. J. Garber & Patel, (1995) studied the effectiveness of four different text messages displayed on PVMS for speeding vehicles. The results showed that the messages were effective in reducing drivers' speed more than the static signs. The authors concluded that PVMS was effective in improving safety at work zones by reducing both, drivers' speed and speed variance.

Wang et al. (2003) found that PVMS equipped with speed radar which display the approaching vehicle's speed and show text messages, were able to reduce speed variance and drivers' speed for about 11.2 kph to 12.8 kph. Speed reduction for the PVMS was higher compared to the speed reduction found for static signs. In addition, the authors studied an innovative message written on a static sign. The message was "Slow Down My Dad Works Here" which was written in a childlike font. The innovative message sign showed some effect in reducing the speed by approximately 2.9 kph during daylight. The speed was observed to decrease more over time compared to the immediate speed reduction after the sign installation.

Fontaine et al. (2000) study results showed that PVMS was effective in reducing drivers' speed by 3 kph, whereas when the PVMS was combined with speed display panel for the approaching vehicle, the speed was reduced by up to 16 kph with lower percentage of speeding vehicles. The results were in line with Brewer et al. (2006) study who found that PVMS which show text message and display drivers' speeds had greater effect in reducing motorists' speeds at work zones compared to the static signs (see Figure 5). In addition, the authors found that using two PVMSs would results in improving speed reduction.

Figure 5. PVMS showing text message and driver's approaching speed (Brewer et al., 2006).

Meyer (2004) reported that the VMS equipped with a radar had only a novelty effect meaning that speed reduction was not sustained over time. Another study by Dixon & Wang (2002) found that the speed feedback system was effective in reducing the speed by 9.6 to 12.9 kph, however, the effect was localized at the panel location and did not extend to the work activity area.

Zech et al. (2008) who conducted a field experiment which included about 180,000 vehicles also found that PVMS were effective in reducing motorists' speed. However, speed standard variation was increased. The authors suggested that the proper selection and implementation of PVMS messages can be an effective tool to reduce both, motorists' speed and standard deviation which lead in increasing work zone safety.

McCoy et al. (1995) found that showing approaching drivers' speed on a speed display panel with a static sign showing the speed limit helped in reducing the speed by 6 to 8 kph. Moreover, the technique reduced the percentage of drivers exceeding the speed limit by 20% to 40%. Another study by Fontaine & Carlson (2001) indicated that the use of PVMS and showing the driver' speed could reduce the speed by up to 14.5 kph.

Bai et al. (2010) analyzed drivers' speed with response to three scenarios. The first scenario was when the PVMS was turned on showing text message, while the second scenario was when the PVMS was turned off. The third scenario was static sign showing road work ahead. Vehicles were categorized into three categories: passenger cars, semitrailers and trucks. Study results stated that static signs were more effective in reducing the speed of passenger cars and semitrailers than the two other scenarios, however, PVMS reduced trucks' speed by 7.6 kph which was significantly more than the static sign. The authors reported that the results of the PVMS are very important because 43% of the collected data truck vehicles.

Domenichini et al. (2017) tested different configurations for work zones of a two lane highway in a driving simulator study. Some of these configurations were different median widths, different lane widths, the use of different perceptual treatments and the use of one PVMS in the advance warning area. The Results showed that the PVMS was effective in reducing the speed, however, speed reduction was localized at that area only, which means that after passing the sign, drivers increased their speeds again. The highest speed reduction and lowest speed variance was found for the perceptual treatment of using tall and densely spaced vertical delineators installed on the median barrier within the whole advance warning and transition areas.

Zhang & Gambatese John (2017) found that a combination of regulatory speed limit sign, speed display panels and PVMS were effective in reducing vehicles' speeds at the end of the tapper area by approximately 5.6 kph while the treatment was not effective in reducing the speed at the work zone activity area.

A study in United Arab Emirates (UAE) was conducted to examine the effectiveness of PVMS in work zones through surveys and field deployment of PVMS in a four lanes dual carriageway (Ahmed et al., 2016). Despite the results of the surveys which showed that drivers considered PVMS effective tools in improving traffic safety at work zones, speed field data showed that drivers were not responding with the displayed messages on the PVMS, which made the authors to conclude that PVMS were not effective in reducing drivers' traveling speed at work zones in the UAE.

Y. Huang & Bai, (2014) studied in a field experiment the effectiveness of using graphic aided PVMS in reducing drivers' speeds at work zones. The study compared three situations: PVMS which shows text message only, PVMS which shows graphics only and PVMS which shows both text and graphics. In the case of showing both text and graphics, the PVMS was designed for two phases as shown in Figure 6. Results indicated that aiding text PVMS with graphic reduced the mean speed of vehicles between 13% and 17% compared to the traditional PVMS which shows only text messages. On another study, drivers were asked through a survey about their opinion in using graphic aided PVMS (Yilei Huang & Bai, 2018). The results of the survey supported other studies which indicate that adding graphic to text message can improve the effectiveness of the sign since all drivers correctly interpreted the graphical work zone sign. Moreover, the results suggested that 52% to 71% of drivers prefer to see graphics in PVMSs deployed at work zones.

Figure 6. Graphic aided PVMS (Y. Huang & Bai, 2014).

Y. Bai et al. (2015) studied the effective location of the PVMS in reducing passenger cars and trucks speed difference. Three different locations to deploy the PVMS before the first TTC static sign (i.e. “ROAD WORK AHEAD”) were evaluated. The three locations were 750 ft, 575 ft, and 400 ft before the static sign. Study results showed PVMS deployment location significantly impacted speed variance between vehicles. The smallest speed difference between passenger cars and trucks was achieved when the PVMS was deployed 575 ft before the work zone.

In a driving simulator study, Strawderman et al. (2013) studied the effect of design and location of the work zone warning sign on drivers' speed. The study found that as the warning sign is located more upstream of the work zone, higher speed reduction was observed. Moreover, the design of the VMS significantly affected drivers' speed reduction.

B. R. Ullman et al. (2011) and B. Ullman et al. (2012) evaluated through surveys the using of truck-mounted VMS at work zones (see Figure 7). The findings indicated that all signs symbols (i.e. accident symbol, lane-blocked symbol and the work zone symbol) which were used were well understood by drivers and enhanced drivers' ability to understand the situation which they faced. The authors recommended that when applicable, truck-mounted VMS should contain graphics.

Figure 7. Truck-mounted VMS showing closed right lane (B. Ullman et al., 2012).

Several studies indicated that enforcement methods are the most effective methods in reducing drivers' speed at work zones (Debnath et al., 2012; Debnath et al. 2015; Nnaji et al., 2019; Zech et al., 2005). Ravani & Wang (2018) tested the impact of four levels of police deployment in reducing drivers' speeds in a real-world environment (see Figure 8). The first level was VMS equipped with a police lighting. The second level was the addition of a stopped police car to the VMS. The third level involved one stopped police car only, while the fourth level involved stopped and active police cars to stop any speeding driver. The study concluded that for urban environments, the first and second levels were effective in reducing motorists' speeds, however, the standard deviation of speed was increased. For rural environment, the third level was found the most effective in reducing the speeds and decreasing speed variance. The study concluded that any level of police deployment can improve drivers' speed reduction.

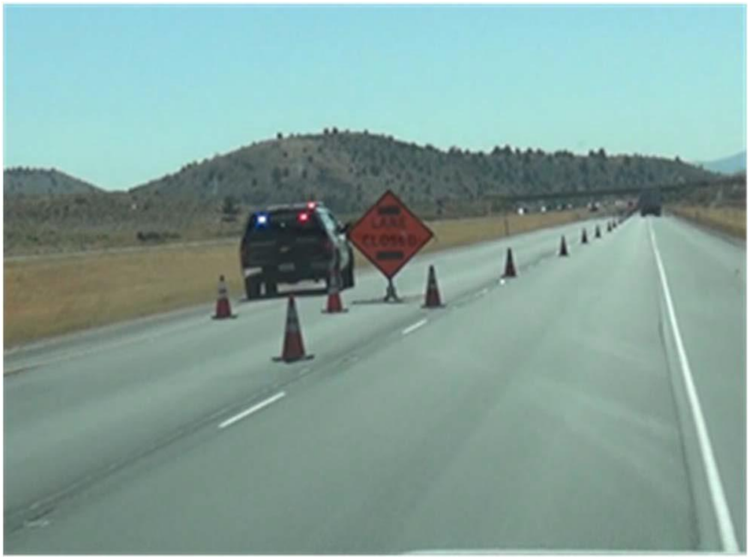


Figure 8. Police presence at work zone (Ravani & Wang, 2018).

Benekohal et al. (2008) investigated the impact of a radar speed photo enforcement on speed reduction within work zones in the U.S.A. The system consisted of two radars installed inside a van vehicle: the first radar shows the drivers' speed for warning and gives them a chance to reduce their speeds, while the second radar takes a picture for speeding drivers. The authors found the system as an effective tool in decreasing the percentage of drivers who exceed the speed limits to 8% at the van location which led to an increase of drivers' compliance with the work zone speed limits. However, speed reduction for cars downstream the van vehicle was not significant.

Regarding physical treatments, Zech et al. (2005) studied the deployment of rumble strips with and without the presence of a police car. Results showed that when the police vehicle was not present, rumble strips reduced passenger cars' speed by 3.86 kph, however, when a police car was present, drivers' speed were reduced from 4.83 kph to 9.66 kph. The findings of the rumble strips for speed reduction were similar to Fontaine & Carlson (2001) study, of which, a speed reduction of 3.2 kph was achieved for passenger cars. Speed reduction for trucks was higher which ranged between 3.2 kph and 11.3 kph. An illustration for the rumble strips is shown in Figure 9.

Figure 9. The installation of the rumble strips (Fontaine & Carlson, 2001).

Sun et al. (2011) found that rumble strips reduced the speed by 6 kph with a 2.9% speed compliance. Moreover, the study compared when the strips were placed perpendicular to the driving lane with the situation of placing them at an angle which revealed no significant difference in terms of speed reduction between both placements.

However, when the strips were placed at an angle, a vertical movement of the strips was observed up to 3.73 cm for every 100 wheels passing on it.

Another study by Elghamrawy et al. (2012) invistigated the performance of placing temporary rumble strips on work zone edges to prevent distracted motorists from intruding into the work zone area. The study evaluated the rumble strips based on vehicle type, vehicle speed, number of strips per set, type of the rumble strip and strips spacing. The authors recommended to use rumble strips with larger widths and to increase the number of strips per set as possible while keeping it practical and feasible.

Yang et al. (2015) used portable plastic rumble strips to improve safety at short term work zones. The finding showed positive results for speed reduction and speed variance. Results of speed variance was not significantly different between before the installation of the rumble strips and after the installation. Rumble strips led to a reduction of 10% and 13.8% in speed for right and left lanes respectively compared the speed before the installation of the strips. The authors reported that it is easy to install and remove the portable plastic rumble strips unlike other traditional rumble strips.

Kang & Momtaz (2018) studied drivers' compliance with work zone signs using auditory warning system (AWS) generated from pavement surface using a driving simulator. The results showed that the system increased drivers' compliance with the speed reduction and lane changing VMSs. Drivers compliance to the lane change VMS with the AWS was improved by 28% compared to the situation without the AWS. For speed reduction VMS, the AWS improved the compliance rate by 17% and improved speed reduction by 3.9 kph compared to the situation without the AWS.

2.2.2 Lane changing strategies

When coming to lane merging strategies at work zones, there are mainly three types: conventional merge, early merge and late merge, both early and late merge are further divided into two types which are static and dynamic (Yulong & Leilei, 2007; Idewu & Wolshon, 2010; Qi & Zhao, 2017).

The concept of early merge is to encourage motorists to change their driving lane early and merge to the open lane by putting additional signs in the advance warning area. This technique is not preferable under high volume traffic condition. Early merge objective is to reduce speed variance between drivers which results from merging and lane changing conflicts by encouraging drivers in merging to the open lane as early as possible (i.e. farthest upstream point) (Yuan et al., 2019). Under low and moderate traffic volumes, early merge strategy can significantly improve traffic safety (McCoy et al., 1999; McCoy and Pesti 2001).

For late merge configuration, drivers are encouraged through signs to drive on both lanes (i.e. closed and open lanes) until the end of the advance warning area at which, drivers are informed to merge there. According to Idewu & Wolshon (2010), this technique may be dangerous for drivers in low volume traffic conditions. Another study by Beacher (2004) which was conducted to investigate the benefit of the late merge configurations, found no significant difference of work zone throughput volumes between the conventional MUTCD merge and the late merge. According to Hang et al. (2018), drivers avoid late lane merging maneuvers to reduce the risk of getting into a collision.

Hang et al. (2018) studied the effect of three locations (i.e. 250, 500 and 750 m) of the lane-end sign to deploy it before the starting of the transition zone using a high-fidelity driving simulator. Results showed that the highest traffic efficiency was achieved when the lane-end sign was located at 500 m before the transition zone. The results also indicated that male and taxi drivers changed their driving lane earlier that female and regular drivers respectively.

Radwan et al. (2011) compared in a simulation study using VISSIM six scenarios for the dynamic lane merge (DLM) system with and without variable speed limit (VSL) signs. Summary of scenarios is presented in Table 1. The findings indicated that for low and medium volume conditions, no significant difference between the scenarios was found.

Table 1 Summary of the Six Scenarios (Radwan et al., 2011)

Scenario	Late DLM	Early DLM	VSL
1	x	x	x
2	x	x	✓
3	x	✓	✓
4	✓	x	✓
5	x	✓	x
6	✓	x	x

Rayaprolu et al. (2013) compared the operational efficiency of joint lane merge (JLM) configuration with the conventional lane merge (CLM) configuration. The JLM configuration gives drivers equal right of way because both, the closed and open lanes are merged simultaneously to one lane. The difference between both configurations is illustrated in Figure 10. For low flow rates, both configurations showed similar performance for average delay time and work zone throughput, however, for high flow rates, the operational efficiency of the JLM was more than the CLM configuration. The safety performance in terms of uncomfortable deceleration and speed variance for both, JLM and CLM configurations was studied by Ishak et al. (2012). The findings revealed that speed variance was not significantly different between both configurations within the advance warning area, however, CLM had lower frequency of uncomfortable decelerations. For other work zone sections (i.e. transition and buffer area), CLM showed better safety performance than JLM for moderate and high flow rates. The authors reported that the results are inconclusive to determine which configuration is safer than the other when considering the overall work zone area.

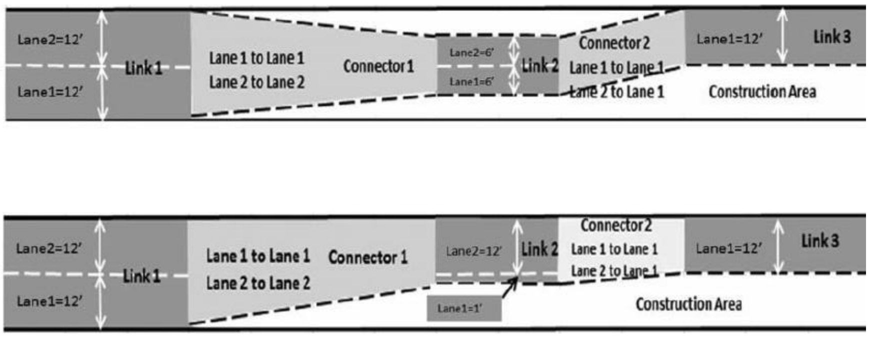


Figure 10. Illustration of JLM and CLM (Ishak et al., 2012).

Another research by Idewu & Wolshon (2010) studied the impact of JLM on vehicles' merging speeds. The study was based on a field experiment where the JLM was implemented. Results showed that vehicles' merging speed for the JLM configuration were smaller than the CLM. The authors stated that drivers in the JLM were more cautious since the JLM makes drivers on both lanes to merge into one lane which made drivers to drive slower.

Harb et al. (2011) compared conventional merge configuration with dynamic early and dynamic late merge configurations. PVMS was deployed to show early merging advisory message for the early dynamic merge configuration, and to show late advisory message for the late dynamic merge configuration. Results showed that the dynamic early merge strategy significantly improved the work zone capacity. In addition, the rate of early mergers was the highest in the early merge strategy compared to the other two strategies which made the authors to conclude that drivers were complying with the displayed messages on the PVMS.

Gundana et al. (2018) found that if more that 25% of drivers decided to stay in the closed lane and merge late, a significant expected drop in the efficiency will occur. He et al. (2016) identified drivers who travel with high speed and merge close to the merging point as aggressive drivers. Moreover, the study stated that 25% of drivers changed their lane from the open lane to the closed lane just to overtake a slowing moving vehicle even they knew that the lane in closed after 30 m.

Yulong & Leilei (2007) proposed an intelligent lane merge control system which choose late or early merge strategy based on the traffic volume. For low traffic volumes, the system act as dynamic early merge system by informing drivers to merge early to the open lane through VMSs, while for heavy traffic condition, the system switch to dynamic late merge control by informing drivers through VMSs to use both lanes until the merging point. The simulation results showed that the adaptive system outperformed other lane control strategies in improving both safety and capacity of work zones.

Qi & Zhao (2017) studied the effectiveness of signalized lane control strategy at work zones merging points. The data was collected from the field and were used in simulation models. The authors tested the model under different traffic volumes and cycle lengths. The results indicated that using signalized lane control strategy can significantly reduce lane change conflicts, however, the strategy could increase rear-end conflicts. The authors recommended to use the proposed strategy when the speed at the work zone drops by more than 50% due to any reason to prevent the late merge behavior. The data was collected from a five-lane highway with one closed left lane, however, the signal was only implemented to the left and second lanes only as shown in Figure 11.

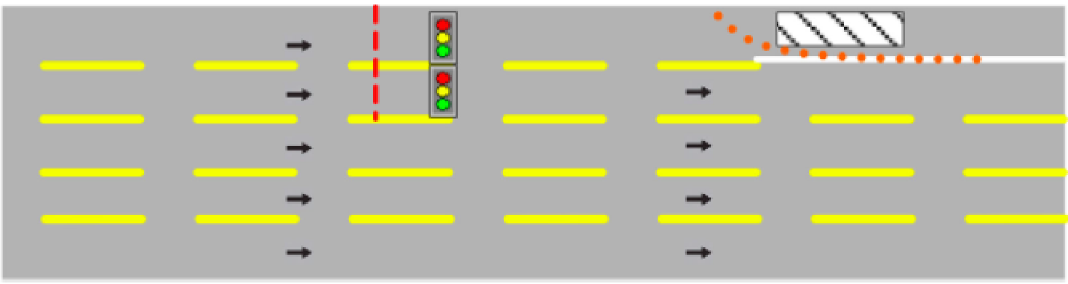


Figure 11. Illustration of the signalized lane merge control at work zones (Qi & Zhao, 2017).

Another simulation experiment studied the lane-based signal merging strategy (Yuan et al., 2019). The strategy is based on giving the right of way for drivers on different lanes to pass through the open lane at work zones. The study results suggested that the strategy outperformed other lane merging strategies such as late merge, early merge and conventional merge at high volume traffic conditions. The authors furthermore tested the strategy under fixed and dynamic cycle lengths and phase sequences. The dynamic case showed better performance in terms of work zone hourly throughput, average number of stops, average stop delays by vehicle and average delay time by vehicle.

Li et al. (2015) studied socio-demographics (i.e. gender, age, education and driving experience) impact of drivers on their lane changing distance and response time with driver smart advisory system which informs drivers about entering a work zone area. Results showed that driver smart advisory system helped drivers in performing the lane changing in shorter distance and less time compared to the results without the smart advisory system. However, the smart system hided the impact of drivers' socio-demographics impact on their lane changing.

Based on the literature review, different countermeasures and strategies which have been implemented at work zone either on real or simulated environment have focused on single parameter such as speed reduction or lane changing. None have studied the combined effect of countermeasure on several parameters. Moreover, the effectiveness of VMSs at works have been studied by several authors, however, animation-based VMSs have not been studied at work zones.

CHAPTER 3: METHODOLOGY

3.1 Participants

A total of seventy volunteers holding a valid Qatari passenger car driving license participated in this study. Recruitment of participant was carried out through advertisements which were posted on social media networks and face-to-face recruitment inside Qatar University campus. Participants were asked to register through (http://www.qatardrivingsimulator.com) website providing their contact information (see Figure 12). All participants were instructed not to drink (except water) or eat at least two hours before the start of the experiment. This protocol was followed to meet the minimum requirement of the standard simulation sickness survey (Kennedy et al., 1993). However, two participants were not able to complete the experiment because they were affected by simulation sickness. In addition, two participants were considered as outliers. Thus, a total of 66 subjects were considered in the analysis of this study. Out of the total number of participants, 46 were males and 20 were females representing 17 different countries. Mean age of participants was 24.8 years ranging from 19 to 69 years with a standard deviation of 8.3 years. The low mean value of age was because most participants (62%) were Qatar University students. In terms of driving experience, the mean value was 5.7 years ranging from 1 to 49 years and a standard deviation of 7.1 years. Participants' socio-demographic characteristics are presented in Table 2.

Table 2. Socio-Demographic Characteristics of Participants

Factor	Subgroup	Participants	Total
Gender	Male	46	66
	Female	20	
Age (years)	Below 30	58	66
	Between 30 and 64	7	
	65 and more	1	
Ethnicity	Arab	50	66
	Non-Arab	16	

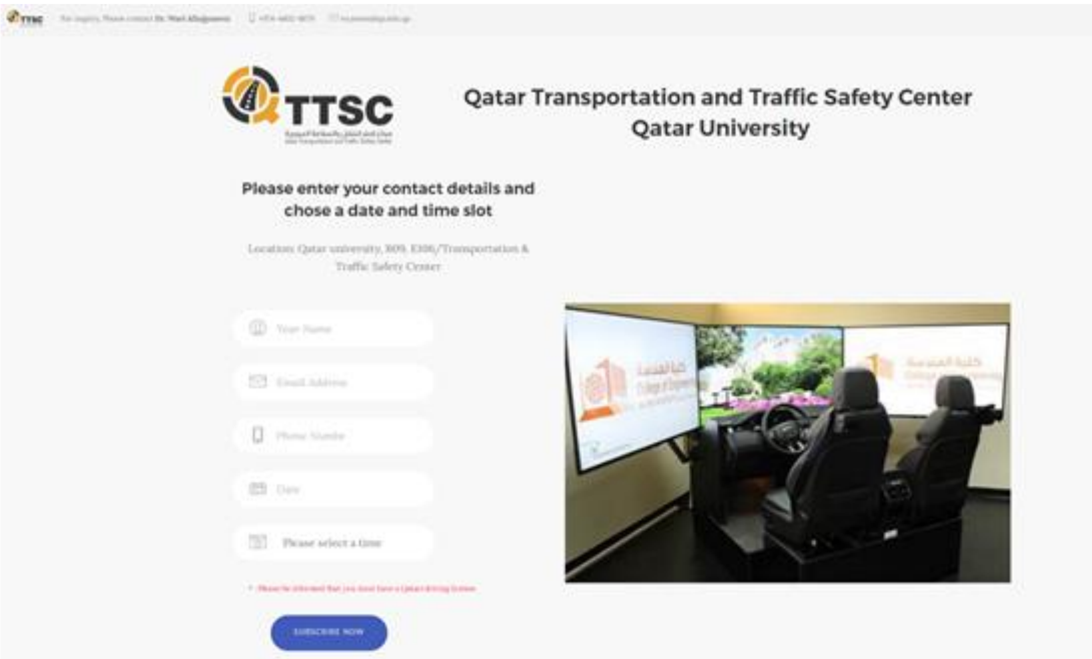


Figure 12. Recruitment website for participants' registration.

3.2 Apparatus

The driving simulator located at Qatar University was used in this study (see Figure 13). The simulator consists of two main units: the first unit is the driving unit which is a fixed-base Range Rover Evoque cockpit equipped with all tools and functions provided in the real car such as automatic gearbox, pedals, speedometer, indicators and force-feedback steering wheel which simulate the condition when hitting an object. The second unit consist of three large LCD screens having a field of view (FOV) of 135^o with 5760 x 1080 pixels resolution and refresh rate of 60 HZ. Both components are interfaced with CalPot32 software and STISIM Drive 3 offering high speed sound processing and graphics. The driving simulator is capable of collecting numerous numbers of parameters at 0.1 s interval. Some examples of these variables are longitudinal/lateral travelling speed (m/s), longitudinal/lateral acceleration/deceleration (m/s^2), lateral vehicle position (m), etc. It is worthy to mention that the driving simulator has been validated for both objective and subjective validity in a recent study (Hussain et al., 2019b). Moreover, the simulator has been used to conduct several studies (Almallah et al., 2020; Hussain et al., 2020a; Hussain et al., 2020b; Hussain et al., 2019b; Reinolsmann et al., 2019b)

Figure 13. Qatar Transportation and Traffic Safety Center' driving simulator.

3.3 Simulation run

Work zone components and elements in this study were designed based on Qatar Work Zone Traffic Management Guide (QWZTMG). According to the manual, there are 5 components for work zone: advance warning area, transition area, longitudinal safety buffer, work area and termination area. For highways with speed limit of 100 kph, the length of the advance warning area is 1000 m with 6 main static signs, while the length of the transition area (tapper area) is 100 m. All sign distances were taken with reference to the start of the transition area which was considered as the reference point (i.e. merging point). In this study, each sign of the advance warning area was replaced with an innovative VMS. The detailed illustration of work zone components and the location of each sign is shown in Figure 14 and Table 3. Two scenarios (i.e. Control and VMS) were tested for each of the two situations (i.e. situation 1 and situation 2). In situation1, drivers were asked to drive on the left lane, while for situation 2, drivers were asked to drive on the second lane.

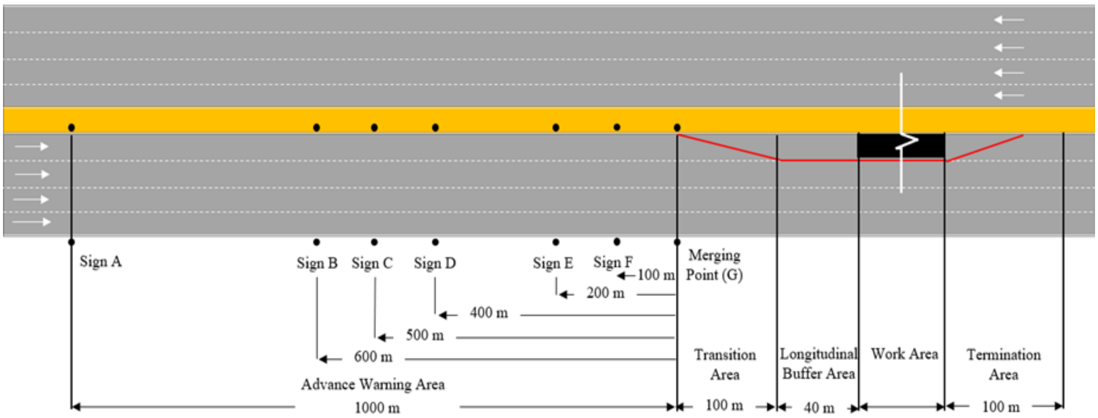
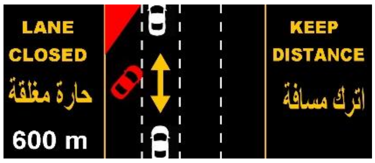


Figure 14. Illustration of work zone component and signs locations.

Table 3. Sign Designs for Control and VMS Scenarios

Sign Symbol	Location (Merging Point = 0)	Control Scenario	VMS Scenario
A	-1000		
B	-600		
C	-500		
D	-400		
E	-200		 
F	-100		

3.3.1 Control scenario

The first sign of the advance warning area is the work zone sign (Sign A) (T200) which indicate that the driver is entering to a work zone area. The sign is placed at 1000 m before the merging point. The second sign (Sign B) (T201) is placed 600 m before the merging point and shows that the left lane is closed using arrows and 600 m is written below the arrows. Number of arrows indicate the number of driving lanes characterized by the highway. The third sign (Sign C) (T101) is placed 500 m before the merging point and shows the temporary speed limit of 80 kph with a written text of "AHEAD" with the same meaning is written also in Arabic. Then, the fourth sign (Sign D) (T201) is identical to the second sign but 400 m is written instead of the 600 m. The sign is placed 400 m before the merging point. The fifth sign (Sign E) (T201) is placed 200 m before the merging point and shows curved left lane arrow to the right with 200 m written below the arrows. The sixth sign (Sign F) (T102) shows the temporary speed limit again but without the written text and it is placed 100 m before the merging point. According to the QWZTMG, each sign should be placed at both side of the highway (i.e. right shoulder and median) as illustrated in Figure 14.

3.3.2 VMS scenario

As mentioned earlier, each sign of the control scenario was replaced with an innovative VMS. Two (Sign B and Sign D) of the six signs were replaced by animation-based VMSs. All distances were kept the same as the control scenario, however, each VMS was placed only on one side of the highway (highway median). Sign A of the control scenario was replaced with a roadside work zone VMS. The edges of the triangle inside the sign and small circles at each corner of the sign flash with amber color (see Table 2). Sign B was replaced with a truck-mounted cantilever animation-based VMS. The sign shows the four lanes of the highway with one vehicle on the left lane and two vehicles on the second lane. The red vehicle on the left lane is merging between the two white vehicles. At the same time, two-sided arrow between the two white vehicles stretches and elongate to encourage drivers in keeping enough distance to let the left vehicle to merge. Moreover, "LANE CLOSED" and "KEEP DISTANCE" alongside with the Arabic meaning were written on the sides of the sign and a 600 m was written below. Sign C was replaced with a roadside VMS showing the temporary speed limit of 80 kph and amber color circle on each corner of the sign flashes. Sign D was replaced with a roadside animation-based VMS showing the four lanes of the highway with vehicles on left and second lanes. The left lane is showing to be closed and the left lane vehicle which was in front of the second lane vehicle attempts to merge to the second lane. A written text of “LANE CLOSED” with the Arabic meaning and 400 m were written on the right of side of the sign. Sign E was replaced with a two-phase roadside VMS. The first phase shows danger with “LANE END” and the Arabic meaning as a written text with 200 m below the text. The second phase shows curved arrow to the right and “MERGE RIGHT” with the Arabic meaning below it. Amber flashing circle was on each corner of the sign. Sign F was replaced with the same sign which was replaced for sign C.

3.3.3 Left lane triggered vehicle

For situation 2 (driving on the second lane), when the driver was entering the work zone area, a triggered vehicle driving on the left lane was designed to be ahead of the driver’s position. The triggered vehicle was designed to travel at a low speed making the driver able to approach it. When the longitudinal spacing between the triggered vehicle and the driver becomes 50 m, the triggered vehicle will travel with the same speed as the driver’s speed. The triggered vehicle is released with a speed of 5.4 kph lower than the driver’ speed, when the driver was 150 m before Sign B which mean that the triggered vehicle was 100 m before Sign B. In this case, the driver will have the option of either reducing the speed and give space for the left lane vehicle to merge, or to accelerate and pass the left lane vehicle. The left lane triggered vehicle was designed to merge at 150 m before the start of the transition area (i.e. merging point).

3.4 Experimental Procedures

Upon the arrival of each participant to the driving simulator lab at Qatar Transportation and Traffic Safety Center (QTTSC), the participant was introduced to the research team with a brief introduction about the driving simulator. An informed consent form was signed by each participant which contains information about simulation sickness and the right of the participant to stop the experiment at any time. Moreover, the informed consent form provided information about the right of the research team to use the collected data for research purpose only. Then, participants were asked to fill a pre-test questionnaire focusing on demographic features (i.e. age, gender, nationality) and driving experience. Moreover, pictures of the innovative VMSs which are used in the experiment were introduced to reduce any bias results that would be generated due to the lack of knowledge and to ensure that all participants understand the new designed innovative VMSs. However, the objectives and purpose of the study were not told or shared with any participant. After that, a familiarization drive for approximately 5 minutes was undertaken. During the familiarization drive, participants were asked to drive with different speeds and stop several times to estimate the minimum stopping distance accurately. Before the start of the official experiment, participants were asked to certify that they have sufficiently familiarized themselves with the driving simulator. In addition, before the start of each experimental drive, participants were given the following instructions: "You will be driving on different road sections, the speed limits on the rural highway are 120 kph on some sections and 100 on other section and the speed limits on urban highway is 80 kph. Follow traffic rules and drive as you normally drive in real roads. Remember that you have the choice of quitting the experiment for any reason and at any time". Since a separate driving runs were tested for each situation (i.e. situation 1 and situation 2), participants were given extra information for each situation. For situation 1, participants were given the extra following instruction: “keep driving on the left lane and only change your lane when you feel that you need to”. For situation 2, the following extra instruction were given: “keep driving on the second lane and do not change your lane”. A short break was offered to participants between the two experimental runs. After completing both runs, each participant was asked to fill a post-test questionnaire focusing on the subjective evaluation of the VMSs used in the experiment. The total duration of the whole experiment was approximately 60 minutes. Data collection took more than a month with an average of 3 participant tested per day. An overview about experiment procedures is presented in Table 4.

Table 4. Overview of Experimental Procedure

	Procedure step	Task	Duration
1	Welcome and pre-test questionnaires	• Sign informed consent • Discussion about the countermeasures • Pre-questionnaire	15
2	Driving simulator familiarization drive	• Warm up drive	5
3	Experimental test drives	• Collect data for the test conditions	25
4	Post-test questionnaires	• Post evaluation Questionnaire	15

3.4.1 Operational conditions

- Separate simulator room, air-conditioned to 18-19 degrees
- In case of simulator sickness symptoms, sugar holding beverage (e.g. coke) or candy is provided for the participant, the possibility to sit and take a short rest is granted. In case of serious simulator sickness symptoms: calling for medical assistance
- Participants are asked to come to the simulator facility on their own, or with someone who can drive the participant. Advice is given in case of simulator sickness to wait until the participant has recovered and feels ready to travel home. The participant signs the consent form to declare that he has read and will obey these rules

3.5 Analysis

Several parameters were collected in this study using STISIM Drive Software. The collected data which is used in this study include driver longitudinal distance from the start of the simulation run (m), elapsed time (s), vehicle's lateral position (m), longitudinal ACC/DEC (m/s^2), longitudinal travelling speed (m/s), number of crashes and the spacing with the frontal vehicles (m). All parameters mentioned earlier were recorded at every 0.1 s of elapsed time.

All parameters mentioned earlier were extracted for each 1 m for the 1500 m analysis section (1250 m before the merging point and 250 m after the merging point). In this study the merging point was considered as the reference point. For speed and ACC/DEC, point data of constant 50 m spacing were considered (31 points). Other from that, driver's lateral position data was extracted to study lane changing maneuvers, and the standard deviation (SD) of lateral position for 50 m zones was extracted. Lateral position data was calculated from left lane edge line to the middle of the simulator vehicle. Moreover, spacing between driver and the triggered left lane merging vehicle along the analysis section was extracted. Since all participants were exposed to same scenarios and same situations, a within-subject repeated measures analysis of variance (ANOVA) was applied for the analysis of speed, ACC/DEC and SD of lateral position. Moreover, two-tailed/paired t-test was conducted on specific points for the analysis of speed. The independent variables in this study are Situation (2), Scenario (2) and Point (31)/Zones (30). All statistical tests were conducted using SPSS with a p-value of 0.05.

Outlier analysis was conducted on each participant separately for the 124 potential combinations (i.e. 2 situations x 2 scenarios x 31 points). For this, if any participant had 3 interquartile range (i.e. extreme outlier) in more than 10% of the total combination, the participant was considered as an outlier. As a result, 2 participants were considered as outliers.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Speed results

The results from within-subject ANOVA test for the speed analysis at 95% confidence interval for the overall model are presented in Table 5. The results show a significant main effect for the three main factors which are ‘Situation’ ($F_{(1,65)} = 13.9$, $p<0.001$), ‘Scenario’ ($F_{(1,65)} = 27.1$, $p<0.001$) and ‘Point’ ($F_{(3,172)} = 53.2$, $p<0.001$). This denotes that independent of other factors, drivers’ traveling speed were significantly different between both situations, both scenarios and along the analyzed road segment (31 points). Moreover, the two-way interaction effects of ‘Scenario x Point’ ($F_{(14,277)} = 4.2$, $p<0.001$) was also significant. This means that drivers’ traveling speed was significantly different between both scenarios along the analyzed road segment. The interaction effects of ‘Situation x Scenario’ and ‘Situation x Point’ were not significant. Further analysis of speed was carried out to investigate the within-subject effects of each situation separately. Table 6 shows the results of situation 1, while Table 7 shows the results of situation 2. Results show that both situations revealed a significant main effects of the factors ‘Scenario’ [Situation 1: ($F_{(1,65)} = 7.4$, $p = .008$); Situation 2: ($F_{(1,65)} = 20.8$, $p<0.001$)] and ‘Point’ [Situation 1: ($F_{(2,157)} = 24.9$, $p<0.001$); Situation 2: ($F_{(4,238)} = 36.5$, $p<0.001$)]. This means that independent of any other factor, the traveling speeds for each situation were significantly different between both scenarios (i.e. control and VMS) and along the analysis segment. Moreover, the interaction effect of ‘Scenario x Point’ was significant for both situations [Situation 1: ($F_{(4,244)} = 5.3$, $p = 0.001$); Situation 2: ($F_{(5,297)} = 9.3$, $p<0.001$)].

Table 5. Analysis of Speed: Within-Subject ANOVA Test (Greenhouse-Geisser) for Overall Model

Effect	F	Dfs	p
Situation	13.9	1, 65	**<.001**
Scenario	27.1	1, 65	**<.001**
Point	53.2	3, 172	**<.001**
Situation x Scenario	3	1, 65	.108
Situation x Point	1	3, 197	.532
Scenario x Point	4.2	14, 277	**<.001**
Situation x Scenario x Point	1.6	4, 280	0.18

Table 6. Analysis of Speed: Within-Subject ANOVA Test (Greenhouse-Geisser) for Situation 1

Effect	F	Dfs	p
Scenario	7.4	1, 65	**.008**
Point	24.9	2, 157	**<.001**
Scenario x Point	5.3	4, 244	**.001**

Table 7. Analysis of Speed: Within-Subject ANOVA Test (Greenhouse-Geisser) for Situation 2

Effect	F	Dfs	p
Scenario	20.8	1, 65	**<.001**
Point	36.5	4, 238	**<.001**
Scenario x Point	9.3	5, 297	**<.001**

Two-tailed/paired t-test for each situation was carried out to investigate if the traveling speed is significantly different between the two scenarios at different points. The first point was taken before entering the work zone area which is 1250 m before the merging point while the last point is at 50 m after the merging point. Regardless of the first and last points, other points were taken at every sign location and 50 m before each sign. For each point, mean speed, standard deviation and the difference in the mean speed between both scenarios are presented. Moreover, the two-tailed/paired t-test results are also presented. Table 8 exhibits the results for situation 1, while Table 9 exhibits the results for situation 2. Starting from situation 1, where drivers were traveling on the left lane, the difference in the mean traveling speed was not significant between control and VMS scenarios for the first three points located at 1250, 1050 and 1000 m before the merging point. The difference in mean speeds for the first three points which is until Sign A between both scenarios were not significant. The mean speed difference between both scenarios was 0.1 kph. Then, from -650 m until the last point, the traveling speed for the VMS scenario was significantly lower than the traveling speed for the control scenario. The mean difference in speed was ranging between 3 kph and 6.3 kph. The highest difference of 6.3 kph was found at 550 m before the merging point.

Similar results were found for situation 2 of which drivers were travelling on the second lane. From Table 9, the difference in the mean speed between VMS and control scenarios for the first three points was not significant. Afterward, the difference for all other points was significant. The highest difference in the traveling speed between both scenarios (11.1 kph) was located at 450 m w before the merging point. Compared to situation 1, higher speed reduction between control and VMS scenarios were found for all points. Moreover, the mean speed for both scenarios at all points was lower compared to situation 1.

Table 8. Analysis of Speed: T-Test (Paired/Two-Tailed) for Situation 1

Point	Scenario	Descriptive			T-test		
		Mean	Std. Dev	$V_{CONTROL} - V_{VMS}$	df	t stat	P-value
-1250	Control VMS	100.8 100.9	8.2 11.3	-0.1	65	-0.038	0.97
-1050	Control VMS	101.1 101.2	8.2 12.1	-0.1	65	-0.068	0.946
-1000	Control VMS	101.3 101.4	8.5 11.5	-0.1	65	-0.061	0.952
-650	Control VMS	102.3 96.8	7.8 9.8	5.5	65	4.317	**<.001**
-600	Control VMS	102.1 95.9	8.4 9.9	6.2	65	4.865	**<.001**
-550	Control VMS	101 94.7	9.5 10.6	6.3	65	4.767	**<.001**
-500	Control VMS	99.1 93.4	10.7 11.5	5.7	65	4.117	**<.001**
-450	Control VMS	97.2 92.7	12 12	4.5	65	3.027	**0.003**
-400	Control VMS	95.6 91.9	13.2 12.7	3.7	65	2.437	**0.018**
-250	Control VMS	94.4 91.4	14 13.1	3	65	2.0	**0.0496**
-200	Control VMS	95 91.3	13.5 13.6	3.7	65	2.49	**0.015**
-150	Control VMS	95.1 91.1	13.3 13.7	4	65	1.669	**0.005**
-100	Control VMS	95 91	13.1 13.9	4	65	2.966	**0.004**
-50	Control VMS	95 90.8	13.4 14.2	4.2	65	3.045	**0.003**
0	Control VMS	95.1 90.6	14.1 14.5	4.5	65	3.029	**0.004**
50	Control VMS	95.1 90.6	14.8 14.3	4.5	65	3.073	**0.003**

Table 9. Analysis of Speed: T-Test (Paired/Two-Tailed) for Situation 2

Point	Scenario	Descriptive			T-test		
		Mean	Std. Dev	$V_{CONTROL} - V_{VMS}$	df	t stat	P-value
-1250	Control VMS	98.5 98.1	9.0 8.4	0.4	65	0.415	0.68
-1050	Control VMS	98.6 96	8.5 10.6	2.6	65	1.976	0.052
-1000	Control VMS	98.2 96	9.0 10.9	2.2	65	1.620	0.11
-650	Control VMS	99.4 91.1	12.7 13.7	8.3	65	5.203	**<.001**
-600	Control VMS	99.2 89	12.7 13.7	10.2	65	6.559	**<.001**
-550	Control VMS	98.7 87.7	13.4 13.3	11	65	6.737	**<.001**
-500	Control VMS	97.7 86.7	14.6 12.9	11	65	5.948	**<.001**
-450	Control VMS	96.5 85.4	16.2 12.7	11.1	65	5.498	**<.001**
-400	Control VMS	95.4 85.0	16.8 12.5	10.4	65	4.98	**<.001**
-250	Control VMS	91.9 85	17.3 12.9	6.9	65	3.187	**0.002**
-200	Control VMS	91.1 85.4	16.7 12.4	5.7	65	2.804	**0.006**
-150	Control VMS	90.4 85.8	16.5 12.3	4.6	65	2.376	**0.02**
-100	Control VMS	90.7 85.8	16.1 12.3	4.9	65	2.883	**0.005**
-50	Control VMS	91 85.5	15 11.8	5.5	65	3.577	**<.001**
0	Control VMS	91.1 85.1	15.4 10.9	6	65	3.59	**<.001**
50	Control VMS	92.6 85.4	14.4 10.4	7.2	**65**	4.616	**<.001**

To illustrate more the results of Table 8 and Table 9, Figure 15 and Figure 16 show mean speed profiles comparing control and VMS scenarios for each situation separately. The x-axis shows driver's position (m) with respect to the merging point (i.e. Point G), while the y-axis represents drivers' traveling speed (kph). Each sign is presented in the figure as a vertical line with its symbol. Moreover, speed limits upstream and at the work zone are presented in both figures. For situation 1, drivers were traveling with the same mean speed for both scenarios when approaching the work zone sign (Sign A). After 100 m of passing Sign A, drivers started to reduce their speed in the VMS scenario only, while they did not reduce their speed in the control scenario. The mean speed difference at the location of sign B was 6.2 kph. Afterward, drivers on both scenarios reduced their speed until sign D where the speed was kept approximately steady. The speed difference at the location of the second speed limit sign (Sign F) was 4 kph. For situation 2, the same trend was observed, drivers in the VMS scenario reduced their speeds in advance and more compared to the control scenario reaching a mean difference of 10.2 kph at sign B and 4.9 kph at Sign F. One of the main finding of this study is that VMSs motivated drivers to reduce their speed earlier in the advance warning area. Moreover, higher speed reduction was found for VMS scenario for both, left and second lane drivers compared to the control scenario.

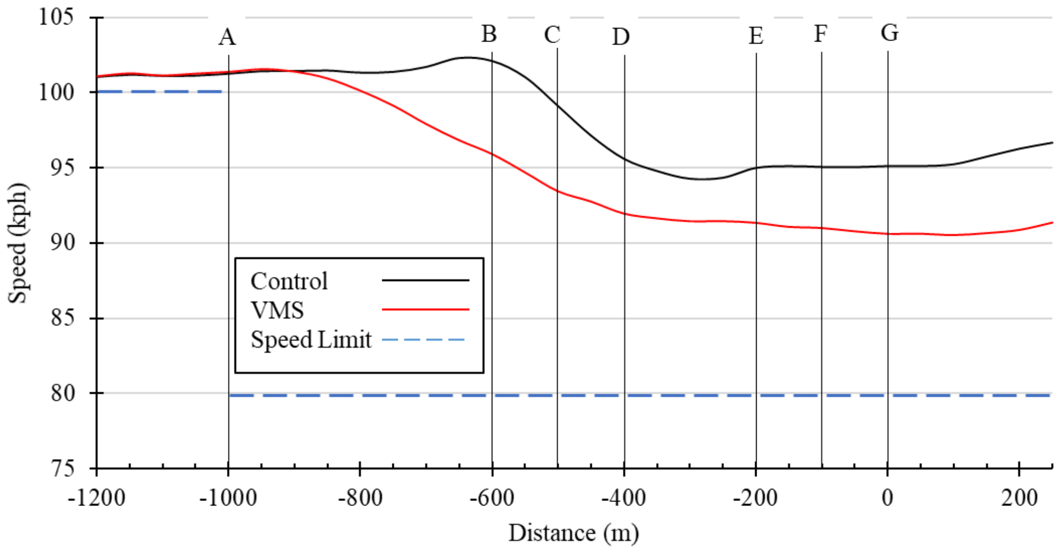


Figure 15. Mean speed profile of drivres for situation 1.

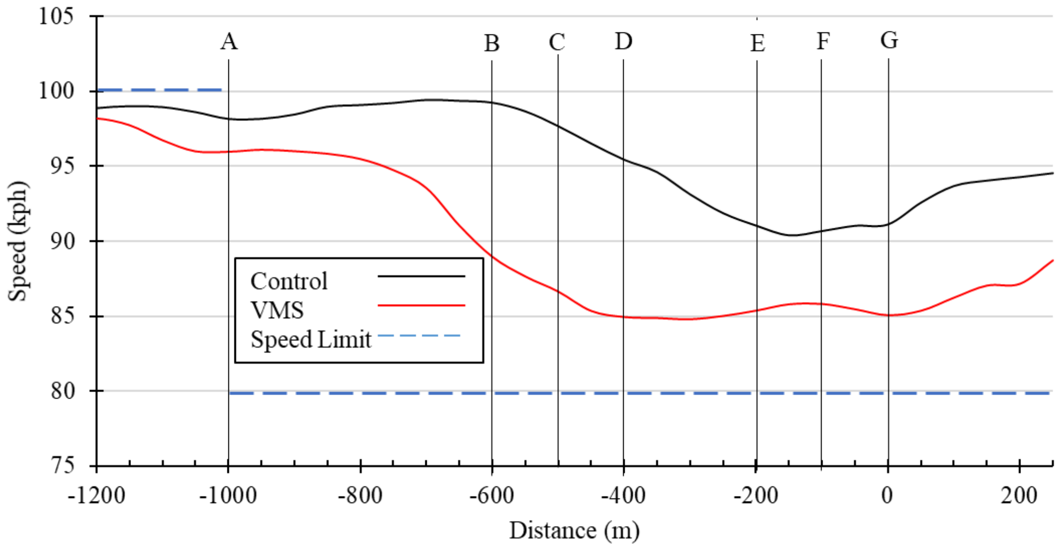


Figure 16. Mean speed profile of drivres for situation 2.

In this study, compared to the control scenario, VMSs were effective in reducing drivers' mean speed by 6.3 and 11.1 kph for left and second lane drivers, respectively. Ahmed et al. (2016) study which was conducted in one of the gulf countries (i.e. UAE) found that no significant reduction in drivers' speed at work zones was observed after the deployment of PVMS. However, in this study, drivers in both situations drove significantly lower in the VMS scenario compared to the control scenario. The fact that drivers did not comply with the temporary speed limit of 80 kph, could be attributed to the general speeding behavior at work zones and the aggressive speeding behavior characterized by drivers in Gulf countries (Domenichini et al., 2017; Ahmed et al., 2016; Timmermans et al., 2019a). Although some studies reported inconclusive results for speed reduction through the deployment of VMS. Speed reduction results of this study are in line with other studies which show that the use of VMSs at work zones significantly reduce drivers' speed (Ravani & Wang, 2018; Y. Huang & Bai, 2014).

The mean speed recorded at sign A (i.e. work zone sign) was approximately the same for both scenarios. Sign A in VMS scenario did not have impact on drivers' traveling speed. The reason of this could be that drivers did not feel that they need to reduce their speed at this point, as drivers usually travel with speeds they find it to be appropriate for the current situation (Paolo & Sar, 2012; Brewer et al., 2006; Ullman & Brewer, 2014). In VMS scenario, drivers started to reduce their speeds approximately 300 m before Sign B which means that even if the sign did not show the speed limit, the animation-based sign helped in reducing drivers' speed. This could be explained by that the animation-based VMS was effective in attracting drivers' attention which made them to reduce their speeds. In a recent study by Hussain et al. (2020a), found that animation-based VMSs were effective in preventing red light running at intersections. For both situations, the maximum speed reduction for VMS scenario compared to control scenario was observed within the location of Sign C (i.e. speed limit sign) meaning that speed limit VMS has greater impact on driver' speed reduction when compared with traditional static signs (La Torre & Nocentini, 2013; N. J. Garber & Patel, 1995).

4.2 ACC/DEC results

Table 10 presents the results from within-subject ANOVA test for the overall model for the longitudinal ACC/DEC along the 1500 m analysis segment. The results show a significant main effect of the factors 'Scenario' ($F_{(1,65)} = 17$, $p<.001$) and 'Point' ($F_{(12,792)} = 8.2$, $p<.001$). This indicate that independent of any other factor, ACC/DEC were significantly different between the two scenarios and along the analysis segment. The main effect of the factor 'Situation' was not significant meaning that drivers' mean ACC/DEC for both situations were not significantly different. The two-way interaction effect of factor 'Scenario x Point' ($F_{(13,872)} = 4.1$, $p<.001$) was significant meaning that drivers' mean longitudinal ACC/DEC was significantly different between both scenarios along the analysis section. Furthermore, the three-way interaction effect of the factor 'Situation x Scenario x Point' was significant. This means that mean ACC/DEC was significantly different along the analysis section between the two scenarios for each situation taken separately. Similar results were found for situation 1 presented in Table 11, and situation 2 presented in Table 12 taken separately.

Table 10. Analysis of ACC/DEC: Within-Subject ANOVA Test (Greenhouse-Geisser) for the Overall Model

Effect	F	Dfs	p
Situation	0.03	1, 65	.867
Scenario	17	1, 65	**<.001**
Point	8.2	12, 792	**<.001**
Situation x Scenario	0.1	1, 65	.718
Situation x Point	1.7	12, 796	.055
Scenario x Point	4.1	13, 872	**<.001**
Situation x Scenario x Point	1.9	13, 863	**.022**

Table 11. Analysis of ACC/DEC: Within-Subject ANOVA Test (Greenhouse-Geisser) for Situation 1

Effect	F	Dfs	p
Scenario	6.3	1, 65	**.014**
Point	5.5	10, 631	**<.001**
Scenario x Point	2.6	12, 784	**.022**

Table 12. Analysis of ACC/DEC: Within-Subject ANOVA Test (Greenhouse-Geisser) for Situation 2

Effect	F	Dfs	p
Scenario	9	1, 65	**.004**
Point	4.8	14, 878	**<.001**
Scenario x Point	3.3	13, 874	**<.001**

Mean longitudinal ACC/DEC are plotted in Figure 17 and Figure 18 for each situation separately. The location of each sign in the advance warning area is identified in the figure with its symbol. In situation 1 which is shown in Figure 17, drivers in the VMS scenario decelerated gradually reaching the highest mean deceleration of -0.2 m/s^2 which was between Sign A and Sign B. However, for the control scenario, drivers accelerated before Sign B which was followed by an abrupt deceleration of -0.35 m/s^2 which occurred just before the location of Sign C (i.e. speed limit sign). The figure shows that drivers in the VMS scenario did not accelerate which support speed figure (i.e. Figure 15) showing that drivers kept reducing their traveling speed. For control scenario, drivers accelerated and increased their speeds at the location of Sign E.

For Situation 2 which is shown in Figure 18, in VMS scenario, drivers' mean deceleration was -0.39 m/s^2 before Sign B. Drivers kept decelerating until Sign D which they reached the desired speed. This confirms the high speed reduction of 10 m/s (shown in Figure 16) before Sign D. For control scenario, drivers started to decelerate at the location of Sign B reaching a minimum deceleration of -0.23 m/s^2.

In both situation, drivers started to decelerate earlier in the VMS scenario compared to the control scenario. Despite that drivers in both situations for the two scenarios decelerated within the comfortable rates recommended by AASHTO (2018), ACC/DEC results support speed data which shows that drivers in the VMS scenario decelerated earlier compared to the control scenario. The higher speed reduction achieved in situation 2 for both, VMS and control scenarios indicate that drivers were reducing their speed to give more space and let the left lane frontal vehicle to merge.

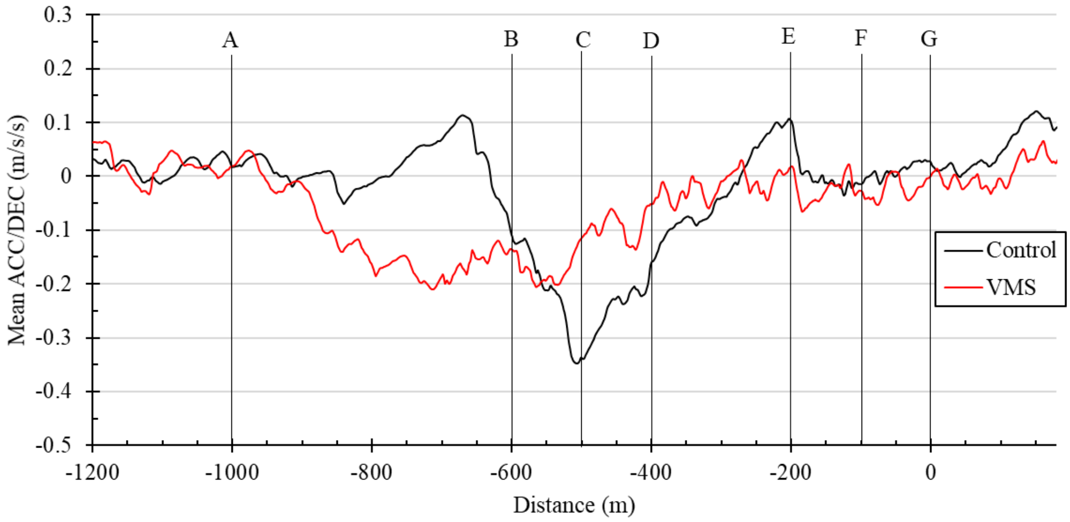


Figure 17. Mean ACC/DEC proflie of drivers for situation 1.

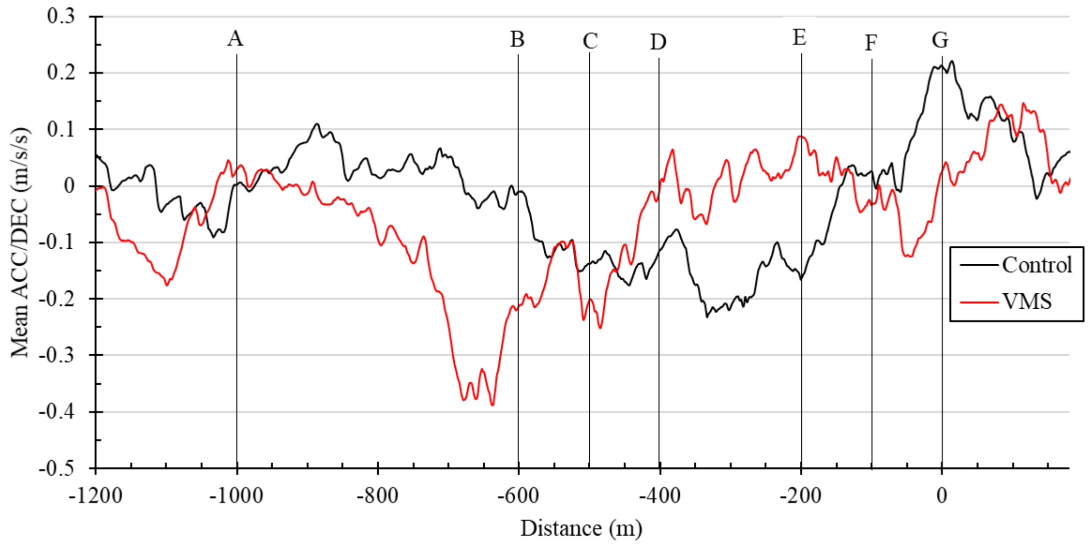


Figure 18. Mean ACC/DEC proflie of drivers for situation 2.

4.3 Lane changing results

Mean lateral position of drivers in situation 1 is illustrated in Figure 19. From the figure, drivers in the VMS scenario initiated lane changing maneuver after at the location of Sign B (i.e. 600 before the merging point) and crossed the lane dividing line at 440 m before the merging point. In Control scenario, drivers' lane changing initiating point was at 450 m before the merging point and crossed the lane dividing line at 300 m before the merging point. This means that Sign B and Sign D which were animation-based VMS showing a closed left lane and a merging vehicle were effective in motivating drivers to change their driving lanes in advance (i.e. earlier by 150 m) compared to the control static signs. Two-tailed/paired t-test showed significant difference in mean lateral position between both scenarios ($t\text{-test}_{(1499)}$: -27.8, $p<0.001$).

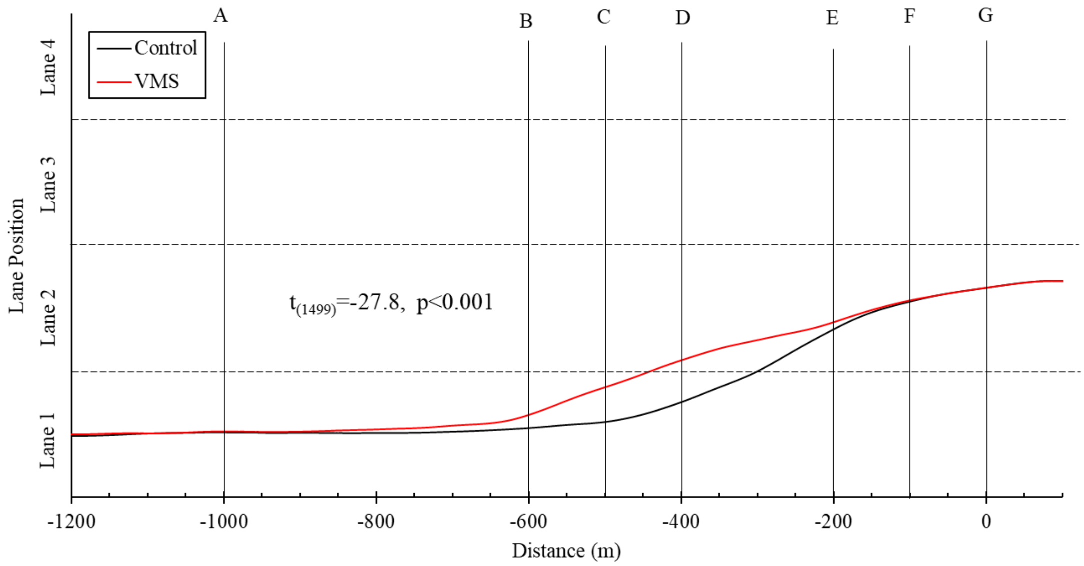


Figure 19. Lateral position profiles for drives for situation 1

Furthermore, Table 13 shows the results of the within-subject ANOVA of the SD of lateral position based on 50 m zones for situation 2. The analysis was conducted for situation 2 only, because in situation 2, drivers were driving on the second lane only and did not change their driving lane, while for situation 1, drivers had to change their lane before the merging point. For this, it was irrelevant to investigate SD of lateral position for situation 1. Results show that the factor 'Scenario' ($F_{(1,64)} = 2.1$, p=.148) was not significant indicating that VMS scenario did not affect drivers' lane position variations compared to the control scenario.

Table 13. Analysis of SD of Lateral Position: Within-Subject ANOVA Test (Greenhouse-Geisser) for Situation 2

Effect	F	Dfs	p
Scenario	2.1	1, 64	.148
Zone	4.0	8, 540	**<.001**
Scenario x Zone	1.2	10, 645	.286

Lateral position results indicated that drivers initiated lane changing maneuvers by 150 m earlier in the VMS scenario compared to the control scenario. Drivers in the VMS scenarios started to change their driving lane 600 m before the merging point. Several studies suggested that developing strategies which encourage drivers for early merging could reduce the rate of rear-end crashes (Ishak et al., 2012; Weng et al., 2015; Meng and Weng, 2011). According to Lv et al. (2013) and Zheng (2014), at low volume conditions, drivers' lane changing maneuvers are barely affected by external factors. In this study, drivers were driving at low volume condition where there was no other vehicles driving on the adjacent second lane which could affect their lane changing decision. Drivers were instructed to change their lane when the feel that they need to. However, when comparing the results for both scenarios, the animation-based VMSs were effective in making drivers to perform an early lane changing maneuvers.

It can be concluded that VMSs were effective in encouraging left lane drivers to change their driving lane earlier compared to the static signs. Moreover, VMSs did not confuse drivers on the second lane which was indicated by the SD of their lateral position.

4.4 Spacing results

As indicated earlier, for situation 2, when drivers were driving on the second lane, a triggered left lane vehicle was designed to drive in front on the driver and merge to the second lane before the merging point. Since participant were told to drive only on the second lane, any participant who changed the driving lane to the third lane to avoid the left lane merging vehicle was excluded. In total, 1 and 3 participants changed their lane to the third lane in VMS and control scenarios respectively are were excluded. Moreover, to study the spacing between drivers and the triggered vehicle, participants were also excluded if they accelerated to pass the left lane triggered vehicle. For this, 6 participants were excluded from VMS scenario and 10 participants were excluded from control scenario.

Figure 20 shows the mean longitudinal spacing profile between the driver and the triggered vehicle for the two scenarios. The x-axis shows the triggered vehicle position with reference to the merging point, and the y-axis shows the spacing between the driver and the left lane triggered vehicle. Since the triggered vehicle was traveling in front of the driver, driver's position at any point is equal to the summation of the triggered vehicle position and the spacing. As indicated earlier and as shown in the figure, triggered vehicle was released 100 m before the location of Sign B. After the release, the spacing was decreasing in both scenarios, however, the spacing in the VMS scenario reached a minimum value of 45 m and started to increase when the triggered vehicle was at 585 m (i.e. driver position was 630 m) before the merging point. Then the spacing kept in increasing reaching a maximum value of 71 m at the triggered vehicle lane changing point. On the other hand, spacing in the control scenario reached the minimum value of 37 m when the triggered vehicle was at 400 m (i.e. driver position was at 437 m) before the merging point. After that, spacing was slightly increased until the left lane vehicle indicator was turned on where the spacing was increased in a higher trend reaching a spacing of 48 m at the left vehicle lane changing point. The difference in spacing between both scenarios at the left vehicle lane changing point was 23 m. Spacing data for both scenarios at sign locations with the significance (Two-tailed/unpaired t-test) are presented in Table 14. The table shows that at all selected points, the difference in the spacing between both scenarios was significant.

It can be observed from the results that Sign B and Sign D were effective in conveying the message of keeping spacing with the left lane merging vehicle. VMSs motivated drivers in keeping more longitudinal distance with the left lane merging vehicle. The main reason that the spacing started to increase in the control scenario is when the indicator for the left lane vehicle was turned on. However, in VMS scenario, when the left lane vehicle indicator was turned on, drivers were already reducing their traveling speed and the spacing was increasing in a higher tend compared to the control scenario. The design of VMSs of the proposed system was effective in conveying the required message as the design of VMSs plays a significant factor in drivers' understandability (Y. Huang & Bai, 2014).

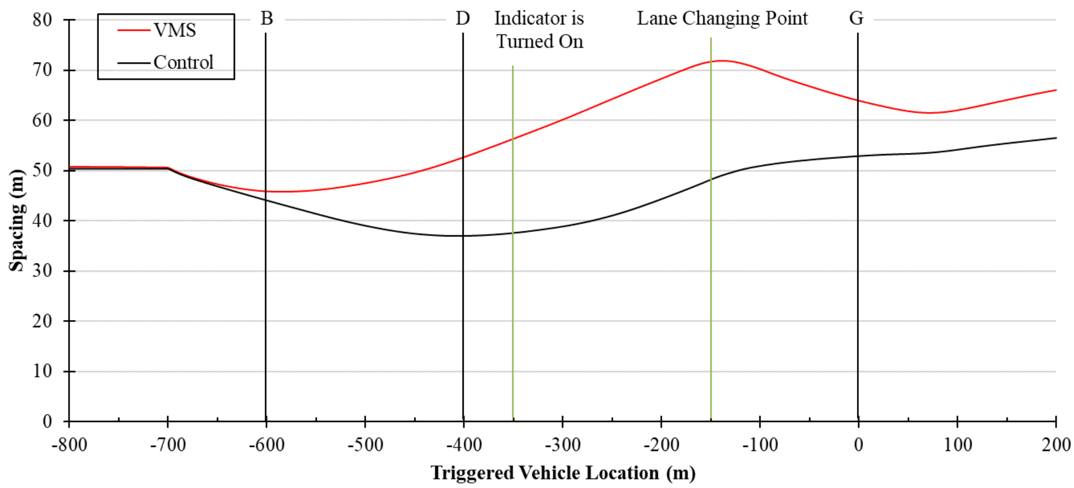


Figure 20. Mean spacing results of drivers for situation 2.

Table 14. Spacing (m) at Selected Locations for Situation 2

Location	Control Mean	VMS Mean	Mean Difference	p
Sign B	44.1	45.9	1.8	**<.001**
Sign D	37	52.7	15.7	**<.001**
Indicator	37.6	56.3	18.7	**<.001**
Lane Changing	48.2	71.7	23.5	**<.001**
G	52.9	63.9	11	**.008**

4.5 Subjective evaluation

After the completion of the two experimental runs, participants were asked to fill a post-test questionnaire focusing on two main parts. The first part focused on the overall performance of both scenarios. The second part focused on comparing specific signs (i.e. Sign B, C and D) of the control and VMS scenarios. Rating 1 indicates the lowest rating, while rating 5 represents the highest rating. For each question, mean and SD of the rating were calculated. The results are indicated in Table 15.

Results indicate that for all questions, VMSs got higher mean rating with lower SD. Participants perceived the VMSs to improve work zone safety (Mean: 4.39). Moreover, VMSs got higher rating in terms of catching drivers' attention (Mean: 4.45) and visibility (Mean: 4.55) compared to the static signs. For speed, the rating of Sign C in motivating drivers to reduce their speed was 3.82 compared to 3.44 for the static sign. Although that the lowest rating in the VMS scenario was for Sign C, speed results as was illustrated earlier showed that the highest reduction in speeds was within the location of the sign.

Results on questions regarding situation 1 supports lane changing results where participants indicated that Sign B (Mean: 4.32) and Sign D (Mean: 4.35) in the VMS scenario motivated them to merge earlier to the second lane. In addition, situation 2 results also support the spacing results of which Sign B (Mean: 4.42) and Sign D (Mean: 4.36) in the VMS scenario got higher rating than the static signs in motivating drivers to give more spacing with the left lane frontal vehicle to merge to the second lane. The highest rating in the VMS scenario was that VMSs were more visible followed by the question which indicate that VMSs caught drivers' attention. The results of the post-test questionnaire supports the results obtained for speed, ACC/DEC, lane position and spacing, of which VMSs showed to be more effective than the static signs as a potential treatment for improving traffic safety of work zones.

Table 15. Post-Test Questionnaire Results

			No. of responses for each rating					Mean Rating	Sample Size
			1	2	3	4	5		
Overall	Improving work zone safety	Static	1	14	14	28	9	3.45	66
		VMS	0	0	6	28	32	4.39	
	Catching your attention	Static	0	9	23	24	10	3.53	66
		VMS	0	0	4	28	34	4.45	
	Visibility	Static	0	9	11	28	18	3.83	66
		VMS	0	1	5	17	43	4.55	
Speed	Did sign C motivate you to reduce your speed	Static	3	6	30	13	14	3.44	66
		VMS	3	4	13	28	18	3.82	
Situation 1	Did sign B motivate you to merge in advance	Static	3	6	23	23	11	3.5	66
		VMS	1	3	5	22	35	4.32	
	Did sign D motivate you to merge in advance	Static	4	7	15	33	7	3.48	66
		VMS	2	2	6	17	39	4.35	
Situation 2	Did sign B motivate you to keep distance with the merging vehicle	Static	7	9	29	13	8	3.09	66
		VMS	0	1	4	27	34	4.42	
	Did sign D motivate you to allow the merging vehicle to merge in front of you	Static	5	11	25	19	6	3.15	66
		VMS	0	2	6	24	34	4.36	

4.6 Study limitations

One of the limitations that need to be addressed in this study is that the study was conducted using a fixed-base medium fidelity driving simulator which could lower the level of realism. However, as mentioned earlier, the simulator has been validated objectively and subjectively in a recent study (Hussain et al., 2019b). Another limitation is that in situation 2, two points were fixed for the left lane triggered vehicle for all participants which could not be the case in real world. The first point was at which the spacing between the left lane triggered vehicle and the drivers was released, while the second was at which the left lane triggered vehicle merge to the second lane. This was done in order to compare the results of the two scenarios.

CHAPTER 5: CONCLUSION AND RECOMMENDATION

5.1 Conclusion

This research investigated the safety impacts of a series of innovative VMSs at work zones. The system based of innovative VMSs was compared with untreated scenario (i.e. control scenario) composed of a series of static signs. The control scenario was designed based on the Qatar Work Zone Traffic Management Guide. Within-subject ANOVA and two-tailed/paired t-test were conducted to study different parameters such as speed reduction, ACC/DEC, lane changing maneuvers and space headway between vehicles. Each participant drove on two situations (i.e. left and second lane) and was tested for two scenarios (i.e. control and VMS). The results can be concluded in the following points:

- Results showed that VMS scenario was more effective than the control scenario for higher and early speed reduction within the advance warning area.
- For both situations, drivers started to reduce their traveling speed 300 m earlier in VMS scenario compared to the control scenario.
- The proposed system was effective in reducing drivers' speed by 6.3 kph and 11.1 kph for left and second lane drivers respectively.
- In both scenarios, drivers reduced their speed gradually until reaching the desired speed.
- Left lane drivers initiated lane changing maneuvers 150 m earlier in the VMS scenario compared with the control scenario.
- Results showed that the proposed system did not affect drivers' lane position variations for second lane drivers.
- Space headways between drivers and merging vehicles improved significantly from 37.6 m in the control scenario to 56.3 m in the VMS scenario.

- Post-test questionnaire results supported the results of this study in showing that VMSs are more effective than static signs in improving traffic safety at work zones.

Overall, the proposed VMS system was effective in improving safety at work zones in terms of speed reduction, lane changing location and headways between through and merging vehicle.

5.2 Recommendation and future research

Taking into account the results from this study, the VMS based system is recommended to policy makers as a potential treatment to improve safety at work zones. Real-world implementation of the VMS based system would allow the practitioners to investigate the long-term safety impacts.

Further research to study the safety impact of the proposed system on different road classifications (i.e. urban and rural) with different speed limits (i.e. 80 and 120 kph) and different closed lanes (i.e. left and right lanes) will allow us to have a better understanding about the effectiveness of the proposed VMS based system in improving safety at work zones. The effect of the animation-based VMSs on attracting drivers can be studied using an eye tracking system. Future research can also investigate the impact of different designs of the innovative VMSs on driving behavior at work zones.

Investigating the intrapersonal analysis can also be a recommendation for future research. The intrapersonal analysis means that each participant will run the experiment several times and the results can be compared with the interpersonal analysis of this study to see if the results of both analyses are consistent. Moreover, the results of this study can be as part of inputs for microsimulation software which can be used for the integration of traffic simulation and driving simulation. Finally, the effect of using

VMSs in reducing fuel consumption, life cycle cost and CO_2 emissions of vehicles can also be studied in future research.

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APPENDIX A: PRE-QUESTIONNAIRE

Dear Participant

Please fill in this document in anticipation. If a question is unclear, you can openly ask and the researcher will make it clear for you.

Thank you for your cooperation

****

1. Gender

◯ Male (1)

◯ Female (2)

2. Date of Birth

	Month	Day	Year
Please Select: (1)	▼ January (1 ... December (12)	▼ 1 (1 ... 31 (31)	▼ 1900 (1 ... 2049 (150)

3. Current address (City)

____

4. The highest education you have completed (with diploma)

- ◯ Below High School (1)
- ◯ High School (2)
- ◯ Bachelor Degree (3)
- ◯ Higher Degree (Masters or Doctorate) (4)

5. What is your profession?

- ◯ Employed full time (1)
- ◯ Employed part time (2)
- ◯ Unemployed (3)
- ◯ Student (4)
- ◯ Businessman/ business woman (5)
- ◯ Housewife/ househusband (6)

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6. What is your nationality?

▼ Afghanistan (1) ... Zimbabwe (1357)

7. In which year have you obtained your driving license?

Year (3)	▼ 1900 (1) ... 2049 (150)

8. When did you obtain your Qatari driving license?

	Month	Year

Please Select: (1)	▼ January (1 ... December (12) ▼ 1900 (1 ... 2049 (150)

9. Do you own a car?

◯ Yes (1)

◯ No (2)

10. Does your car have an automatic or manual gearbox?

◯ Manual (1)

◯ Automatic (2)

11. How many kilometers do you drive on average in a year?

◯ 0 to 4,999 km (1)

◯ 5,000 to 9,999 km (2)

◯ 10,000 to 14,999 km (3)

◯ 15,000 to 19,999 km (4)

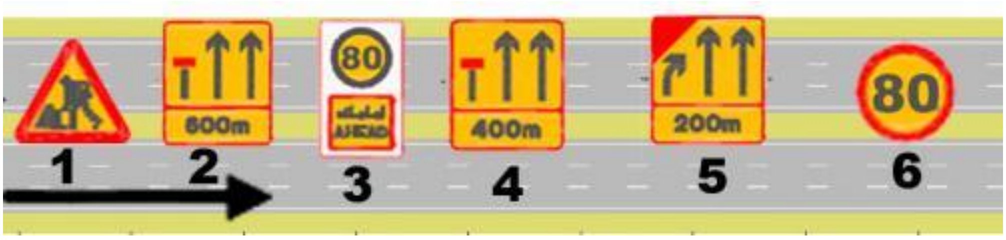
◯ 20,000 to 25,000 km (5)

◯ More than 25,000 km (6)

TTSC
مركز قطر للنقل والسلامة المرورية
Qatar Transportation and Traffic Safety Center

During the simulation drives you approached work-zones, where* temporary *speed limit was reducing from 100 kph to 80 kph and inner most lane was closed. There were two cases;

Case 1: The default series of static signs as shown below;



Case 2: The series of animation based signs as shown below;

Page Break

Q1

How would you rate the following cases in terms of improving road safety at work zones?

	Extremely useful	Very useful	Moderately useful	Slightly useful	Not at all useful
Case 1: The default series of static signs	○	○	○	○	○
Case 2: The series of animation based signs	○	○	○	○	○

Q2

How would you rate the following cases in terms of catching drivers attention?

	Extremely useful	Very useful	Moderately useful	Slightly useful	Not at all useful
Case 1: The default series of static signs	○	○	○	○	○
Case 2: The series of animation based signs	○	○	○	○	○

Q3

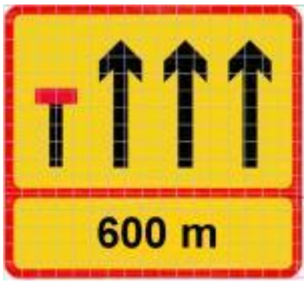
How would you rate the following cases in terms of visibility?

	Extremely good	Somewhat good	Neither good nor bad	Somewhat bad	Extremely bad
Case 1: The default series of static signs	○	○	○	○	○
Case 2: The series of animation based signs	○	○	○	○	○

Page Break

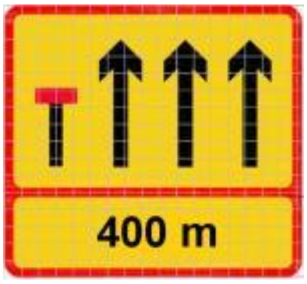
Q4

To what extent did the following signs motivate you to keep distance from the front vehicles, while you were driving on the second lane from the left?

	Extremely motivated	Very motivated	Somewhat motivated	Slightly motivated	Not at all motivated
Static sign 	○	○	○	○	○
Animation based gantry 	○	○	○	○	○

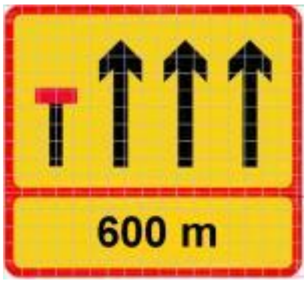
Q5

To what extent did the following signs motivate you to allow the merging vehicle to merge in front of you, while you were driving on the second lane from the left?

	Extremely motivated	Very motivated	Somewhat motivated	Slightly motivated	Not at all motivated
Static sign 	◌	◌	◌	◌	◌
Animation based sign 	◌	◌	◌	◌	◌

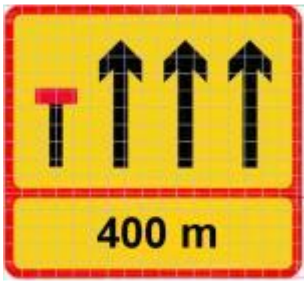
Q6

To what extent did the following signs motivate you to merge to the right lane in advance, while you were driving on the most left lane?

	Extremely motivated	Very motivated	Somewhat motivated	Slightly motivated	Not at all motivated
Static sign 	○	○	○	○	○
Animation based gantry 	○	○	○	○	○

Q7

To what extent did the following signs motivate you to merge to the right lane in advance, while you were driving on the most left lane?

	Extremely motivated	Very motivated	Somewhat motivated	Slightly motivated	Not at all motivated
Static sign 	○	○	○	○	○
Animation based sign 	○	○	○	○	○

Q8

To what extent did the following signs motivate you to reduce your speed?

	Extremely motivated	Very motivated	Somewhat motivated	Slightly motivated	Not at all motivated
Static sign 	○	○	○	○	○
VMS sign 	○	○	○	○	○

Q9

If you have any comments or suggestions, please mention below

Q10

Please insert the participation code: