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16. Abstract

Portable changeable message signs (PCMSs) have been employed in highway work zones as an innovative temporary traffic control (TTC) device in the United Stated for many years. The traditional message format on a PCMS is text-based, which has been found to have several limitations in recent studies, such as confusing drivers and delaying their responses during driving, being difficult to read for older drivers and non-English-speaking drivers, and having a short range of legibility. The use of graphic-aided messages on PCMSs has many advantages over text-based PCMSs based on a number of previous laboratory simulation experiments. This research project used field experiments and driver surveys to determine the effectiveness of a graphic-aided PCMS on reducing vehicle speed and drivers' acceptance of utilizing a graphic-aided PCMS in the upstream of a one-lane two-way rural highway work zone. Field experiment were conducted to compare the effectiveness of text PCMS, graphic-aided PCMS, and graphic PCMS on reducing vehicle speed in a highway work zone in Kansas , and to develop regression models of the relationship between mean vehicle speed and distance under three PCMS conditions. Driver surveys were conducted to evaluate drivers' opinions on the implementation of a graphic-aided PCMS in the highway work zone. The findings showed that 1) using a text, a graphic-aided, and a graphic PCMS resulted in a mean vehicle speed reduction of 13%, 10%, and 17%, respectively; 2) using a graphic-aided PCMS reduced mean vehicle speed more effectively than using a text PCMS from 1,475 ft to 1,000 ft in the upstream of a work zone; using a graphic PCMS reduced mean vehicle speed more effectively than using a text PCMS from 1,475 ft in the upstream of the work zone to the location of the second TTC sign (W20-4 sign); 3) the majority of drivers understood the work zone and flagger graphics and believed the graphics drew their attention more to the work zone traffic conditions; and 4) more drivers preferred the information to be presented in the graphic-aided and graphic formats if the graphic-aided and graphic PCMSs were available.

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DETERMINING THE EFFECTIVENESS OF GRAPHIC-AIDED DYNAMIC MESSAGE SIGNS IN WORK ZONES

Final Report
July 2011

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Chapter 1 Introduction

1.1 Background

The U.S. Interstate Highway System and many state and local highways were built between the 1950s and the 1970s, most of which were designed to last 25 to 30 years before major pavement rehabilitation was needed. In the past decade, many highways in the National Highway System (NHS) had been resurfaced, and as a result, travelers had encountered more work zones on highways. According to Federal Highway Administration (FHWA)'s statistics, an average of 23,745 miles of roadway had improvement projects underway per year from 1997 to 2001 (FHWA, 2001), and an estimated 3,110 work zones were present on the NHS during the peak summer roadwork season of 2001 (FHWA, 2002).

The majority of road work takes place on existing highways already carrying traffic, and therefore these work zones create an inevitable disruption on regular traffic flows, which leads to safety problems. To improve highway work zone safety, great efforts have been devoted across the country for decades. Congress addressed its concern with work zone safety in the Intermodal Surface Transportation Efficiency Act of 1991, where the Secretary of Transportation was required to develop and implement a work zone safety program and uniform accident reporting for fatalities, injuries and highway construction site accidents (FHWA, 1991). In the National Highway System Designation Act of 1995, Congress addressed some work zone safety initiatives which required the Secretary of Transportation to utilize a variety of methods to increase safety at highway construction sites, including encouraging the use of enforceable speed limits in work zones and developing training programs for work site designers and construction workers to promote safe work zone practices (FHWA, 1998). The Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users included a number of provisions emphasizing highway work zone safety and other work zone-related issues (FHWA, 2005). In addition, the FHWA and the American Association of State Highway and Transportation Officials (AASHTO) have played the leading role in this area and have developed practical highway work zone safety guides and programs. Many state Departments of Transportation (DOTs) have initiated research projects to improve work zone safety. Other interested organizations and individuals have also participated in this campaign by conducting meaningful research on various work zone safety issues (Li, 2007).

Despite the efforts that have been made so far, highway work zone safety still remains unsatisfactory nationwide. According to the National Highway Traffic Safety Administration's Fatality Analysis Reporting System, an average number of 964 people were killed in work zone crashes each year since 2000, compared with an average number of 721 fatalities each year from 1982 to 1999, which increased by about 34%. The average percentage of work zone fatalities in total fatalities also climbed from 1.7% between 1982 and 1999 to 2.4% in the recent decade. Figure 1.1 illustrates the growing trend of the number and percentages of work zone fatalities from 1982 to 2009. Although the number of work zone fatalities has dropped since 2002, there were still several hundred losses of life and nearly 40,000 people injured in work zone crashes each year (FHWA, 2011). The direct cost of highway work zone crashes, estimated based on crash data from 1995 to 1997, was as high as $6.2 billion per year- an average cost of $3,687 per crash (Mohan and Gautam, 2002). These alarming numbers have raised an imperative need to improve work zone safety.

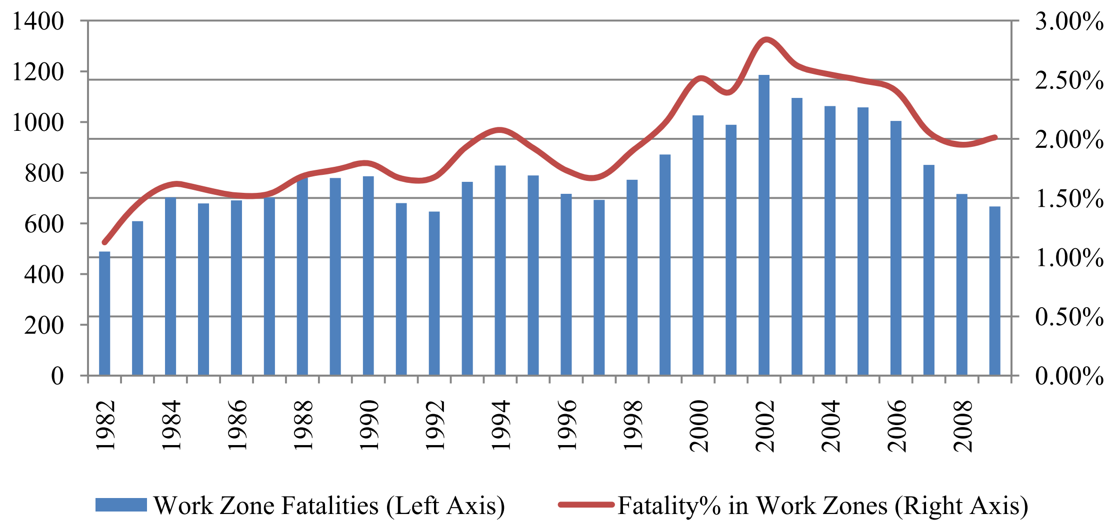

Figure 1.1 Number and Percentages of Work Zone Fatalities from 1982 to 2009

1.2 Problem Statement

To improve highway work zone safety, numerous traffic control devices have been developed and implemented nationwide. As the engineering standard of highway traffic control devices, the Manual on Uniform Traffic Control Devices (MUTCD) presents a number of temporary traffic control (TTC) devices to provide reasonably safe and efficient traffic flow during road construction and maintenance, including flaggers, traffic signs, TTC signals, channelizing devices, rumble strips, pavement markings, lighting devices, arrow panels, and portable changeable message signs (PCMSs). Among these TTC devices, the PCMS is an innovative traffic control device which is capable of displaying one or more alternative messages to inform motorists of unusual driving conditions (FHWA, 2009). A PCMS, as one type of changeable message signs (CMSs), is housed on a trailer or on a truck bed and can be deployed quickly for meeting the temporary requirements frequently found in work zones or accident areas (FHWA, 2003). It can capture motorists' attention, display information that is difficult to accomplish with static signing, and can be used to supplement other required signing.

The traditional type of a PCMS is text-based and has been in place for decades. Many recent studies, however, have pointed out that although text message is the existing message format on a PCMS, it has several limitations. Wang et al. (2007) argued that lengthy and complex text messages could be confusing to drivers and delay their responses during driving, especially for older drivers and nonnative-English-speaking drivers. Nsour (1997) found that reading text messages on a PCMS was one of the most difficult tasks for elderly drivers when compared to young drivers. Ullman et al. (2009) discovered that at prevailing highway speeds, drivers were in the legibility range of PCMS messages for about eight seconds or less. The amount of time drivers had to comprehend a message decreased when they were confronted with complex driving and traffic situations, and the difficulty was even more complicated for drivers unfamiliar with the area or English was not their primary language.

The development in sign technology has now allowed for the use of color and full-matrix PCMS and makes it possible to display symbols and other graphic features to drivers. Graphic-aided messages on PCMSs could offer potential advantages over text messages because drivers can read and understand well-designed symbols and graphics quicker and farther upstream of the PCMS (Ullman et al., 2009). In addition, graphic-aided messages could be seen more easily under adverse viewing conditions and be understood better by drivers who do not understand the language in text messages (Wang et al., 2007). Therefore, it is possible that the use of graphic-aided messages on PCMSs can offset some of the limitations of text messages, particularly in complicated driving situations and high information load locations, such as work zones (Ullman et al., 2009).

Although many researchers have realized the advantages of graphic-aided messages, their usage on PCMSs is still new in the United States, and only a handful of studies have been conducted. Colomb et al. (1991), Tsavachidis and Keller (2000), Alkim et al. (2000), and Wang et al. (2007) performed simulation experiments to study drivers' comprehension of graphics on message signs. All these studies, however, were conducted in laboratory environments in which people were able to put maximum effort on the sign reading task. In real-world driving, on the other hand, there are many other needs that could demand attention from the drivers such as lane keeping, speed controlling, and car following. Thus, the results obtained from previous studies only provided a relative performance measure about sign reading in optimal circumstances (Wang and Cao, 2005). To overcome the limitations of the simulator experiments in laboratory environments, there is a need to conduct field experiments in real-world conditions with ongoing traffic.

1.3 Report Organization

This report includes five chapters. This chapter is an introduction to the research background and problem statement. The following chapters are:

Chapter 2: Objectives, Scope, and Methodology. This chapter describes the primary objectives of the study as well as its scope and methodology.

Chapter 3: Literature Review. This chapter presents the findings from a comprehensive literature review on work zone- and CMS-related subjects, including the characteristics of highway work zone crashes, work zone traffic control methods, CMS applications in highway work zones, graphic-aided CMS studies in highway safety, human factors in highway safety, and the statistical methods used in previous research.

Chapter 4: Field Experiment. This chapter describes the designing and conducting of field experiments, including experimental devices and layout, data collection, and data analysis.

Chapter 5: Conclusions and Recommendations. This chapter presents the conclusions of the study and recommendations for future research.

Chapter 2 Objectives, Scope, and Methodology

2.1 Research Objectives

The primary goal of this research project was to determine the effectiveness of graphic-aided PCMSs on reducing vehicle speeds in a one-lane two-way rural highway work zone. This goal will be accomplished through achieving specified research objectives using field experiments and driver surveys. These objectives are summarized as follows:

1. To determine the effectiveness of graphic-aided PCMSs on reducing vehicle speeds in a highway work zone;
2. To compare the effectiveness of a text PCMS, a graphic-aided PCMS, and a graphic PCMS on reducing vehicle speeds in a highway work zone;
3. To develop regression models that describe the relationships between mean vehicle speeds and distances under different PCMS conditions; and
4. To evaluate drivers' opinions on the implementation of graphic-aided PCMSs in a highway work zone.

Objectives 1, 2 and 3 will be achieved using field experiments which include the experimental design, vehicle speed data collection, and the speed data analysis; objective 4 will be accomplished using driver surveys at the field experimental site.

2.2 Research Scope

The scope of this research was limited to measuring the effectiveness of vehicle speed reduction using graphic-aided PCMSs in a one-lane two-way rural highway work zone in Kansas. While construction and maintenance operations were underway, the two-lane highway was reduced to a one-lane two-way work zone. One traffic lane was closed for construction while the other lane was kept in service. This type of the work zone was required temporary traffic signs, flaggers, and a pilot car to coordinate vehicles entering and leaving the site. The traffic volume of selected work zone for this study was moderate so that free flow vehicle speeds could be measured in the upstream of the work zones.

2.3 Research Methodology

The research objectives were achieved using the following four steps:

Step 1: Literature Review. A comprehensive literature review was conducted first to provide the background of highway work zone safety research. The review synthesized the findings from the previous literature on work zone- and CMS-related subjects including the characteristics of highway work zone crashes, work zone traffic control methods, CMS applications in highway work zones, graphic-aided CMS studies in highway safety, human factors in highway safety, and the statistical methods used in these studies. The reviewed literature included, but was not limited to, journal papers, research reports, conference proceedings, theses, dissertations, and Internet publications.

Step 2: Data Collection. Data for this study included vehicle speed data and driver survey results. Vehicle speed data were collected within the area from 1,475 ft upstream to 530 ft downstream of the work zone; driver surveys were conducted at the flagger location where all vehicles had to stop and wait for the pilot car.

Step 3: Data Analysis. Vehicle speed data were analyzed using various statistical methods including frequency analysis, comparison analysis, hypothesis test, and regression models. Driver survey results were analyzed using comparison approaches. Programs SPSS Statistics 17.0 and Microsoft Office Excel 2007 were used in the data analysis.

Step 4: Conclusions and Recommendations. Conclusions were drawn based on the results of the data analyses. The conclusions included the effectiveness of graphic-aided PCMSs on reducing vehicle speeds in a highway work zone, the comparison of the effectiveness of a text PCMS, a graphic-aided PCMS, and a graphic PCMS on reducing vehicle speeds in a highway work zone, as well as drivers' opinions on the implementation of graphic-aided PCMSs in highway work zones. Recommendations for future research were also presented at the end of this report.

Chapter 3 Literature Review

The aging highway system in the United States has led to an increasing demand on existing highway preservation, rehabilitation, expansion, and enhancement. Most of these construction activities require work zones on highways with active traffic. Work zones create an inevitable disruption on regular traffic flows and result in severe traffic delays and safety concerns (Li, 2009). To address these issues, a number of studies on highway work zone safety have been carried out (Bai and Li, 2007). In this chapter, the findings of previous research on work zone- and CMS-related subjects are presented. These subjects include: 1) the characteristics of highway work zone crashes, 2) work zone traffic control methods, 3) CMS applications in highway work zones, 4) graphic-aided CMS studies in highway safety, 5) human factors in highway safety, and 6) the statistical methods used in work zone safety research.

3.1 Introduction to Highway Work Zones

A work zone is an area of a highway with construction, maintenance, or utility work activities, which is typically marked by signs, channelizing devices, barriers, pavement markings, and work vehicles. It extends from the first warning sign or high-intensity rotating, flashing, oscillating, or strobe lights on a vehicle to the END ROAD WORK sign or the last TTC device (FHWA, 2009).

Most highway work zones are divided into four areas: the advance warning area, the transition area, the activity area, and the termination area, as illustrated in Figure 3.1 (FHWA, 2009). The advance warning area is the section of highway where road users are informed about the upcoming work zone. The transition area is the section of highway where road users are redirected out of their normal path and therefore frequently forms a bottleneck which could dramatically reduce the traffic throughput (Li, 2009). The activity area is the section of the highway where the work activity takes place. It is comprised of the work space, the traffic space, and the buffer space. The termination area is the section of the highway where road users are returned to their normal driving path. The termination area extends from the downstream end of the work area to the last TTC device such as END ROAD WORK signs, if posted (FHWA, 2009).

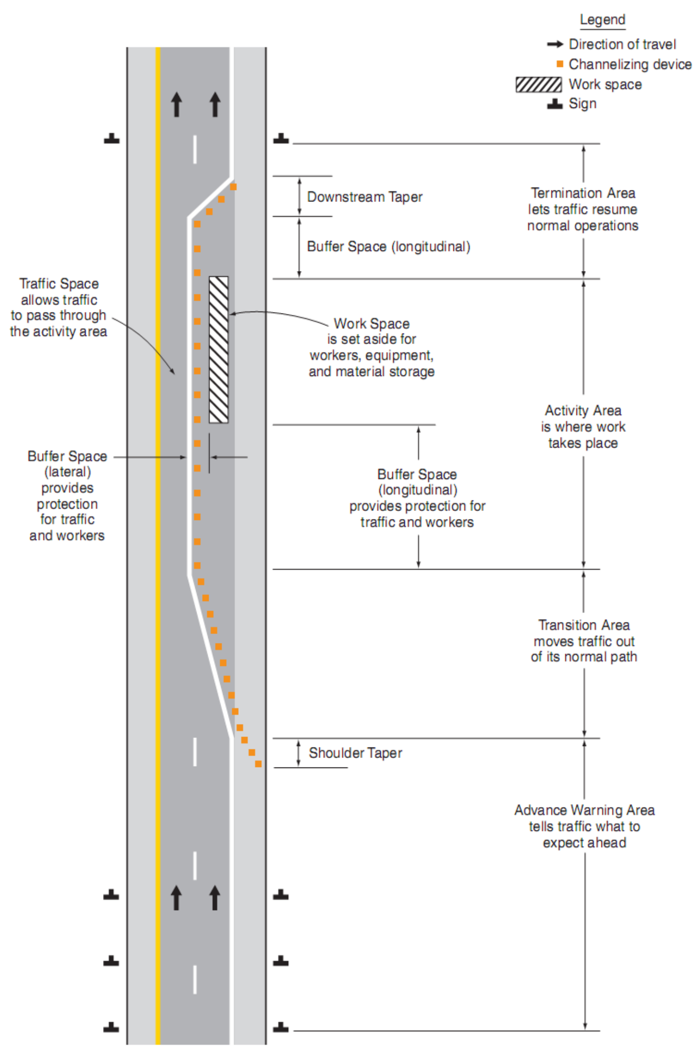

Figure 3.1 Component Areas of a Work Zone (MUTCD 2009 edition, Page 553)

A typical work zone on a two-lane highway, called one-lane two-way work zone, occupies one lane for road work and the other remains open for traffic from both directions. This type of work zone is set up for a short duration (a few hours to several days) and requires frequent movement and re-setup due to the progress of road work. Thus, properly coordinating and safely guiding the traffic from both directions through the work zone become crucial. These one-lane two-way work zones typically utilize traffic control devices such as flaggers and pilot cars to control traffic flows and provide safety for both through travelers and highway workers (Li, 2009). According to MUTCD, such work zones may require the proper implementation of following traffic control methods (FHWA, 2009):

- Configuration of flagger control. When a one-lane, two-way work zone is short enough to allow a flagger to see from one end of the zone to the other, a single flagger may be used to control traffic. For relatively long work zones, traffic needs to be controlled by a flagger at each end of the work zone. These flaggers should be able to communicate with each other orally, electronically, or with manual signals. In addition, flaggers should coordinate the traffic so that the vehicles stopping on the other end do not proceed until the platoon from the opposite direction travels through.
- Proper use of pilot vehicle. A pilot car may be used in a one-way, two-lane work zone to guide a queue of vehicles. The operation of a pilot vehicle should be coordinated with flagging operations or other controls at each end of the work zone. A PILOT CAR FOLLOW ME sign should be mounted on a pilot vehicle at

a conspicuous location. The vehicle may also turn on its emergency lights and additional flashers to improve its visibility.

- Other traffic signs and signals. In addition to flaggers and pilot vehicles, other supplemental traffic control methods that could be used in one-lane, two-way work zones include traffic control signals and STOP or YIELD traffic signs. When conditions allow (e.g., drivers are able to see the other end of the work zone and are also sufficiently visible to approaching vehicles), these methods may also be used independently for traffic control.

3.2 Characteristics of Highway Work Zone Crashes

Knowledge of highway work zone crash characteristics helps traffic engineers and researchers to better understand the needs of work zone traffic control (Li, 2009). This section summarizes the findings of previous studies on work zone crash characteristics. Most of these studies were conducted statewide, while a few addressed nationwide work zone safety issues. Due to the diversity of data scopes, the results of some similar studies were inconsistent. The major characteristics of highway work zone crashes are summarized in terms of crash rate, severity, type, time, location, and causal factors.

3.2.1 Crash Rate

Highway work zones inevitably disturb regular traffic flow, result in a decrease of capacity, and therefore create hazardous environments for motorists and workers. Table 3.1 lists previous studies on highway work zone crash rate after the late 1970s. Many studies agreed on the higher crash rates in highway work zones.

Table 3.1 Previous Studies on Crash Rate

Year	Study Data	Location	Researcher	Crash Rate
1978	151 crashes	Ohio	Nemeth and Migletz	Increase
1978	79 projects	Multiple states	Graham et al.	6.9% increase
1988	46 projects	Illinois	Rouphail et al.	Increase
1989	499 crashes	New Mexico	Hall and Lorenz	26% increase
1990	7 projects	Virginia	Garber and Woo	57% -168% increase
1990	2,013 crashes	Kentucky	Pigman and Agent	Increase
1996	25 projects	Indiana	Pal and Sinha	Increase
2002	36 projects	California	Khattak	21.5% increase

Nemeth and Migletz (1978) studied 151 crashes in Ohio and compared the crash rate per million vehicle miles before, during, and after construction and maintenance. The results showed that crash rate during construction increased significantly. Graham et al. (1978) analyzed 79 projects in seven states. As a whole, crash rates increased by 6.8%. The change of crash rate was found to vary substantially among individual projects. Rouphail et al. (1988) selected 46 sites in the Chicago Area Expressway System and collected the crash data from 1980 to 1985. The researchers found that the crash frequency increased in work zones. Hall and Lorenz (1989) found that crashes during construction increased by 26% compared with crashes during the same period in the previous years when no construction occurred in New Mexico. Garber and Woo (1990) selected 7 project sites in Virginia and found that, on average, the crash rates increased by 57% in multilane highway work zones and by 168% in two-lane urban highway work zones. Pigman and Agent (1990) collected 2,013 crashes in Kentucky from 1983 to 1986. The researchers discovered that crash rates during construction exceeded those in the previous period in 14 of 19 sites. Pal and Sinha (1996) found that there was a significant increase of crash rates between normal conditions and road work conditions in Indiana. Khattak et al. (2002) pointed out the rate of total work zone crashes was 21.5% higher than the pre-work zone crash rate and indicated that work zone projects on limited-access roadways were more hazardous than those same segments in the pre-work zone period. These studies demonstrated that the increase in crash rate as a result of highway work zones was highly variable and likely dependent upon specific factors related to traffic conditions, geometrics, and environment.

3.2.2 Crash Severity

When compared with non-work zone crashes, inconsistent conclusions have been reached about whether more severe crashes occur in work zones. Table 3.2 lists previous studies on highway work zone crash severity.

Table 3.2 Previous Studies on Crash Severity

Year	Study Data	Location	Researchers	Crash Severity
1978	151 crashes	Ohio	Nemeth and Migletz	Increase
1981	Work zone crashes	Texas	Richards and Faulkner	Truck-related increase
1981	2127 crashes	Virginia	Hargroves	Less severe
1987	National survey	Multistate	AASHTO	Increase
1988	Crashes in Chicago	Illinois	Rouphail et al.	Less severe
1989	499 crashes	New Mexico	Hall and Lorenz	No significant difference
1990	2,013 crashes	Kentucky	Pigman and Agent	Increase
1990	7 projects	Virginia	Garber and Woo	No significant difference
1995	1982-1986 crashes	Ohio	Ha and Nemeth	Truck-related increase
1995	Crashes in three states	Multistate	Wang et al.	Less severe
2000	181 crashes	Georgia	Daniel et al.	Truck-related increase
2002	1484 crashes	Virginia	Garber and Zhao	Increase
2004	77 fatal crashes	Texas	Schrock et al.	Truck-related increase
2006	157 fatal crashes	Kansas	Li and Bai	Truck-related increase

Nemeth and Migletz (1978) found that the severity of work zone crashes increased, especially for injury crashes. A national study by AASHTO in 1987 discovered that both fatal crash frequency and average fatalities per crash were higher in work zones across the country. Pigman and Agent (1990) concluded that work zone crashes were more severe than other crashes. Garber and Zhao (2002) collected 1,484 crashes from 1996 to 1999 in Virginia and pointed out that more severe crashes happened in work zones. On the other hand, Hall and Lorenz (1989), Garber and Woo (1990) concluded that the severity was not significantly different between work zone crashes and non-work zone crashes. Hargroves (1981), and Ha and Nemeth (1995) found that work zone crashes were less or slightly less severe than other crashes. Work zone crashes involving large trucks were more severe than other crashes. Richards and Faulkner (1981), Pigman and Agent (1990), Ha and Nemeth (1995), Daniel et al. (2000), Schrock et al. (2004), Li and Bai (2006) pointed out the disproportionate number of large trucks involved in fatal and injury crashes.

3.2.3 Crash Type

The prevailing types of work zone crashes varies with times and locations in the work zones. However, results of most previous studies indicated that the rear-end collision was one of the most frequent work zone crash types (Nemeth and Migletz, 1978; Hargroves, 1981; Rouphail et al., 1988; Hall and Lorenz, 1989; Pigman and Agent, 1990; Garber and Woo, 1990; Wang et al., 1995; Ha and Nemeth, 1995; Sorock et al., 1996; Daniel et al., 2000; Mohan and Gautam, 2002; Garber and Zhao, 2002; Chambless et al., 2002; Bai and Li, 2006; Bai and Li, 2007; Li and Bai, 2008). Other major types of work zone crashes include same-direction sideswipe collision (Nemeth and Migletz, 1978; Pigman and Agent, 1990; Garber and Woo, 1990; Li and Bai, 2008), angle collision (Pigman and Agent, 1990), and hit-fixed-object crashes (Nemeth and Migletz, 1978; Hargroves, 1981; Mohan and Gautam, 2002; Garber and Zhao, 2002).

Another major work zone safety concern is the frequent involvement of heavy trucks in work zone crashes. Several studies found that the percentage of truck-involved crashes was much higher in work zones (Pigman and Agent, 1990; AASHTO, 1987) and heavy truck related crashes were more likely to involve multiple vehicles and hence frequently resulted in fatalities and large monetary loss (Pigman and Agent, 1990; Schrock et al., 2004; Hill, 2003). Benekohal et al. (1995) found that 90% of the surveyed truck drivers considered driving through work zones to be more hazardous than in other areas.

3.2.4 Crash Time

Work zone crashes frequently occur in the daytime (Mohan and Gautam, 2002; Chembless et al., 2002; Hill, 2003; Li and Bai, 2006) during the busiest construction season between June and October (Pigman and Agent, 1990). Nighttime work zone crashes, however, were found to be much more severe in most cases (Garber and Zhao, 2002; Pigman and Agent, 1990; AASHTO, 1987). Nemeth and Migletz (1978) found that the proportion of tractor-trailer- or bus- caused crashes at darkness was greater than the proportion of other vehicles, which consequently resulted in more severe crashes due to the large sizes of tractor-trailers and buses.

3.2.5 Crash Location

Researchers of previous studies agreed on the unbalanced crash distribution along the work zone component areas, but they did not reach consistent conclusions on the most dangerous work zone areas. As illustrated in Figure 3.1, the advanced warning area (Pigman and Agent, 1990), the activity area (Garber and Zhao, 2002; Schrock et al., 2004), and the termination area (Nemeth and Migletz, 1978; Hargroves, 1981) were highlighted as the most dangerous areas in terms of severe crash frequency in different literature.

In terms of work zone locations, work zone crashes occurred more frequently on rural highways than urban highways. A national study found that about 68% of all fatal crashes occurred on rural highways (AASHTO, 1987). In particular, the rural interstate systems (Pigman and Agent, 1990; AASHTO, 1987; Chembless et al., 2002) or two-lane highways (Rouphail et al., 1988) were the places where work zone crashes most likely occurred. Pigman and Agent (1990) discovered that the percentage of work zone crashes occurring in rural areas was much higher than in business and residential areas. Daniel et al. (2000) concluded that the fatal crash rate in rural work zones increased by about 13% when work zones were on the road. A recent study by Li and Bai (2006) found that 63% of fatal crashes occurred on two-lane rural highways in Kansas.

3.2.6 Causal Factors

Most previous studies pointed at human errors, such as following too close, driving inattentively, and misjudging, as the most common cause of work zone crashes (Nemeth and Migletz, 1978; Hargroves, 1981; Hall and Lorenz, 1989; Pigman and Agent, 1990; Garber and Woo, 1990; Ha and Nemeth, 1995; Chambless et al., 2002; Li and Bai, 2008). Some studies also indicated that speeding (Garber and Zhao, 2002) and inefficient traffic control (Ha and Nemeth, 1995) were two other factors causing crashes in the work zones. Hill (2003) found that there was a significant difference on types of driver errors between daytime crashes and nighttime crashes. Researchers proved that adverse environmental and road surface conditions did not contribute more to work zone crashes than to crashes at other places (Nemeth and Migletz, 1978; Garber and Woo, 1990).

3.2.7 Summary of Work Zone Crash Characteristics

The characteristics of highway work zone crashes in previous studies are summarized as follow:

1. Researches on highway work zone safety have been carried out in the United States since the 1960s. Most previous studies were conducted statewide and their findings varied in some aspects;
2. Most previous studies agreed that crashes occurred more likely in highway work zones than in non-work zones. Particularly, higher crash rates were found in rural and long-term highway work zones;
3. There were no consistent conclusions on whether work zone crashes were more severe than other crashes. However, previous studies agreed that truck-involved and nighttime work zone crashes were more severe than non-work zone crashes;
4. Rear-end crash was the most frequent crash type in work zone crashes. Same-direction sideswipe, angle collision and head-on collision were also frequently found in work zone crashes. Truck-involved crashes were more frequent and severe in work zones;
5. Most work zone crashes occurred in the daytime. However, work zone crashes during nighttime were more severe than both daytime work zone crashes and non-work zone crashes;
6. No consistent conclusions were reached on the most dangerous areas in work zones. In addition, previous studies showed that vehicles crashes were most likely to occur in the work zones at the rural interstate highways;

7. Human errors and inefficient traffic controls were the major causes of work zone crashes. Adverse environmental factors and road conditions, on the contrary, did not contribute more to work zone crashes than to non-work zone crashes.

3.3 Work Zone Traffic Control Methods

Work zone traffic control has become more important as the emphasis of highway projects is shifted from new construction to rehabilitating and improving existing roads. Highway work zones use TTC devices to provide the continuity of reasonably safe and efficient traffic flows during road work (Li, 2007). According to the MUTCD, commonly used TTC devices in work zones include flaggers, traffic signs, TTC signals, channelizing devices, rumble strips, pavement markings, lighting devices, arrow panels and PCMSs (FHWA, 2009). In addition, law enforcement is another effective method to improve safety in highway work zones. Since excessive travel speed in work zones has been revealed as a major contributing factor to work zone crashes, the main purposes of utilizing these traffic control methods are to reduce and control vehicle speeds in the work zones.

3.3.1 Flaggers

The MUTCD (FHWA, 2009) defines flaggers as qualified personnel uniformed with high-visibility safety apparel and equipped with hand-signaling devices such as STOP/SLOW paddles, lights, and red flags to control road users through work zones. Flaggers should be stationed at a location so that the road users have sufficient distance to stop at an intended stopping point, and should be preceded by an advance warning sign or signs and be illuminated at night (FHWA, 2009).

Richards and Dudek (1986) found that flaggers were most efficient on two-lane, two-way rural highways and urban arterials, where they had the least competition for drivers' attention; flaggers were also well suited for short-duration applications (less than one day) and for intermittent use at long-duration work zones. Richards et al. (1985) found that flaggers contributed 3 to 12 mph speed reduction for vehicles approaching the work zones. McCoy and Bonneson (1993) found that innovative flagging procedures were effective in reducing the speed of vehicles approaching a work zone within the range from 9.2 mph to 15.2 mph. Jones and Cottrell (1999) indicated that the proposed sign, a STOP/SLOW paddle, was for the most part understood by Virginia drivers and appeared to be effective at conveying its message. Hill (2003) proved that flaggers were also effective in reducing fatal crashed in the work zones. Benekohal et al. (1995), however, indicated there was a need for improving flagging for heavy-truck traffic. Their survey showed that one third of the surveyed truck drivers responded that flaggers were hard to see and half of them thought the directions of flaggers were confusing.

3.3.2 Traffic Signs and TTC Signals

According to the MUTCD, traffic signs include regulatory signs, warning signs, and guide signs. Regulatory signs inform road users of traffic laws or regulations and indicate the applicability of legal requirements that would not otherwise be apparent; warning signs notify road users of specific situations or conditions on or adjacent to a roadway that might not otherwise be apparent; guide signs along highways provide road users with information to help them through work zones (FHWA, 2009). Traffic signs in work zones are important in informing travelers about interrupted traffic conditions. Benekohal et al. (1995) conducted a survey and found that 50% of the responding truck drivers wanted to see warning signs 3 to 5 miles in advance. Garber and Woo (1990) found that static traffic signs could effectively reduce crashes in work zones on urban two-lane highways when used together with flaggers.

TTC signals are typically used for conditions such as temporary one-way operations in the work zones with one lane open and work zones involving intersections (Li, 2007). As suggested by the MUTCD, TTC signals should be used with other traffic control devices, such as warning and regulatory signs, pavement markings, and channelizing devices (FHWA, 2009). Hill (2003) analyzed work zone fatal crashes and discovered that certain TTC signals, such as STOP/GO signals, were very effective in reducing fatal crashes in work zones.

3.3.3 Channelizing Devices

Channelizing devices are used to warn road users of changed traffic conditions in work zones and to guide travelers to drive safely and smoothly through work zones (Li, 2007). Channelizing devices include cones, tubular markers, vertical panels, drums, barricades, and temporary raised islands (FHWA, 2009). Pain et al. (1983) concluded that most of channelizing devices were effective in alerting and guiding drivers, but the devices only obtained their maximum effectiveness when properly deployed as a system or array of devices. Garber and Woo (1990), however, found that the use of barricades in any combination of traffic control devices on urban multilane highways seemed to reduce the effectiveness of other traffic control devices.

3.3.4 Rumble Strips

Rumble strips consist of intermittent narrow, transverse areas of rough-textured or slightly raised or depressed road surface that extend across the travel lanes to alert drivers of upcoming work zones through auditory and vibratory warnings (Li, 2007). Meyer (2000) found that the mean vehicle speed decreased by up to 2 mph when removable rumble strips were installed in work zones in Kansas, and concluded that the insignificant speed reduction was probably due to the fact that rumble strips were spaced too close together and were not thick enough. Fontaine and Carlson (2001) found that the portable rumble strips generally did not have a significant impact on average passenger car speed but had a greater impact on mean truck speed. McCoy and Bonneson (1993), however, found that using of rumble strips actually resulted in a small increase in average speed.

3.3.5 Pavement Markings and Lighting Devices

Temporary pavement markings are maintained along paved streets and highways in all long- and intermediate- term stationary work zones. In addition, temporary raised pavement markers and delineators are used sometimes to supplement pavement markings to outline the travel paths (Li, 2007). Pavement markings can also be used to control vehicle speed in work zones. Meyer (2004) conducted a study to evaluate the effectiveness of optical speed bars on reducing vehicle speed in highway work zones in Kansas. Optical speed bars are an innovative speed control technique that uses transverse stripes spaced at gradually decreasing distances on pavement to affect drivers' perception of speed. The study showed that the speed bars had both warning and perceptual effects and were capable of controlling speed and reducing speed variation.

Lighting devices are used based on engineering judgment to supplement retroreflectorized signs, barriers, and channelizing devices. The four types of lighting devices commonly used in work zones are floodlights, flashing warning beacons, warning lights, and steady-burn electric lamps. These devices can attract drivers' attention and illuminate work zones or warn drivers of the complicated travel conditions in both daytime and nighttime (Li, 2007). Previous studies (Huebschman et al., 2003; Arnold, 2003) found that flashing warning lights, especially police vehicles with flashing lights, were one of the most effective approaches to reduce vehicle speed in work zones.

3.3.6 Speed Monitoring Displays

A speed monitoring display (SMD) is a traffic control device that uses radar to measure the speeds of approaching vehicles and shows their speeds to drivers on a digital display panel. Since 1970s, it has been successfully applied both in the United States and abroad. It is intended to slow traffic down by making drivers aware of how fast they are traveling. Previous studies consistently indicated that vehicle speeds were reduced using the SMD method in the work zones.

McCoy et al. (1995) indicated that the mean speeds of vehicles approaching work zones were about 4 mph to 5 mph lower after the speed monitoring displays were installed. Bloch (1998) found that both photo-radar and speed display boards offered better overall results in reducing vehicle speeds and revealed that the devices appeared particularly effective at reducing the speeds of vehicles traveling 10 mph or more over the speed limit. Fontaine and Carlson (2001) pointed out that mean speeds of vehicles were reduced by up to 10 mph when the speed display was present. Pesti and McCoy (2001) found that the SMDs were effective in lowering speeds and increasing the uniformity of speeds over a period of 5 weeks in the work zones on rural interstate highways. Brewer et al. (2006) indicated that devices with the ability to display drivers' speeds had considerable potential for reducing speeds and improving compliance.

3.3.7 Law Enforcement

It was generally agreed that one of the most effective ways of reducing vehicle speed in work zones is to have a police car positioned at the beginning of a work zone with its lights flashing and radar on. Richards et al. (1985) conducted field studies in Texas and concluded that the use of law enforcement was effective in slowing traffic on two-lane two-way highways. A stationary patrol car reduced average speeds by 4 to 12 mph and a circulating patrol car reduced speeds by 2 to 3 mph. Noel et al. (1988) conducted field studies on I-495 in Delaware and indicated that police radars and police controllers were effective in reducing vehicle speeds in the short and long term in freeway work zones; the law enforcement method demonstrated a strong long term speed reduction capability. Benekohal et al. (1992) examined the impact of the presence and absence of marked police cars on vehicle speed at rural interstate work zones in Illinois. The average speeds of cars and trucks were reduced by about 4 and 5 mph, respectively, while a police car was circulating through work zones. In South Dakota, McCoy and Bonneson (1993) found that a stationary police car with an officer inside, its lights flashing, and its radar active reduced the average free-flow speed of vehicles from 30 to 25 mph. Minnesota DOT (1999) discovered that the 85th percentile speed was reduced from 51 to 42 mph, 66 to 58 mph, and 58 to 47 mph on a rural interstate, an urban freeway, and at a metro location, respectively, when positioning a patrol car with its lights and flasher activated approximately 500 to 600 ft from the upstream of the work zones. Huebschman et al. (2003) found that the presence of law enforcement reduced speed by more than 5 mph adjacent to a trooper in Indiana. Arnold (2003) concluded that the presence of a police car was effective on reducing vehicle speed in the work zones in

Virginia through a survey. Miler et al. (2008) indicated that the use of law enforcement reduced vehicle speeds by 5.26 mph in the work zones in Indiana. Although the law enforcement method is an effective way to reduce vehicle speed in the work zones according to previous research, this strategy is limited in use because of its cost. The cost for a police officer, including benefits and 2% portion of supervisor's time, was estimated at $38.75 per hour in 1998 (Bloch, 1998).

3.4 CMS Applications in Highway Work Zones

A changeable message sign (CMS), sometimes referred to as a dynamic message sign (DMS) or variable message sign (VMS), is a traffic control device that is capable of displaying one or more alternative messages to inform motorists of unusual driving conditions. This is achieved through elements on the electronic display of the sign that can be activated to form letters or symbols (FHWA, 2009). A CMS can capture motorists' attention, display information that is difficult to accomplish with static signing, and be used to supplement other required signing. On the other hand, the CMS should not replace any of the signing detailed in the MUTCD and should not be used if standard traffic control devices adequately provide the information the motorist needs to travel safely. There are two types of CMSs based on the mounting location of the message board: permanent/fixed CMSs and portable CMSs (PCMS). A PCMS is housed on a trailer or on a truck bed and can be deployed quickly for meeting the temporary requirements frequently found in work zones or accident areas (FHWA, 2003).

3.4.1 Effectiveness of CMS on Speed Reduction

Richards et al. (1985) found that a CMS could result in a speed reduction between 3 to 9 mph, about 2% to 9%. Richards and Dudek (1986) further commented that a CMS could result in less than 10 mph speed reduction when used alone and would lose its effectiveness when operated continuously for long periods with the same messages. Benekohal and Shu (1992) indicated that placing a CMS in the activity area of a work zone could reduce the average speed of cars by 1.7 mph and the average speed of trucks by 1.4 mph at a point near the CMS. Garber and Patel (1995) pointed out that the CMS was an effective method in reducing speed variance which was also considered helpful to improve work zone safety. They concluded that the CMS was a more effective means than a traditional work zone traffic control device in reducing the number of speeding vehicles in the work zones in Virginia. Huebschman et al. (2003) found that it was not clear that a CMS could reduce fatal crashes resulting from approaching the work zone traffic queue at prevalent speeds. Wang et al. (2003) found that a CMS with radar provided significant speed reduction (7 to 8 mph) for approaching traffic at locations immediately adjacent to the CMS. Ullman et al. (2007) found that the use of sequential PCMSs resulted in comprehensive speed reduction rates compared with those obtained by presenting the same information on a single-phase CMS. Zech et al. (2008) pointed out that a CMS was very effective in reducing vehicle speed by 3 to 7 mph.

3.4.2 CMS Message Design and Display

Dudek and Ullman (2002) studied the dynamic characteristics of CMS messages in a human factors laboratory in Texas to determine the effects of flashing an entire one-frame message, flashing one line of a one-frame message, and alternating text on one line of a three-line CMS while keeping the other two lines of text the same. The results showed that average reading times were significantly higher when the message was flashed. They suggested the following: (a) one-frame VMS messages should not be flashed; (b) a line on a one-frame VMS message should not be flashed; and (c) a line on a two-frame VMS message should not be alternated while other lines are kept the same. Dudek et al. (2006) conducted a further study with a driving simulator to determine the effects of displaying CMS messages with dynamic features consisting of flashing all lines simultaneously in a one-phase, three-line message and flashing the top line of a one-phase, three-line message. The results suggested that flashing an entire one-phase message might have adverse effects on message understanding for drivers who were unfamiliar with this dynamic mode of display, and the average reading time for the flashing line (top line) messages was significantly longer than for the static messages.

Wang and Cao (2005) investigated the influences of the interaction between the display format of PCMS messages and the number of message lines, and the number of driving lanes through a series of laboratory driving simulation experiments. The simulation results showed that discretely displayed messages took less response time than sequentially displayed messages, and single-line messages were better than multiple-line messages. They also found that older drivers exhibited a slower response and less accuracy than younger drivers; female drivers exhibited a slower response but higher accuracy than male drivers. Wang et al. (2006a) did a more in-depth video-based driving simulation study on full-size CMSs and found that the best settings in regard to drivers' preference and response time were messages displayed in amber or amber-green color combination with one frame, minimum flashing, specific wording, and no abbreviations.

All these studies were conducted in laboratory environments in which people who participated in the study did not interact with real traffic. The circumstances allowed the people to put maximum effort on the CMS task, whereas in real-world driving, there are other needs that could demand attention from the drivers such as lane keeping, speed control, and car following. Thus, the results obtained from these studies only provided a relative performance measure about sign reading in optimal circumstances (Wang and Cao, 2005).

3.5 Graphic-aided CMS Studies in Highway Safety

Drivers' ability to spend sufficient time viewing CMSs diminishes when the situation (incident, roadwork, etc.), traffic flow patterns, guide sign reading requirements, and/or the geometry of the road are complex. Graphics displayed on CMSs offer potential advantages because drivers can read and understand well-designed graphics quicker and farther upstream of the sign in comparison to text messages (Ullman et al., 2009). The results of the earliest field and laboratory experiments by Dewar and Swanson (1972), Dewar and Ells (1974), Jacobs et al. (1975), and Ells and Dewar (1979) indicate that good graphic messages have a number of advantages over text messages (Ullman et al., 2009):

- The signs are more legible for a given size and at shorter exposure durations;
- The signs are more easily recognizable when the information is degraded due to poor environmental legibility;
- Drivers can extract information more quickly from graphic messages than text messages; and

- Drivers who have difficulty understanding text messages are able to comprehend graphics.

One of the earliest studies on graphic-aided message signs was conducted in the Netherlands in the early 1980s. Researchers evaluated the graphics adapted from existing European static sign symbols as well as newly designed graphics with regard to comprehension. The results indicated that the graphics for roadwork, congestion or queue, slippery road, two-way traffic, and drawbridge were adequate for use; the graphics tested for crash, skidding danger due to ice or snow, and reduced visibility due to rain or snow were less acceptable; and the graphics for fog and hydroplaning were highly inadequate (Riemersma et al., 1982).

Knoblauch et al. (1995) evaluated five graphic messages, namely congestion or queue (European), crash (European), advance flagger, lane reduction transition, and two-way traffic arrows, for use on PCMSs in the United States. The results showed that 92% of drivers correctly interpreted the European graphic for congestion or queue during daylight conditions when they viewed the sign from 400 ft. However, less than 50% correctly interpreted the message at distances of 570 ft or more. The lane reduction transition graphic was also found to be illegible from distances of 570 ft or more, and was understood by only 80% of drivers when the symbol was viewed at 400 ft. Comprehension levels at night were even lower than in daytime conditions.

Tsavachidis and Keller (2000) conducted a five-year project that opted for a new format of information using color coded network display to represent level of service information in Greater Munich area to overcome the limitations text CMS. The results from laboratory and simulator experiments indicated that a) a network graph should be shown from the drivers' perspective and allow for better orientation by giving the destinations for the displayed roadways; b) the use of only two colors (red for congested and black for not congested) reduced complexity and increased the efficiency of information processing; c) a network graph should be schematic but to a degree that allowed for distinction of its important characteristics; d) an information sign should include a header specifying implicitly its functionality (e.g. CONGESTION INFO) to allow for more efficient information processing; e) parts of the network that were not monitored should also not be shown on a CMS as they increased the complexity of the sign; and f) additional static information signs should be installed upstream of a new information system in order to make drivers alert to the following signs.

Luoma and Rama (2001) evaluated graphics through driver interviews in six European countries. The researchers found that more than 86% of drivers understood two of the graphics for congestion or queue; 91% of the drivers understood one of the graphics for slippery road conditions; and 66% to 72% of drivers understood the crash graphics. The most understood graphic in each of the other categories had the following comprehension values: fog (17%), oncoming vehicle (25%), restricted lane for buses (51%), restricted lane for high-occupancy vehicles (1%), and diversion (23%).

Lerner et al. (2004) investigated the status of application and guidance for the use of animation and color on CMSs. The researchers revealed that neither animation nor color had found widespread use yet in the United States, while Japan and Australia had used color and Europe had applied animation as the subject of demonstration projects. The researchers also indicated that CMS displays in the United States were predominantly alphanumeric text rather than diagrammatic or symbolic/pictorial and that the capabilities offered by full-matrix CMSs for using images, animation, and color did not appear to have been well-considered or well-exploited. They pointed out that animation and color could be used with text messages but might be more compatible with diagrammatic or pictorial displays.

Wang et al. (2007) conducted a human-factors study to assess the effects of adding graphics to CMSs and to identify proper settings and formats for the graphic-aided CMS message displays. A questionnaire survey and a video-based driving simulation were employed in their study. The survey results indicated that a) most people preferred graphic-aided messages to text-only messages; b) amber was the most preferred color followed by red and green; c) no significant difference was detected between negatively contrasted images and positively contrasted; d) the majority of people preferred that a graphic image be placed on the left of the text message; e) messages with a flashing graphic image were significantly preferred over a static graphic image; and f) a diamond-shaped frame was the most preferred for warning messages and a square-shaped frame was the most preferred for regulatory messages. The driving simulation results showed that a) message type, message color, and their interaction were significant; b) age and gender were also found to be significant, but their interaction was not; c) the graphic-aided messages were responded to significantly faster than text-only messages regardless of message color; d) red-colored messages resulted in the slowest response times compared with the other two colors for both types of messages; e) male drivers responded faster than female drivers but females were more accurate than males; f) younger drivers responded much faster and more accurately than older drivers and older drivers' performance was significantly improved by graphic-aided messages; and g) adding graphics improved non-native-English-speaking drivers' understanding of and responses to the messages much more noticeably than native-English-speaking drivers.

3.6 Human Factors in Highway Safety

As stated in Section 3.2.6 Causal Factors, previous studies suggest human errors were the most common cause of highway work zone crashes. As a result, understanding the role of human factors in highway crashes, as well as speed management, highway design, CMS design, and in-vehicle information system is critical for improving highway safety and lowering the probability of work zone crashes.

3.6.1 Highway Crashes

Macdonald (1985) conducted a comprehensive review of the relationship between human factors and road crashes, focusing on driver behavior, inexperienced drivers, driver training, and driver licensing. The findings revealed that the level of driving skill was relatively unimportant in determining a driver's risk of crashing, and some people drove in such a way as to create more opportunities for crashes than others. Age and experience were highly correlated, and their influence on crash rate was probably greater than that of any other driver's personal characteristics. The study also pointed out that effective driver training demanded the establishment of various hazardous situations and maneuvers arising from different road and traffic configurations. The author believed that extremely aggressive or socially maladjusted people should be prevented from holding a driving license, but the sensitivity tests to diagnose such individuals were quite inadequate for general licensing use.

Richman (1985) investigated human factors in alcohol-related crashes. The study discovered that alcohol involvement was reported in 29.8% fatal crashes in 1981, and 94% of alcohol involvement was found in single vehicle crashes between midnight and 6 a.m. Compared with younger drivers, a larger proportion of 30- to 34-year-old drivers had been drinking prior to their crash. Alienated and hostile young men were more likely than others to drink frequently and heavily and to be involved in crashes. Accident-involved drivers seemed generally more likely to have higher blood alcohol levels than non-accident-involved drivers, regardless of drinking frequency. Alcoholics in particular had much higher crash rates than the driving population as a whole, and might also engage in drinking-driving behavior more frequently.

Petridou and Moustaki (2000) reviewed over 100 literatures on road traffic crashes conducted between 1966 and 1998 to delineate human factors causes, and classified these behavioral factors into four categories: (a) those that reduce capability on a long-term basis, including inexperience, aging, disease and disability, alcoholism, and drug abuse; (b) those that reduce capability on a short-term basis, including drowsiness, fatigue, acute alcohol intoxication, short-term drug effects, binge eating, acute psychological stress, and temporary distraction; (c) those that promote risk taking behavior with long-term impact, including overestimation of capabilities, macho attitude, habitual speeding, habitual disregard of traffic regulations, indecent driving behavior, non-use of seat belt or helmet, inappropriate sitting while driving, and accident proneness; and (d) those that promote risk taking behavior with short-term impact, including moderate ethanol intake, psychotropic drugs, motor vehicle crime, suicidal behavior, and compulsive acts.

Smith (2000) investigated three distinct human factors contributing to crashes: alcohol influence, driver fatigue, and distraction by cell phone. The results on alcohol impaired driving indicated that the number of alcohol related fatalities might be underestimated, and some drivers became impaired well before the blood alcohol content reached the legal limit. The use of sobriety checkpoints had been proved to be an effective measure to deter drunk driving. Findings on driver fatigue showed that fatigue could be caused from such activities as social and holiday events, or family gatherings, and most fatigue related crashes occurred between 8 p.m. and 6 a.m. Legislation and enforcement of fatigue related driving was difficult since fatigue was difficult to define. Results on driver distraction by cellular phone use showed that the risk of an accident increased when cell phones were combined with driving, and driver reaction time and mental workload both increased with cell phone usage.

Kim and Boski (2001) examined the patterns of faults among drivers and motorcycle riders involved in 2,774 crashes in Hawaii between 1986 and 1995, and discussed the personal and behavioral characteristics of these drivers and riders. The results showed that among both riders and drivers, inattention and misjudgment were the most prominent crash factors associated with being at fault. Alcohol or drug use was only slightly higher among motorcyclists than among the drivers they collided with. Beyond these similarities, the characteristics indicating fault for drivers and riders diverged. For drivers, major factors included failure to yield, obscured vision, and turning actions. These driver factors could be generalized as crashes that resulted from inattentiveness or being unaware of the presence of the motorcyclists with whom they collided. For riders, major factors included speeding, improper overtaking, and following too closely. These could be generalized as risky riding behaviors.

Stutts et al. (2001) conducted a study on the role of driver distraction in traffic crashes to identify the major sources of distraction to drivers using Crashworthiness Data System data from 1995 to 1999. The results revealed that 48.6% of the drivers were identified as attentive at the time of their crash; 8.3% were identified as distracted, 5.4% as "looked but did not see," and 1.8% as sleepy or asleep. Young drivers (under 20 years of age) were the most likely to be involved in distraction-related crashes. In addition, certain types of distractions were more prominent in certain age groups, for example, adjusting the radio, cassette or CD among the under 20-year-olds; other occupants (e.g., young children) among 20-29 year-olds; and outside objects and events among those age 65 and older. A number of roadway and environmental variables were also examined to determine their relationship to driver distraction, include the higher proportion of adjusting radio/cassette/CD events occurring in nighttime crashes, the higher proportion of moving object in vehicle events occurring in crashes on non-level grade roadways, and the higher proportion of other occupant distractions occurring at intersection crashes.

Guerrero (2003) argued that speeding and alcohol had a significant impact on traffic crashes. The analysis of National Highway Traffic Safety Administration's databases suggested that speeding was identified as a contributing factor in about 30% of all fatal crashes, or almost 64,000 lives lost from 1997 through 2001. 42% of all fatal crashes were alcohol-related, and nearly 18,000 people died in alcohol-related crashes in 2002, of which about 87% were reported to have blood level concentration greater than the standard. For each age category, more male than female drivers were involved in fatal alcohol-related crashes.

Spainhour et al. (2005) investigated heavy-truck-related fatal crashes in 1998 and 1999 and all fatal crashes in 2000 in Florida to provide an in-depth analysis of the causes of crash fatalities. The results indicated that human factors were the primary causative factor in 94% of the fatal crashes, and the most common human factors were alcohol and/or drug use and driver errors, including inattention and decision errors. Not wearing a seat belt was the most common cause of fatality, contributing to fatality among 63% of vehicle occupants. Among truck drivers, the most common contributing factor was inattention, accounting for 43% of the total human factors attributed to truck drivers. Other factors that occur frequently among truck drivers were decision errors, speed, and excess steering input. Compared to other drivers, a high percentage of fatigue, medical, and low speed cases were attributed to truck drivers.

Li and Bai (2007) investigated fatal and injury crashes in Kansas highway work zones between 1992 and 2004 to explore the influence of human factors on the occurrences and characteristics of fatal and injury work zone crashes. The results revealed that the four most frequent driver errors causing work zone crashes were "inattentive driving," "too fast for condition/ exceeded speed limit," "disregarded traffic signs, signals, or markings," and "followed too closely." "Inattentive driving" caused proportionally more multivehicle crashes than single-vehicle crashes in work zones, and this error was most likely to cause severe crashes in work zones with speed limits no higher than 40 mph; "Too fast for condition/exceeded speed limit" tended to cause proportionally more severe crashes in high-speed (51 to 70 mph) work zones and rural work zones; “Disregarded traffic signs, signals, or markings” caused a larger proportion of severe crashes in work zones with speed limits lower than 51 mph than in work zones with higher speed limits; and “followed too closely” driver error caused larger proportions of severe crashes during daytime hours and in work zones with speed limits between 41 and 60 mph. The study also discovered that work zone center/edge lines might lower the odds of severe crashes caused by the “followed too closely” driver error by 19%, while having stop signs/signals in work zones would dramatically increase the odds of a severe crash caused by the same driver error.

Li and Bai (2009) examined the work zone risk factors that could increase the probability of causing fatalities when severe crashes occurred. The severe crashes used in this study included the fatal crashes between 1998 and 2004 and injury crashes between 2003 and 2004 in Kansas highway work zones. The results showed that driver errors including disregarded traffic control, followed too closely, alcohol/drug impairment, and too fast for conditions/speeding could have significant impact on the probability of causing fatalities in severe crashes. Their logistic regression models indicated that the odds of causing fatalities in a severe crash when the disregarded-traffic-control error was present were almost three times as high as those in a severe crash that did not involve this driver error; on the other hand, the odds of involving fatalities when following-too-closely error was present were much lower (by 92%) than those in the cases when the error was not present. The study also found out that alcohol/drug-impairment contributed to about 10% of both the fatal and injury crashes and too-fast-for-conditions/speeding contributed to 5% more injury crashes than fatal crashes.

Zhang (2010) analyzed the impact of alcohol, seat belt use, and speed to traffic crashes. The results showed that the proportion of alcohol involvement was about 5% among property damage only (PDO) crashes, but increased to over 40% in fatal crashes from 2000 to 2004. It was discovered that the proportion of seatbelt use was only 34% in fatal crashes compared with 90% in PDO crashes. About 22% of drivers not wearing a seatbelt were ejected from the vehicle in the crashes while only 1.2% of all crashes had drivers ejected in Louisiana in 2004. The findings also indicated that the average travel speed for fatal crashes was 53 mph, which was 10 mph higher than the severe injury crashes and 23 mph higher than PDO crashes.

3.6.2 Speed Management

FHWA (1996) conducted a before-and-after study in 22 States to determine the effects of changing speed limits on traffic operations and safety for rural and urban roadways. The results showed that neither raising nor lowering the speed limit had much effect on vehicle speeds (mean speeds and the 85th percentile speeds did not change more than 2 mph). The percentage of compliance with the posted speed limits improved when the speed limits were raised. When the speed limits were lowered, compliance decreased. Lowering the speed limit below the 85th percentile or raising the limit to the 85th percentile speed also had little effect on drivers' speeds.

Fitzpatrick et al. (2000) conducted a driver study to identify the factors that affected speed on suburban arterials. The results revealed that the only significant variable for straight sections was the posted speed limit. Without the speed limit, lane width was the only significant variable. On curve sections, the posted speed limit, the deflection angle and the access density classes influenced speed. Without the speed limit, the impact of median presence became significant along with the roadside development.

Feng (2001) studied the relationship between speed and safety in previous literatures, and found out that the presence of a camera could reduce vehicle speeds effectively. Previous results showed that speeding decreased at all sites with cameras, and the greatest decreases in the proportion of speeding vehicles were for vehicles traveling at the highest rates of speed. Previous study also indicated that the media coverage of the use of photo radar affected the behavior of drivers, and an increase in enforcement presence and fully deployed photo radar units reduced speeding even more.

3.6.3 Highway Design

Lunenfeld and Alexander (1984) argued that there was a need to pay particular attention to the roads and environments that were most likely to result in driver errors. Many high accident locations placed heavy or unusual demands on the decision-making capabilities of drivers, such as rural two lane roads, high-speed urban arterials, and city streets. Drivers committed errors when they had to perform several complex tasks at the same time under extreme time pressure. A typical example would be urban locations with closely spaced decision points, intensive land use, complex design features, heavy traffic, and visual clutter. Most drivers were not drunk, drugged, or fatigued at the start of their trips. When drivers overextended themselves, they might ultimately reach a deficient state. Proper highway design could reduce errors committed by competent drivers.

Kanellaidis (1996) carried out a critical review of human factors in highway geometric design, which included two main areas: the effect of geometric design on driver behavior and the consideration of driver behavior variability. The findings showed that, although a variety of highway-design assessment methods with respect to the human factors areas had been suggested, they had not yet been satisfactorily incorporated into highway design guidelines. The author identified two ways which might improve highway design to become more harmonized with driver behavior. First, checks for the safety of design could be included as a feedback loop in the design process. Second, by extending the framework to include a third level of design, as referred to the forgiving value, would be possible to provide improved safety for particular road users, such as older drivers.

3.6.4 CMS Design

Armstrong and Upchurch (1994) conducted a comprehensive human factors study of two light emitting diode (LED) and four shuttered fiber-optic CMSs on the target value (distance when noticed), the legibility distance, and the viewing comfort measurement in Arizona. Data for these parameters were given for an older and a younger group of observers. The results showed that the mean target value ranged between 1,080 ft and 2,841 ft for older observers and between 1,659 ft and 3,087 ft for younger observers in difference light conditions, and the mean legibility distance ranged between 337 ft and 959 ft for older observers and between 554 ft and 1,006 ft for younger observers in difference light conditions. Legibility distance might be decreased by the presence of raindrops, the use of windshield wipers, or the mist sprayed from other vehicles. Observers also reported higher levels of discomfort in viewing the LED signs as opposed to the fiber-optic signs during backlight and wash-out conditions due to glare of the sign face.

Proffitt and Wade (1998) addressed the human factor issues related to the reading and comprehension of CMS messages. The study indicated that about 25% of Virginians age 16 and older were not skilled readers and had difficulty deciphering words. These reading difficulties placed greater demands upon their memory. Providing familiar standardized messages and employing symbols could help these low-skilled readers. Short messages that minimize memory requirements could also be helpful. The same text messages and symbols should be used to describe equivalent situations, and symbolic messages were more effective than text ones. Mixed case letters were preferable to all capitals and abbreviations should be avoided. Novel symbolic messages needed to be assessed for their comprehensibility and some instruction might be required at their introduction. CMSs would be easier to read if they were rotated slightly to the face of the road.

Wang et al. (2006b) conducted a human factors study that assessed drivers' responses to and comprehension of CMS messages displayed in different ways to help enhance message display on CMSs. The study incorporated three approaches in the assessment: questionnaire surveys to investigate the preferences of highway drivers in regards to six message display settings; lab experiments to assess drivers' responses to a variety of CMS messages in a simulated driving environment; and field studies to study drivers' response to CMS in real driving environment and validate results from lab experiments. Questionnaire surveys suggested a CMS message to be a one-frame message with minimum flashing, very specific wording, no abbreviation, and displayed in solid amber or green-amber color combination. Lab simulation experiments found that a static or one-line flashing message displayed in solid amber or green-amber color combination demanded less response time. Results from field studies found that the mean response times to the same CMS message in real driving and in lab setting were very close across all drivers when excluding the difference in the starting time. The experiments also discovered that gender effects were nearly negligible while the age effect was more noticeable.

3.6.5 In-Vehicle Information Systems

U.S. DOT (1996) presented a set of preliminary guidelines for the human factors aspects of in-vehicle crash avoidance warnings. Four specific types of crash avoidance warning devices: blind spot warning devices, backup warning devices, driver alertness monitoring devices, and headway warning devices were addressed, which were selected as prototype examples for the development of human factors functional specifications.

Huey et al. (1996) proposed a set of human factors considerations to develop guidelines for In-Vehicle Crash Avoidance Warning Systems. The driving log recorded information on all near-accident or actual collision incidents over a three month period. The results showed that lane change incidents were the most frequent category, follow by intersection and rear-end incidents. The driver reported himself or herself to be at fault nearly one-third of the time. Overall, the driver reported that he or she was alerted in two-thirds of cases, and distracted by only about 13% of the cases. However, for those incidents where the driver judged himself or herself to be at-fault, distraction was reported about 40% of the cases. In addition, drivers were interviewed to explore their attitudes about various possible in-vehicle warnings. Drivers saw blind-spot/lane-change incidents as a major concern and were most favorable to blind spot monitors. In addition, warning systems favored by drivers included headway monitors and driver impairment monitors.

FHWA (1997) conducted an experiment to examine the effect of Advanced Traveler Information Systems (ATIS) display modality, message style, and display location on driver compliance with safety warnings. ATIS warning messages were presented to drivers using a low-fidelity automotive simulator equipped with an easily reconfigurable ATIS. The results showed that ATIS warnings could generate a greater compliance compared to road signs; however, they might adversely affect trust and self-confidence. Certain ATIS designs might place drivers in a double-bind situation where they did not trust the ATIS, but they also felt that they could not gather the required information themselves, and this double-bind might lead to dissatisfaction with the ATIS. The findings also revealed that ATIS devices could undermine drivers' performance by fostering an overreliance on ATIS information. Their effects on workload, situational awareness, and driving safety measures all supported this assertion, and ATIS design characteristics could exacerbate the overreliance and negatively effect on driving safety.

Kantowitz et al. (1999) investigated some human factor issues relevant to the ATIS design including: (1) the influence of an ATIS on drivers' performance in reduced visibility conditions, (2) the influence of an ATIS on drivers' reactions to unexpected roadway events, and (3) the interaction of an ATIS with a Collision Avoidance System (CAS). Experiments were conducted in a high-fidelity driving simulator, where drivers received roadway-relevant information via CMS posted on the roadway and via an in-vehicle ATIS. Drivers also experienced several unexpected roadway events, some of which triggered a CAS alert. Results showed that mean speed was lower in the ATIS condition than in the CMS condition, which did not alter speed. Effects of ATIS and CMS messages upon driving performance did not depend upon visibility conditions. The results also showed that an ATIS message interfered with the driver's ability to react to a pedestrian road incursion.

Lee et al. (2004) developed the Intersection Crash Avoidance, Violation Warning (ICAV) System, which was a vehicle-based countermeasure to intersection crashes associated with vehicle violations of stop signs and traffic signals. The envisioned system could warn drivers if they were in imminent danger of running a stop sign or a traffic signal. The ICAV had five functional subsystems as essential components: a positioning subsystem to determine the vehicle's current position and positional relationship to intersection features (e.g., the stop line) and geometry; in-vehicle sensor subsystem to assess vehicle dynamic parameters (e.g., vehicle speed); computation subsystem to process data, determine whether an imminent violation warning should be issued; a driver-vehicle interface subsystem to present the warning to the driver; and a communication subsystem to receive critical information (e.g., signal phase and timing data) from the traffic signal.

3.7 Statistical Methods Used in Previous Studies

A number of statistical approaches have been used to analyze the effectiveness of traffic control devices and methods on work zone safety including before-and-after-study, frequency analysis, box plots and scatter plots, Chi-square test, t-test, analysis of variance, correlation, proportionality test, and regression models. These statistical methods were reviewed and presented as follows.

3.7.1 Before-and-after Study

Before-and-after study is a commonly used method in work zone studies. In this kind of studies, crash counts of several years both before and after a treatment are recorded for a test section and a comparison section. Any change in crash rate on the test section after the treatment is checked against the change on the comparison section. If the crash rates are significantly different, it is then concluded that the treatment has been effective. The comparability test of the data is based on the number of crashes that take place on the test section and the comparison section during periods of both the normal operating condition and the work zone condition (Pal and Sinha, 1996). A before-and-after study can be used for different highways or highway entities such as intersections, highway sections, and railroad crossings. The period of time before and after the improvement must be the same and must be long enough to allow the observation of changes in crash occurrence (Elias and Herbsman, 2000).

In field experiments, sufficient data are needed to ensure the accuracy of the analysis. The minimum sample size can be determined for a desired degree of statistical accuracy by using the following equation (Robertson et al., 1994):

$$N = (S * \frac{K}{E})^2$$

Where N = minimum number of measured data;

S = estimated sample standard deviation;

K = constant corresponding to desired confidence level; and

E = permitted error in the average data estimated.

Eckenrode et al. (2007) used 5.0 as the standard deviation to determine the effectiveness of drone radar in South Carolina. For a 95% confidence level, K equals

1.96E. E reflects the precision of the observed speeds and is the maximum tolerance for errors in the data collection. In this study, a value of 1.0 mph was assumed for E. Thus, the minimum sample size at the 95% confidence level was 96.

3.7.2 Frequency Analysis

Frequency analysis is particularly useful for describing discrete categories of data, which may be time dependent or space dependent. The frequency analysis involves structuring a frequency distribution by arranging the observed or measured data in classes or groups and by identifying the different class frequencies with a lower limit and an upper limit. For every set of data, there are various measures of central tendency including the mean, standard deviation, mode, and median. In most statistical analysis cases, the mean (μ) gives an estimate of the central tendency of the mass of data, and the standard deviation (σ) gives an estimate of the closeness of the data to the mean (Scheaffer and McClave, 1995). The equation of the cumulative frequency is:

$$F_c = \frac{M}{N+1}$$

Where M = the rank number;

N = the number of data; and

F_c = the cumulative frequency (%).

As the minimum value of M is 0 and the maximum is N, the value of F_c ranges between 0 and 1 or 100%, which is the frequency of non-exceedance (%), or the percentage of data with values smaller than the value considered. The value $1-F_c$ indicates the frequency of exceedance F_e. When the data and its frequencies are shown on a graphic diagram, the data tend to form a curved line despite the existence of scatter. The curved line indicates the type of frequency distribution and the scatter is assumed to stem from random variation (Oosterbaan, 2002).

3.7.3 Box Plots and Scatter Plots

A box plot is a convenient way of graphically illustrating groups of numerical data through their five-number summaries: the smallest observation (sample minimum), lower quartile (Q1), median (Q2), upper quartile (Q3), and largest observation (sample maximum), as shown in Figure 3.2. Besides, box plots depict differences between measurements or values without making any assumptions of the underlying statistical distribution (Scheaffer and McClave, 1995).

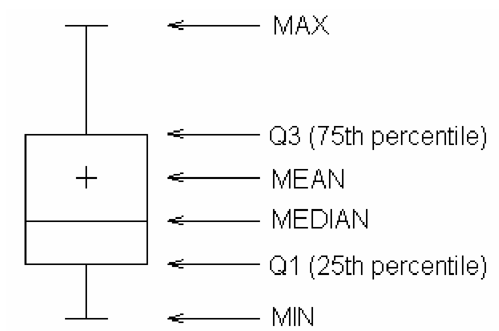

Figure 3.2 An Annotated Sketch of Box Plot

A scatter plot, as illustrated in Figure 3.3, provides a graphical display of the relationship between two variables. The variable that is considered as an independent variable is plotted on the X-axis and the dependent variable is plotted on the Y-axis. Scatter plots are especially useful to provide a pictorial representation of the degree and direction of correlation. However, there is not necessarily a cause and effect relationship between two variables. Both variables could be related to a third variable that explains their variation or there could be some other cause. Nevertheless, it is useful in the early stages of analysis to explore data before actually calculating a correlation coefficient or fitting a regression line or curve (Scheaffer and McClave, 1995).

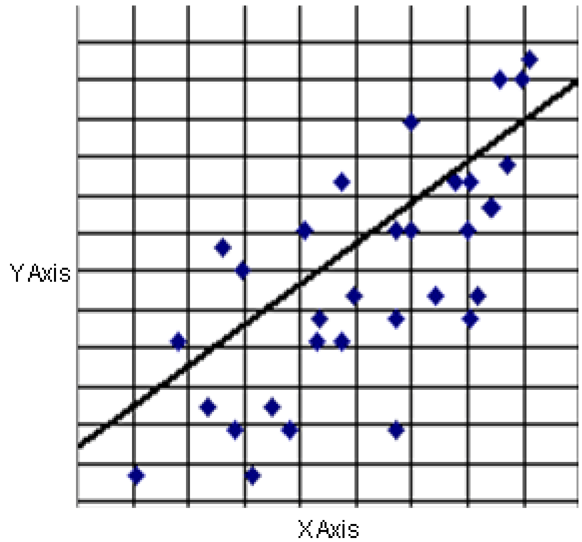

Figure 3.3 An Annotated Sketch of Scatter Plot

3.7.4 Chi-Square Test

The chi-square (χ^2) is a nonparametric statistical test commonly used to compare observed data in which the sampling distribution of the test statistic is a chi-square distribution. It means that the sampling distribution can be made to approximate a chi-square distribution as closely as desired by making the sample size large enough. In a chi-square test, a value is obtained from the data by utilizing the chi-square procedures that are then compared to the critical value from a chi-square distribution table, which is calculated in reference to the degrees of freedom parallel to that of the data of chi-square test. If the resultant value of the chi-square test is greater than or equal to the critical value of the table, the null hypothesis could be rejected; otherwise, the null hypothesis could not be rejected (Scheaffer and McClave, 1995). The equation to calculate chi-square (χ^2) is:

$$\chi^2 = \sum_{i=1}^{n} \frac{(o_i - e_i)^2}{e_i}$$

Where o_i = an observed value;

e_i = an expected value;

n = the number of expected values; and

χ^2 = the chi-square value.

That is, chi-square is the sum of the squared difference between the observed and expected data, divided by the expected data in all possible categories. The procedure for interpreting the χ^2 value is as follows (Scheaffer and McClave, 1995):

1. Determine the degrees of freedom (*df*), which can be calculated as the number of categories in the problem minus 1;
2. Determine a relative standard to serve as the basis for accepting or rejecting the hypothesis. The relative standard commonly used in research is $p > 0.05$. The p value is the probability that the deviation of the observed from that expected is due to chance alone; and
3. Refer to the chi-square distribution table. Using the appropriate degrees of freedom, the value closest to the calculated chi-square should be located in the chi-square distribution table. And the closest p value associated with the chi-square and degrees of freedom should be determined.

3.7.5 T-test

The t-test, also called student's t-test, is most commonly used when the test statistic would follow a normal distribution with the best estimate of the mean μ but unknown variance. The t-test is primarily used for determining the statistically significant difference between two sample means and confidence intervals of the difference between two population means. When dealing with inferences about the means of matched pairs, the following equation is used to test the hypothesis for matched pairs (Triola 2004):

$$t = \frac{\overline{d} - \mu_d}{\frac{S_d}{\sqrt{n}}}$$

Where μ_d = mean value of the differences *d* for the population of all matched pairs;

$\overline{d}$ = mean value of the differences *d* for the paired sample data;

s_d = standard deviation of the differences *d* for the paired sample data;

n = number of pairs of data; and

df = n−1.

3.7.6 Analysis of Variance

Analysis of Variance (ANOVA) is an effective tool allowing the simultaneous comparison of populations to determine if they are identical or significantly different. It is a parametric test that assumes the distribution is known or the sample is large, so that a normal distribution could be assumed (Fellows and Liu, 2008). In ANOVA models, there are one-way layout and two-way layout where the factors are either crossed or nested.

One-way ANOVA has a single factor with several levels and multiple measurements at each level. With the one-way layout, the mean of the measurements can be calculated within each level of available factor and the residuals will show the variation within each level. The grand mean can also be obtained from averaging the means of each level; and as follows, the deviation of the mean of each level from the grand mean can be used to determine the level effects (Mason et al., 2003). As results, the variation can be compared within levels to the variation across levels. The following is an equation of the one-way model:

$$y_{ij} = m + a_i + e_{ij}$$

Where y = the response variable for the j^{th} data value in the i^{th} level;

m = the common value (grand mean);

a_i = the level effect (the deviation of each level mean from the grand mean); and

e_{ij} = the residual or the error of the j^{th} data value in the i^{th} level.

When there are two factors with at least two levels and one or more observations at each level, two-way crossed or nested ANOVA would be used for the analysis of data. In case of every level of factor, a, occurring with every level of factor, and b, the two-way crossed layout would be used to estimate the effect of each factor (Main Effects) as well as any interaction between the factors. If there are k observations at each combination of i levels of factor a and j levels of factor b, then the two-way layout would have an equation as follows (Scheaffer and McClave, 1995):

$$y_{ijk} = m + a_i + b_j + (ab)_{ij} + e_{ijk}$$

Where y_{ijk} = the k^{th} data value for the j^{th} level of factor b and the i^{th} level of factor a;

m = the common value (grand mean);

a_i = the level effect for factor a;

b_j = the level effect for factor b;

$(ab)_{ij}$ = the interaction effect; and

e_{ijk} = the residual.

3.7.7 *Correlation*

A correlation is a single number that describes the degree of relationship between two variables. In statistics, the value of the correlation coefficient varies between +1.0 and −1.0. When the value of the correlation coefficient lies around ±1.0, it is said to be a perfect degree of association between the two variables. In other words, a correlation of +1.0 means that two variables are proportional to each other and a correlation of −1.0 means that two variables are inversely proportional to each other. As the value goes towards 0, the relationship between the two variables will be weaker. To make the value of the correlation coefficient easier to understand, the value of the correlation coefficient is squared. The square of the correlation coefficient is equal to the percentage with which the variation of one variable is related to the variation of the other variable. While using the correlation technique, it is important to understand that it only works on linear relationships and not on curvilinear relationships (Scheaffer and McClave, 1995).

Pearson Correlation is widely used in statistics to measure the degree of the relationship between the linear related variables in which both variables should be normally distributed (Scheaffer and McClave, 1995). The following formula is used to calculate the Pearson Correlation:

$$r = \frac{n\sum_{i=1}^{n} x_i y_i - \sum_{i=1}^{n} x_i \sum_{i=1}^{n} y_i}{\sqrt{n\sum_{i=1}^{n} x_i^2 - \left(\sum_{i=1}^{n} x_i\right)^2}\sqrt{n\sum_{i=1}^{n} y_i^2 - \left(\sum_{i=1}^{n} y_i\right)^2}}$$

Where r = Pearson Correlation coefficient;

n = the number of values in each data set;

$\sum_{i=1}^{n} x_i y_i$ = sum of the products of paired scores;

$\sum_{i=1}^{n} x_i$ = sum of x scores;

$\sum_{i=1}^{n} y_i$ = sum of y scores;

$\sum_{i=1}^{n} x_i^2$ = sum of squared x scores; and

$\sum_{i=1}^{n} y_i^2$ = sum of squared y scores.

3.7.8 Proportionality Test

The proportionality test can be used to determine the significance of distributions. The proportionality test is a test of the quality of two independent means, namely p_1 and p_2, which are the probabilities of success resulting from two different processes. The test statistic is the Z value, which is given as (Garber and Zhao, 2002):

$$Z = \frac{p_1 - p_2}{\sqrt{p(1-p)[(\frac{1}{n_1}) + (\frac{1}{n_2})]}}$$

Where $p_1 = \frac{Y_1}{n_1}$;

$$p_2 = \frac{Y_2}{n_2};$$

$$p = \frac{Y_1 + Y_2}{n_1 + n_2};$$

Y_1 and Y_2 = the number of successes for population 1 and 2, respectively; and

n_1 and n_2 = population sample sizes.

3.7.9 Regression Analysis

Regression modeling is one of the most widely used statistical modeling techniques (Mason et al., 2003). Regression analyses are generally limited by the number of influencing factors that can be included and their capability of measuring the combined effect of the influencing factors (Song and AbouRizk, 2008). A regression model is a function of variables *x* and β which gives the following equation (Scheaffer and McClave, 1995):

$$y = f(x, \beta)$$

Where y = the dependent variable;

x = the independent variables; and

β = unknown parameters (may be a scalar or a vector of length k).

These variables stand in a causal relation to one another. The regression model was developed to detect the presence of a mathematical relation between two or more variables subject to random variation, and to test if such a relation, whether assumed or calculated, is statistically significant. Some of the well-established regression methods include linear and non-linear, two-variable and multi-variable, and ratio method and least-squares method (Oosterbaan, 2002). A number of regression models have been utilized to conduct crash analyses in previous studies.

Venugopal and Tarko (2000) developed Poisson and negative binomial models to predict the number of work zone crashes, and found that traffic volume, the length of work zones, and duration of work were significant factors. In addition, the cost and type of work zone were also critical factors to work zone safety.

Elias and Herbsman (2000) developed a multivariable regression model to relate the expected number of crashes in a road with certain characteristics of that road. In essence, fitting a multivariable model is to estimate the expected number of crashes of some kind as a function of some selected independent variables. These independent variables are specific characteristics of a roadway such as traffic flow, road-section length, number of lanes, shoulder width, and among others. The basis of this multivariable regression method is the assumption that the expected crash frequencies are associated with causal factors in an orderly fashion.

Binary logistic regression model is a statistical technique developed for describing the relationship between a set of independent explanatory variables and a dichotomous response variable or outcome. Since binary logistic regression model is a direct probability model which has no requirements on the distributions of the explanatory variables or predictors, it is more flexible and more likely to yield accurate results in traffic crash analyses (Harrell, 2001).

Many other researchers have also developed logistic regression models in traffic safety analyses. Dissanayake and Lu (2002), Hill (2003), and Li and Bai (2006) developed regression models to organize crash severity from the lowest to the highest using the SAS software package. Their models took several important crash factors into account, such as gender, driver impairment, and geometric conditions of crash sites.

3.8 Summary of Literature Review

As the first step of this study, a comprehensive literature review was conducted to synthesize the background knowledge about highway work zone safety from previous research. The review covered several subjects relevant to work zone safety including the characteristics of work zone crashes, work zone traffic control methods, CMS applications in work zones, graphic-aided CMS studies in work zone safety, human factors in work zone safety, and the statistical methods used in these studies. Results of the literature review are summarized as follows.

Many research efforts have been devoted to investigating highway work zone crash characteristics. Most of the previous work zone crash studies were based on statewide crash data; only a few studies used multi-state data. Some studies emphasized crash rate and severity, while others focused on crash type, time, location, and casual factors. Because of the limitations on the data collection in different research projects, the conclusions were not always consistent on the same subject. Among the findings, most studies generally agreed that crashes were more likely to occur in highway work zones than in non-work zones, truck-involved and nighttime work zone crashes were more severe than non-work zone crashes, and human errors and inefficient traffic controls were the major causes of work zone crashes.

Various studies have evaluated the effectiveness of commonly used work zone traffic control devices and methods, including flaggers, traffic signs, TTC signals, channelizing devices, rumble strips, pavement markings, lighting devices, arrow panels, PCMSs, and law enforcement. These traffic control devices and methods are employed to reduce and control vehicle speed in work zones since excessive travel speed has been revealed as a major contributing factor to work zone crashes.

CMS, as a traffic control device capable of conveying real-time information to warn motorists of unusual driving conditions, has been studied in a number of research projects to determine its effectiveness on vehicle speed reduction. Graphic-aided CMS could offer potential advantages over traditionally text-based CMS because drivers can read and understand well-designed graphics quicker and farther upstream of the sign. Being a new format displayed on the CMS, the effectiveness of graphic-aided messages has not been studied thoroughly in the United States. Only a handful of such studies were conducted in laboratory environments.

Since human behavior errors have been pointed out as the most common cause of highway work zone crashes in many studies, a comprehensive review of the role of human factors in highway crashes was conducted. Driver skill, alcohol involvement, driver fatigue and distraction, misjudgment, speeding, and disregarding traffic control were identified to be the major contributing human factors to highway crashes. Previous literature of human factors in speed management, highway design, CMS design, and in-vehicle information system were also reviewed to better understand the role of human factors in highway safety.

In addition, the statistical methods used in previous studies to analyze the effectiveness of traffic control devices and methods on work zone safety were reviewed including before-and-after-study, frequency analysis, box plots and scatter plots, Chi-square test, t-test, analysis of variance, correlation, proportionality test, and regression models. The results of literature review indicated that these statistical methods were very powerful tools to reveal the characteristics and causes of work zone crashes.

Chapter 4 Field Experiment

After the literature review, field experiments were designed and conducted in the summer of 2010 in a one-lane two-way rural highway work zone in Kansas. The objective of the field experiments was to determine the effectiveness of graphic-aided PCMSs on reducing vehicle speed in the upstream of one-lane two-way work zone. In this chapter, the design of field experiments is briefly introduced first, including experimental location, speed measurement devices and methods. Then, data collection procedures and data analysis results are presented in detail. Finally, conclusions are drawn at the end of this chapter based on research findings.

4.1 Experiment Design

4.1.1 Experiment Devices and Installation

There were two major tasks in the field experiments: measuring vehicle speed and surveying driver. Vehicle speed data were collected and analyzed to determine the effectiveness of graphic-aided PCMSs on reducing vehicle speeds. Driver surveys were conducted to evaluate drivers' opinions on the implementation of graphic-aided PCMSs in highway work zones. A full-matrix PCMS was utilized to display text messages and graphics, and five speed sensors were used to collection vehicle speed data. In addition, questionnaires were developed for driver surveys.

4.1.1.1 Full-Matrix PCMS

A Wanco WTMMB-SLL full-matrix PCMS was utilized to display text messages and graphics. Specifications of the PCMS are shown in Table 4.1.

Table 4.1 Specifications of the Full-Matrix PCMS

Dimension	138 in. tall x 159 in. wide
Display Resolution	4 amber LEDs form each pixel
Matrix	48 pixels wide, 27 pixels high
Smallest characters	4 lines, 12 characters
Largest characters	1 line, 6 characters
Legibility	Approx. 600 to 3200 ft.
Power	675 Ah batteries with solar panels

The PCMS was programmed to display messages in two phases and it took three seconds to switch from one phase to another. The text messages used in the field experiments were "WORKZONE AHEAD SLOWDOWN" and "FLAGGER AHD PREP TO STOP" (flagger ahead prepare to stop). Two graphics used in the field experiments were similar to the W20-7 and W21-1 signs specified by the MUTCD, as displayed in Figure 4.1. During the field experiment, the PCMS was set up in three conditions. The first condition was to display text messages only (text PCMS) as shown in Figure 4.2. The second condition was to display text and graphic messages (graphic-aided PCMS) as shown in Figures 4.3 and 4.4. The last condition was to display graphics only (graphic PCMS) as shown in Figure 4.5. The PCMS was placed on the shoulder of the highway approximately 3 ft from the edge of the pavement to minimize the interference with the traffic flow.

W21-1 Sign

Work Zone Sign on PCMS

W20-7 Sign

Flagger Sign on PCMS

Figure 4.1 Comparison of Signs in MUTCD and PCMS

Figure 4.2 Text PCMS

Figure 4.3 Graphic-aided PCMS with the Work Zone Graphic

Figure 4.4 Graphic-aided PCMS with the Flagger Graphic

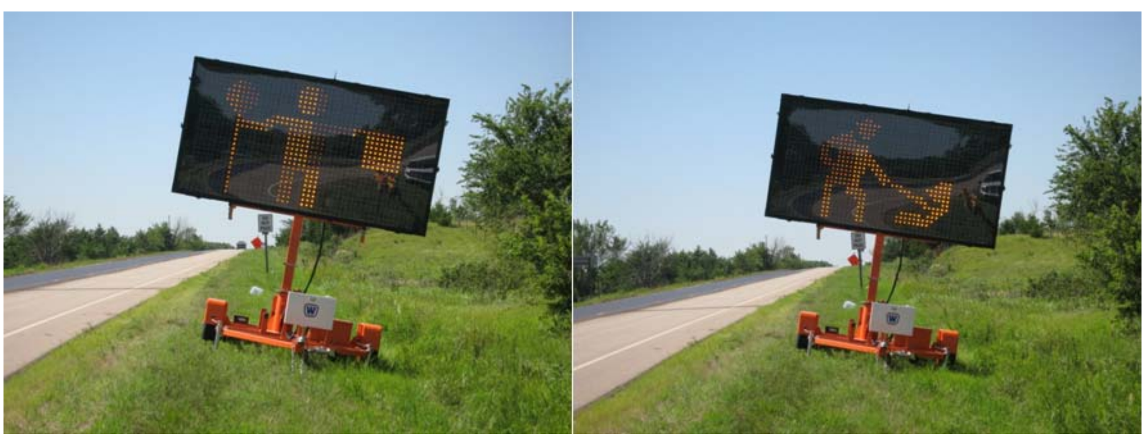

Figure 4.5 Graphic PCMS

4.1.1.2 Speed Measurement Sensors

Five JAMAR TRAX Apollyon speed measurement sensors were used to record data including date, time, number of axels, wheelbase, and vehicle speed. Each sensor was connected with two road tubes. One end of each road tube was linked to the sensor and the other end was plugged into a plastic end plug. The two road tubes were placed on the surface of pavement, perpendicular to the flow of traffic, as shown in Figure 4.6. The distance between these two tubes was two feet. Each tube was secured by four 2 in x 2 in and one 2 in x 1 in mastic tapes (rubberized asphalt) on the pavement, as shown in Figure 4.7. The speed sensors were placed on the shoulder of the highway (see Figure 4.8). Specifications of the speed sensor and road tubes are presented in Table 4.2.

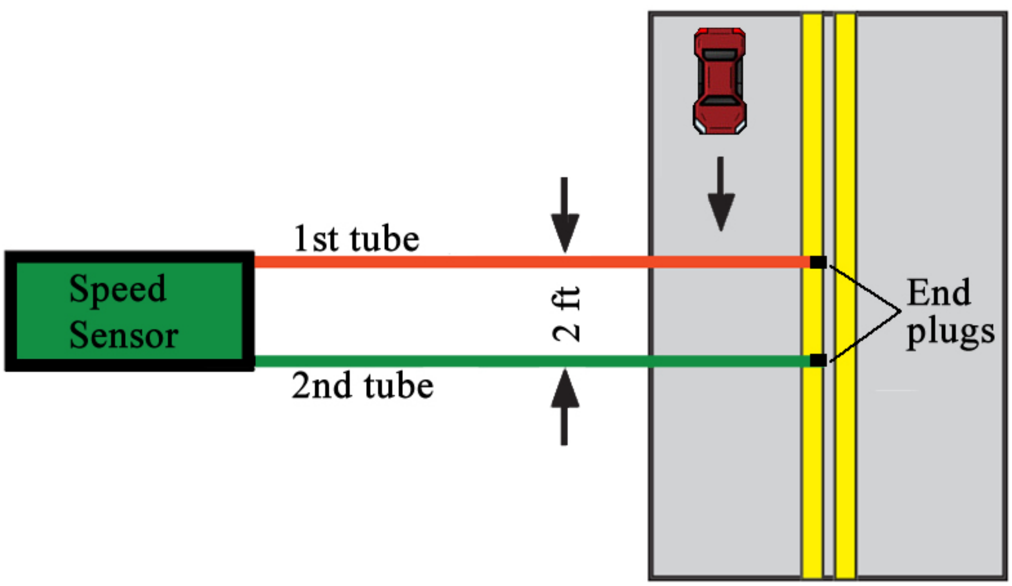

Figure 4.6 Road Tubes Configuration

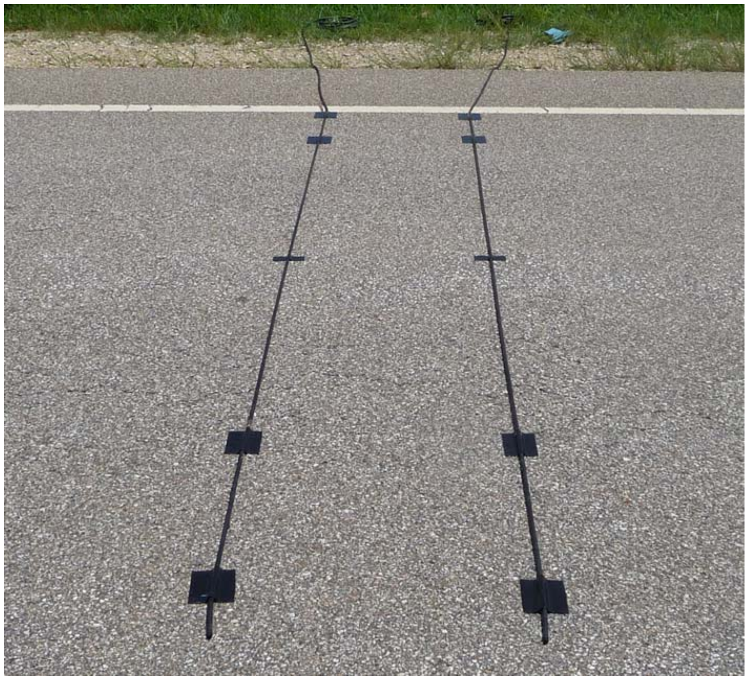

Figure 4.7 Installation of Road Tubes

Figure 4.8 A Speed Sensor Connected with Road Tubes

Table 4.2 Specifications of the Speed Sensor and Road Tubes

Speed Sensor		Road Tube	
Dimension	8.25 in x 6.5 in x 3.5 in	Length	50 ft
Weight	2.5 lbs	Inner Diameter	0.187 in
Power	Lithium batteries, up to 10 years	Outer Diameter	0.365 in
Memory	8 MB	Material	ASTM D-2000 3BA 620 A_{14} C_{12} F_{17} G_{21}
Temperature	-40F to 165F		

4.1.2 Driver Survey Questionnaires

Four questionnaires were designed for the text PCMS, two graphic-aided PMCSs, and the graphic PMCS, respectively. Four multiple-choice questions were asked in each questionnaire in an effort to determine the drivers' acceptance of the graphic-aided PCMS and their opinions on its implementation in a work zone. Examples of four questionnaires are attached in Appendixes A.1 to A.4. A questionnaire used for the graphic-aided PCMS with a work zone sign is discussed below in detail. The first question is:

1. *Did you see a **graphic** displayed on the Portable Changeable Message Sign (PCMS) when you were approaching the work zone?* (with the Figure 4.9)

W21-1

Figure 4.9 A Graphic-aided PCMS showed in Questionnaires

This was a *Yes-No* question. If a driver answered "*No,*" the survey would be terminated; otherwise, the second question would be asked, which was:

2. *How did you interpret the meaning of this graphic?*

This question was designed to gather the drivers' interpretation of the graphic shown on the PCMS. The possible responses included: *1) Work zone/Work zone ahead/Someone working*, *2) Get confused*, *3) Don't know*, and *4) Other*. If a driver responded to the question as "*Other*," then he/she could explain the reason in his/her own words. The third question was:

3. *Did you think that the* ***graphic*** *drew your attention more to the work zone traffic conditions?*

This question was designed to verify if a graphic-aided PMCS could more effectively alert drivers who approach the work zone. Answers for this question included: *1) Yes*, *2) No*, and *3) Don't know*. A response of "*No*" indicated that the driver considered a graphic-aided PMCS to have no effectiveness in drawing more of his/her attention to the work zone conditions. The last survey question was:

4. *Do you prefer the warning signs to be displayed in the graphical format or text format?*

This question was designed to evaluate drivers' opinions on the implementation of the graphic-aided PCMS. The possible options included: *1) Graphical format*, *2) Graphical and text format*, *3) Text format*, *4) No difference*, *5) Don't care*, *6) Don't know*, and *7) Other*. "*No difference*" could be chosen if the driver believed that the graphic-aided or graphic PMCS made no difference to him/her compared with the text PMCS; "*Don't care*" would be selected if the driver did not concern what format of message was displayed on the PCMS. The "*Other*" option was available for drivers to explain if they had different thoughts other than the provided answers.

In addition to the above questions, other related information was recorded such as date and time, weather condition, type of vehicles, and gender of the surveyed drivers. The classification of vehicle types was based on the one used by KDOT Motor Vehicle Accident Report (DOT FORM No. 850 Rev. 1-2003). The light-duty vehicles such as passenger cars, minivans, pickups, campers or RVs, sport utility vehicles (SUVs), and all-terrain vehicles (ATVs) were classified as vehicles; the heavy vehicles such as single large trucks, truck and trailers, tractor-trailers, and buses were classified as trucks.

4.1.3 Field Experiment Layout

The location of a PCMS in the upstream of a work zone depends on a sufficient sight distance for drivers to recognize displayed messages and take necessary actions. In the field experiments, drivers were required to slow down and be prepared to stop, which were minor driving actions according to the Portable Changeable Message Sign Handbook (FHWA, 2003). For a minor action, 500 ft to 1,000 ft is required for reaction time regardless of speed. A driver's decision point was defined at the location of the first MUTCD-defined TTC sign in the upstream of work zone: the W20-1 sign "ROAD WORK AHEAD." Since drivers were required to take only minor actions, the PCMS was placed 575 ft upstream of the W20-1 sign.

The proper placement of the speed sensors plays a key role in an accurate speed measurement. The appropriate locations of the speed sensors could help to better understand drivers' reactions after they recognize the messages on the PCMS. In the field experiments, five speed sensors were installed to measure a speed reduction profile for each passing vehicle to determine the extent of vehicle speed reduction at different locations from the PCMS in the upstream of the work zone.

As illustrated in Figure 4.10, speed sensor 4 (S4) was installed at the same location as the W20-1 sign (the beginning of the work zone) to measure vehicle speeds when vehicles were entering the work zone. Speed sensor 3 (S3) was installed 500 ft upstream from the W20-1 sign, right after the PCMS (75 ft) to collect vehicle speeds when vehicle were passing the PCMS; speed sensor 2 (S2) was installed 500 ft upstream from S3 and speed sensor 1 (S1) was installed 475 ft upstream from S2 to gather vehicle speeds when vehicles were approaching the PCMS. Speed sensor 5 (S5), as a complement of the above four sensors, was installed at the same location as the second TTC sign (the W20-4 sign “ONE LANE ROAD AHEAD”), which was 530 ft downstream from S4, to determine if vehicles would continue to reduce speed after entering the work zone. The location of sensor 1 was defined as the original coordinate point.

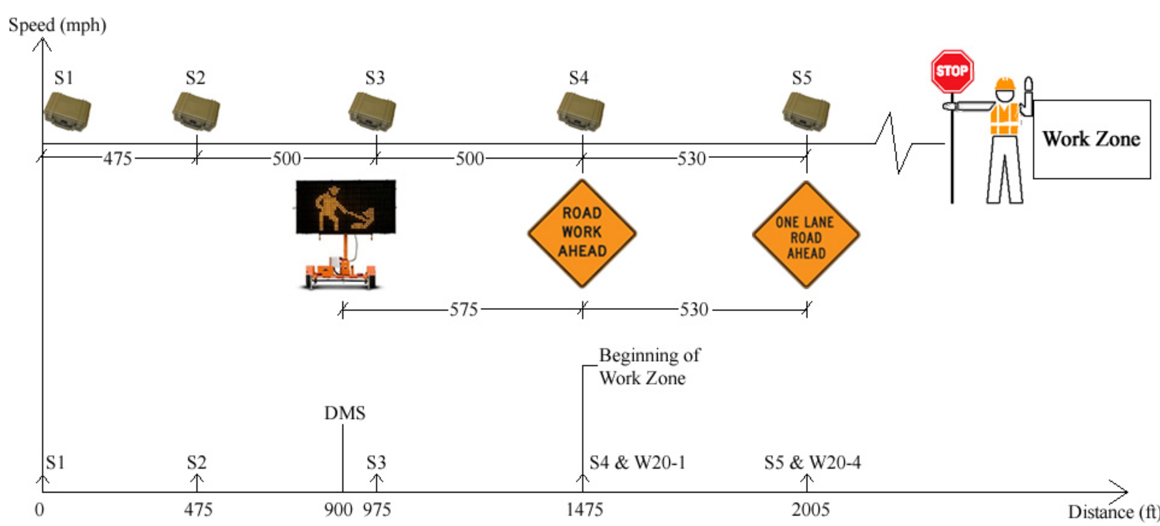

Figure 4.10 Field Experiment Layout

4.1.4 *Work Zone Location and Conditions*

Because field experiments were designed to determine the effectiveness of graphic-aided PCMSs on reducing vehicle speeds in the one-lane two-way work zone on a rural highway, the following requirements had to be met when selecting the work zone for the field experiments (Li, 2009):

- The experimental site is a one-lane two-way work zone located on a rural highway. Roadway type and work zone configurations are important for speed research. The traffic flow on urban two-lane roadways is considerably affected by factors such as high traffic volume and traffic signals. Thus, the speed limits for urban highways are typically lower than 55 mph. A rural highway, on the other hand, does not have these limitations. In addition, drivers have to stop in a one-lane two-way work zone, thus give researchers an ideal opportunity to conduct driver surveys.
- Traffic volume should be moderate. Traffic characteristics including traffic volume and headways are critical factors for the success of this study. The moderate traffic volume will be able to provide mostly free flow conditions and consequently ensure the accuracy of vehicle speed measurements.
- The minimum safety conditions must be met. The PCMS is usually placed on or just outside the shoulder. A PCMS could become a roadside hazard if not protected from an errant vehicle. The space must be available for setting up the PCMS without interfering with the traffic flow, and research personnel must be able to collect data safely.

Based on the above requirements for the field experiments, one work zone located at the Highway K-13, between Highway US-24 and Highway K-16, was selected as the experimental site shown in Figure 4.11. This highway section is a two-lane rural highway with the total length of about 14 miles and a speed limit of 65 mph, and located about 6 miles north of Manhattan, KS. According to the 2010 KDOT Traffic Flow Map, the annual average daily traffic (AADT) for the selected section of K-13 was 1,160 vehicles per day (vpd) at the north end and 1,650 vpd at the south end (traffic counts recorded between July 2008 and June 2009). A noteworthy percentage of the traffic on this highway section was local traffic entering or leaving Manhattan, KS.

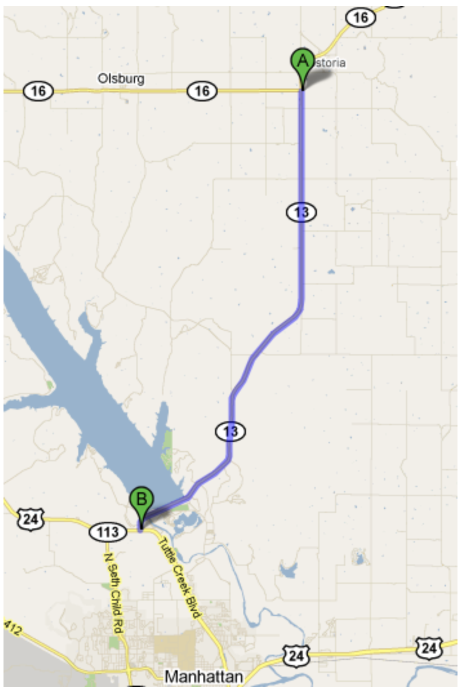

Figure 4.11 Selected Work Zone on K-13 between K-16 and US-24

A pavement replacement project started on July 21st, 2010 at the north end of the highway section, and field experiment (except for driver surveys for the text PCMS) was conducted from July 21st to August 4th. The construction project was a paving operation to rehabilitate the roadway surface using a hot-in-place asphalt recycling technique. The construction process required one traffic lane to be closed for pavement hot-in-place recycling while the other lane was kept in service. When construction operations were underway, the two-lane highway was reduced to a one-lane two-way work zone. A flagger was used at each end of the work zone for traffic control and a pilot car was employed to guide through traffic. All passing vehicles had to stop before the flagger and wait for the pilot car. The work zone was moved forward once to twice per day depending on the project progress.

Driver surveys for the text PCMS were conducted between September 20th and October 1st, 2010 in a work zone on Highway US-36 between Highway K-87 and Marysville, KS, which was also a one-lane two-way rural highway work zone. It had the total length of about 14 miles, and the highway section had a speed limit of 65 mph and the AADT of 2,410 to 4,110 vpd. The construction project was also a paving operation.

4.2 Data Collection

4.2.1 Data Collection Procedures

Data collection included vehicle speed data collection and driver surveys, which were conducted at the same time but at different locations. Speed data were collected within the area from 1,475 ft upstream to 530 ft downstream of the beginning of the work zone (the location of W20-1 sign), according to the experimental layout in Figure 4.10. Driver surveys were conducted at the flagger locations where all vehicles had to stop and wait for the pilot car.

4.2.1.1 Vehicle Speed Data Collection

Vehicle speeds were collected using five speed sensors as introduced earlier. Speed data were first stored directly into the sensor memory chip, then were exported to a flash driver, and finally were downloaded to a computer for reading, formatting, and editing. Raw data (.dmp files) were first read by the software JAMAR TRAXPro and converted to editable TRAXPro Count files (.tf2 files), and then exported to the Excel Software to select proper display format as shown in Table 4.3. The interpretation of raw data is as follows:

Table 4.3 Example of Exported Raw Data Spreadsheet

Start Date: 8/3/2010
Start Time: 6:46:00 AM
Site Code: 1

Veh. No.	Date	Time	Lane	Axles	Spec	Class	Length (In Inches)	Speed (In MPH)	Gap (In Seconds)	Follow (In Inches)	Axle 1-2	Axle 2-3
1	8/3/2010	6:47:45 AM	1	2	2	2	117	68	105	9999	117	
2	8/3/2010	6:47:48 AM	1	0	0	14	0	0	0	0		
3	8/3/2010	6:48:47 AM	1	2	3	3	143	69	62	9999	143	
4	8/3/2010	6:48:48 AM	1	2	2	2	109	78	1	1373	109	
5	8/3/2010	6:49:21 AM	1	2	2	2	108	64	33	9999	108	
6	8/3/2010	6:49:55 AM	1	2	2	2	100	63	34	9999	100	
7	8/3/2010	6:50:26 AM	1	2	2	2	115	53	31	9999	115	
8	8/3/2010	6:51:29 AM	1	2	3	3	139	67	63	9999	139	
9	8/3/2010	6:52:50 AM	1	2	2	2	115	61	81	9999	115	
10	8/3/2010	6:54:29 AM	1	3	11	8	365	57	99	9999	160	205

- Start Date and Time: date and time when the speed sensor was turned on.
- Site Code: recording the experimental location. In this example, it was sensor 1 location.
- Veh. No.: the number of recorded vehicles.
- Date and Time: date and time when a vehicle datum was recorded.

- Lane: the lane that the recorded vehicle was on. Lane values were all equal to 1 in this example because only upstream traffic speed data were collected in the experiment.
- Axels: the number of axles that the recorded vehicle had.
- Class: the vehicle classification categorized by the software. For example, Class 1 represents motorcycles; Class 2 represents passenger cars; Class 3 represents pickups, vans and other 2-axle, 4-tire single unit vehicles; Class 8 represents four or less axle single trailer trucks; Class 9 represents five-axle single trailer trucks; and Class 14 represents unclassified vehicles.
- Length: the wheelbase between the first and the last axles of the recorded vehicle.
- Speed: the instantaneous speed that the recorded vehicle had when passing the sensor.
- Gap: the time gap between two recorded vehicles.
- Follow: the distance between two recorded vehicles. The value 9,999 in the example means the distance was greater than the maximum value that could be recorded.
- Axle 1-2 and 2-3: the wheelbase between the first and second axles, and the second and the third axles. The sum of all wheelbases made up vehicle length.

Each speed sensor had a built-in real-time clock that had been adjusted to exactly the same date and time up to seconds before collecting data. When the speed of a passing vehicle was captured by all five sensors, the recorded data would have a time gap between 5 to 8 seconds between two adjacent sensors. Therefore, the time gap was used to identify if the speed data collected by the five sensors belonged to the same vehicle. In addition, wheelbase and number of axels could help to identify the classification of recorded vehicles.

A collected vehicle datum was valid if all five speed sensors had correctly captured the passing vehicle speed. If any sensor recorded a speed datum improperly, then the speed datum of that vehicle had to be discarded. Some factors could interfere with the drivers of vehicles and cause speed data to be incorrectly recorded including the inference of pedestrians, low-speed farm vehicles, and construction-related vehicles that either had very low speed or whose drivers had been well aware of the upcoming work zone conditions. Another exception was that vehicles with more than five axles were occasionally recorded as two vehicles following quite closely by a speed sensor. In such situation, the incorrect datum had to be compared with the other four recorded data of the same vehicle and manually modified to its proper value.

After raw speed data were collected, they were gone through an extensive screening process described as follows. The raw data were first thoroughly screened by matching speed data recorded by all five sensors to individual vehicles using the time gap method described earlier. If any of the five speed data for a single vehicle was missing, this vehicle had to be discarded from the dataset. Next, a vehicle speed datum would be discarded if vehicle speed, length, or other values were recorded inaccurately by any of the sensors. In addition, any vehicle speed datum recorded under 20 mph by all five sensors was omitted because the vehicle was a construction-related vehicle or a low-speed farm vehicle. Finally, the average length was calculated for each vehicle by averaging the wheelbases recorded by each speed sensor to classify each recorded vehicle. Through this initial data screening, raw data were condensed and sorted, as shown in

Table 4.4, before using a statistical analysis program to perform further calculations and analyses.

Table 4.4 Example of Sorted Data Spreadsheet

Veh. No.	Date	Time	Ave. Length (in)	Speed (mph)				
				Sensor 1	Sensor 2	Sensor 3	Sensor 4	Sensor 5
1	8/3/2010	6:47:45 AM	115	68	65	64	62	62
2	8/3/2010	6:48:47 AM	109	78	80	83	78	75
3	8/3/2010	6:48:48 AM	141	69	67	70	67	70
4	8/3/2010	6:49:21 AM	108	64	63	65	64	67
5	8/3/2010	6:49:55 AM	99	63	61	60	58	57
6	8/3/2010	6:50:26 AM	128	53	49	62	62	63
7	8/3/2010	6:52:50 AM	114	61	57	59	57	55
8	8/3/2010	6:54:29 AM	401	57	57	53	49	46

4.2.1.2 Driver Survey Data Collection

Driver surveys were conducted at the locations where flaggers stopped the through traffic. The major advantage of surveying drivers at the flagger locations was that drivers had to stop there and wait for the pilot car, which could typically take 10 to 15 minutes. A single survey, according to the on-site trials, would take up to three minutes in most cases. Thus, surveys could be completed during drivers' waiting time without interrupting traffic and causing further traffic delay that could cause drivers' resistance. As a result, a higher percentage of successful surveys were realized. Figure 4.12 shows a driver survey being conducted.

Figure 4.12 A Driver Survey Being Conducted

4.2.2 Collected Datasets

<u>4.2.2.1 Vehicle Speed Data</u>

A total of 1,115 vehicle speed data were collected during field experiments, as shown in Table 4.5. Among these speed data, 345 were collected for the text PCMS; 367 were captured for the graphic-aided PCMS; and 403 were recorded for the graphic PCMS. An example of collected vehicle speed data is presented in Table 4.4, and a portion of vehicle speed data sheet is attached in Appendix B.

Table 4.5 Summary of Vehicle Speed Data

Types of PCMS	No. of Speed Data
Text	345
Graphic-aided	367
Graphic	403
Total	1,115

4.2.2.2 Driver Survey Data

A total of 524 driver surveys were conducted during field experiments, as shown in Table 4.6. Among these driver surveys, 149 were conducted for the text PCMS with the message of "WORKZONE AHEAD SLOWDOWN" and "FLAGGER AHD PREP TO STOP;" 125 were conducted for the graphic-aided PCMS with the message of "WORKZONE AHEAD SLOWDOWN" and the W21-1 sign; 124 were conducted for the graphic-aided PCMS with the message of "FLAGGER AHD PREP TO STOP" and the W20-7 sign; and 126 were conducted for the graphic PCMS with the W21-1 sign and the W20-7 sign. A portion of driver survey data sheet is attached in Appendix C.

Table 4.6 Summary of Driver Survey Data

Types of PCMS	Displayed Message	No. of Driver Surveys
Text	"WORKZONE AHEAD SLOWDOWN" and "FLAGGER AHD PREP TO STOP"	149
Graphic-aided	"WORKZONE AHEAD SLOWDOWN" and W21-1 Sign	125
	"FLAGGER AHD PREP TO STOP" and W20-7 Sign	124
Graphic	W21-1 Sign and W20-7 Sign	126
Total		524

4.3 Data Analysis

4.3.1 Results of Speed Data Analyses

Collected vehicle speed data were analyzed using SPSS Statistics 17.0. Speed data under each of the three PCMS conditions were analyzed first using descriptive statistics, then the percentages of speed reduction were compared among the three PCMS conditions using independent two-sample t-tests, and finally, regression models were built to describe the speed reduction profile for each PCMS condition.

4.3.1.1 Descriptive Statistics

1. Text PCMS

As shown in Table 4.7, for a total of 345 speed data, the minimum speed varied between 45 mph and 21 mph while the maximum speed changed between 83 mph and 78 mph from Sensor 1 to Sensor 5. Speed range (maximum speed minus minimum speed) varied from 38 mph to 57 mph. The mean speed and median speed both decreased from 64 mph at Sensor 1 to 56 mph at Sensor 5. The 85th percentile speed declined from 70 mph to 65 mph. The standard deviation of vehicle speed at the five sensor locations varied between 7.0 and 8.7.

Table 4.7 Descriptive Statistics for Speed Data of Text PCMS

No.	No. of Data	Min. Speed (mph)	Max. Speed (mph)	Range (mph)	Mean Speed (mph)	Median Speed (mph)	Standard Deviation	85th Percentile (mph)
Sensor 1	345	45	83	38	64	64	7.0	70
Sensor 2	345	37	83	46	62	62	8.7	71
Sensor 3	345	28	83	55	59	59	8.5	67
Sensor 4	345	31	78	47	57	57	7.9	65
Sensor 5	345	21	78	57	56	56	8.6	65

The box plot, as illustrated in Figure 4.13, gives a more detailed view of the distribution of the speed data of the text PCMS. From the top to the bottom, the five horizontal lines describe the largest observation (sample maximum), upper quartile (the 75th percentile), median, lower quartile (the 25th percentile), and the smallest observation (sample minimum), respectively. The speed values declined gradually from Sensor 1 to Sensor 5. Dots represent observations that are considered outliers. The lowest outlier at Sensor 5 was 8 mph lower than the second lowest one, resulting in the greatest speed range of 57 mph.

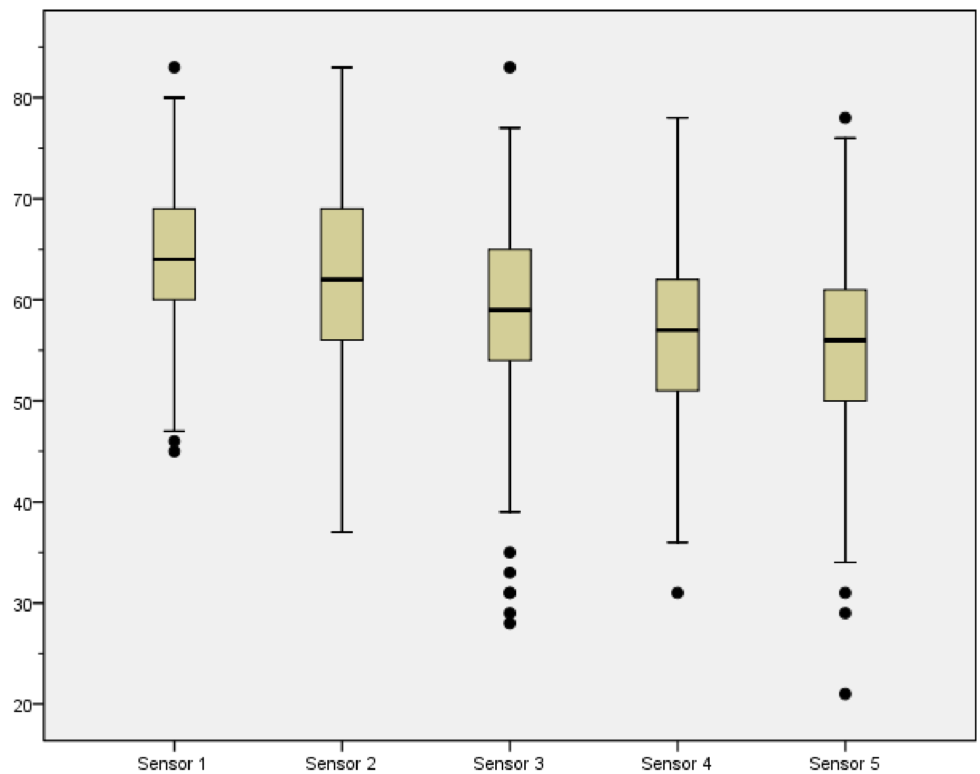

Figure 4.13 Box Plot for Speed Data of Text PCMS

2. Graphic-aided PCMS

Table 4.8 shows the descriptive statistics for speed data of the graphic-aided PCMS. For a total of 367 speed data, the minimum speed varied from 45 mph at Sensor 1 to 31 mph at Sensor 5 and the maximum speed changed from 84 mph at Sensor 1 to 76 mph at Sensor 5; the speed range varied from 34 mph to 45 mph. Mean speed decreased from 65 mph to 59 mph, whereas median speed declined from 66 mph to 60 mph. The 85th percentile speed was reduced from 70 mph to 66 mph. It is noted that Sensor 4, placed at the location of the W20-1 sign, had the lowest values for the minimum, maximum, mean, median, and the 85th percentile speeds, and these values were all one mph lower than those at Sensor 5, which was 530 ft downstream. The standard deviation of vehicle speed at the five sensors varied between 5.5 and 7.6.

Table 4.8 Descriptive Statistics for Speed Data of Graphic-aided PCMS

No.	No. of Data	Min. Speed (mph)	Max. Speed (mph)	Range (mph)	Mean Speed (mph)	Median Speed (mph)	Standard Deviation	85^{th} Percentile (mph)
Sensor 1	367	45	84	39	65	66	5.5	70
Sensor 2	367	42	76	34	63	63	5.6	68
Sensor 3	367	38	77	39	61	61	6.8	68
Sensor 4	367	30	75	45	58	59	7.5	65
Sensor 5	367	31	76	45	59	60	7.6	66

The box plot for speed data of the graphic-aided PCMS is displayed in Figure 4.14. While the speed values decreased moderately from Sensor 1 to Sensor 4, they rose slightly at Sensor 5. A considerable number of outliers appeared below the smallest observation at each sensor; some extreme outliers, represented by asterisks, were observed at Sensor 1.

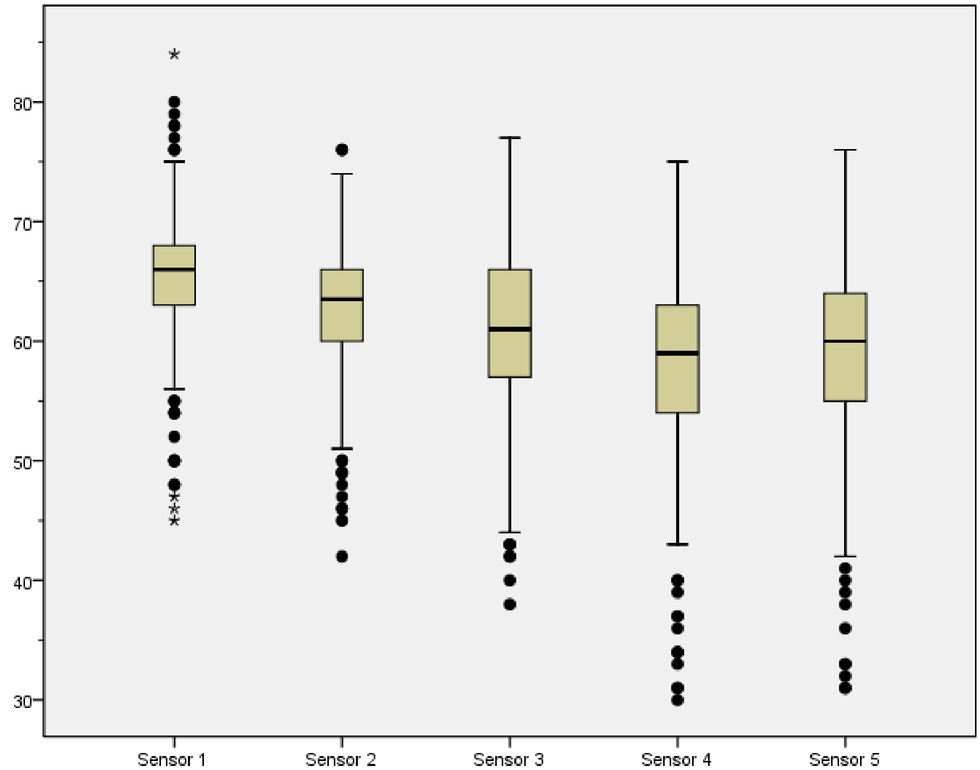

Figure 4.14 Box Plot for Speed Data of Graphic-aided PCMS

3. Graphic PCMS

Descriptive statistics for speed data of the graphic PCMS is shown in Table 4.9. For a total of 403 speed data, the minimum speed varied between 42 mph and 29 mph; the maximum speed changed from 77 mph to 74 mph. Speed range varied from 35 mph to 46 mph. Mean speed was reduced from 63 mph to 52 mph while median speed decreased from 64 mph to 53 mph; both declined by 11 mph. The 85th percentile speed decreased by 8 mph from 69 mph to 61 mph. The standard deviation of vehicle speed for the five sensors ranged between 6.3 and 8.1.

Table 4.9 Descriptive Statistics for Speed Data of Graphic PCMS

No.	No. of Data	Min. Speed (mph)	Max. Speed (mph)	Range (mph)	Mean Speed (mph)	Median Speed (mph)	Standard Deviation	85th Percentile (mph)
Sensor 1	403	42	77	35	63	64	6.3	69
Sensor 2	403	41	76	35	61	62	7.0	68
Sensor 3	403	33	76	43	58	58	7.5	65
Sensor 4	403	34	74	40	55	55	7.4	63
Sensor 5	403	29	75	46	52	53	8.1	61

Figure 4.15 illustrates the box plot for speed data of the graphic PCMS. The upper quartile, median, lower quartile, and the smallest observation of speed data decreased gradually from Sensor 1 to Sensor 5 whereas the largest observation decreased within a smaller range. Most outliers appeared below the smallest observations while only two stood higher than the largest observations.

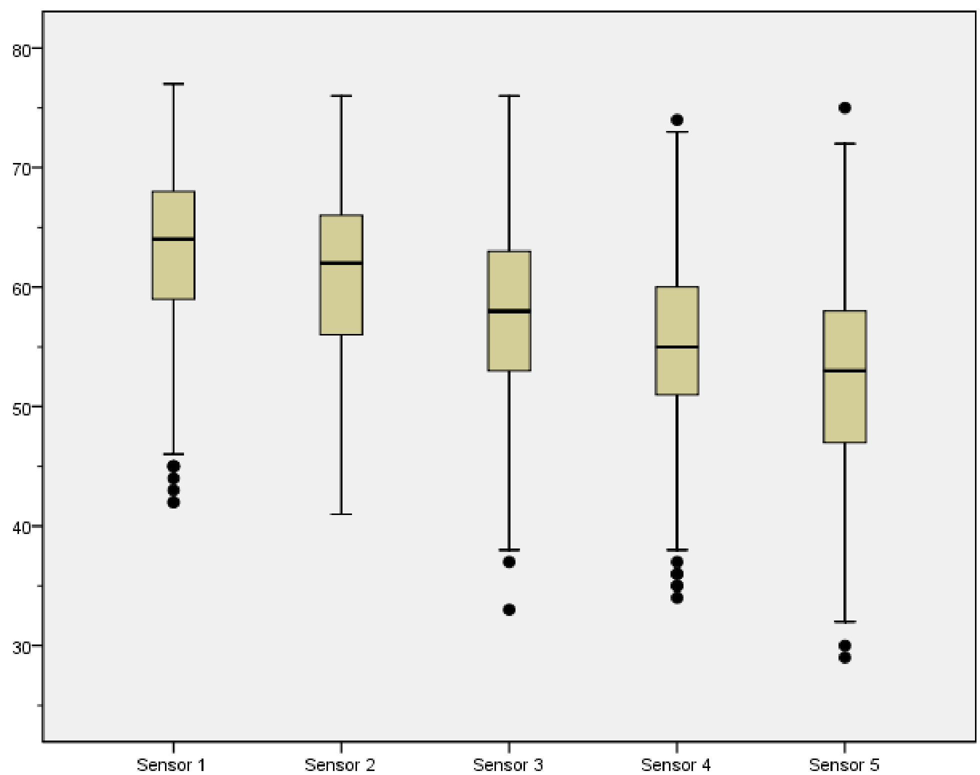

Figure 4.15 Box Plot for Speed Data of Graphic PCMS

4.3.1.2 Comparison Analyses

1. Comparison of Mean Speed Reduction

Table 4.10 shows the details of the percentage of mean speed reduction for each PCMS condition between two adjacent speed sensors. For the text PCMS condition, the mean vehicle speed began from 64 mph at Sensor 1. It was reduced by 2 mph at Sensor 2, 3 mph at Sensor 3, then 2 mph at Sensor 4, and finally 1 mph at Sensor 5 until it reached 56 mph. In terms of percentages, the mean vehicle speed dropped by 3%, 5%, 3%, and 2% at Sensors 2, 3, 4, and 5, respectively. The percentage of the total speed reduction from Sensor 1 to Sensor 5 was 13%.

Table 4.10 Percentage of Mean Speed Reduction

No.	Text PCMS		Graphic-aided PCMS		Graphic PCMS	
	Mean Speed (mph)	% of Reduction	Mean Speed (mph)	% of Reduction	Mean Speed (mph)	% of Reduction
Sensor 1	64		65		63	
		3%		4%		4%
Sensor 2	62		63		61	
		5%		3%		5%
Sensor 3	59		61		58	
		3%		4%		4%
Sensor 4	57		58		55	
		2%		-1%		5%
Sensor 5	56		59		52	
Total	-	13%	-	10%	-	17%

Note: Total % of Reduction=(Mean Speed of Sensor 1- Mean Speed of Sensor 5)/ Mean Speed of Sensor 1 ×100%

For the graphic-aided PCMS condition, the mean vehicle speed started at 65 mph at Sensor 1. It declined by 2 mph each at Sensors 2 and 3, decreased by another 3 mph at Sensor 4, and then regained by 1 mph at Sensor 5. The percentage of speed reduction between Sensors 1 to 4 was around 3% to 4%, while it fell to -1% between Sensors 4 and 5. The percentage of the total speed reduction from Sensor 1 to Sensor 5 was 10%.

For the graphic PCMS condition, the mean vehicle speed at Sensor 1 was 63 mph. It dropped by 2 mph at Sensor 2, and then decreased by 3 mph at each following sensor location until it reached 52 mph at Sensor 5. The percentage of speed reduction was around 4% to 5% between two adjacent sensors, and the percentage of the total speed reduction from Sensor 1 to Sensor 5 was 17%.

Therefore, comparing the percentages of mean speed reduction for three PCMS conditions, the graphic PCMS resulted in the largest percentage of mean speed reduction of 17%, the text PCMS had a moderate percentage of mean speed reduction of 13%, and the graphic-aided PCMS had the smallest percentage of mean speed reduction of 10%. Figure 4.16 illustrates the profiles of the mean speed reduction associated with distance for three PCMS conditions.

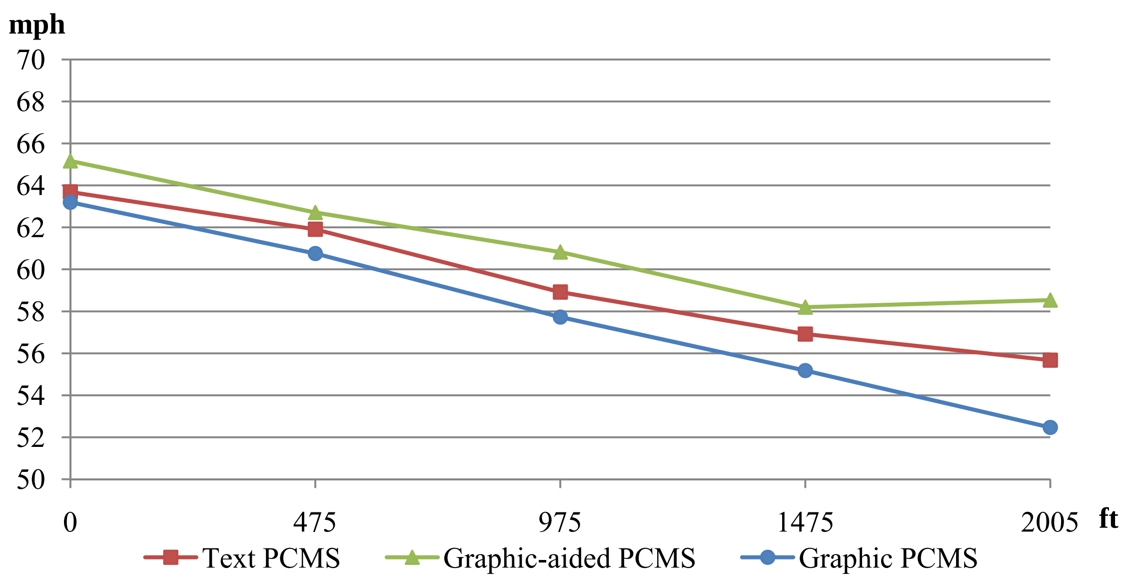

Figure 4.16 Mean Speed Reduction Profile

2. Independent Two-sample T-test

Independent two-sample t-tests were conducted to determine if the mean speeds at the same sensor location were statistically the same for three PCMS conditions. It was assumed that if the mean speeds were statistically the same at one sensor location but not statistically the same at another sensor location for different PCMS conditions, the effectiveness of different PCMS conditions on reducing the mean vehicle speeds would be different. Therefore, one two-sample t-test was conducted for the mean speeds at each sensor location between every two PCMS conditions, which made up a total of 15 two-sample t-tests.

In the independent two-sample t-tests, the null hypothesis (H_0) and the alternative hypothesis (H_1) were defined as:

$$H_0\colon \mu_1 = \mu_2$$

$$H_1\colon \mu_1 \neq \mu_2$$

where μ_1 = the mean speed at a sensor location for one PCMS condition; μ_2 = the mean speed at the same sensor location for the another PCMS condition. In other words, the interpretation of the null hypothesis is that the mean speeds at a sensor location were statistically the same for the two compared PCMS conditions, and the alternative hypothesis is that the mean speeds at a sensor location were statistically not the same for the two compared PCMS conditions. A 95% level of confidence was used in the t-tests and a p-value no greater than 0.05 would indicate that the null hypothesis could be confidently rejected.

Table 4.11 shows the results of p-values in t-tests for mean speeds at each sensor location between two compared PCMS conditions. The only two p-values larger than

0.05 occurred at the Sensor 2 location when comparing the text PCMS condition with the graphic-aided PCMS condition and at the Sensor 1 location when comparing the text PCMS condition with the graphic PCMS condition. Therefore, comparing the text PCMS condition with the graphic-aided PCMS condition, the mean vehicle speeds were statistically the same at Sensor 2 location but not the same at sensor locations of 1, 3, 4, and 5; comparing the text PCMS condition with the graphic PCMS condition, the mean vehicle speeds were statistically the same at Sensor 1 location but not the same at sensor locations 2 to 5; comparing the graphic-aided PCMS condition with the graphic PCMS condition, the mean vehicle speeds were statistically not the same at all sensor locations.

Table 4.11 P-Values in Independent Two-sample T-tests

Location	Text vs. Graphic-aided	Text vs. Graphic	Graphic-aided vs. Graphic
Sensor 1	0.002	**0.312**	0.000
Sensor 2	**0.143**	0.045	0.000
Sensor 3	0.001	0.042	0.000
Sensor 4	0.027	0.002	0.000
Sensor 5	0.000	0.000	0.000

Based on the results of t-tests and the Figure 4.16, the following conclusions were reached. First, comparing the graphic-aided PCMS condition with the text PCMS condition, the mean vehicle speed was significantly reduced from the Sensor 1 location to the Sensor 2 location in the upstream of the work zone using the graphic-aided PCMS; the mean vehicle speed was significantly reduced from the Sensor 2 location to the Sensor 5 location using the text PCMS. In other words, using a graphic-aided PCMS could reduce the mean vehicle speed more effectively than using a text PCMS from 1,475 ft to 1,000 ft in the upstream of a work zone, but less effectively than using a text PCMS from 1,000 ft in the upstream of a work zone to the W20-4 sign. Second, comparing the graphic PCMS condition with the text PCMS condition, the mean vehicle speed was significantly reduced from the Sensor 1 location to the Sensor 5 location using the graphic PCMS. In other words, using a graphic PCMS could reduce the mean vehicle speed more effectively than using a text PCMS from 1,475 ft in the upstream of a work zone to the W20-4 sign. Finally, no conclusion could be drawn when comparing the graphic-aided PCMS condition with the graphic PCMS condition because the mean vehicle speeds were statistically not the same at all sensor locations.

4.3.1.3 Regression Models

Mathematical models were developed to describe the mean vehicle speed profiles in the upstream of a work zone. The possible models include parabolic, hyperbolic, power, exponential, logarithmic, and polynomial function models. After a number of trials, the polynomial function was selected as the most desired regression model as it could best fit the collected mean speed data and most clearly show the relationship between the mean vehicle speed and the distance.

The general polynomial function of the regression model is

$$y = a_0 + a_1 x + a_2 x^2 + a_3 x^3 + \cdots + a_n x^n$$

where y = the mean vehicle speed, x = the distance between Sensor 1 location and a vehicle location in the upstream of a work zone as shown in Figure 4.10, and $a_0, a_1, a_2, a_3 \cdots a_n$ = the parameters yet to be determined. When $a_2 = a_3 = \cdots = a_n = 0$, the regression model becomes a linear regression model; otherwise, the model is nonlinear.

1. Linear Regression Model

The linear regression model is

$$y = a_0 + a_1 x$$

where y = the mean vehicle speed, x = the distance between Sensor 1 location and a vehicle location in the upstream of a work zone, a_0 = the mean speed at Sensor 1 location, which is the initial speed, and a_1 = the reduction rate of the mean speed in mph/ft.

A linear regression model describing the mean vehicle speed profile in the upstream of a work zone under the text PCMS condition is

$$y = 64 - 0.0042x \tag{4.1}$$

A linear regression model describing the mean vehicle speed profile in the upstream of a work zone under the graphic-aided PCMS condition is

$$y = 65 - 0.0034x \tag{4.2}$$

A linear regression model describing the mean vehicle speed profile in the upstream of a work zone under the graphic PCMS condition is

$$y = 63 - 0.0056x \tag{4.3}$$

Figure 4.17 illustrates the linear regression models of the three PCMS conditions. The linear function of the graphic PCMS condition can most accurately fit the collected mean speed data as the fit line intersects all five data points (R^2 = 0.999). The linear function of the text PCMS condition has some slight deviations from the collected mean speed data from sensor locations 2 to 5 (R^2 = 1.000). The linear function of the graphic-aided PCMS condition also has some moderate deviations from the collected mean speed data at sensor locations 4 and 5 (R^2 = 0.993).

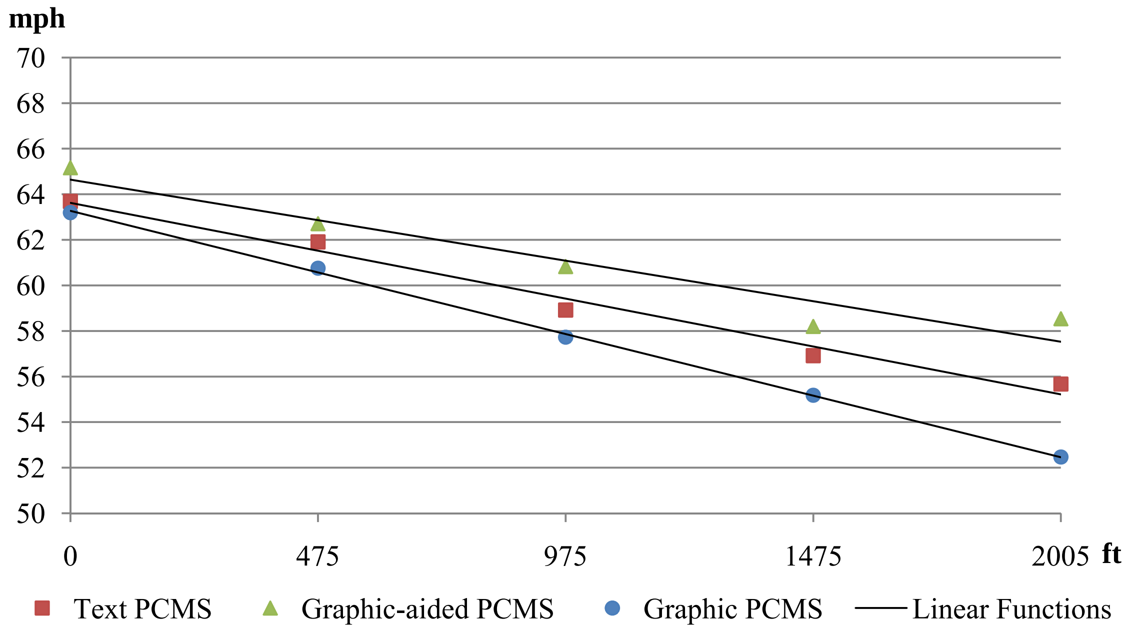

Figure 4.17 Linear Regression Models of Three PCMS Conditions

When comparing the reduction rates of the mean speed, the graphic PCMS condition had the largest reduction rate of 0.0056 mph/ft, the text PCMS condition had a moderate reduction rate of 0.0042 mph/ft, and the graphic-aided PCMS condition had the smallest reduction rate of 0.0034 mph/ft. In other words, the linear regression models suggest that using a graphic PCMS can reduce the mean vehicle speed the most, using a graphic-aided PCMS can reduce the mean vehicle speed the least, and using a text PCMS falls in the middle.

2. Nonlinear Regression Model

Since the linear functions could not best fit the mean speed profiles under the text PCMS condition and the graphic-aided PCMS condition, nonlinear regression models were developed to seek the improvement.

(1) Quadratic Function

A quadratic function is described as:

$$y = a_0 + a_1 x + a_2 x^2$$

where y = the mean vehicle speed, x = the distance between Sensor 1 location and a vehicle location in the upstream of a work zone, a_0 = the mean speed at Sensor 1 location, which is the initial speed, and a_1, a_2 = the parameters yet to be determined.

A quadratic function describing the mean vehicle speed profile in the upstream of a work zone under the text PCMS condition is

$$y = 64 - 0.0062x + 1.0073 \times 10^{-6} x^2 \tag{4.4}$$

A quadratic function describing the mean vehicle speed profile in the upstream of a work zone under the graphic-aided PCMS condition is

$$y = 65 - 0.0065x + 1.5760 \times 10^{-6} x^2 \tag{4.5}$$

Figures 4.18 and 4.19 illustrate the quadratic functions of the text PCMS condition and the graphic-aided PCMS condition. The quadratic function of the text PCMS condition has a minor deviation at Sensor 2 location (R^2 = 0.972), while the quadratic function of the graphic-aided PCMS condition has a small deviation at Sensor 4 location (R^2 = 0.933). The quadratic functions intersect all other mean speed data points.

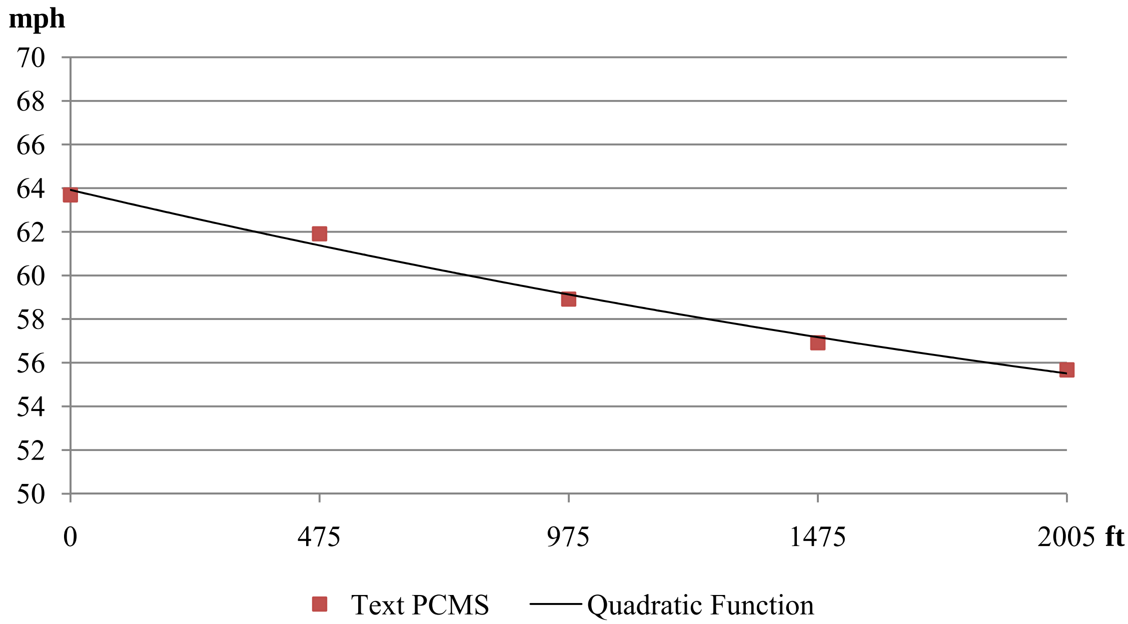

Figure 4.18 Quadratic Function of Text PCMS Condition

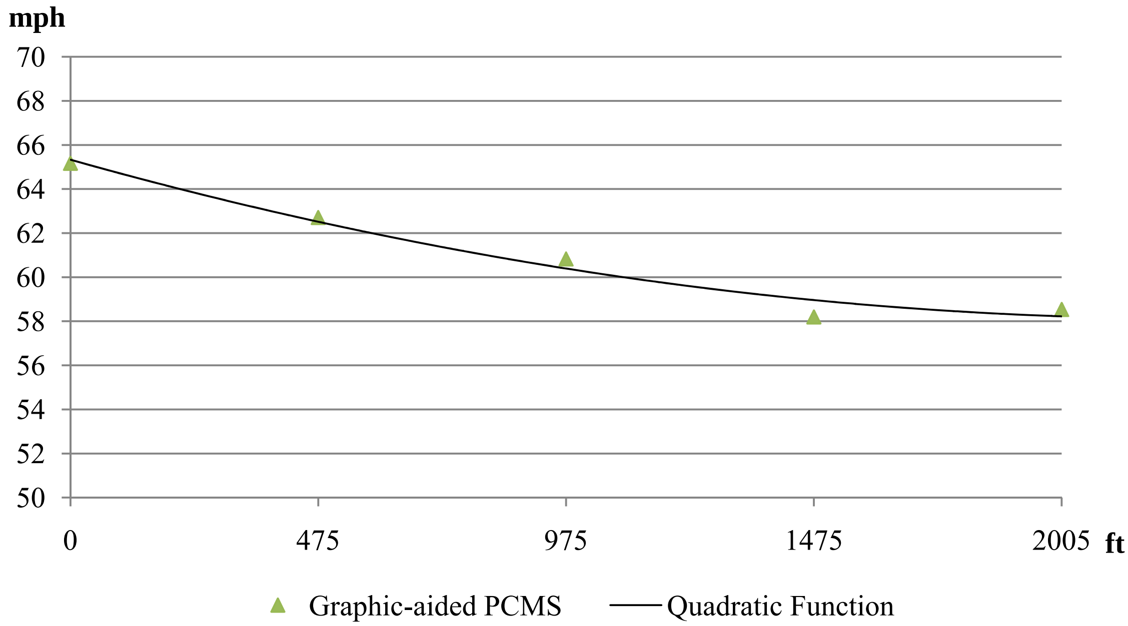

Figure 4.19 Quadratic Function of Graphic-aided PCMS Condition

(2) Cubic Function

A cubic function can be described as:

$$y = a_0 + a_1 x + a_2 x^2 + a_3 x^3$$

where y = the mean vehicle speed, x = the distance between Sensor 1 location and a vehicle location in the upstream of a work zone, a_0 = the mean speed at Sensor 1 location, which is the initial speed, and a_1, a_2, a_3 = the parameters yet to be determined.

A cubic function describing the mean vehicle speed profile in the upstream of a work zone under the text PCMS condition is

$$y = 64 - 0.0035x - 2.7694 \times 10^{-6} x^2 + 1.2542 \times 10^{-9} x^3 \qquad (4.6)$$

A cubic function describing the mean vehicle speed profile in the upstream of a work zone under the graphic-aided PCMS condition is

$$y = 65 - 0.0009x - 6.2415 \times 10^{-6} x^2 + 2.5961 \times 10^{-9} x^3 \qquad (4.7)$$

Figures 4.20 and 4.21 illustrate the cubic functions of the text PCMS condition and the graphic-aided PCMS condition. Both curves intersect all the mean speed data points and thus were the best models to describe the mean vehicle speed profile in the upstream of a work zone for the text PCMS condition and the graphic-aided PCMS condition.

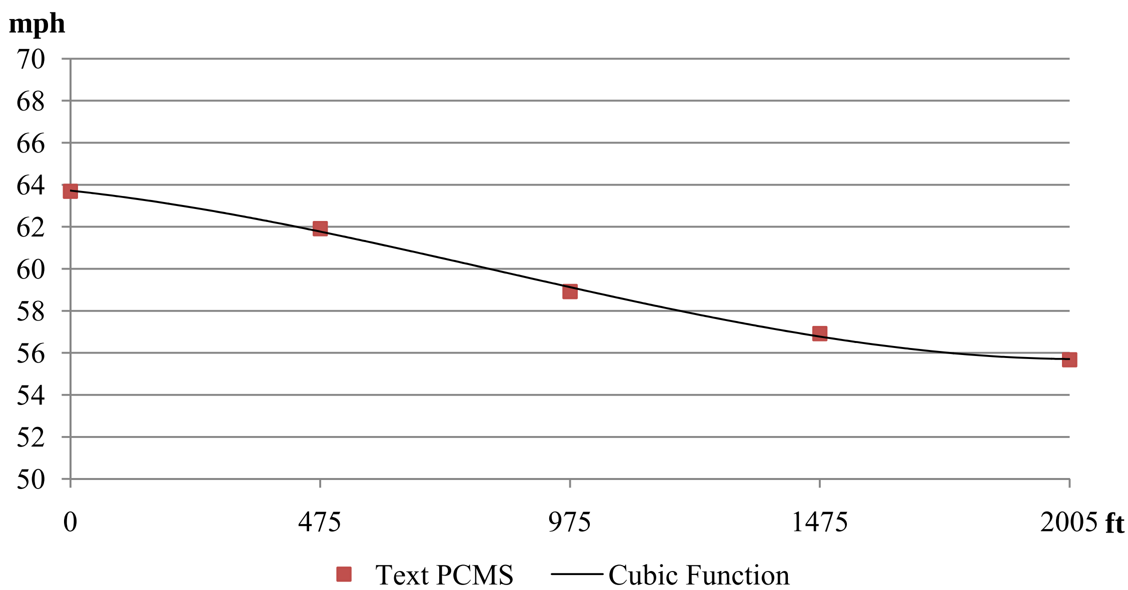

Figure 4.20 Cubic Function of Text PCMS Condition

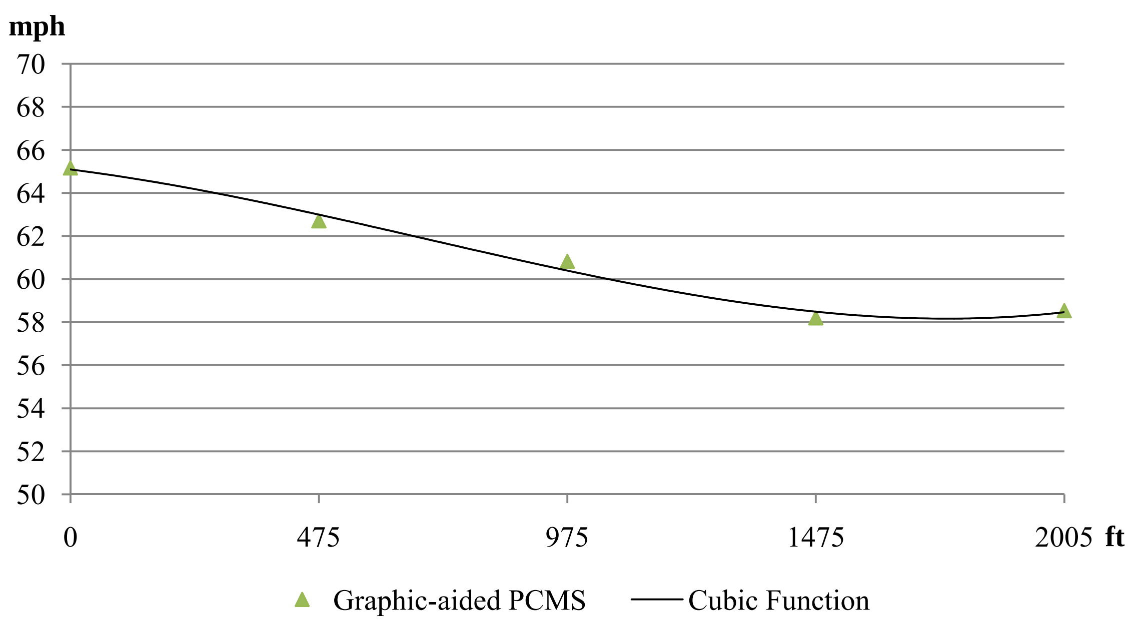

Figure 4.21 Cubic Function of Graphic-aided PCMS Condition

4.3.2 Driver Survey Results

A total of 524 driver surveys were performed during the field experiments, of which the surveys of the text PCMS condition were conducted two months after the surveys of the graphic-aided and graphic PCMS conditions at a different work zone with similar roadway conditions.

<u>*4.3.2.1 Driver Survey Feedback*</u>

1. Driver Survey of Text PCMS Condition

149 drivers participated in the driver survey of the text PCMS condition, including 98 male drivers (66%) and 51 female drivers (34%). The driver survey results are described as follows.

Question 1: *Did you see the Portable Changeable Message Sign (PCMS) when you were approaching the work zone?* All drivers (100%) responded *Yes*.

Question 2: *Did you understand the messages displayed on the PCMS?* All drivers (100%) answered *Yes*.

Question 3: *Did you think that the PCMS drew your attention more to the work zone traffic conditions?* 97% of drivers selected *Yes* and 3% of drivers selected *No*.

Question 4: *Do you prefer the warning signs to be displayed in the graphical format or text format?* As illustrated in Figure 4.22, the majority (64%) of drivers preferred the text format; 16% of drivers chose the graphic-aided format; 5% of drivers liked the graphic format; 14% of respondents thought there was no difference between the text format and the graphic format; the remaining 1% did not care about the message format.

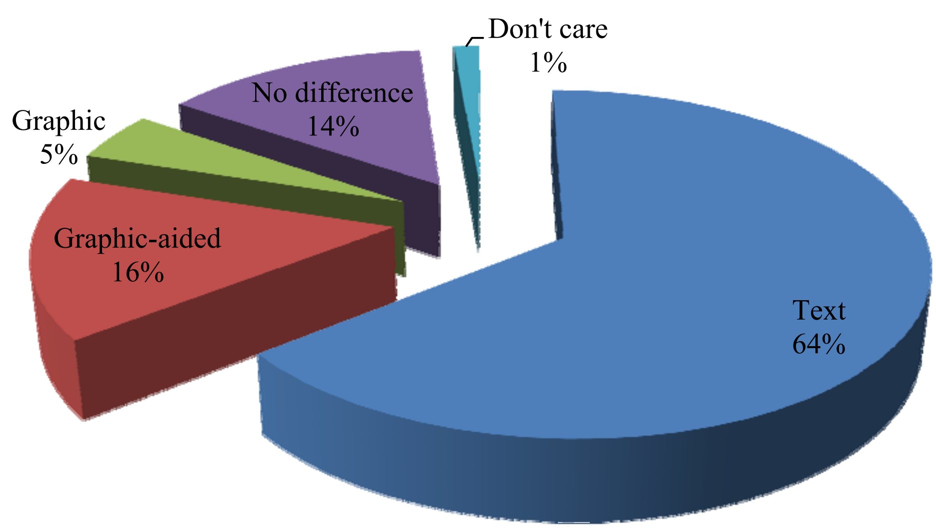

Figure 4.22 Drivers' Preferences on Message Format of Text PCMS Condition

The number of drivers who answered survey question 4 was further analyzed by their gender and results are presented in Table 4.12. 63% of male drivers preferred the sign displayed in text format, 3% less than the percentage of female drivers. On the other hand, 2%, 1%, and 1% more male drivers than female drivers chose the graphic-added format, graphic format, and the no difference option, respectively. 1% of male drivers and 2% of female drivers did not care about the message format. In general, the percentages of male and female drivers selecting each format were quite similar. Text format was the majority choice for both male and female drivers in the surveys for the text PCMS condition.

Table 4.12 Driver Gender Proportion of Text PCMS Condition

Answer	Overall		Male		Female	
	Frequency	Percentage	Frequency	Percentage	Frequency	Percentage
Text	96	64%	62	63%	34	66%
Graphic-aided	23	16%	16	16%	7	14%
Graphic	7	5%	5	5%	2	4%
No difference	21	14%	14	15%	7	14%
Don't care	2	1%	1	1%	1	2%
Don't know	0	0%	0	0%	0	0%
Other	0	0%	0	0%	0	0%
Total	149	100%	98	100%	51	100%

2. Driver Survey of Graphic-aided PCMS Condition

(1) Graphic-aided PCMS with Work Zone Graphic

125 driver surveys were conducted for the graphic-aided PCMS with the work zone graphic (the W21-1 sign), of which 69 respondents (55%) were male drivers and 56 respondents (45%) were female drivers. The driver survey results are presented as follows.

Question 1: *Did you see a **graphic** displayed on the Portable Changeable Message Sign (PCMS) when you were approaching the work zone?* All drivers (100%) responded *Yes*.

Question 2: *How did you interpret the meaning of this graphic?* Most drivers (88%) selected *Work zone/Work zone ahead/Someone working*; 11% of drivers, however, got confused about this graphic-aided message; and the other 1% chose *Other*.

Question 3: *Did you think that the **graphic** drew your attention more to the work zone traffic conditions?* 82% of drivers selected *Yes* and 16% of drivers selected *No*; the remaining 2% answered *Don't know*.

Question 4: *Do you prefer the warning signs to be displayed in the graphical format or text format?* Results are illustrated in Figure 4.23. Around one fourth of drivers preferred the text format (24%), graphic-aided format (26%), and graphic format (26%). 18% of respondents said no difference between the text format and the graphic format; the remaining 1% of drivers answered *Don't know*.

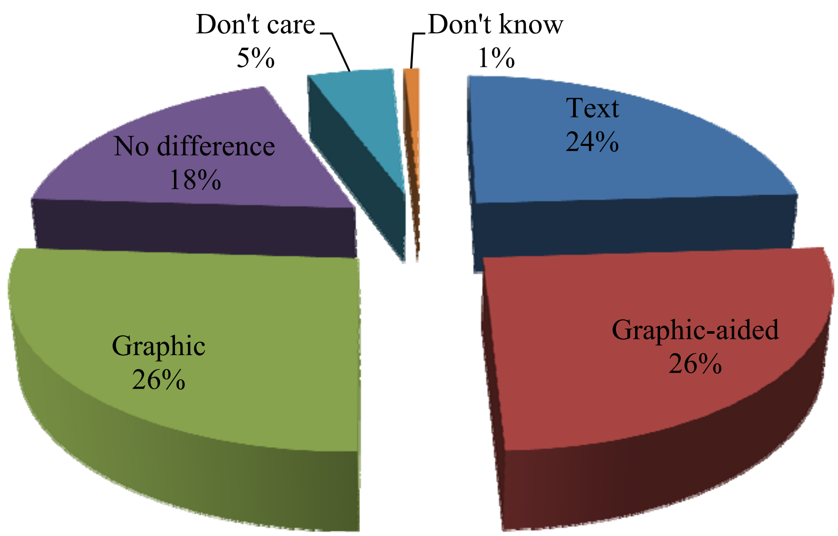

Figure 4.23 Drivers' Preferences on Message Format of Graphic-aided PCMS with Work Zone Sign Condition

The number of drivers who answered survey question 4 was further analyzed by their gender and results are presented in Table 4.13. While about a quarter of male and female drivers liked the text format sign, their preferences on the graphic-aided and graphic format signs varied a lot. More female drivers chose the graphic-aided format sign than the male drivers (34% vs. 19%), and more male drivers selected the graphic format sign than the female drivers (33% vs. 18%). On the other hand, a similar percentage of male and female drivers (18% to 19%) thought the text format and graphic format signs made no difference to them. 3% of male drivers and 7% of female drivers did not care about the message format. Another 1% of male drivers did not know how to choose the formats.

Table 4.13 Driver Gender Proportion of Graphic-aided PCMS with Work Zone Sign Condition

Answer	Overall		Male		Female	
	Frequency	Percentage	Frequency	Percentage	Frequency	Percentage
Text	30	24%	17	25%	13	23%
Graphic-aided	32	26%	13	19%	19	34%
Graphic	33	26%	23	33%	10	18%
No difference	23	18%	13	19%	10	18%
Don't care	6	5%	2	3%	4	7%
Don't know	1	1%	1	1%	0	0%
Other	0	0%	0	0%	0	0%
Total	125	100%	69	100%	56	100%

(2) Graphic-aided PCMS with Flagger Graphic

124 drivers responded to the surveys for the graphic-aided PCMS with the flagger graphic, of which 65 drivers (52%) were male and 59 drivers (48%) were female. The driver survey results are presented as follows.

Question 1: *Did you see a **graphic** displayed on the Portable Changeable Message Sign (PCMS) when you were approaching the work zone?* All drivers (100%) responded *Yes*.

Question 2: *How did you interpret the meaning of this graphic?* All drivers (100%) chose *Flagger/Flagger ahead/Flagger present/Need to stop*.

Question 3: *Did you think that the* ***graphic*** *drew your attention more to the work zone traffic conditions?* 90% of drivers answered *Yes*; 7% of drivers answered *No*; the remaining 3% selected *Don't know*.

Question 4: *Do you prefer the warning signs to be displayed in the graphical format or text format?* As illustrated in Figure 4.24, only 3% of drivers preferred the text format; the majority of drivers (52%) chose the graphic format; 19% of drivers liked the graphic-aided format; 19% of respondents thought there was no difference between the text format and the graphic format; 6% of drivers did not care about the message format; and the remaining 1% answered *Other*.

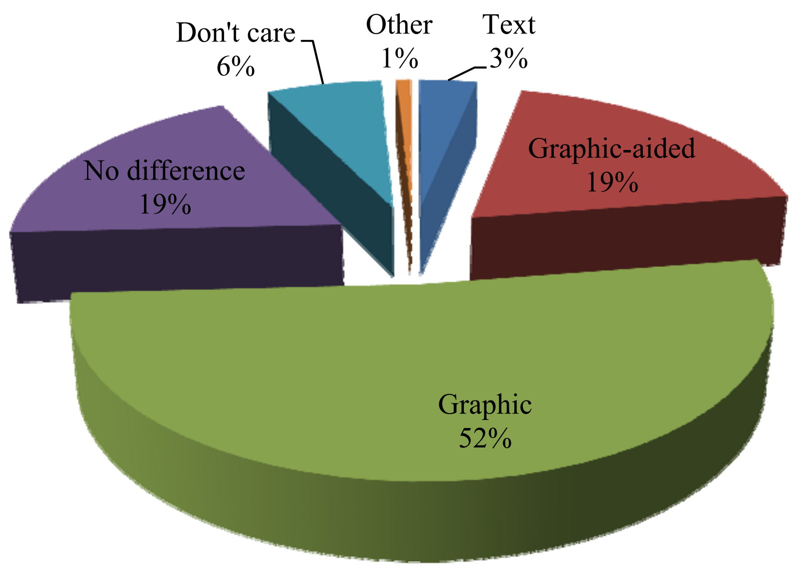

Figure 4.24 Drivers' Preferences on Message Format for Graphic-aided PCMS with Flagger Sign Condition

The number of drivers who answered survey question 4 was further analyzed by their gender and results are presented in Table 4.14. Male and female drivers made different choices for most of the options. 5% of male drivers selected the text format, 3%

more than the percentage of female drivers. More female drivers preferred the graphic-aided format sign (24% vs. 15%), while more male drivers liked the graphic format sign (57% vs. 45%). 15% of male drivers felt no difference between the text and graphic format signs, and so did 22% of female drivers. A similar percentage (6% to 7%) of both male and female drivers did not care about the message format, and 2% of male drivers answered *Other*. Overall, the graphic format was the choice of the majority, followed by the graphic-aided format, and the text format gained only a slight share. More male drivers chose the graphic format, while more female drivers selected the graphic-aided format.

Table 4.14 Driver Gender Proportion for Graphic-aided PCMS with Flagger Sign Condition

Answer	Overall		Male		Female	
	Frequency	Percentage	Frequency	Percentage	Frequency	Percentage
Text	4	3%	3	5%	1	2%
Graphic-aided	24	19%	10	15%	14	24%
Graphic	64	52%	37	57%	27	45%
No difference	23	19%	10	15%	13	22%
Don't care	8	6%	4	6%	4	7%
Don't know	0	0%	0	0%	0	0%
Other	1	1%	1	2%	0	0%
Total	124	100%	65	100%	59	100%

3. Driver Survey of Graphic PCMS Condition

126 drivers answered the questionnaires in the survey for the graphic PCMS condition, including 69 male drivers (55%) and 57 female drivers (45%). The driver survey results are presented as follows.

Question 1: *Did you see two **graphics** displayed on the Portable Changeable Message Sign (PCMS) when you were approaching the work zone?*, all drivers (100%) responded *Yes*.

Question 2: *How did you interpret the meanings of these two graphics?* For the work zone sign, most drivers (79%) selected *Work zone/Work zone ahead/Someone working*; 16% of drivers, however, got confused about this graphic, and the other 5% did not understand it. For the flagger graphic in Question 2, all drivers (100%) chose *Flagger/Flagger ahead/Flagger present/Need to stop*.

Question 3: *Did you think that the* ***graphics*** *drew your attention more to the work zone traffic conditions?* 87% of drivers answered *Yes* and 13% answered *No*.

Question 4: *Do you prefer the warning signs to be displayed in the graphical format or text format?* As illustrated in Figure 4.25, a small number (12%) of drivers liked the text format, while the majority (45%) preferred the graphic format. 21% of drivers chose the graphic-aided format, and a similar percentage of respondents did not see the difference between the text format and the graphic format. 1% of drivers did not care about the message format, and another 1% did not know how to make the selection.

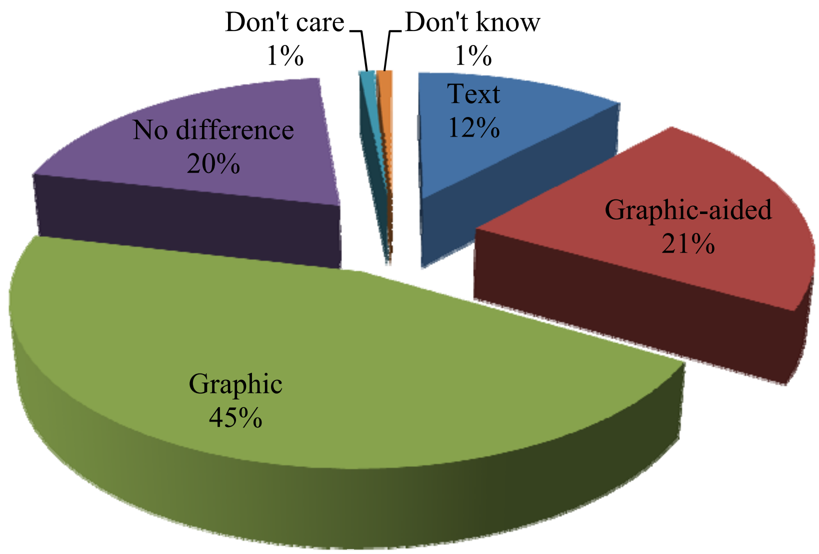

Figure 4.25 Drivers' Preferences on Message Format for Graphic PCMS Condition

The number of drivers who answered survey question 4 was further analyzed by their gender and results are presented in Table 4.15. 17% of male drivers preferred the text format, which was chosen by only 5% of female drivers. A similar percentage of both male (20%) and female drivers (23%) selected the graphic-aided format. The majority of drivers, 42% for male and 49% for female, chose the graphic format. 17% male drivers and 23% of female drivers said no difference between the text format and the graphic format signs. 2% of male drivers did not care about the message format, and another 2% did not know how to make the selection. Generally speaking, a larger percentage of male drivers preferred the text format sign than the female drivers, while a larger percentage of female drivers preferred the graphic-aided and graphic format signs.

Table 4.15 Driver Gender Proportion for Graphic PCMS

Answer	Overall		Male		Female	
	Frequency	Percentage	Frequency	Percentage	Frequency	Percentage
Text	15	12%	12	17%	3	5%
Graphic-aided	27	21%	14	20%	13	23%
Graphic	57	45%	29	42%	28	49%
No difference	25	20%	12	17%	13	23%
Don’t care	1	1%	1	2%	0	0%
Don’t know	1	1%	1	2%	0	0%
Other	0	0%	0	0%	0	0%
Total	126	100%	69	100%	57	100%

4.3.2.2 Comparison of Driver Survey Results

Comparative analyses were made among the results of the four driver surveys. Since all drivers responded that they saw the text and graphic messages on the PCMS, no comparison was conducted for the visibility of messages on the PCMS.

1. Drivers' Understanding of Meaning of Graphics on PCMS

Table 4.16 shows the comparison of drivers' understanding of graphics on the PCMS in survey question 2. All drivers could understand the meaning of the flagger graphic displayed on the graphic-aided and graphic PCMSs. 88% of drivers were able to interpret the meaning of the work zone graphic on the graphic-aided PCMS, and 79% of drivers could understand it on the graphic PCMS. In other words, 12% of drivers could not understand the meaning of the work zone graphic on the graphic-aided PCMS, and 21% of drivers either misunderstood this graphic or had no idea about it on the graphic PCMS. Therefore, the work zone graphic together with the text "WORKZONE AHEAD SLOWDOWN" on the graphic-aided PCMS was easier to be understood correctly by 9% more drivers than the work zone graphic displayed alone on the graphic PCMS. The flagger graphic, on the other hand, could be interpreted correctly by all drivers no matter it was displayed with or without the text "FLAGGER AHD PREP TO STOP."

Table 4.16 Comparison of Drivers' Understanding of Graphics on PCMS

Survey Response	Graphic-aided PCMS		Graphic PCMS	
	W21-1 Sign with Text	W20-7 Sign with Text	W21-1 Sign	W20-7 Sign
Work zone	88%	-	79%	-
Get confused	11%	-	16%	-
Don't know	0%	-	5%	-
Other	1%	-	0%	-
Flagger	-	100%	-	100%
Get confused	-	0%	-	0%
Don't know	-	0%	-	0%
Other	-	0%	-	0%
Total	100%	100%	100%	100%

Note: W21-1 Sign – Work Zone; W20-7 Sign – Flagger

2. Effectiveness of PCMS on Drawing Drivers' Attention

Table 4.17 shows the comparison of the effectiveness of PCMS on drawing drivers' attention in survey question 3. 97% of drivers thought the text PCMS drew their attention more to the work zone traffic conditions. The graphic-aided PCMS with the flagger graphic, which was the PCMS understood by all respondents, drew 90% of drivers' attention more to the work zone traffic conditions. 82% of drivers paid more attention to the work zone traffic conditions after they saw the graphic-aided PCMS with the work zone graphic. Although the work zone graphic in the graphic PCMS was interpreted correctly by the least percentage of drivers, the graphic PCMS still drew 87% of drivers' attention more to the work zone traffic conditions. It was likely that the well-understood flagger graphic in the graphic PCMS helped to gain this percentage of drivers' attention.

Table 4.17 Comparison of Effectiveness of PCMS on Drawing Drivers' Attention

Survey Response	Text PCMS	Graphic-aided PCMS		Graphic PCMS
		W21-1 Sign with Text	W20-7 Sign with Text	
Yes	97%	82%	90%	87%
No	3%	16%	7%	13%
Don't know	0 %	2 %	3%	0%
Total	100%	100%	100%	100%

Note: W21-1 Sign – Work Zone; W20-7 Sign – Flagger

3. Drivers' Preferences for Message Format on PCMS

The comparison of driver's preferences for message format on the PCMS is shown in Table 4.18. 64% of drivers chose the text format when they saw the text PCMS, but the percentage dropped dramatically to 24% when the drivers saw the graphic-aided PCMS with the work zone graphic, and this percentage declined even further to only 3%

for the graphic-aided PCMS with the flagger graphic. The percentage of drivers choosing the text format, when they saw a graphic PCMS, was 12%. The graphic format, on the contrary, had a completely different drivers' preference compared with the text format. Only 5% of drivers preferred the graphic format when they saw the text PCMS. When the graphic-aided PCMS with the work zone graphic was displayed, 26% of drivers liked the graphic format; when the graphic-aided PCMS with the flagger graphic was shown, the percentage of drivers in favor of the graphic format doubled immediately to 52%. The percentage of drivers with the preference for the graphic format also remained high at 45% when they saw a graphic PCMS. The graphic-aided format had more stable percentages of drivers' selections compared with the other two formats. 16% of drivers liked the graphic-aided format when the text PCMS was displayed, 26% drivers chose it when the graphic-aided PCMS with the work zone graphic was displayed; 19% of drivers selected it when the graphic-aided PCMS with the flagger graphic was shown; and 21% of drivers preferred it when the graphic PCMS was displayed. About 14% to 20% of drivers saw no difference between the text format and the graphic format, and about 1% to 6% of drivers did not care about the message format on the PCMS. Another slight 1% to 2% of drivers chose *Don't know* or *Other* options. In general, the majority of drivers liked the text format when they only saw the text PCMS, but preferred the graphic format when they saw the graphic-aided PCMS and the graphic PCMS. Drivers' preferences were distributed more evenly to the three message formats when they saw the graphic-aided PCMS with the work zone graphic. The graphic-aided and graphic formats were the choices of the majority (52% to 71%) when a graphic-aided or a graphic PCMS was present.

Table 4.18 Comparison of Driver's Preferences to Message Format on PCMS

Survey Response	Text PCMS	Graphic-aided PCMS		Graphic PCMS
		W21-1 Sign with Text	W20-7 Sign with Text	
Text	64%	24%	3%	12%
Graphic-aided	16%	26%	19%	21%
Graphic	5%	26%	52%	45%
No difference	14%	18%	19%	20%
Don't care	1%	5%	6%	1%
Don't know	0%	1%	0%	1%
Other	0%	0%	1%	0%
Total	100%	100%	100%	100%

Note: W21-1 Sign – Work Zone; W20-7 Sign – Flagger

4.3.2.3 Discussion of Survey Results

While the drivers were answering survey questions, many of them expressed their opinions towards the graphic-aided and graphic PCMS, which could possibly explain how the drivers made their choices in the questionnaire, especially for their preferences on the message format. Following are some examples of drivers' thoughts about the graphic-aided PCMS and the graphic PCMS.

Some drivers preferred the graphic-aided or graphic PCMS because they thought the large graphic on the PCMS could "catch their eyes" from far away. Compared with text PCMS, the graphic-aided or graphic PCMS can be recognized from a longer distance. Some drivers liked the graphic-aided PCMS with the flagger graphic because they would know what was going on ahead of them "without thinking" after seeing it. This could easily explain why the flagger graphic in the graphic-aided and graphic PCMSs was understood correctly by all the drivers.

Some drivers selected the text PCMS because it is the existing message format in Kansas, and they could actually "read English." Some drivers complained about the graphic-aided and graphic PCMSs with the work zone graphic. They were confused or not able to understand what the person in the graphic was doing. Among them, most interpreted it as “a person opening an umbrella;” while some saw it as “a person power washing.” A comparison of the graphic on the PCMS and the W21-1 sign is shown in Figure 4.26. The graphic on the PCMS did have some difference with the W21-1 sign, particularly at the right lower corner where the confusions are. The confusions made some drivers think while driving and this is why they did not like the graphic-aided or the graphic PCMS. Therefore, the graphic has to be clearly designed to express its meaning before being displayed on PCMS.

W21-1 Sign Work Zone Sign on PCMS

Figure 4.26 Comparison of Work Zone Graphic on PCMS with W21-1 Sign

Chapter 5 Conclusions and Recommendations

5.1 Conclusions

Rural two-lane highways constitute the majority of the Kansas highway system. Each year reconstruction and maintenance operations on these highways require the setup of a large number of one-lane two-way work zones. Previous studies showed that crashes in one-lane two-way work zones on rural highways accounted for 63% of the fatalities and a third of the injuries in Kansas (Bai and Li, 2007). To improve work zone safety, many types of traffic control devices have been developed and employed, including PCMSs. Traditional PCMSs use text messages to warn drivers about the traffic conditions in a work zone. Results of previous studies indicated that there were several weaknesses for a text PCMS. For example, the required reading time for some drivers such as elderly drivers might be longer and they might not be able to catch the entire message when passing through a PCMS. In addition, some drivers were not able to understand messages in English and a text PCMS was therefore useless for them. To overcome these shortfalls, graphics displayed either alone or supplemented by text messages have been proposed to be incorporated in a PCMS. A graphic-aided PCMS could be identified easier, quicker, and from a greater distance. So far a few researchers had utilized the driving simulation method to evaluate the effectiveness of a graphic-aided PCMS. However, its effectiveness on highways had not been studied.

To close the knowledge gap, field experiment was designed and conducted to determine the effectiveness of graphic-aided PCMS on reducing vehicle speed in the upstream of one-lane two-way rural highway work zone in Kansas. The speed data and driver survey data of the text, graphic-aided, and graphic PCMS conditions were analyzed and compared, and a summary of the conclusions is given as follows.

Using a text, a graphic-aided, and a graphic PCMS resulted in a mean vehicle speed reduction of 13%, 10%, and 17%, respectively. Linear regression models suggest that the text, the graphic-aided, and the graphic PCMS had a mean speed reduction rate of 0.0042 mph/ft, 0.0034 mph/ft, and 0.0056 mph/ft, respectively in the upstream of a work zone.

Using a graphic-aided PCMS reduced mean vehicle speed more effectively than using a text PCMS from 1,475 ft to 1,000 ft in the upstream of a work zone, but less effectively than the text PCMS from 1,000 ft in the upstream of the work zone to the W20-4 sign (see Figure 4.10). Using a graphic PCMS reduced mean vehicle speed more effectively than using a text PCMS from 1,475 ft in the upstream of the work zone to the W20-4 sign.

88% and 79% of drivers understood the work zone graphic (W21-1 sign) on the graphic-aided and the graphic PCMSs, respectively. All drivers correctly interpreted the flagger graphic on the graphic-aided and the graphic PCMSs. 97% of drivers thought the text PCMS drew their attention more to the work zone traffic conditions when they only saw the text PCMS; 82% to 90% of drivers believed the graphic-aided PCMS drew their attention more to the work zone traffic conditions when they saw the graphic-aided PCMS; 87% of drivers thought the graphic PCMS drew their attention more to the work zone traffic conditions when they saw the graphic PCMS.

The text format was preferred by 64% of drivers when the text PCMS was displayed, by 24% and 3% of drivers when the graphic-aided PCMSs with the work zone graphic and the flagger graphic were presented, respectively, and by 12% of drivers when the graphic PCMS was shown. On the contrary, the graphic format was chosen by 5% of drivers when the text PCMS was displayed, by 26% and 52% of drivers when the graphic-aided PCMSs with the work zone graphic and the flagger graphic were presented, respectively, and by 45% of drivers when the graphic PCMS was shown. The graphic-aided format was selected by 16% of drivers when the text PCMS was displayed, by 26% and 19% of drivers for the graphic-aided PCMSs with the work zone graphic and the flagger graphic were presented, respectively, and by 21% of drivers when the graphic PCMS was shown.

Based on the speed data analysis results, it was concluded that the graphic-aided and graphic PCMSs were effective on reducing vehicle speeds in the upstream of one-lane two-way work zone. Driver survey results indicated that the majority of drivers preferred to have graphics displayed on the PCMS in the work zones.

5.2 Recommendations

The authors would like to make several recommendations based on the results of this research project. First, the government agencies and the construction industry should develop the guidelines and the procedures to incorporate the graphics in the PCMS, so that the graphic-aided PCMSs could be utilized in the highway work zones. Second, since the field experiments were only conducted in one work zone during this project, thus, it is recommend that additional field experiments need to be performed to validate the results concluded from this project. Third, since some drivers indicated in the surveys that they could not understand the meaning of the work zone graphic displayed on the PCMS, thus there is a need to improve the representation of this graphic, which is very important before the implementation of the graphic-aided PCMS. The graphic-aided PCMS will have less value if drivers cannot understand its meaning. Finally, there is a need to test the effectiveness of graphics display on the fixed dynamic message sign on the urban highways.

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Appendix A Sample Questionnaires

Appendix A.1 A Sample Questionnaire for Text PCMS

Date: Time: Weather:

1: Did you see the Portable Changeable Message Sign (PCMS) when you were approaching the work zone?

Yes______ No______

If the answer is YES, then, continue the survey. If the answer is NO, stop the survey.

2: Did you understand the messages displayed on the PCMS?

Yes______ No______

3: What actions did you take after you saw the PCMS?

Slow down______ Look for more information______

Do nothing______ Take other actions______________________

4: Did you think that the PCMS drew your attention more to the work zone traffic condition?

Yes______ No______

5: Do you prefer the use of a PCMS to alert drivers about the upcoming work zones in addition to the existing sign?

Yes______ No______

6: Do you prefer the warning signs to be displayed in the graphical format or text format?

Graphical format_____________ No difference ______

Graphical and text format______ Don't care_________

Text format _________________ Don't know________

Other____

Vehicle Type: Driver Gender: M_____ F_____

Appendix A.2 A Sample Questionnaire for Graphic-aided PCMS with Text “WORKZONE”

Date: **Time:** **Weather:**

1: Did you see a **graphic** displayed on the Portable Changeable Message Sign (PCMS) when you were approaching the work zone?

W21-1

Yes _____ No _____

If the answer is YES, then, continue the survey. If the answer is NO, stop the survey.

2: How did you interpret the meaning of this graphic?

W21-1 Graphic

1) Work zone/Work zone ahead/Someone working
2) Get confused
3) Don't know
4) Other____________________

3: Did you think that the **graphic** drew your attention more to the work zone traffic conditions?

Yes _____ No ______ Don't know _______

4: Do you prefer the warning signs to be displayed in the graphical format or text format?

1) Graphical format
2) Text format
3) No difference
4) Don't care
5) Don't know
6) Other___________________

Vehicle Type: **Driver Gender:** **M** **F**

Appendix A.3 A Sample Questionnaire for Graphic-aided PCMS with Text "FLAGGER"

Date: **Time:** **Weather:**

1: Did you see a **graphic** displayed on the Portable Changeable Message Sign (PCMS) when you were approaching the work zone?

W20-7

Yes _____ No _____

If the answer is YES, then, continue the survey. If the answer is NO, stop the survey.

2: How did you interpret the meaning of this graphic?

W20-7 Graphic

1) Flagger/Flagger ahead/Flagger present/Need to stop
2) Get confused
3) Don't know
4) Other____________________

3: Did you think that the **graphic** drew your attention more to the work zone traffic conditions?

Yes _____ No ______ Don't know _______

4: Do you prefer the warning signs to be displayed in the graphical format or text format?

1) Graphical format
2) Text format
3) No difference
4) Don't care
5) Don't know
6) Other___________________

Vehicle Type: **Driver Gender:** **M** **F**

Appendix A.4 A Sample Questionnaire for Graphic PCMS

Date: **Time:** **Weather:**

1: Did you see the two **graphics** displayed on the Portable Changeable Message Sign (PCMS) when you were approaching the work zone?

W21-1

W20-7

Yes _____ No _____

If the answer is YES, then, continue the survey. If the answer is NO, stop the survey.

2: How did you interpret the meanings of these two graphics?

W21-1 Graphic

1) Work zone/Work zone ahead/Someone working
2) Get confused
3) Don’t know
4) Other_____________________

W20-7 Graphic

1) Flagger/Flagger ahead/Flagger present/Need to stop
2) Get confused
3) Don’t know
4) Other_____________________

3: Did you think that the **graphics** drew your attention more to the work zone traffic conditions?

Yes _____ No ______ Don’t know _______

4: Do you prefer the warning signs to be displayed in the graphical format or text format?

1) Graphical format
2) Text format
3) No difference
4) Don’t care
5) Don’t know
6) Other__________________

Vehicle Type: **Driver Gender:** **M** **F**

Appendix B A Portion of Vehicle Speed Data

Veh. No.	Date	Time	Ave. Length	Speed				
				Sensor 1	Sensor 2	Sensor 3	Sensor 4	Sensor 5
1	7/23/2010	7:37:38 AM	124	65	64	50	49	49
2	7/23/2010	7:38:16 AM	109	66	69	62	53	45
3	7/23/2010	7:38:18 AM	116	63	66	59	56	48
4	7/23/2010	7:38:27 AM	110	70	76	69	53	47
5	7/23/2010	7:38:51 AM	124	65	64	56	58	51
6	7/23/2010	7:39:55 AM	115	72	71	45	44	56
7	7/23/2010	7:40:32 AM	107	71	73	55	52	55
8	7/23/2010	7:41:17 AM	106	66	68	56	51	52
9	7/23/2010	7:42:41 AM	117	69	69	60	61	58
10	7/23/2010	7:42:58 AM	150	63	64	56	50	44
11	7/23/2010	7:44:02 AM	144	71	74	70	66	62
12	7/23/2010	7:44:04 AM	111	68	69	66	64	60
13	7/23/2010	7:44:22 AM	126	75	77	68	64	64
14	7/23/2010	7:45:23 AM	122	64	66	59	51	49
15	7/23/2010	7:45:24 AM	111	63	66	61	50	48
16	7/23/2010	7:47:17 AM	124	65	68	58	52	52
17	7/23/2010	7:50:23 AM	117	76	78	67	64	63
18	7/23/2010	7:51:08 AM	114	67	69	61	57	58
19	7/23/2010	7:54:08 AM	123	60	59	55	53	50
20	7/23/2010	7:54:47 AM	106	61	62	55	48	48
21	7/23/2010	7:57:04 AM	108	69	69	61	63	56
22	7/23/2010	7:58:09 AM	146	65	64	55	54	54
23	7/23/2010	8:01:13 AM	116	61	61	55	55	52
24	7/23/2010	8:02:05 AM	139	64	66	57	54	49
25	7/23/2010	8:02:26 AM	114	70	70	62	59	58
26	7/23/2010	8:03:19 AM	116	58	55	46	41	44
27	7/23/2010	8:03:42 AM	114	68	71	67	67	61
28	7/23/2010	8:03:44 AM	114	69	68	60	60	56
29	7/23/2010	8:03:53 AM	133	69	72	67	60	53
30	7/23/2010	8:11:26 AM	105	65	73	69	65	56
31	7/23/2010	8:11:36 AM	117	72	75	71	71	71
32	7/23/2010	8:13:07 AM	320	57	60	55	51	48
33	7/23/2010	8:13:08 AM	113	55	60	56	50	49
34	7/23/2010	8:17:58 AM	112	75	75	66	66	64
35	7/23/2010	8:18:04 AM	115	70	74	67	62	63
36	7/23/2010	8:19:22 AM	112	64	64	60	52	48
37	7/23/2010	8:21:12 AM	114	63	63	53	49	51
38	7/23/2010	8:21:19 AM	110	72	72	61	58	57
39	7/23/2010	8:22:15 AM	126	65	61	51	47	49
40	7/23/2010	8:24:57 AM	106	69	71	69	59	57
41	7/23/2010	8:25:06 AM	115	74	77	72	74	63
42	7/23/2010	8:26:06 AM	395	49	50	45	44	42
43	7/23/2010	8:26:13 AM	111	68	63	54	48	42
44	7/23/2010	8:27:09 AM	125	59	57	53	52	51
45	7/23/2010	8:27:39 AM	107	68	69	64	61	59
46	7/23/2010	8:32:21 AM	216	63	62	58	60	54

Appendix C A Portion of Driver Survey Data

No.	Q1	Q2	Q3	Q4	Veh. Type	Gender
1	1	1	1	2	5	1
2	1	1	1	4	5	1
3	1	1	1	2	5	1
4	1	1	1	2	5	1
5	1	1	1	5	1	1
6	1	1	1	2	1	2
7	1	1	1	2	2	2
8	1	1	1	2	2	2
9	1	1	1	2	1	1
10	1	1	1	3	3	1
11	1	1	1	3	4	2
12	1	1	1	3	1	1
13	1	1	1	2	5	1
14	1	1	1	2	2	2
15	1	1	1	3	3	1
16	1	1	1	2	2	1
17	1	1	1	2	1	2
18	1	1	1	3	5	1
19	1	1	1	3	1	2
20	1	1	1	1	4	1
21	1	1	1	3	7	1
22	1	1	1	3	5	1
23	1	1	1	4	3	1
24	1	1	1	4	1	1
25	1	1	1	5	2	2
26	1	1	1	2	1	2
27	1	1	1	3	4	1
28	1	1	1	3	1	1
29	1	1	1	2	1	2
30	1	1	1	2	2	2

Note: Q1: 1=Yes, 2=No
Q2: 1=Yes, 2=No
Q3: 1=Yes, 2=No, 3=Don't Know
Q4: 1=Graphical, 2=Text, 3=Graphical and Text, 4=No Differnce, 5=Don't Care, 6=Don't Know, 7=Other
Veh. Type: 1=Sedan, 2=SUV, 3=Pickup, 4=Minivan, 5=Truck, 6=Motorcycle, 7=bus
Gender: 1=Male, 2=Female