Determining the Effectiveness of Graphic-aided Portable Changeable Message Signs in Highway Work Zones

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Abstract

Portable changeable message signs (PCMSs) have been employed in highway work zones as a temporary traffic control device in the United Stated for many years. The traditional message format on PCMSs 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 elderly drivers and non-English-speaking drivers, difficult to see under adverse viewing conditions, 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 was conducted using field experiments and driver surveys to determine the effectiveness of graphic-aided PCMS in reducing vehicle speeds in the upstream of one-lane two-way rural highway work zones. Field experiments and surveys were designed and conducted in two phases. Field experiment Phase I was performed to compare the effectiveness of a text PCMS, two text-graphic PCMSs, and a graphic PCMS in reducing vehicle speeds in highway work zones. Through the driver surveys in Phase I, it was found that 12% to 21% of drivers were confused by the work zone graphic. Therefore, field experiment Phase II was conducted to compare the effectiveness of five graphic-aided PCMSs with the original work zone graphic and two redesigned work zone graphics (two alternative graphics) in reducing vehicle speeds. In addition, driver survey

Phase II was performed to determine drivers' acceptance of the implementation of graphic-aided PCMS in highway work zones.

Vehicle speed data and driver survey data were analyzed using a variety of statistical methods, including frequency analysis, linear and nonlinear regression models, hypothesis tests, independent two-sample t-tests, and Chi-square tests of independence. The major findings of this research project included the comparison of the effectiveness of text, text-graphic, and graphic PCMSs in reducing mean vehicle speeds in the upstream of highway work zones; the comparison of the effectiveness of graphic-aided PCMSs with the original and alternative work zone graphics in reducing mean vehicle speeds; and drivers' perception of graphics on PCMSs, acceptance of graphic-aided PCMSs, and preferences of message formats under different PCMSs.

Based on the findings, recommendations were made for future research and implementation of graphic-aided PCMSs in the work zones. The results of this study provided valuable knowledge to government agencies and the transportation industry on how to regulate and utilize graphic-aided PCMSs in highway work zones.

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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 decades, many highways in the National Highway System (NHS) have been resurfaced, and as a result, public travelers have encountered many work zones on highways. According to the Federal Highway Administration (FHWA)'s statistics, an average of 23,745 miles of roadway had improvement projects underway each 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 flow, 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 improve 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 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 − an increase of about 34%. The average percentage of work zone fatalities to 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 percentage of work zone fatalities from 1982 to 2009. Although the number of work zone fatalities has dropped since 2002, there are 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.

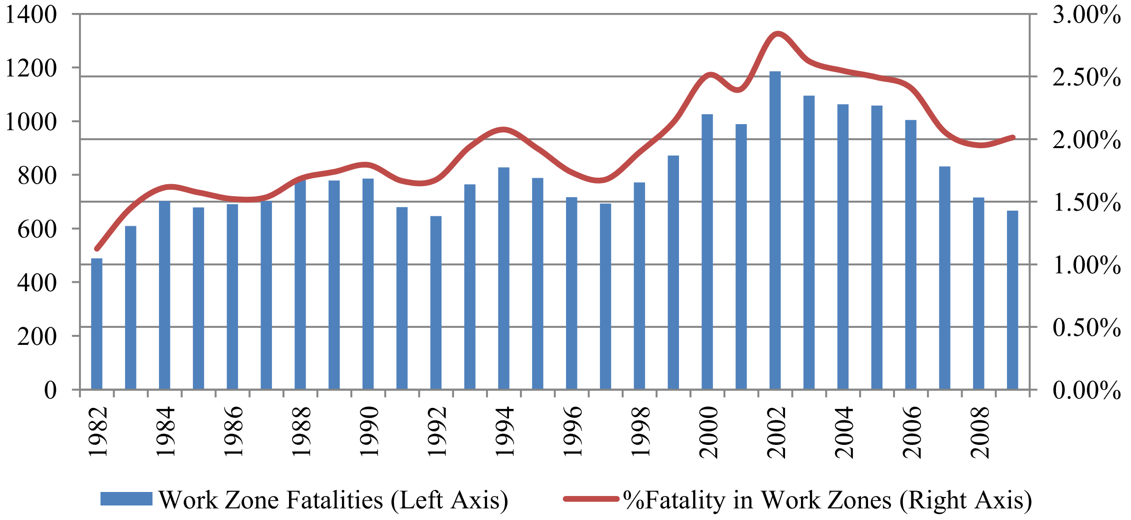

Figure 1.1 Number and Percentage of Work Zone Fatalities from 1982 to 2009

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 capable of displaying a variety of 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 to meet the temporary requirements frequently found in work zones or accident areas. It can capture motorists' attention, display information that is difficult to accomplish with static signing, and can be used to supplement other required signing (FHWA, 2003).

The traditional type of PCMS is a text-based device and has been in use for decades. Many recent studies, however, have pointed out that using text messages on PCMS 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 elderly drivers and non-English-speaking drivers. Nsour (1997) found that reading text messages on PCMS was one of the most difficult tasks for elderly drivers 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 severe for drivers unfamiliar with the area or English was not their primary language (Ullman et al., 2009).

The development in sign technology has now allowed for the use of color and full-matrix PCMS and has made 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 using graphic-aided messages on PCMSs can overcome some of the limitations of text messages, particularly in complicated driving conditions and locations with high information load, such as work zones (Ullman et al., 2009).

Although the advantages of graphic-aided messages have been realized for many years, their use 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), Wang et al. (2007), and Ullman et al. (2009) performed simulation experiments to study drivers' comprehension of graphics on message signs. All of these studies, however, were conducted in laboratory environments in which subjects 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 drivers, such as lane keeping, speed controlling, and car following. Thus, the results obtained from these simulation studies only provided a relative performance measure on sign reading in optimal circumstances (Wang and Cao, 2005).

Therefore, there is a need to conduct field experiments in the real-world driving conditions with ongoing traffic. This type of study could overcome the limitations of the simulation experiments in laboratory environments and is able to collect vehicle speed data from drivers during their ordinary trips. Although PCMS has been employed to control traffic in highway work zones for many years, graphic-aided PCMS has not been used in work zones, and its effectiveness in improving highway work zone safety has not yet been determined.

1.3 Dissertation Organization

This dissertation includes six 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 this 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 crashes in highway work zones, 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 Phase I. This chapter details the design and performance of field experiment Phase I, which aimed to determine the effectiveness of graphic-aided PCMS in reducing vehicle speeds in highway work zones. This chapter includes experimental devices and layout, data collection procedure, and the results of data analyses.

Chapter 5: Field Experiment Phase II. This chapter elaborates the design and performance of field experiment Phase II, which was designed to compare the effectiveness of different graphic-aided PCMSs in reducing vehicle speeds in highway work zones. And

Chapter 6: Conclusions and Recommendations. This chapter summarizes the field experiments, discusses the limitations of this study, concludes the findings from data analyses, and recommends potential improvements for future research on graphic-aided PCMS.

Chapter 2 Objectives, Scope, and Methodology

In this research project, a text PCMS refers to a PCMS displaying only text messages; a graphic-aided PCMS refers to a PCMS that is capable of displaying graphics. A graphic-aided PCMS is further categorized into two types: a text-graphic PCMS that displays both text messages and graphics, and a graphic PCMS that displays only graphics.

2.1 Research Objectives

The primary goals of this research project are to determine the effectiveness of graphic-aided PCMS in reducing vehicle speeds and to evaluate drivers' acceptance of the implementation of graphic-aided PCMS in the upstream of one-lane two-way rural highway work zones. The goals were accomplished through achieving specified research objectives using field experiments and driver surveys. These objectives are summarized as follows:

1. To design field experiments to determine the effectiveness of text PCMS, text-graphic PCMS, and graphic PCMS in reducing vehicle speeds;
2. To conduct field experiments in the upstream of highway work zones using PCMSs and speed measurement sensors to collect vehicle speed data;
3. To compare the effectiveness of text PCMS, text-graphic PCMS, and graphic PCMS in reducing vehicle speeds in the upstream of highway work zones;

4. To compare the effectiveness of different graphic-aided PCMSs in reducing vehicle speeds; and
5. To evaluate drivers' acceptance of the implementation of graphic-aided PCMS in the upstream of highway work zones.

Objectives 3 and 4 were achieved by conducting field experiments, collecting vehicle speed data, and analyzing speed data using statistical methods; objective 5 was accomplished by conducting driver surveys along with the field experiments, and analyzing survey results using mathematical approaches.

2.2 Research Scope

The field experiments and driver surveys were performed in one-lane two-way rural highway work zones in Kansas. When construction and maintenance operations are underway on a two-lane highway, one traffic lane is closed while the other lane is kept in service; the two-lane highway is converted to a one-lane, two-way work zone. The work zone requires temporary traffic signs, flaggers, and a pilot car to coordinate vehicles entering and leaving the site. The traffic volume of the work zones for this study should be moderate so that free flow vehicle speeds could be collected in the upstream of the work zones.

2.3 Research Methodology

The research objectives were achieved using the following five steps:

1. Literature review. A comprehensive literature review was conducted first to provide the background on highway work zone safety research. The review synthesized the findings from previous literature on work zone- and CMS-related subjects, including the characteristics of crashes in highway work zones, 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 books, journal papers, research reports, conference proceedings, theses, dissertations, and Internet publications.
2. Design of field experiments and driver surveys. Field experiment Phase I was designed to collect vehicle speed data and obtain drivers' opinions under text, text-graphic, and graphic PCMS conditions. Field experiment Phase II was designed to collect vehicle speed data and evaluate drivers' perception under different graphic-aided PCMS conditions.
3. Data collection. Data for this study included vehicle speed data and driver survey data. Vehicle speed data were collected within an area from 1,475 ft upstream to 530 ft downstream of the beginning of the work zone. Driver surveys were conducted at the flagger station where all drivers had to stop and wait for the pilot car.

4. Data analysis. Vehicle speed data and driver survey results were analyzed using various statistical methods, including frequency analysis, linear and nonlinear regression models, hypothesis tests, independent two-sample t-tests, and Chi-square tests of independence. The statistical program IBM SPSS Statistics 20 was used in the data analysis.
5. Conclusions and recommendations. Conclusions were drawn based on the results of data analysis. The major findings included the comparison of the effectiveness of text, text-graphic, and graphic PCMSs in reducing mean vehicle speeds in the upstream of highway work zones; the comparison of the effectiveness of different graphic-aided PCMSs in reducing mean vehicle speeds; and drivers' perception of graphics on PCMSs, acceptance of graphic-aided PCMSs, and preferences of message formats under different PCMSs. Based on these findings, recommendations were made for future research and implementation of graphic-aided PCMS in highway work zones.

Chapter 3 Literature Review

The aging highway system in the United States has led to an increasing demand on highway preservation, rehabilitation, expansion, and enhancement. Most of these construction activities require the establishment of work zones on highways with active traffic. Work zones create an inevitable disruption on regular traffic flow and result in severe traffic delays and safety concerns (Li, 2011). Previous studies showed that 63% of fatal crashes and a third of injury crashes in Kansas happened in work zones on two-lane highways (Bai and Li, 2007). To address these issues, a number of studies on highway work zone safety have been carried out. In this chapter, a brief introduction to highway work zones is given first. Then, the findings of previous research on work zone- and CMS-related subjects are presented. These subjects include: 1) the characteristics of crashes in highway work zones, 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 previous research.

3.1 Introduction to Highway Work Zones

The MUTCD defines a highway work zone as an area of a highway with construction, maintenance, or utility work activities. "A work zone 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).

Based on the MUTCD, highway work zones can be divided into four areas: the advance warning area, the transition area, the activity area, and the termination area, as illustrated in Figure 3.1. "The advance warning area is the section of highway where road users are informed about the upcoming work zone or incident area. 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. 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).

A typical work zone on a two-lane highway occupies one lane for road work, and the other remains open for traffic from both directions. This type of work zones is set up for 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. According to the MUTCD, such work zones may require the proper implementation of the following traffic control methods (FHWA, 2009):

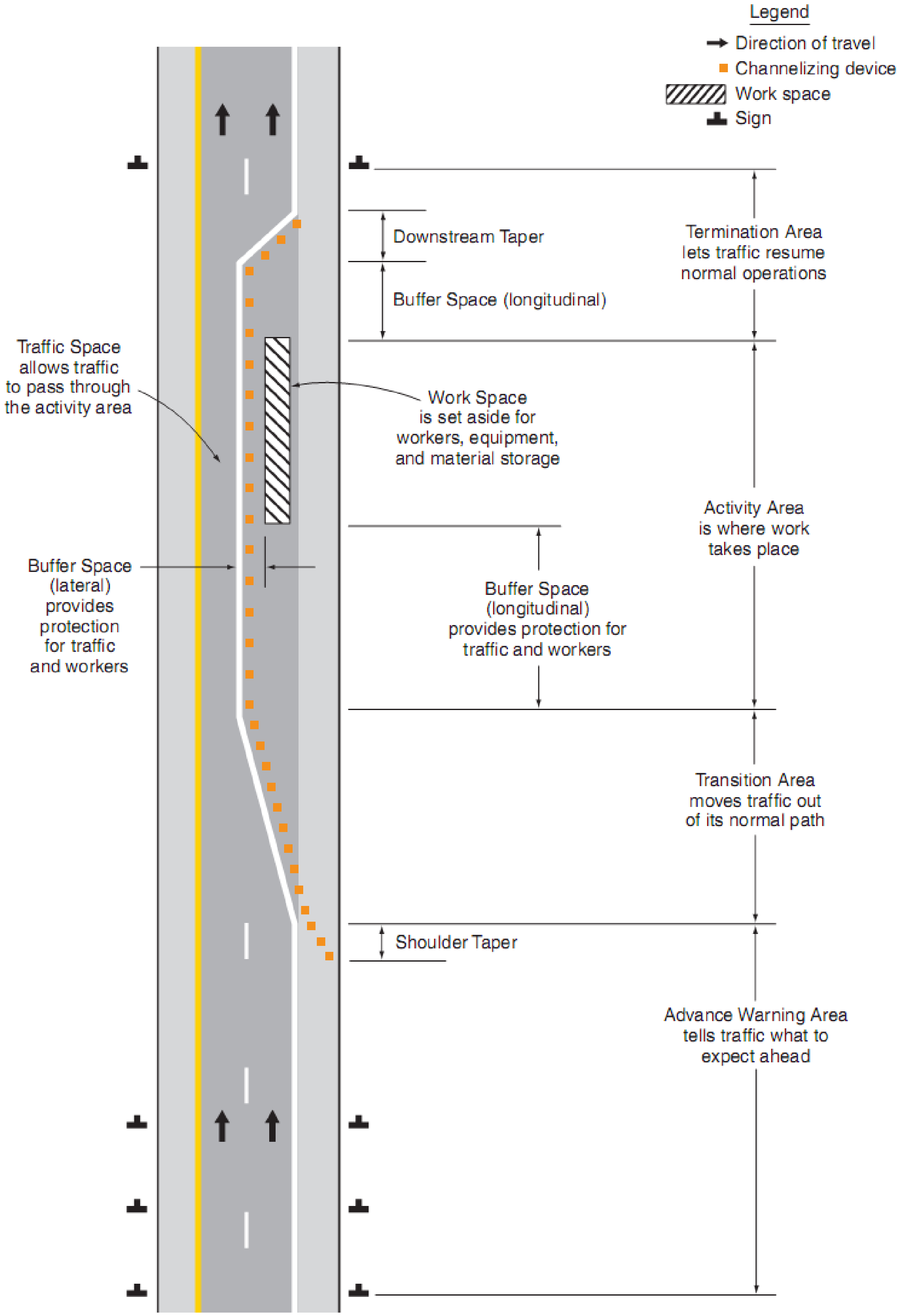

Figure 3.1 Component Areas of a Work Zone (MUTCD 2009 edition, Page 553)

- “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 Crashes in Highway Work Zones

Knowledge of the characteristics of crashes in highway work zones helps traffic engineers and researchers to better understand the needs of work zone traffic control (Li, 2011). This section summarizes the findings of previous studies on the characteristics of crashes in work zones. 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 crashes in highway work zones 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 crash rates in highway work zones after the late 1970s. Many studies agreed on 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 the crash rate during construction increased significantly. Graham et al. (1978) analyzed 79 projects in seven states and concluded that 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 discovered 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, and concluded 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 crash rate in work zones 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 environmental conditions.

3.2.2 Crash Severity

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

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 crash severity in work zones 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 crashes in work zone 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) and 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 crashes in work zones were less or slightly less severe than other crashes. Crashes in work zones 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 crashes in work zones varied with time and location. However, results of most previous studies indicated that rear-end collision was one of the most frequent crash types in work zones (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 crash types in work zones 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 crash (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; Hill, 2003; Schrock et al., 2004). 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

Crashes in work zones were found to occur frequently 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 crashes in work zones, 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 semi-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 semi-trailers and buses.

3.2.5 Crash Location

Researchers of previous studies agreed on the unbalanced crash distribution along the different work zone 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 the frequency of severe crashes in different literature.

In terms of work zone locations, crashes in work zones 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 system (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%. 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 crashes in work zones (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 work zones. Hill (2003) found that there was a significant difference on types of driver errors between crashes in the daytime and in the nighttime. Researchers proved that adverse environmental and road surface conditions did not contribute more to crashes in work zones than at other locations (Nemeth and Migletz, 1978; Garber and Woo, 1990).

3.2.7 Summary of Characteristics of Crashes in Work Zones

The characteristics of crashes in highway work zones 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 more likely occurred 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 crashes in work zones were more severe than other crashes. However, previous studies agreed that truck-involved and nighttime crashes in work zones were more severe than non-work zone crashes;
4. Rear-end crash was the most frequent crash type in work zones. 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 crashes in work zones occurred in the daytime. Work zone crashes during nighttime, however, 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 crashes were more likely to take place in rural interstate highway work zones;
7. Human errors and inefficient traffic controls were the major causes of crashes in work zones. 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 been receiving increasing attention as the emphasis of highway projects has 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 flow during road work. 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 crashes in work zones, the main purpose of these traffic control methods is to reduce and control vehicle speeds in work zones.

3.3.1 Flaggers

The MUTCD 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) believed that flaggers contributed a 3 to 12 mph speed reduction for vehicles approaching work zones. McCoy and Bonneson (1993) found that innovative flagging procedures were effective in reducing the speed of vehicles approaching a work zone between 9.2 mph and 15.2 mph. Jones and Cottrell (1999) indicated that a STOP/SLOW paddle was understood most by Virginia drivers and appeared to be effective in conveying its message. Hill (2003) proved that flaggers were also effective in reducing fatal crashes in 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 work zones with one lane open and work zones involving intersections (Li, 2007). As suggested in 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 fatal crashes in work zones 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 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 rumble strips actually resulted in a small increase in average vehicle speed. Heaslip et al. (2010) conducted a closed-course feasibility study on the use of portable rumble strips in work zones with the duration of one day or less. The study showed that the best solution for most short-term work zones was the latest generation of plastic rumble strips.

3.3.5 Pavement Markings and Lighting Devices

Temporary pavement markings are maintained along paved streets and highways in 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 speeds in work zones. Meyer (2004) conducted a study to evaluate the effectiveness of optical speed bars on reducing vehicle speeds 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 retro-reflectorized 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, illuminate work zones, and 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 speeds 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 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 in 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 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 speeds 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 short and long term freeway work zones. 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 work zones. Huebschman et al. (2003) found that the presence of law enforcement reduced vehicle speeds by more than 5 mph adjacent to a trooper in Indiana. Arnold (2003) concluded that the presence of a police was effective in reducing vehicle speeds in work zones in Virginia through a survey. Miller et al. (2008) indicated that the use of law enforcement reduced vehicle speeds by 5.26 mph in work zones in Indiana. Although the law enforcement method is an effective way to reduce vehicle speeds in 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% 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 by displaying information that is difficult to accomplish with static signing, and can be used to supplement other required signing. On the other hand, a CMS should not be used to 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 a 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 passenger vehicles 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 considered helpful to improve work zone safety. They concluded that the CMS was a more effective means than traditional work zone traffic control devices in reducing the number of speeding vehicles in work zones in Virginia. Huebschman et al. (2003) found that it was not clear, however, 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 by 7 to 8 mph for approaching traffic at locations immediately adjacent to the CMS. Ullman et al. (2007) concluded 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 speeds 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 CMS messages should not be flashed; (b) a line on a one-frame CMS message should not be flashed; and (c) a line on a two-frame CMS 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 among the display format of PCMS messages, 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 elderly 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. (2006b) 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 subjects did not interact with real traffic. The circumstances allowed the test subjects to put maximum effort on the CMS content, whereas in real-world driving, there are other needs that could demand attention from the drivers such as lane keeping, speed controlling, 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).

3.4.3 Legibility of CMS Message

Cai (2011a) conducted a comprehensive review of literature on legibility of characters and identified ten critical legibility factors including (1) age of observers, (2) acuity of observers, (3) character height, width, or strokewidth, (4) viewing distance, (5) viewing angles (horizontal, vertical, or incident angles), (6) visual angle subtense of characters, (7) font, (8) target luminance, background luminance, or surrounding luminance, (9) luminance contrast, and (10) color contrast. Garvey (2002) synthesized the legibility of VMS based on a number of previous studies and summarized most of the above critical legibility factors.

Garvey (2002) believed that visual acuity could be broadly defined as the ability to discriminate fine detail, which was assumed to be stroke-width on VMS. "The visual angle of the stroke-width was considered to be the minimum angle of resolution, which was used by a number of researchers to predict sign legibility distance for a range of individual visual acuities".

"Character height had the greatest impact on the distance at which a sign could be read, and the legibility distance continued to improve with increases in character height" (Garvey and Mace, 1996). Dudek (1997) recommended a character height of 18 inches for freeways and between 10 and 18 inches for non-freeway applications. Garvey and Mace (1996) revealed proportional improvement in legibility distance with increased character height up to about 8 inches. Garvey and Mace (1996) discovered an improvement in VMS legibility distance with increases in width-to-height ratio up to 1:1, or characters with equal width and height. Dudek (1991) reported that a width-to-height ratio 5:7 matrix is slightly more legible than a 4:7 matrix. Wourms et al. (2001) recommended that the width-to-height ratio ranged from 3:5 to 4:5 and the stroke width to-height ratio ranged from 1:6 to 1:8.

Garvey et al. (2001) discovered that stroke-width resolution alone did not determine letter acuity. "After replacing the letters on a standard Snellen chart with letters displayed in thirteen different fonts, it was found that to be read at the same distance, letters in some fonts had to be twice the height of letters in other fonts." A follow-up study found that "acuity could be influenced by reader's familiarity with the font, and that the acuity for a given font could actually improve with practice. There was not, however, much flexibility in VMS font design as the VMS signs were restricted by a matrix format." Dudek (1991), Bentzen and Easton (1996), and Garvey and Mace (1996) recommended fonts displayed using a 5×7 character matrix for VMS. Garvey and Mace (1996) found little variability in performance using different fonts within the 5×7 format.

Garvey and Mace (1996) suggested 30 cd/m^2 for nighttime luminance and 1000 cd/m^2 for bright daytime viewing. They also found that as visual acuity decreased, more light was needed to achieve equivalent performance. Dudek (1991) recommended a nighttime luminance from 30 to 230 cd/m^2. Sivak and Olson (1985) recommended a luminance contrast ratio of 12:1 for static traffic signs based on previous research. Colomb and Hubert (1991) found improved daytime legibility for VMS to level off between 8% and 20% contrast. Dudek (1991) concluded that luminance contrast ratio between 8:1 and 12:1 should be used for light emitting technologies and 40% daytime and 50% nighttime contrast for light reflecting technologies for VMS. Stainforth and

Kniveton (1996) suggested a generally accepted luminance contrast ratio for VMS of 10:1.

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) indicated that good graphic messages have a number of advantages over text messages:

- "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 (Riemersma et al., 1982). 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.”

Knoblauch et al. (1995) evaluated five graphic messages, namely congestion or queue (using European graphic), crash (using European graphic), 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 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 of 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 the effectiveness of 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 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 this study. The survey results indicated that "a) most subjects 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 subjects 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 significantly affected drivers' responses; b) subjects' age and gender were also found to significantly affected drivers' responses, but their interaction did 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 elderly drivers, and elderly 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."

Ullman et al. (2009) studied drivers' understanding of the roadwork symbol using laboratory instruments in four cities in Texas. Laboratory surveys were conducted in both English and Spanish in San Antonio, TX and El Paso, TX, including 721 surveys in English and 241 surveys in Spanish. The results discovered that "both text and symbol representations of roadwork were understood by over 80 percent of the participants. The English-speaking group of participants had a higher comprehension level for the text version of the design, while the Spanish-speaking group had a greater understanding of the symbol." The researchers concluded that "the symbol for roadwork was better understood by the Spanish-speaking participants and should be used in graphic designs, and the use of a symbol to indicate a work zone did not have a negative impact on viewing times."

3.6 Human Factors in Highway Safety

As stated in Section 3.2.6, previous studies suggest human errors are the most common cause of highway work zone crashes. As a result, understanding the nature of human factors in vehicle 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 crashes in the work zones.

3.6.1 Vehicle Crashes

Macdonald (1985) conducted a comprehensive review of the relationship between human factors and vehicle 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 researcher 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 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 literature on vehicle crashes 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 using cell phones while 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 "inattention and misjudgment were the most prominent crash factors associated with being at fault for both riders and drivers. 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 the 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 elderly. 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 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. An 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 traffic 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. "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. In addition, the study discovered that work zone center/edge lines might lower the odds of severe crashes caused by this driver error by 19%, while having stop signs/signals in work zones would dramatically increase the odds of a severe crash caused by this 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% in property damage only (PDO) crashes from 2000 to 2004 but increased to over 40% in fatal crashes." 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 Louisiana in 2004 while only 1.2% of all crashes had drivers ejected." 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 laser pilot study and an individual driver pilot study to identify the factors that affected speed on suburban arterials. The results revealed that "the only significant variable for straight roadway sections was posted speed limit; without a speed limit, the lane width was the only significant variable. On curve roadway sections, posted speed limit, deflection angle and access density classes influenced speed; without a speed limit, the impact of median presence became significant along with roadside development."

Feng (2001) studied the relationship between speed and safety, and found out that the presence of a camera could reduce vehicle speeds effectively. The 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." The study also indicated that "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 and operation 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 were suggested, they had not yet been satisfactorily incorporated into highway design guidelines." The researcher 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, and 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 special road users, such as elderly 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 target value (distance when noticed), legibility distance, and viewing comfort measured in Arizona. An elderly and a younger group of observers participated in the study. The results showed that “the mean target value ranged between 1,080 ft and 2,841 ft for elderly 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 elderly 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 the glare of the sign face.”

Proffitt and Wade (1998) addressed the human factors issues related to the reading and comprehension of CMS messages. The study indicated that “about 25% of Virginians age 16 and elderly 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. (2006a) 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 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 was very close across all subjects 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 factor 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 selected as prototype examples for the development of human factors functional specifications.

Huey et al. (1996) presented a set of human factor 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. “Lane change incidents were the most frequent category followed by intersection and rear-end incidents. The drivers reported themselves to be at fault nearly one-third of the time. Overall, the drivers reported that they were alert in two-thirds of cases, and distracted in only about 13% of the cases. However, for those incidents where the driver judged him or herself to be at-fault, distraction was reported in about 40% of the cases. In addition, drivers were interviewed to explore their attitudes towards various possible in-vehicle warnings. Drivers recognized blind-spot/lane-change incidents as a major concern and were most favorable to blind spot monitors. In addition, warning systems favored by subjects included headway monitors and driver impairment monitors.”

FHWA (1997) conducted an experiment to examine the effectiveness of Advanced Traveler Information Systems (ATIS) display modality, message style, and display location on driver compliance with warnings and driving safety. 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 driver performance by fostering an overreliance on ATIS information."

Kantowitz et al. (1999) investigated some human factor issues relevant to the ATIS design, including: "(1) the influence of an ATIS on driver 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 (ICAV) warning 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 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 sensors to assess vehicle dynamic parameters (e.g., vehicle speed); computations to process data, and determine whether an imminent violation warning should be issued; a driver-vehicle interface to present the warning to the driver; and a communications subsystem to receive critical information (e.g., signal phase and timing data) from the traffic signal.”

3.7 Statistical Methods Used in Work Zone Safety Studies

A number of statistical approaches have been used to analyze the effectiveness of traffic control devices and methods in work zone safety studies, including before-and-after-study, frequency analysis, box plot and scatter plot, Chi-square test, t-test, analysis of variance, correlation, proportionality test, and regression models.

3.7.1 Before-and-after Study

Before-and-after study is a commonly used method in work zone studies. Using this method, crash counts of a period of time 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 is 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 conditions (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 (Makkonen, 2008). 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 Plot and Scatter Plot

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 (Rousseeuw, 1999).

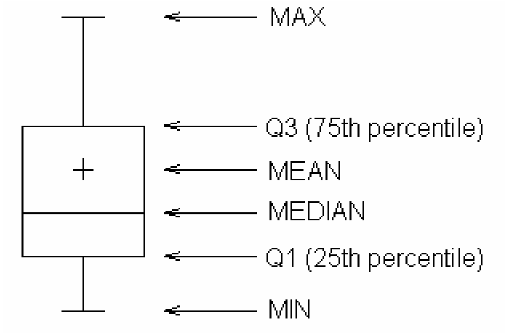

Figure 3.2 An Annotated Sketch of Box Plot

A scatter plot, as illustrated in Figure 3.3, provides a graphical display of the relationship between two variables. The variable that might be considered 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 (Utts, 2005).

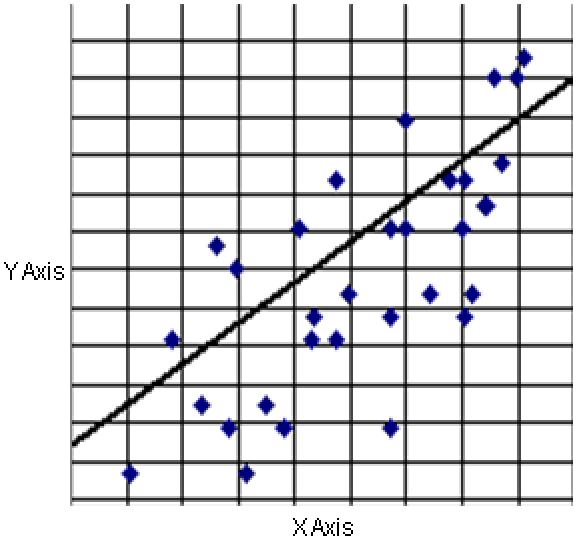

Figure 3.3 An Annotated Sketch of Scatter Plot

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 obtained from the chi-square procedures is 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 (Corder and Foreman, 2009). 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 (Corder and Foreman, 2009):

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. 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 may be assumed (Fellows and Liu, 2008). In ANOVA models, there are one-way layouts and two-way layouts where the factors are either crossed or nested.

A 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 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 of the form:

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

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; as the value goes towards 0, the relationship between the two variables will be weaker. 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. 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 (Rodgers and Nicewander, 1988).

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 (Rodgers and Nicewander, 1988). 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 is 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 (Scheaffer and McClave, 1994):

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

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 (Kutner et al., 2004):

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

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 forms 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 some 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 certain 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 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 a 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 analyze 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 research project, a comprehensive literature review was conducted to synthesize the background knowledge from previous studies. The review covered several subjects relevant to highway work zone safety, including the characteristics of crashes in highway work zones, 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. Results of the literature review are summarized as follows.

Many research efforts have been devoted to investigating the characteristics of crashes in highway work zones. Most of the previous studies on work zone crashes 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 from these studies. 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 crashes in work zones were more severe than non-work zone crashes; and human errors and inefficient traffic controls were the major causes of crashes in work zones.

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 were employed to reduce and control vehicle speed in work zones since the excessive travel speed was 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 in reducing vehicle speeds. 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. Having a new message format, graphic-aided CMSs have been found in only a handful of studies in the United States, and most of these studies were conducted in laboratory environments.

Since human behavior errors have been pointed out as the most common cause of crashes in highway work zones in many studies, a comprehensive review of the role of human factors in vehicle 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 approaches 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 plot and scatter plot, Chi-square test, t-test, analysis of variance, correlation, proportionality test, and regression models.

Through the comprehensive literature review on highway work zone safety, it was found that only a handful of studies on graphic-aided PCMSs were conducted, all of which were simulator-based studies in laboratory environments. Therefore, there is a need to conduct field experiments for graphic-aided PCMSs in the real-world driving conditions with ongoing traffic. This type of studies could overcome the limitations of the simulator experiments in laboratory environments and collect vehicle speed data from drivers in their ordinary trips. The next chapter details the design and performance of field experiment Phase I.

Chapter 4 Field Experiment Phase I

Field experiment Phase I was conducted in the summer of 2010 in a one-lane two-way rural highway work zone in Kansas. The objective of field experiment Phase I was to determine and compare the effectiveness of text, text-graphic, and graphic PCMSs in reducing vehicle speeds in the upstream of the one-lane two-way work zone. In this chapter, the design of field experiment Phase I is introduced first, including experimental devices, layout and location, and the design of survey questionnaires, followed by data collection procedure and the results of data analyses.

4.1 Experiment Design

4.1.1 Experiment Devices and Installation

There were two major tasks in field experiment Phase I: measuring vehicle speeds and conducting driver surveys. Vehicle speed data were collected and analyzed to determine the effectiveness of graphic-aided PCMSs in reducing vehicle speeds in the upstream of the work zone. Driver surveys were conducted to evaluate drivers' acceptance on the implementation of graphic-aided PCMS in the highway work zone. A full-matrix PCMS was utilized to display text messages and graphics, and five speed measurement 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 Wanco WTMMB-SLL Full-Matrix PCMS

Dimension	138 in. tall × 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	Approximately 600 to 3,200 ft
Power	675 Ah batteries with solar panels

The PCMS was programmed to display two text messages and two graphics. The two text messages were WORKZONE AHEAD SLOWDOWN, and FLAGGER AHD PREP TO STOP (flagger ahead prepare to stop), as seen in Figure 4.1. The two graphics were a work zone graphic which was designed similar to the W21-1 sign specified by the MUTCD, as illustrated in Figure 4.2, and a flagger graphic which was designed similar to the W20-7 sign specified by the MUTCD, as displayed in Figure 4.3.

Work Zone Text Message

Flagger Text Message

Figure 4.1 Text Messages Displayed on PCMS

W21-1 Sign Work Zone Graphic on PCMS

Figure 4.2 Work Zone Graphic in MUTCD and on PCMS

W20-7 Sign Flagger Graphic on PCMS

Figure 4.3 Flagger Graphic in MUTCD and on PCMS

Using these two text messages and two graphics, the PCMS was set up under three conditions:

- A text PCMS displaying two text messages, as shown in Figure 4.4,
- Two text-graphic PCMSs, one displaying text message WORKZONE AHEAD SLOWDOWN and the work zone graphic, as shown in Figure 4.5, and the other displaying text message FLAGGER AHD PREP TO STOP and the flagger graphic, as shown in Figure 4.6, and
- A graphic PCMS displaying two graphics, as shown in Figure 4.7.

The text-graphic PCMS and the graphic PCMS were also referred as the graphic-aided PCMSs. Each PCMS condition had two phases, switching from one to the other every three seconds.

Figure 4.4 Text PCMS

Figure 4.5 Text-graphic PCMS with the Work Zone Graphic

Figure 4.6 Text-graphic PCMS with the Flagger Graphic

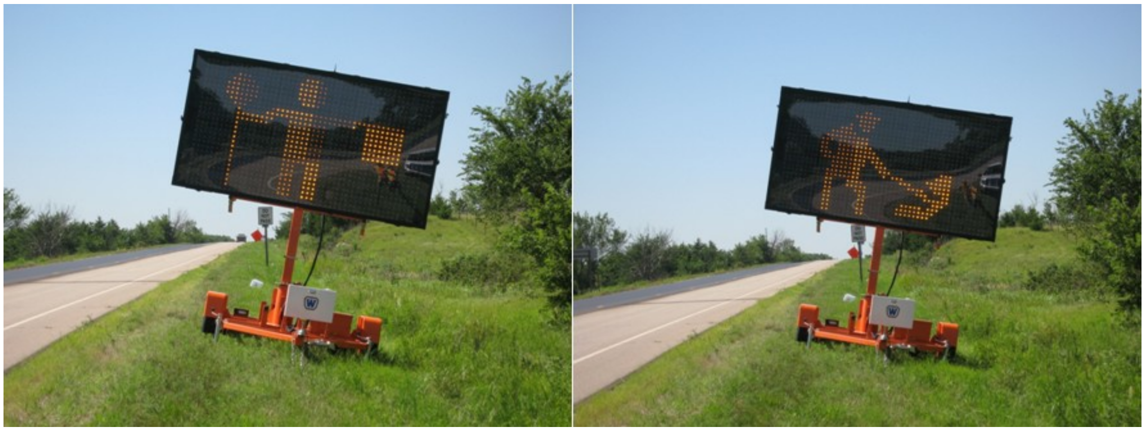

Figure 4.7 Graphic PCMS

The MUTCD requires PCMSs to be placed off the shoulder of the roadway (FHWA, 2009). In the field experiments, the PCMSs were placed on the foreslope of the highway approximately 3 ft from the edge of the pavement to minimize the interference with the traffic flow. In addition, the PCMSs were turned around 3 degrees toward the direction of traffic flow to reduce glare, as suggested by the Portable Changeable Message Sign Handbook (FHWA, 2003). Since the PCMSs were placed about 12 ft off the center line of the highway, there was a slight viewing angle between traffic flow and drivers' sight to the PCMSs. Cai (2011b) studied the relationship between legibility and viewing angles, and concluded that the influence to legibility was negligible when the viewing angles were smaller than 65.7°. Therefore, the influence of viewing angles to the legibility of PCMSs was not considered in this research project.

4.1.1.2 Speed Measurement Sensors

Five JAMAR TRAX Apollyon speed measurement sensors were used to collect speed 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 to keep the tube airtight. The two road tubes were placed on the surface of pavement with two ft spacing, perpendicular to the flow of traffic, as shown in Figure 4.8. Each tube was secured by five mastic tapes (rubberized asphalt) on the pavement, as shown in Figure 4.9. The speed sensors were placed on the foreslope of the highway, as seen in Figure 4.10. Specifications of the speed sensor and road tubes are presented in Table 4.2.

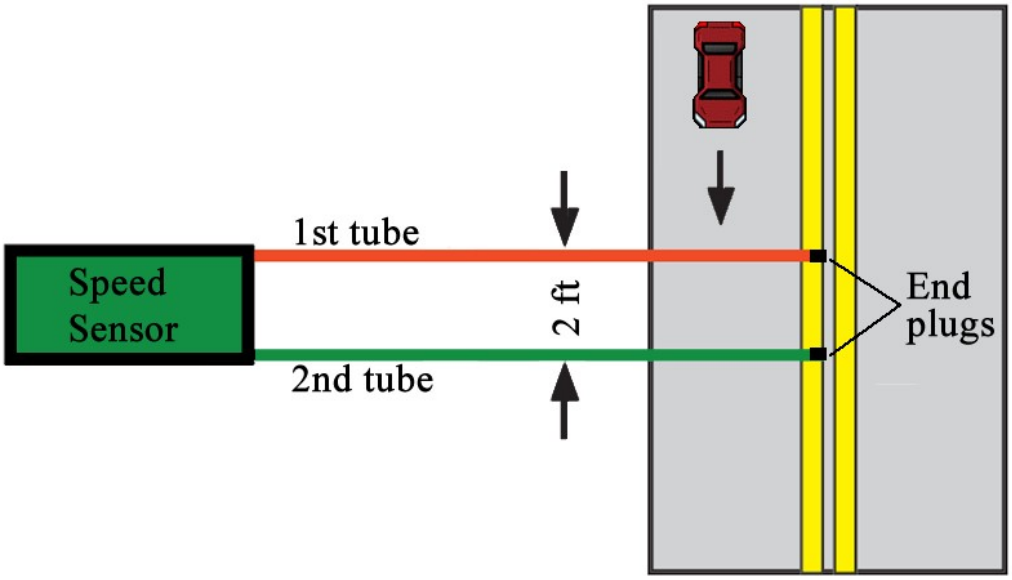

Figure 4.8 Configuration of Speed Measurement Sensor and Road Tubes

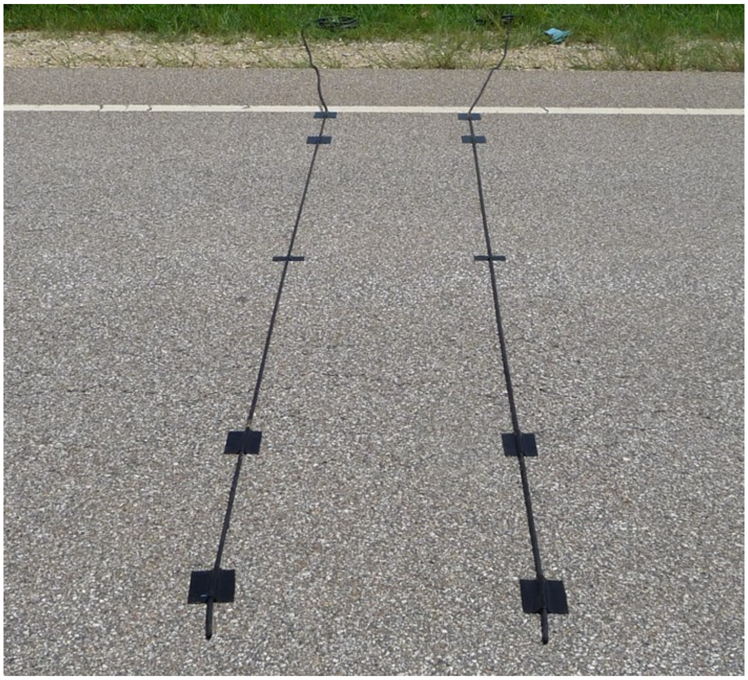

Figure 4.9 A Set of Installed Road Tubes

Figure 4.10 A Speed Measurement Sensor Connected with Road Tubes

Table 4.2 Specifications of JAMAR TRAX Apollyon Speed Sensor and Road Tubes

Speed Sensor		Road Tube	
Dimension	8.25 in × 6.5 in × 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 Field Experiment Layout

The location of 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 experiment, drivers were required to slow down and be prepared to stop. According to the Portable Changeable Message Sign Handbook, these actions belong to minor driving actions, for which 500 ft to 1,000 ft is required for reaction time regardless of speed (FHWA, 2003). In this study, the decision point for the minor actions was considered as the location of the first temporary traffic sign (TTS) in the upstream of work zones defined by the MUTCD, which was the W20-1 sign ROAD WORK AHEAD. Based on the research findings of Li and Bai (2012) on the optimal deployment location of a PCMS, the PCMS used in the field experiments was placed 575 ft upstream of the W20-1 sign.

The proper placement of the speed sensors plays a key role for accurate speed measurement. The appropriate locations of the speed sensors could help to better understand drivers' reactions after they recognize the text messages and graphics on the PCMS. In the field experiments, five speed sensors were installed to measure the speed reduction of each passing vehicle to determine the speed reduction rates under different PCMS conditions.

As detailed in Figure 4.11, Sensor 4 (S4) was installed at the same location of the W20-1 sign, the beginning of work zone, to measure vehicle speeds when entering the work zone; Sensor 3 (S3) was installed 500 ft away upstream from the W20-1 sign, 75 ft after the PCMS, to collect vehicle speeds when passing the PCMS; Sensor 2 (S2) was installed 500 ft away upstream from S3; Sensor 1 (S1) was installed 475 ft away upstream from S2 to gather vehicle speeds when drivers were approaching the PCMS; Sensor 5 (S5) was installed at the same location of the second TTS (the W20-4 sign: ONE LANE ROAD AHEAD), which was 530 ft away downstream from S4 and the W20-1 sign, to determine if vehicles would continue to reduce speeds after entering the work zone. If the location of S1 was defined as the original coordinate (0 ft), then the locations of S2, S3, S4, and S5 were at 475 ft, 975 ft, 1,475 ft, and 2,005 ft, respectively, and the PCMS was at 900 ft.

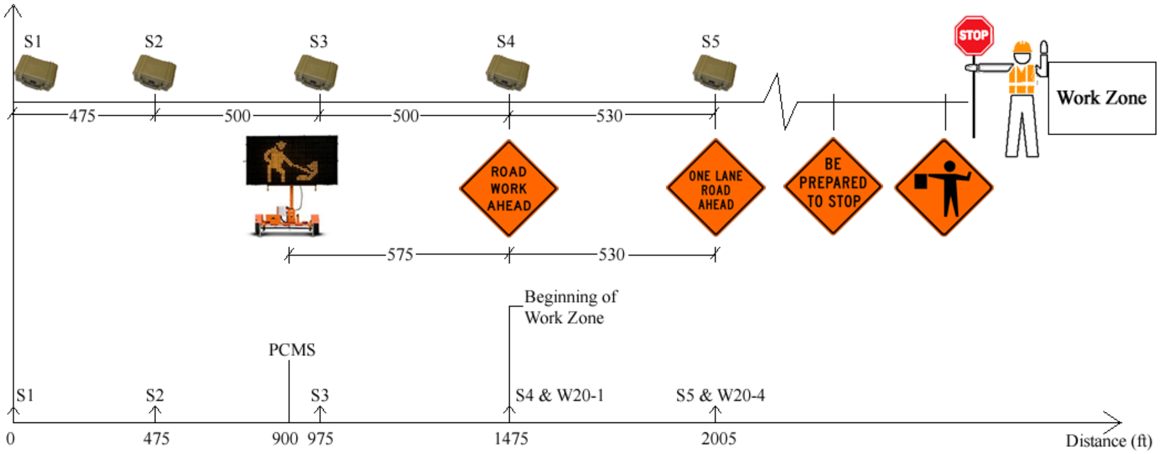

Figure 4.11 Layout of Field Experiment Phase I

4.1.3 Work Zone Location and Conditions

Because field experiment Phase I was designed to determine the effectiveness of graphic-aided PCMS in reducing vehicle speeds in a 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 experiment (Li, 2011):

- "The experiment 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, and speed limits for these highways are typically lower than 55 mph. Rural highways, on the other hand, do not have these limitations. In addition, urban work zones with multiple open lanes do not require traffic to stop and, therefore, may not suffer as severely from rear-end collision problems as one-lane, two-way work zones in a rural areas, where complete stops are required for through traffic. In addition, one-lane, two-way work zones that require traffic stops 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. 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 highway shoulders. A PCMS could become a roadside hazard if not protected from an errant vehicle. Adequate 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 experiment, a work zone located on K-13 between K-16 and US-24 (about 6 miles north of Manhattan, KS) was selected, as shown in Figure 4.12. This highway section is a two-lane rural highway with a total length of about 14 miles and a speed limit of 65 mph. According to the 2010 Kansas DOT (KDOT) Traffic Flow Map, the annual average daily traffic (AADT) of this highway section 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 K-13 was local traffic entering or leaving Manhattan, KS.

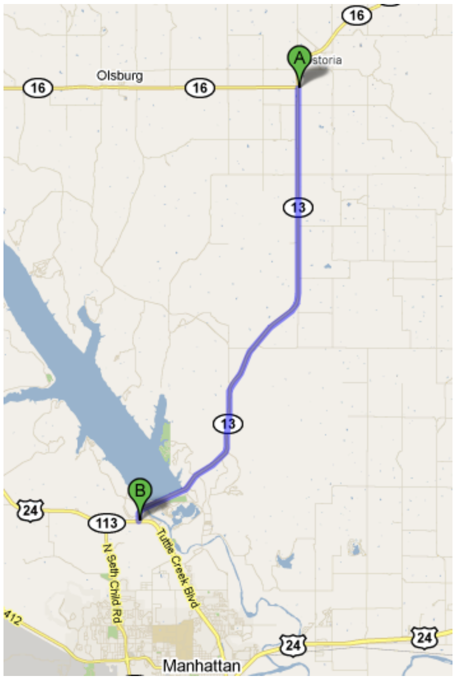

Figure 4.12 Location of Work Zone for Field Experiment Phase I

Field experiment Phase I (except for driver surveys under the text PCMS condition) was conducted from July 21st to August 4th, 2010. The construction project was a paving operation to rehabilitate the roadway surface. The construction process required one traffic lane to be closed for pavement resurfacing while the other lane was kept in service. When construction operations were underway, the two-lane highway was converted 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 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 project progress.

Driver surveys under the text PCMS condition were conducted between September 20th and October 1st, 2010 in a work zone on US-36 between K-87 and

Marysville, KS, which was also a one-lane two-way rural highway work zone. It had a total length of about 14 miles, and the highway section had a speed limit of 65 mph and an AADT of 2,410 to 4,110 vpd. The construction project was a paving operation as well.

4.1.4 Driver Survey Questionnaires

One specific questionnaire was designed for each of the text PCMS, two text-graphic PMCSs, and the graphic PMCS. Four multiple-choice questions were asked in each survey to determine the drivers' acceptance of the graphic-aided PCMS and evaluate their opinions on its implementation in work zones. Samples of the four questionnaires are attached in Appendixes A.1 to A.4 (questions 3 and 5 in Appendix A.1 were not applied in this research project). A questionnaire used for the text-graphic PCMS with the work zone graphic is introduced here 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?*

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 "*Other*" to this question, 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 be used to alert drivers more effectively when they were approaching the work zone. Answers to 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 as not being able to draw more of his/her attention to the work zone conditions than regular warning signs. The last 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 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 text-graphic 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 about the format of message displayed on 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, time, weather condition, vehicle type, and gender of the surveyed drivers. Vehicles were categorized into sedan (including coupe, hatchback, and convertible), SUV, pickup, truck (including semi-trailer), van (including minivan), motorcycle, and bus.

4.2 Data Collection

4.2.1 Data Collection Procedure

Data collection included collecting vehicle speed data and conducting driver surveys. Speed data were collected within an 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 experiment layout in Figure 4.11. Driver surveys were conducted at the flagger stations 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 in Section 4.1.1.2. Speed data were first stored directly in the sensors, then exported to a flash drive, and finally downloaded to a computer for reading 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 as an Excel spreadsheet, as shown in Table 4.3. The interpretation of raw data is described as follows:

Table 4.3 Example of Raw Data Spreadsheet

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

Veh. No.	Date	Time	Lane	Axles	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	117	68	105	9999	117	
2	8/3/2010	6:47:48 AM	1	0	14	0	0	0	0		
3	8/3/2010	6:48:47 AM	1	2	3	143	69	62	9999	143	
4	8/3/2010	6:48:58 AM	1	2	2	109	78	11	9999	109	
5	8/3/2010	6:49:21 AM	1	2	2	108	64	33	9999	108	
6	8/3/2010	6:49:55 AM	1	2	2	100	63	34	9999	100	
7	8/3/2010	6:50:26 AM	1	2	2	115	53	31	9999	115	
8	8/3/2010	6:51:29 AM	1	2	3	139	67	63	9999	139	
9	8/3/2010	6:52:50 AM	1	2	2	115	61	81	9999	115	
10	8/3/2010	6:54:29 AM	1	3	8	365	57	99	9999	160	205

- Start Date and Start Time: the date and time when the speed sensor was turned on.
- Site Code: a number to record the experimental location. In this example, it was Sensor 1.
- Veh. No.: the number of recorded vehicles.
- Date and Time: the date and time when a vehicle datum was recorded.
- Lane: the lane that the recorded vehicle was on. All lane values were 1 in this example because only upstream traffic was collected.
- Axels: the number of axles that the recorded vehicle had.
- Class: the vehicle classification set by JAMAR TRAXPro. For example, 1 for motorcycles, 2 for passenger cars, 3 for pickups, vans and other 2-axle, 4-tire single unit vehicles, 8 for four or less axle single trailer trucks, 9 for five-axle single trailer trucks, and 14 for unclassified vehicles.

- Length: the wheelbase between the first and last axles of the recorded vehicle.
- Speed: the instantaneous speed that the recorded vehicle was traveling when passing the location of a 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.

After all the raw speed data were collected, they went through an extensive screening process. The raw data were first thoroughly screened by matching speed data recorded by all five sensors to individual vehicles. Each speed sensor had a built-in clock, and the five sensors had been adjusted to exactly the same minute and second before collecting data. When the speed of a vehicle was captured, the recorded speed data would have a time gap around 5 to 8 seconds between each two adjacent sensors. This time gap was used to identify if the speed data collected by the five sensors belonged to the same vehicle. In addition, the wheelbase and the number of axels could also help to identify individual vehicles. If any of the five speed data of 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. A collected vehicle datum was valid only if all five speed sensors had correctly captured the vehicle speeds. If any sensor recorded a speed datum improperly, then the five speed data 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 speeds or whose drivers were well aware of the upcoming work zone conditions. Another exception was that vehicles with more than five axles were occasionally recorded by a speed sensor as two vehicles following quite closely. In such situations, the incorrect datum had to be compared with the other four recorded data of the same vehicle and manually corrected to its proper value. In addition, any vehicle with speed recorded under 20 mph by all five sensors was omitted, because the vehicle was considered as a construction-related vehicle or a low-speed farm vehicle.

Finally, the average length of each vehicle was calculated by averaging the total wheelbases recorded by five speed sensors to classify each recorded vehicle. Through this initial data screening, raw data were condensed and sorted before using statistical program IBM SPSS Statistics 20 to perform further calculations and analyses. An example of sorted date is shown in Table 4.4.

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	6:48:58 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 stations was that drivers had to stop there and wait for the pilot car, which would 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 which could cause drivers' resistance. As a result, a high percentage of successful surveys were realized. Figure 4.13 shows a driver survey being conducted.

Figure 4.13 A Driver Survey Being Conducted

4.2.2 Collected Datasets

4.2.2.1 Vehicle Speed Data

A total of 1,115 valid vehicle speed data were collected during field experiment Phase I, as shown in Table 4.5. Among these speed data, 345 were collected under the text PCMS; 367 were captured under the text-graphic PCMSs; and 403 were recorded under the graphic PCMS. A sample of vehicle speed data sheet is attached in Appendix B.

Table 4.5 Summary of Vehicle Speed Data Collected in Field Experiment Phase I

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

4.2.2.2 Driver Survey Data

A total of 524 driver surveys were conducted during field experiment Phase I, as shown in Table 4.6. Among these driver surveys, 149 were conducted under the text PCMS; 125 were conducted under the text-graphic PCMS with the work zone graphic; 124 were conducted under the text-graphic PCMS with the flagger graphic; and 126 were conducted under the graphic PCMS. A sample of driver survey data sheet in field experiment Phase I is attached in Appendix C.1.

Table 4.6 Summary of Driver Survey Data Collected in Field Experiment Phase I

Types of PCMS		No. of Driver Surveys
Text		149
Text-graphic	Work Zone Graphic	125
	Flagger Graphic	124
Graphic		126
Total		524

4.3 Data Analysis

4.3.1 Results of Speed Data Analyses

Collected vehicle speed data were analyzed using IBM SPSS Statistics 20. Speed data under each of the three PCMS conditions were analyzed using descriptive statistics first, then the percentages of speed reduction were compared among the three PCMSs using independent two-sample t-tests, and finally, regression models were developed to illustrate the profile of mean speed reduction under 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 of Speed Data under Text PCMS

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

The box plot, as illustrated in Figure 4.14, gives a more detailed view of the distribution of speed data under 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 were considered outliers. In statistics, an outlier is defined as an observation that is numerically distant from the rest of the data (Barnett and Lewis, 1994). An outlier is determined using interquartile range (IQR), which is the difference between the upper and lower quartiles. A datum greater than 1.5×IQR from the upper quartile or smaller than 1.5×IQR from the lower quartile is considered as an outlier (Frigge et al., 1989).

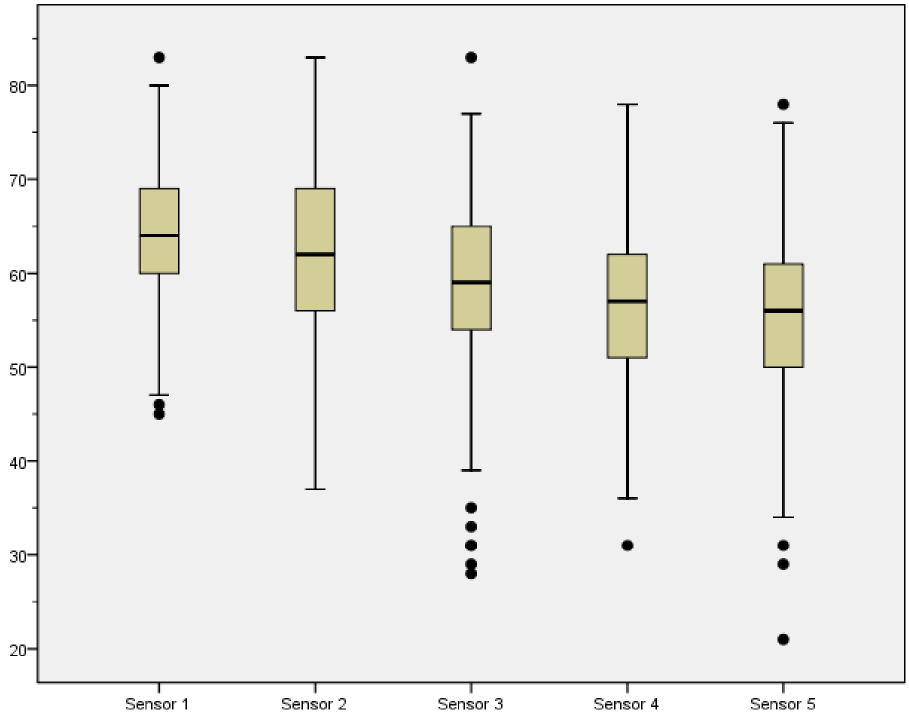

Figure 4.14 Box Plot of Speed Data under Text PCMS

2. Text-graphic PCMS

Table 4.8 shows the descriptive statistics of speed data under text-graphic PCMSs. For a total of 367 speed data, the minimum speed varied from 45 mph to 31 mph from Sensor 1 to Sensor 5, and the maximum speed changed from 84 mph to 76 mph; 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 was noted that Sensor 4, placed at the location of the W20-1 sign, had the lowest values of 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 of Speed Data under Text-graphic PCMS

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

The box plot of speed data under text-graphic PCMSs is displayed in Figure 4.15. 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 (farm vehicles and construction-related vehicles), represented by asterisks, were observed at Sensor 1. A datum greater than

3×IQR from the upper quartile or smaller than 3×IQR from the lower quartile is considered as an extreme outlier (Frigge et al., 1989).

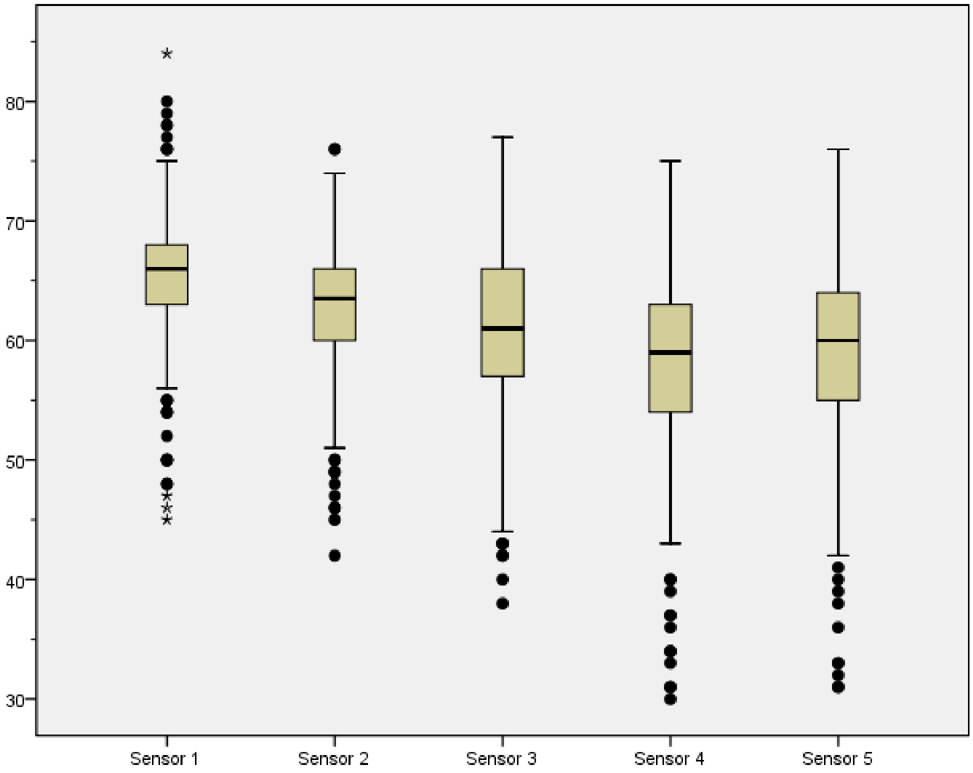

Figure 4.15 Box Plot of Speed Data under Text-graphic PCMS

3. Graphic PCMS

Descriptive statistics of speed data under 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, and the maximum speed changed from 77 mph to 74 mph from Sensor 1 to Sensor 5. 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 of Speed Data under Graphic PCMS

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

Figure 4.16 illustrates the box plot of speed data under 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.

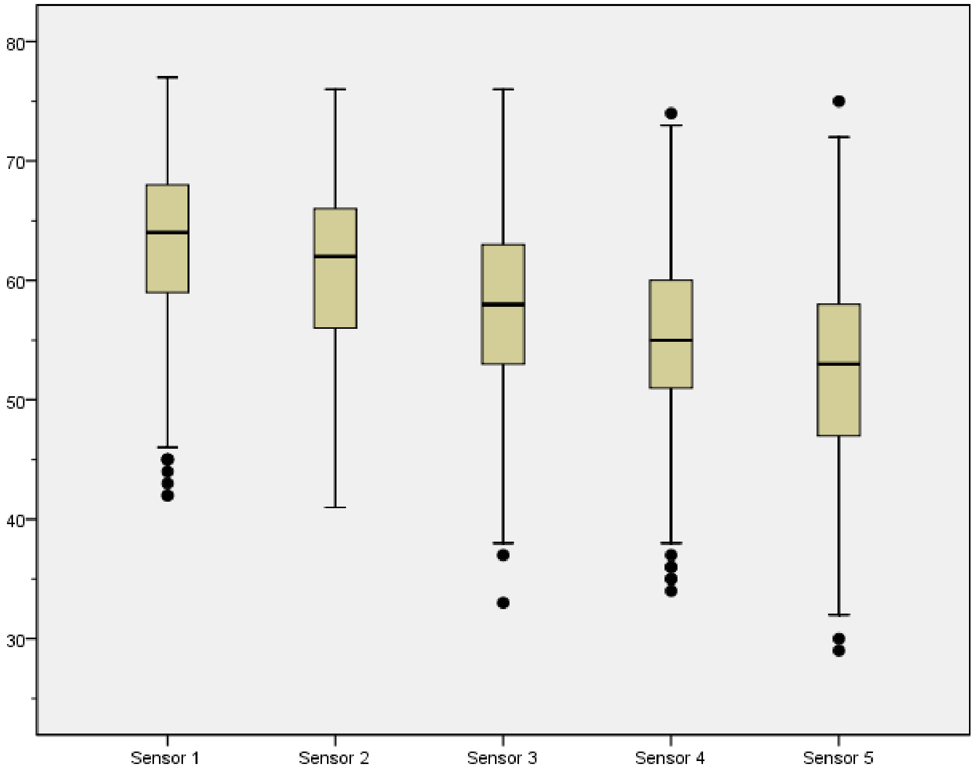

Figure 4.16 Box Plot of Speed Data under Graphic PCMS

4.3.1.2 Comparison Analyses

1. Mean Speed Reduction

Table 4.10 shows the details of the summary of mean speed reduction under each PCMS condition between two adjacent speed sensors. Under the text PCMS, 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 total speed reduction from Sensor 1 to Sensor 5 was 13%.

Table 4.10 Summary of Mean Speed Reduction in Field Experiment Phase I

No.	Text PCMS		Text-graphic 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%

Under the text-graphic PCMSs, the mean vehicle speed started at 65 mph at Sensor 1. It declined by 2 mph at Sensors 2 and 3, decreased by 3 mph at Sensor 4, and then regained by 1 mph at Sensor 5. The percentage of speed reduction was 4% from Sensor 1 to Sensor 2, 3% from Sensor 2 to Sensor 3, and 4% from Sensor 3 to Sensor 4.

The mean speed regained 1% from Sensor 4 to Sensor 5. The percentage of total speed reduction from Sensor 1 to Sensor 5 was 10%.

Under the graphic PCMS, 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 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 total speed reduction from Sensor 1 to Sensor 5 was 17%.

Therefore, comparing the percentages of mean speed reduction under 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 text-graphic PCMS resulted in the smallest percentage of mean speed reduction of 10%. Figure 4.17 illustrates the profiles of mean speed reduction under three PCMS conditions.

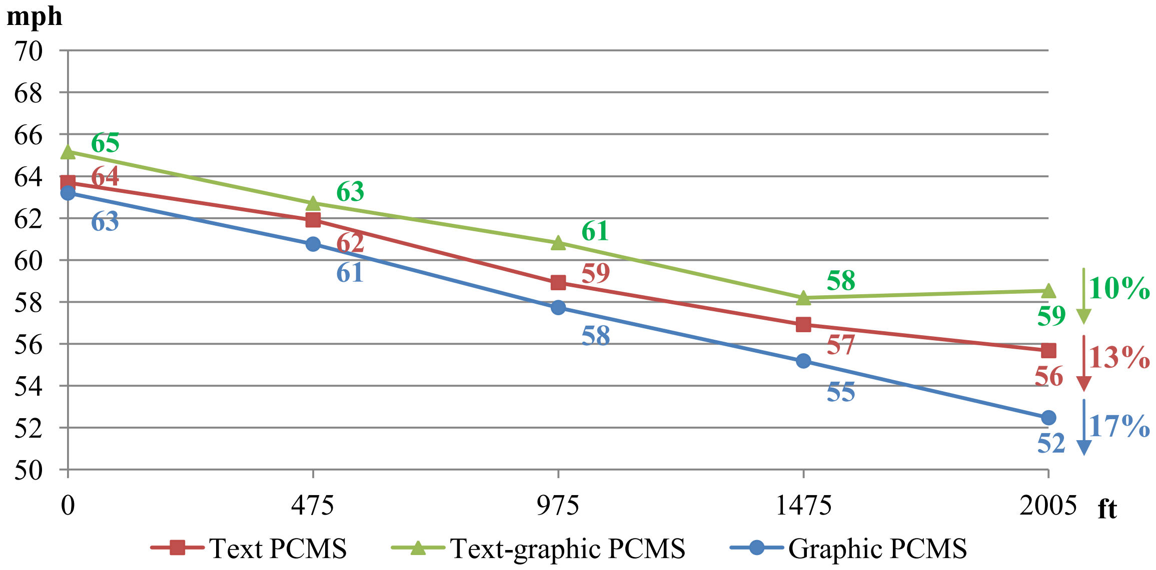

Figure 4.17 Mean Speed Reduction Profile in Field Experiment Phase I

2. Equality of Mean Speeds

Independent two-sample t-tests were conducted to determine if the mean speeds at the same sensor location were statistically equal under the three PCMS conditions. It was assumed that if the mean speeds were statistically equal at one sensor location but not statistically equal at another sensor location under different PCMS conditions, the effectiveness of different PCMSs in reducing 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, an example of the null hypothesis (H_0) and an example of the alternative hypothesis (H_1) were defined as:

$$H_0: \mu_1 = \mu_2$$

$$H_1: \mu_1 \neq \mu_2$$

where μ_1 = the mean speed at a sensor location under one PCMS condition; μ_2 = the mean speed at the same sensor location under another PCMS condition. The interpretation of the null hypothesis is that the mean speeds at a sensor location were statistically equal under the two compared PCMS conditions, and the alternative hypothesis is that the mean speeds at a sensor location were statistically unequal under 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 of t-tests for mean speeds at each sensor location between each two compared PCMSs. Two p-values were found greater than 0.05 (0.143 and 0.312), which indicate that mean vehicle speeds were statistically equal at two sensor locations. The first location was at Sensor 2 when comparing the text PCMS with the text-graphic PCMS. Table 4.10 and Figure 4.17 show that mean vehicle speeds were larger at Sensors 1, 3, 4, and 5 under the text-graphic PCMS than under the text PCMS. Therefore, using the text-graphic PCMS could reduce mean vehicle speeds more effectively than the text PCMS from 1,475 ft (location of Sensor 1) to 1,000 ft (location of Sensor 2) in the upstream of a work zone, but less effectively than the text PCMS from 1,000 ft in the upstream of a work zone to the location of the W20-4 sign (location of Sensor 5), and the difference is statistically significant.

Table 4.11 P-Values of T-tests in Field Experiment Phase I

Location	Text vs. Text-graphic	Text vs. Graphic	Text-graphic 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

The second location where mean vehicle speeds were statistically equal was at Sensor 1 when comparing the text PCMS with the graphic PCMS. Table 4.10 and Figure 4.17 show that mean vehicle speeds were larger at Sensors 2, 3, 4, and 5 under the text PCMS than under the graphic PCMS. Therefore, using the graphic PCMS could reduce mean vehicle speeds more effectively than the text PCMS from 1,475 ft in the upstream of a work zone to the location of the W20-4 sign, and the difference is statistically significant.

When comparing text-graphic PCMS with graphic PCMS, Table 4.11 shows that no p-value at the five sensors was greater than 0.05, indicating that the mean vehicle speeds were statistically unequal at all of the five sensor locations under these PCMS conditions. Therefore, the difference of effectiveness of text-graphic PCMS and graphic PCMS in reducing mean vehicle speeds could not be determined.

3. 85th Percentile Speed Reduction

Table 4.12 shows the summary of 85th percentile speed reduction in field experiment Phase I. The 85th percentile speed was reduced by 5 mph or 7% using the text PCMS, by 4 mph or 6% using the text-graphic PCMSs, and by 8 mph or 12% using the graphic PCMS. The results indicated that using the graphic PCMS reduced the 85th percentile speed more effectively than using the text and text-graphic PCMSs. Vehicles travelling above the 85th percentile speed can cause more severe crashes if they collide with a queue of vehicles near the flagger station, because the speed difference between a stopped vehicle and a vehicle travelling above the 85th percentile speed is considerably larger than the speed difference between a stopped vehicle and a vehicle travelling at prevailing speeds.

Table 4.12 85th Percentile Speed Reduction in Field Experiment Phase I

Type of PCMS	85th Percentile Speed (mph)					Speed Reduction	
	S1	S2	S3	S4	S5	mph	%
Text	70	71	67	65	65	5	7%
Text-graphic	70	68	68	65	66	4	6%
Graphic	69	68	65	63	61	8	12%

4.3.1.3 Regression Analyses

Mathematical models could be developed to describe the mean vehicle speed profiles in the upstream of a work zone. These models might 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 from Sensor 1 to a vehicle in the upstream of a work zone as shown in Figure 4.9, and $a_0, a_1, a_2, a_3 \cdots a_n$ = the parameters 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 from Sensor 1 to a vehicle in the upstream of a work zone, a_0 = the mean speed at Sensor 1, which is the initial speed, and a_1 = the reduction rate of the mean speed in mph/ft.

A linear regression model (R^2 = 0.997) describing the mean vehicle speed profile in the upstream of a work zone under the text PCMS condition is

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

A linear regression model ($R^2 = 0.971$) describing the mean vehicle speed profile in the upstream of a work zone under the text-graphic PCMS condition is

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

A linear regression model ($R^2 = 0.871$) describing the mean vehicle speed profile in the upstream of a work zone under the graphic PCMS condition is

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

Figure 4.18 illustrates the linear regression models of mean speed reduction under the three PCMS conditions. When comparing the reduction rates of the mean speed, the graphic PCMS resulted in the largest reduction rate of 0.0056 mph/ft, the text PCMS had a moderate reduction rate of 0.0042 mph/ft, and the text-graphic PCMSs resulted in the smallest reduction rate of 0.0034 mph/ft. Using these linear regression models, the mean vehicle speed at any location from 1,475 ft in the upstream of a work zone to the W20-4 sign under each PCMS condition could be predicted.

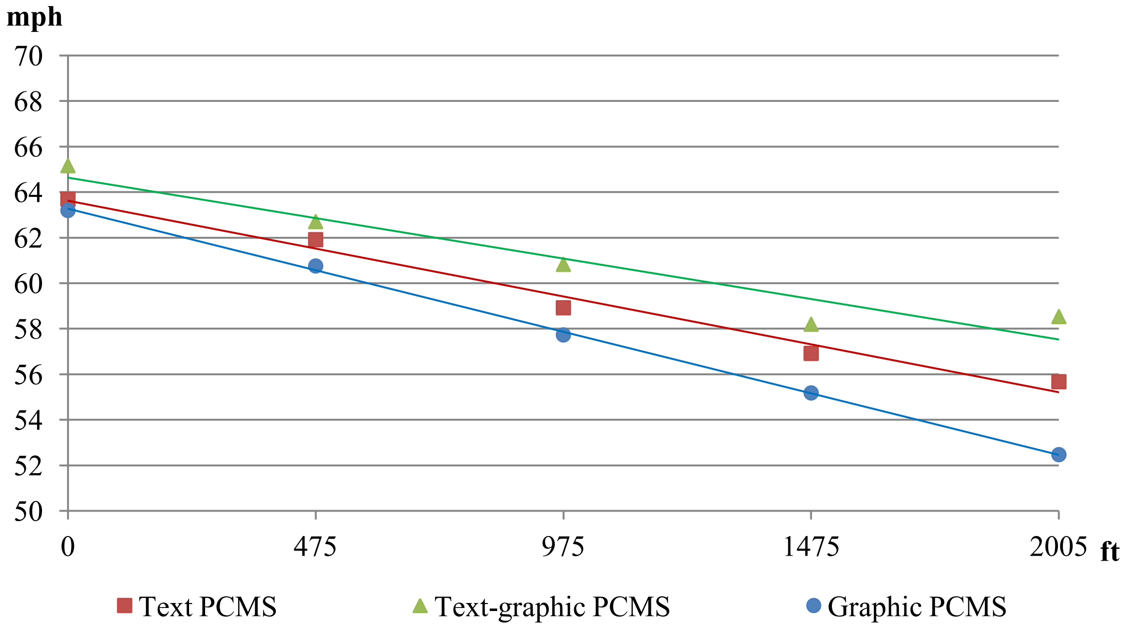

Figure 4.18 Linear Regression Models of Mean Speed Reduction

2. Nonlinear Regression Model

Nonlinear regression models were also developed to seek the improvement of mean speed profiles of text and text-graphic PCMS conditions.

(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 from Sensor 1 to a vehicle in the upstream of a work zone, a_0 = the mean speed at Sensor 1, which is the initial speed, and a_1, a_2 = the parameters to be determined.

A quadratic function ($R^2 = 0.9895$) describing the mean vehicle speed profile in the upstream of a work zone under the text PCMS condition is

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

A quadratic function ($R^2 = 0.9727$) describing the mean vehicle speed profile in the upstream of a work zone under the text-graphic PCMS condition is

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

Figure 4.19 and Figure 4.20 illustrate the quadratic functions of the text PCMS condition and the text-graphic PCMS condition, respectively.

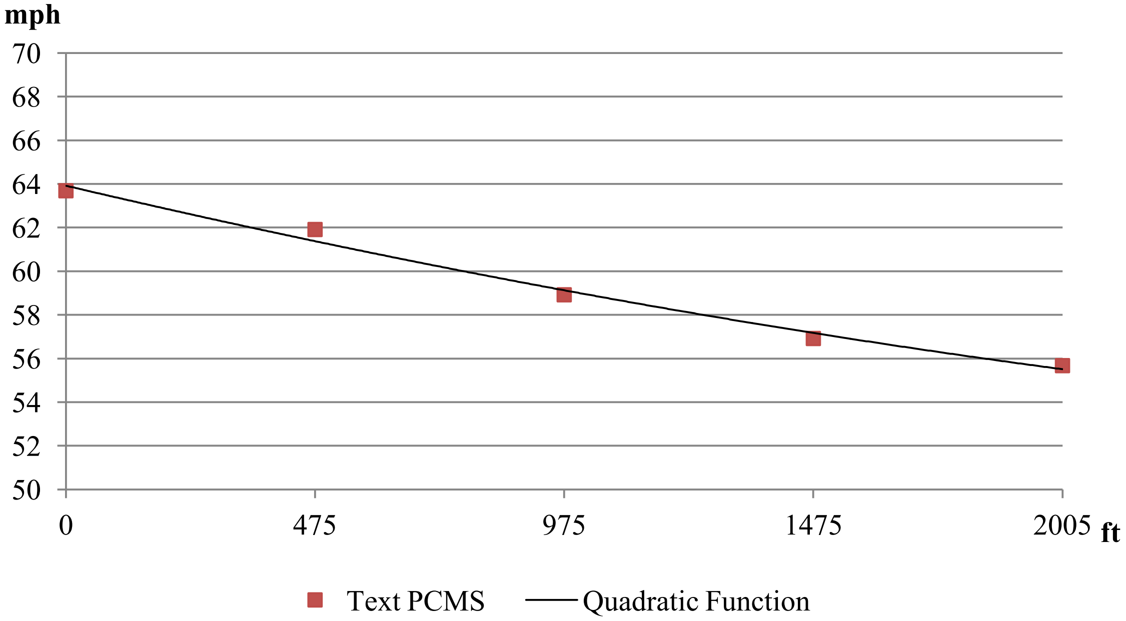

Figure 4.19 Quadratic Function of Mean Speed Reduction under Text PCMS

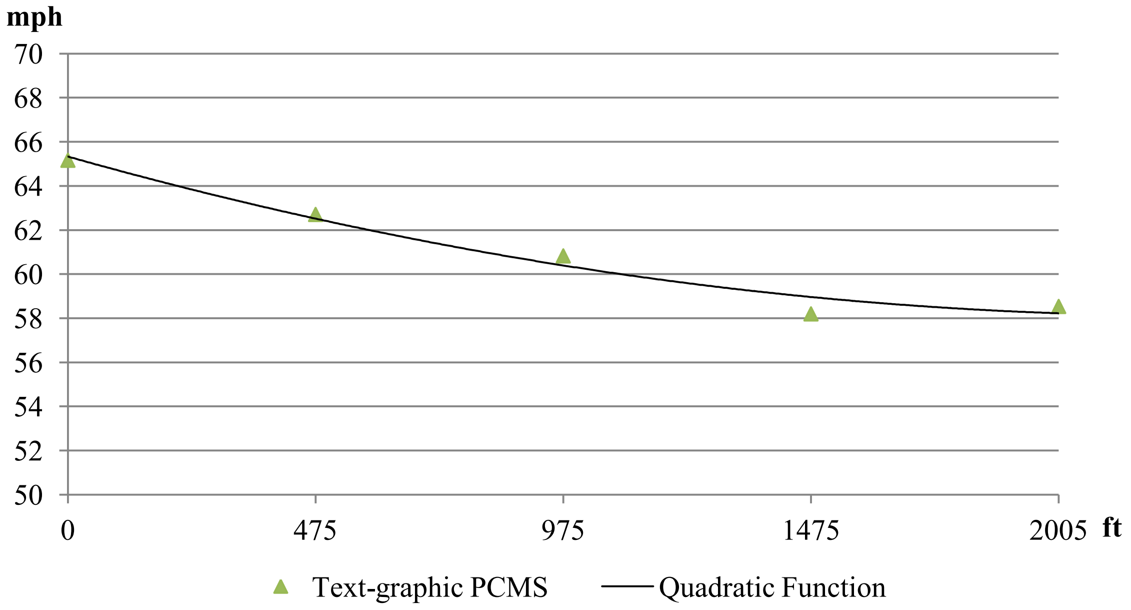

Figure 4.20 Quadratic Function of Mean Speed Reduction under Text-graphic PCMS

(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 from Sensor 1 to a vehicle in the upstream of a work zone, a_0 = the mean speed at Sensor 1, which is the initial speed, and a_1, a_2, a_3 = the parameters to be determined.

A cubic function (R^2 = 0.9981) describing the mean vehicle speed profile in the upstream of a work zone under the text PCMS condition is

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

A cubic function (R^2 = 0.9894) describing the mean vehicle speed profile in the upstream of a work zone under the text-graphic PCMS condition is

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

Figure 4.21 and Figure 4.22 illustrate the cubic functions of the text PCMS condition and the text-graphic PCMS condition, respectively.

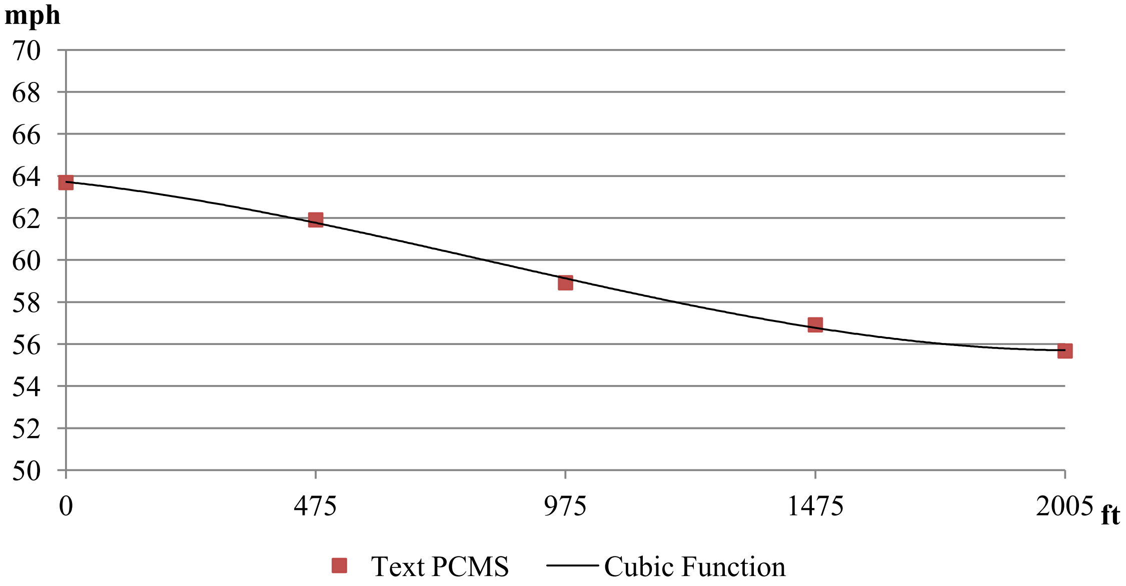

Figure 4.21 Cubic Function of Mean Speed Reduction under Text PCMS

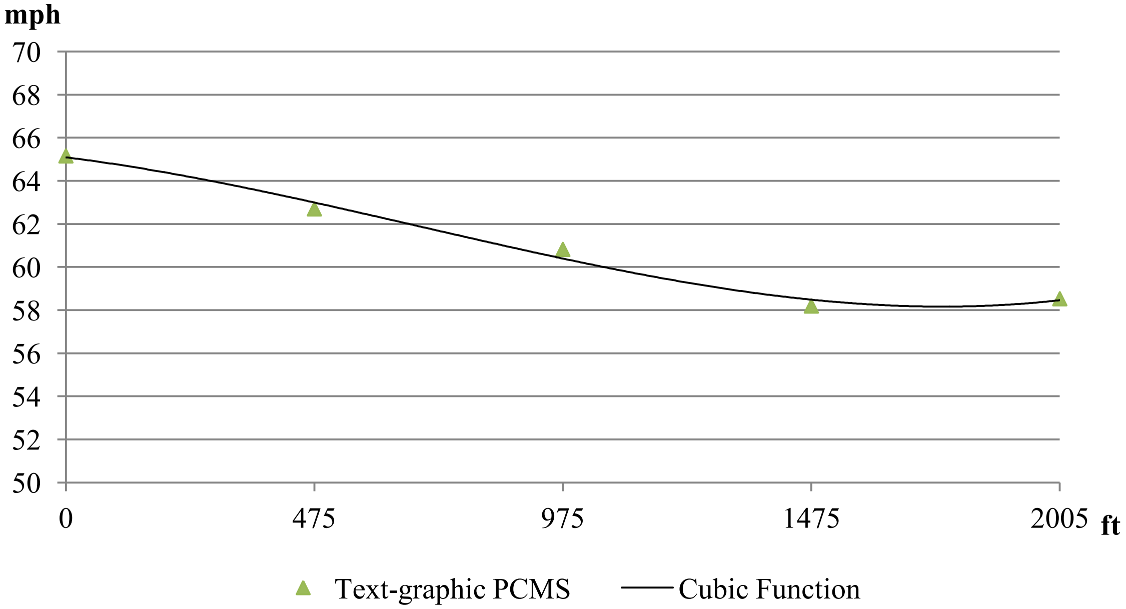

Figure 4.22 Cubic Function of Mean Speed Reduction under Text-graphic PCMS

4.3.2 Results of Driver Survey Analyses

A total of 524 driver surveys were performed during field experiment Phase I, among which the surveys under the text PCMS were conducted two months later than the surveys of the text-graphic and graphic PCMSs at a different work zone with similar roadway conditions.

4.3.2.1 Driver Survey Results

1. Text PCMS

149 drivers participated in the driver survey under the text PCMS, including 98 male drivers (66%) and 51 female drivers (34%). The driver survey results are described as follows (questions 3 and 5 in Appendix A.1 were not applied in this research project).

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 4: *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 6: *Do you prefer the warning signs to be displayed in the graphical format or text format?* As illustrated in Figure 4.23, the majority (64%) of drivers preferred the text format; 16% of drivers chose the text-graphic 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.

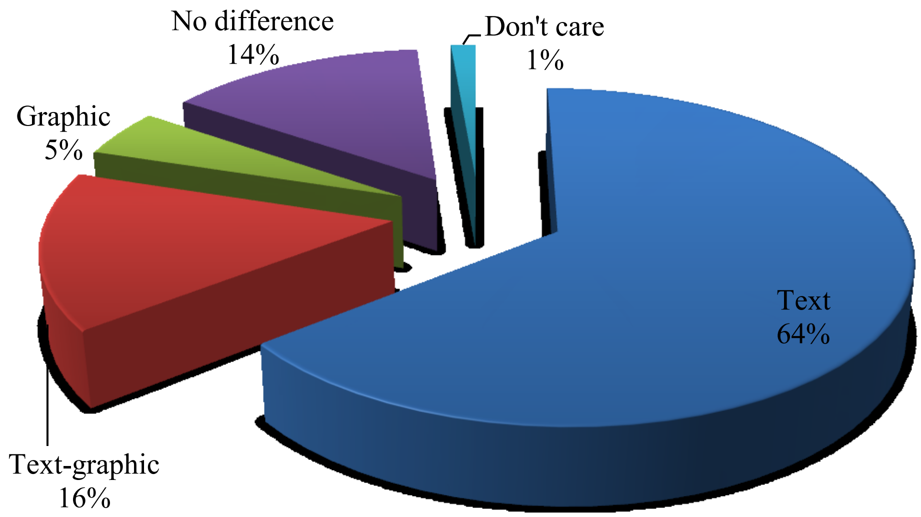

Figure 4.23 Drivers' Preferences to Message Format under Text PCMS

The number of drivers who answered Question 6 was further analyzed by their gender, and results are presented in Table 4.13. 63% of male drivers preferred the PCMS to be 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 text-graphic 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 when they only saw the text PCMS.

Table 4.13 Drivers' Preferences to Message Format Associated with Drivers' Gender under Text PCMS

Answer	Overall		Male		Female	
	Frequency	Percentage	Frequency	Percentage	Frequency	Percentage
Text	96	64%	62	63%	34	66%
Text-graphic	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. Text-graphic PCMS

(1) Text-graphic PCMS with Work Zone Graphic

125 driver surveys were conducted under the text-graphic PCMS with the work zone graphic, among 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 text-graphic 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 4.24. Around one fourth of drivers preferred the text format (24%), text-graphic format (26%), and graphic format (26%). 18% of the respondents said there was no difference between the text format and the graphic format; the remaining 1% of drivers answered *Don't know*.

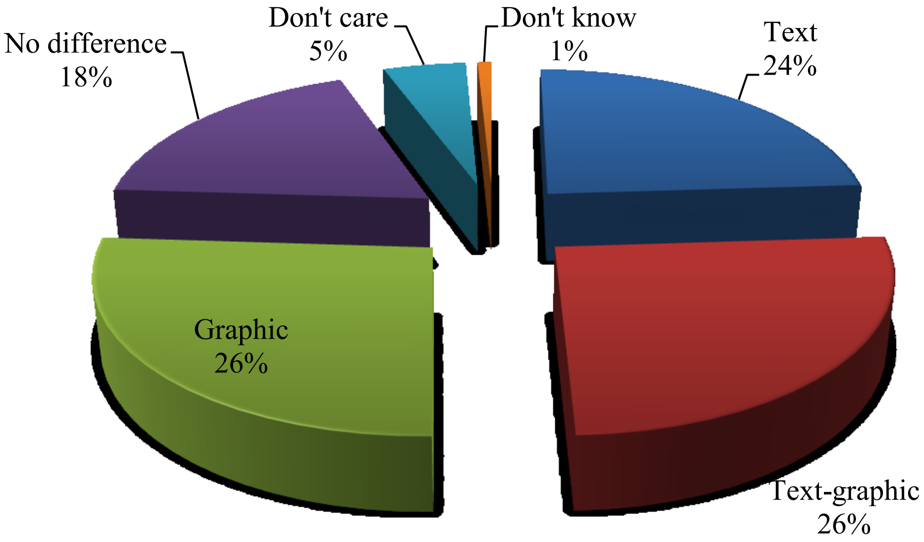

Figure 4.24 Drivers' Preferences to Message Format under Text-graphic PCMS with Work Zone Graphic

The number of drivers who answered Question 4 was further analyzed by their gender, and the results are presented in Table 4.14. While about a quarter of male and female drivers liked the text format, their preferences to the text-graphic and graphic format varied. More female drivers chose the text-graphic format than the male drivers (34% vs. 19%), and more male drivers selected the graphic format 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 PCMSs made no difference to them. 3% of male drivers and 7% of female drivers did not care about the message format on PCMS. Another 1% of male drivers did not know how to choose the message format. Therefore, although the overall percentages of drivers choosing text, text-graphic, and graphic format are similar, more male drivers preferred the graphic format PCMS and more female drivers preferred the text-graphic format PCMS.

Table 4.14 Drivers' Preferences to Message Format Associated with Drivers' Gender under Text-graphic PCMS with Work Zone Graphic

Answer	Overall		Male		Female	
	Frequency	Percentage	Frequency	Percentage	Frequency	Percentage
Text	30	24%	17	25%	13	23%
Text-graphic	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) Text-graphic PCMS with Flagger Graphic

124 drivers responded to the surveys under the text-graphic PCMS with the flagger graphic, among 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* ***<u>graphic</u>*** *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 4.25, only 3% of drivers preferred the text format; the majority of drivers (52%) chose the graphic format; 19% of drivers liked the text-graphic 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*.

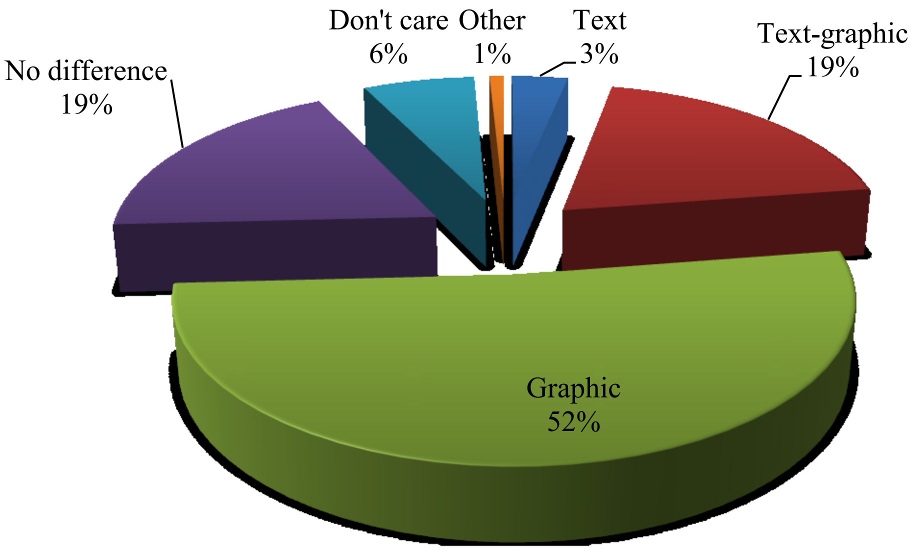

Figure 4.25 Drivers' Preferences to Message Format under Text-graphic PCMS with Flagger Graphic

The number of drivers who answered Question 4 was further analyzed by their gender, and results are presented in Table 4.15. 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 text-graphic format (24% vs. 15%), while more male drivers liked the graphic format (57% vs. 45%). 15% of male drivers saw no difference between the text and graphic format, 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 text-graphic format, and the text format gained only a slight share. More male drivers chose the graphic format, while more female drivers selected the text-graphic format.

Table 4.15 Drivers' Preferences to Message Format Associated with Drivers' Gender under Text-graphic PCMS with Flagger Graphic

Answer	Overall		Male		Female	
	Frequency	Percentage	Frequency	Percentage	Frequency	Percentage
Text	4	3%	3	5%	1	2%
Text-graphic	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. Graphic PCMS

126 drivers answered the questionnaires in the survey under 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 graphic, 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 4.26, a small percentage (12%) of drivers liked the text format, while the majority (45%) preferred the graphic format. 21% of drivers chose the text-graphic 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.

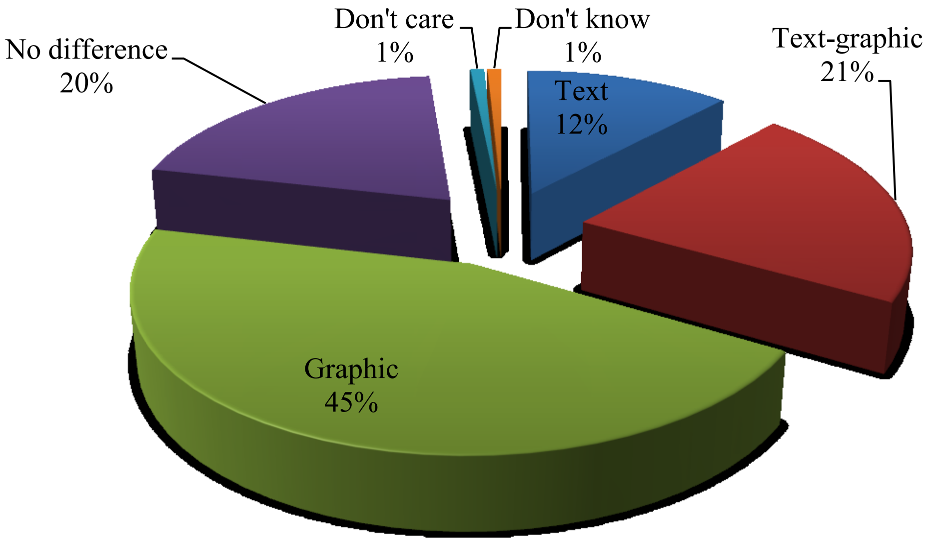

Figure 4.26 Drivers' Preferences to Message Format under Graphic PCMS

The number of drivers who answered Question 4 was further analyzed by their gender, and results are presented in Table 4.16. 17% of male drivers preferred the text format, which was chosen by only 5% of female drivers. A similar percentage (20% to 23%) of both male and female drivers selected the text-graphic format. The majority of drivers, 42% for male and 49% for female, chose the graphic format. 17% male drivers and 23% of female drivers saw no difference between the text format and the graphic format. 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 than female drivers, while a larger percentage of female drivers liked the text-graphic and graphic formats.

Table 4.16 Drivers' Preferences to Message Format Associated with Drivers' Gender under Graphic PCMS

Answer	Overall		Male		Female	
	Frequency	Percentage	Frequency	Percentage	Frequency	Percentage
Text	15	12%	12	17%	3	5%
Text-graphic	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 Analyses

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 drivers' recognition of messages on the PCMS.

1. Drivers' Understanding of Meaning of Graphics on PCMS

Table 4.17 shows the comparison of drivers' understanding of graphics on the PCMS in Question 2. All drivers could understand the meaning of the flagger graphic displayed on the text-graphic and graphic PCMSs. 88% of drivers were able to interpret the meaning of the work zone graphic on the text-graphic PCMS, and 79% of drivers could correctly understand it on the graphic PCMS. In other words, 12% of drivers could not understand the meaning of the work zone graphic on the text-graphic PCMS, and 21% of drivers either misunderstood this graphic or had no idea about it on the graphic PCMS. In other words, the work zone graphic together with the text WORKZONE AHEAD

SLOWDOWN on the text-graphic PCMS was easier to be correctly understood by 9% more drivers than the work zone graphic 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 4.17 Comparison of Drivers' Understanding of Graphics on PCMS

Survey Response	Text-graphic PCMS		Graphic PCMS
	Work Zone Graphic	Flagger Graphic	
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%

2. Effectiveness of PCMS in Drawing Drivers' Attention

Table 4.18 shows the comparison of the effectiveness of PCMS in drawing drivers' attention in Question 3. 97% of drivers thought the text PCMS drew their attention more to the work zone traffic conditions. The text-graphic PCMS with the flagger graphic, correctly 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 text-graphic PCMS with the work zone graphic. Although the work zone graphic on 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 on the graphic PCMS helped to gain this percentage of drivers' attention.

Table 4.18 Comparison of Effectiveness of PCMS in Drawing Drivers' Attention

Survey Response	Text PCMS	Text-graphic PCMS		Graphic PCMS
		Work Zone Graphic	Flagger Graphic	
Yes	97%	82%	90%	87%
No	3%	16%	7%	13%
Don't Know	0 %	2 %	3%	0%
Total	100%	100%	100%	100%

3. Drivers' Preferences to Message Format on PCMS

The comparison of drivers' preferences to message format on PCMS in Question 4 is shown in Table 4.19. 64% of drivers chose the text format when they only saw the text PCMS, but the percentage dropped dramatically to 24% when the drivers saw the text-graphic PCMS with the work zone graphic, and this percentage declined even further to only 3% under the text-graphic PCMS with the flagger graphic. 12% of drivers chose the text format when they saw a graphic PCMS. 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 text-graphic PCMS with the work zone graphic was displayed, 26% of drivers liked the graphic format; when the text-graphic PCMS with the flagger graphic was shown, the percentage of drivers in favor of the graphic format doubled to 52%. The percentage of drivers preferring the graphic format also remained high at 45% when they saw a graphic PCMS. The text-graphic format had more even percentages of drivers' selections compared with the other two formats. 16% of drivers liked the text-graphic format when the text PCMS was displayed; 26% drivers chose it when the text-graphic PCMS with the work zone graphic was displayed; 19% of drivers selected it when the text-graphic 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 (since graphics had never been used on PCMSs in Kansas), but preferred the graphic format when they saw the text-graphic PCMS with the flagger graphic and the graphic PCMS. Drivers' preferences were distributed more evenly to the three message formats when they saw the text-graphic PCMS with the work zone graphic. The text-graphic and graphic formats were the choices of the majority of drivers (52% to 71%) when a text-graphic or a graphic PCMS was displayed to them.

Table 4.19 Comparison of Driver's Preferences to Message Format on PCMS

Survey Response	Text PCMS	Text-graphic PCMS		Graphic PCMS
		Work Zone Graphic	Flagger Graphic	
Text	64%	24%	3%	12%
Text-graphic	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%

4.4 Summary of Field Experiment Phase I

4.4.1 Discussion

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

Some drivers preferred the text-graphic or graphic PCMS because they thought the large graphic on the PCMS could "catch their eyes" from far away. Compared with text PCMS, the text-graphic or graphic PCMS can be recognized from a longer distance. Some drivers liked the text-graphic 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 on the text-graphic 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 text-graphic and graphic PCMSs with the work zone graphic. They were confused or not able to understand what the man in the graphic was doing. Among them, most interpreted it as "a man opening an umbrella," while some saw it as "a man power-washing." The comparison of the work zone graphic in MUTCD (the W21-1 sign) and on PCMS is shown in Figure 4.2. The work zone graphic on the PCMS did have some variances with the W21-1 sign, particularly at the lower right corner where the confusions came from.

The confusions made some drivers think while driving, and this was the reason why they might not like the text-graphic or the graphic PCMS. Therefore, the graphic has to be designed to clearly express its meaning before being displayed on PCMS.

4.4.2 Summary

Rural two-lane highways constitute the majority of the Kansas highway system. Maintaining the conditions of these rural highways requires 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, various types of traffic control devices have been developed and employed, including the PCMS. A traditional PCMS uses text messages to warn drivers about the traffic conditions in work zones. Results of previous studies indicated that there were several limitations of using 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 by a PCMS. In addition, some drivers were not able to understand messages in English, and a text PCMS was therefore useless for them (Wang et al., 2007). To overcome these limitations, graphics displayed either alone or supplemented by text messages have been proposed to be incorporated in PCMSs. A graphic-aided PCMS could be identified easier, quicker, and from a longer distance. A few researchers applied driving simulation methods to evaluate the effectiveness of graphic-aided PCMS. However, its effectiveness in reducing vehicle speeds in highway work zones has not been studied yet.

Field experiment Phase I was designed to determine the effectiveness of graphic-aided PCMS in reducing vehicle speeds in the upstream of one-lane two-way rural highway work zones. A full-matrix PCMS was employed to display text messages and graphics, and five speed sensors were used to collection vehicle speed data. The PCMS was programmed to display two text messages WORKZONE AHEAD SLOWDOWN and FLAGGER AHD PREP TO STOP, as shown in Figure 4.1, and two graphics similar to the W21-1 and the W20-7 signs specified by the MUTCD, as displayed in Figure 4.2 and Figure 4.3. In field experiment Phase I, the PCMS was set up in three conditions, including a text PCMS that displayed only text messages (Figure 4.4), two text-graphic PCMSs that displayed both text messages and graphics (Figure 4.5 and Figure 4.6), and a graphic PCMS that displayed only graphics (Figure 4.7).

Field experiment Phase I was conducted in a rural highway work zone on K-13 between US-24 and K-16, and the experimental layout is illustrated in Figure 4.11. Speed Sensor 4 was installed at the beginning of work zone, which is the location of the W20-1 sign. Sensors 1, 2, 3 were installed 1,475 ft, 1,000 ft, and 500 ft in the upstream of Sensor 4, respectively, while Sensor 5 was install 530 ft downstream of Sensor 4, which is the location of the W20-4 sign. The PCMS was placed 575 ft upstream of the beginning of work zone between Sensor 2 and Sensor 3. Driver surveys were conducted at the locations where flaggers stopped the through traffic. One specific questionnaire was designed for each of the text PCMS, two text-graphic PMCSs, and the graphic PMCS. Samples of questionnaires are attached in Appendixes A.1 to A.4.

A total of 1,115 valid vehicle speed data were collected during field experiment Phase I, among which 345 were collected under the text PCMS, 367 were captured under the text-graphic PCMSs, and 403 were recorded under the graphic PCMS. A total of 524 driver surveys were performed, among which 149 were conducted under the text PCMS, 125 were conducted under the text-graphic PCMS with the work zone graphic, 124 were conducted under the text-graphic PCMS with the flagger graphic, and 126 were conducted under the graphic PCMS.

Through the comparison of mean speed reduction, it was found that using a text, a text-graphic, 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 text-graphic, 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.

The results of independent two-sample t-tests suggested that using a text-graphic PCMS reduced mean vehicle speeds 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 a text PCMS from 1,000 ft in the upstream of the work zone to the W20-4 sign. Using a graphic PCMS reduced mean vehicle speeds more effectively than using a text PCMS from 1,475 ft in the upstream of the work zone to the W20-4 sign.

The results of driver surveys revealed that 88% and 79% of drivers understood the work zone graphic on the text-graphic PCMS and the graphic PCMS, respectively. All drivers correctly interpreted the flagger graphic on the text-graphic PCMS and the graphic PCMS. 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 text-graphic PCMS drew their attention more to the work zone traffic conditions when they saw the text-graphic PCMS; 87% of drivers thought the graphic PCMS drew their attention more to the work zone traffic conditions when they saw the graphic PCMS.

It was also found that the text format was preferred by 64% of drivers when the text PCMS was displayed; by 24% and 3% of drivers when the text-graphic 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 text-graphic 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 text-graphic format was selected by 16% of drivers when the text PCMS was displayed; by 26% and 19% of drivers for the text-graphic PCMSs with the work zone graphic and the flagger graphic were presented, respectively; and by 21% of drivers when the graphic PCMS was shown.

Chapter 5 Field Experiment Phase II

The results of driver surveys in field experiment Phase I indicated that between 12% and 21% of drivers got confused when the work zone graphic was displayed on the text-graphic and graphic PCMSs. Some drivers expressed their thoughts through the surveys that they had to think to understand the work zone graphic when approaching the work zone. This thinking-and-driving behavior could increase drivers' reaction time, delay their braking action, and make the drivers fail to reduce speed when they were approaching the work zone. Thus, drivers' confusion on the work zone graphic might have affected the mean speed reduction under the text-graphic and graphic PCMS conditions. Therefore, field experiment Phase II was designed and aimed to determine and compare the effectiveness of two alternative work zone graphics in reducing vehicle speeds in the upstream of a one-lane two-way rural highway work zone.

5.1 Experiment Design

5.1.1 Experiment Devices and Installation

The same full-matrix PCMS and speed measurement sensors introduced in Section 4.1.1 were employed in field experiment Phase II using the same installation procedures. The PCMS was programmed to display two alternative work zone graphics, as shown in Figure 5.1, as well as the original work zone graphic used in field experiment Phase I, as shown in Figure 5.2.

Alternative Work Zone Graphic One Alternative Work Zone Graphic Two

Figure 5.1 Alternative Work Zone Graphics in Field Experiment Phase II

Figure 5.2 Original Work Zone Graphic in Field Experiment Phase I

The three work zone graphics were first displayed on three text-graphic PCMSs with the text WORKZONE AHEAD SLOWDOWN to compare the effectiveness of the original and alternative work zone graphics in reducing vehicle speeds. Then, the two alternative work zone graphics were displayed with the flagger graphic on two graphic PCMSs, respectively, and the effectiveness of two graphic PCMSs in reducing vehicle speeds was compared. Each PCMS condition included two phases, switching from one to the other every three seconds. Therefore, in field experiment Phase II, the PCMS was set up under three text-graphic conditions and two graphic conditions, which were:

- Text-graphic PCMS Alternative One: displaying text WORKZONE AHEAD SLOWDOWN and alternative work zone graphic one, as shown in Figure 5.3,
- Text-graphic PCMS Alternative Two: displaying text WORKZONE AHEAD SLOWDOWN and alternative work zone graphic two, as shown in Figure 5.4,
- Text-graphic PCMS Original: displaying text WORKZONE AHEAD SLOWDOWN and the original work zone graphic, as shown in Figure 5.5,
- Graphic PCMS Alternative One: displaying alternative work zone graphic one and the flagger graphic, as shown in Figure 5.6, and
- Graphic PCMS Alternative Two: displaying alternative work zone graphic two and the flagger graphic, as shown in Figure 5.7.

Figure 5.3 Text-graphic PCMS Alternative One

Figure 5.4 Text-graphic PCMS Alternative Two

Figure 5.5 Text-graphic PCMS Original

Figure 5.6 Graphic PCMS Alternative One

Figure 5.7 Graphic PCMS Alternative Two

5.1.2 *Field Experiment Layout*

The layout of field experiment Phase II was exactly the same as the layout of field experiment Phase I, as introduced in Section 4.1.2.

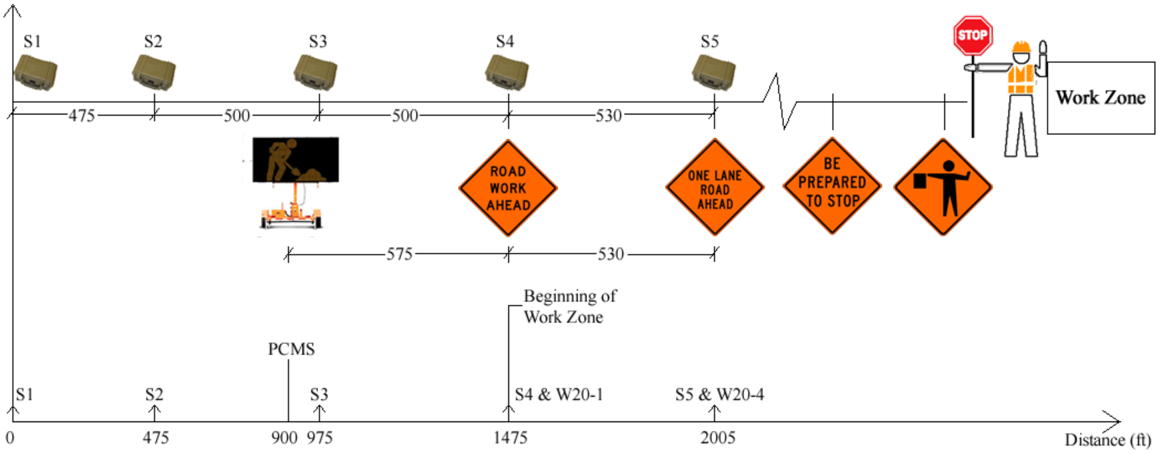

Figure 5.8 Layout of Field Experiment Phase II

5.1.3 *Work Zone Location and Conditions*

A highway work zone located on US-75 between Burlington, KS and I-35, as shown in Figure 5.9, was selected for field experiment Phase II. This highway section is a two-lane rural highway with a total length of about 15 miles and a speed limit of 65 mph. According to the 2010 KDOT Traffic Flow Map, the AADT of the selected section of US-75 was 3,680 vpd at the north end and 5,000 vpd at the south end, with around 600 being commercial trucks (traffic counts recorded between July 2008 and June 2009). Field experiment Phase II was conducted from July 14th to 27th, 2011. The construction project was also a paving operation similar to the road work in field experiment Phase I, which required a pilot car and two flaggers for traffic control, as introduced in Section 4.1.3.

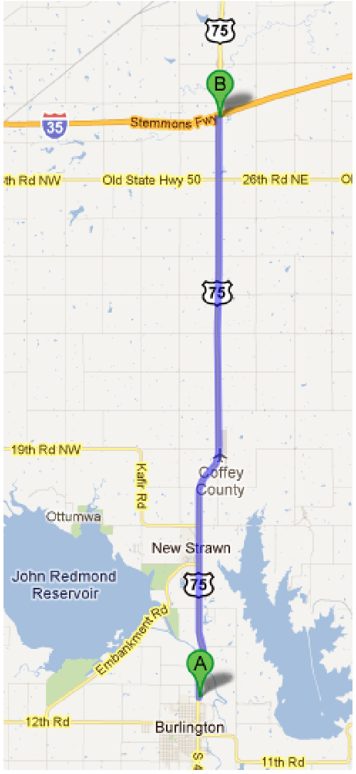

Figure 5.9 Location of Work Zone for Field Experiment Phase II

5.1.4 Driver Survey Questionnaires

Driver surveys were conducted to determine drivers' acceptance of the two alternative work zone graphics in comparison with the original work zone graphic. Questionnaires in field experiment Phase II, attached in Appendixes A.5, A.6, and A.7, were designed similar to the questionnaires used in field experiment Phase I, except for adding a fifth question, which was drivers' age category. Driver's age was grouped into seven categories, which were less than 19, 19 to 24, 25 to 34, 35 to 44, 45 to 54, 55 to 64, and over 65. Drivers' ages were collected in field experiment Phase II to identify the relationship between age and drivers' preferences to message format on PCMS. The other questions in the questionnaires were introduced in Section 4.1.4.

5.2 Data Collection

Vehicle speed data and driver survey data were collected using the same methods and procedures as in field experiment Phase I, as described in Section 4.2.1. Speed data were collected using five speed sensors within an 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 experiment layout in Figure 5.8. Driver surveys were conducted at the flagger stations where all vehicles had to stop and wait for the pilot car.

5.2.1 Vehicle Speed Data

A total of 2,676 valid vehicle speed data were collected during field experiment Phase II, as shown in Table 5.1. Among these speed data, 540, 541, and 519 were collected under text-graphic PCMSs Alternative One, Alternative Two, and Original, respectively; 536 and 540 speed data were captured under graphic PCMSs Alternative One and Alternative Two, respectively.

Table 5.1 Summary of Vehicle Speed Data Collected in Field Experiment Phase II

Types of PCMS		No. of Speed Data
Text-graphic	Alternative One	540
	Alternative Two	541
	Original	519
Graphic	Alternative One	536
	Alternative Two	540
Total		2,676

5.2.2 Driver Survey Data

A total of 454 driver surveys were conducted during field experiment Phase II, as shown in Table 5.2. All driver surveys were conducted under text-graphic PCMSs, including 149 under text-graphic PCMS Alternative One, 149 under text-graphic PCMS Alternative Two, and 156 under text-graphic PCMS Original. A sample of the driver survey data sheet in field experiment Phase II is attached in Appendix C.2.

Table 5.2 Summary of Driver Survey Data Collected in Field Experiment Phase II

Types of PCMS		No. of Driver Surveys
Text-graphic	Alternative One	149
	Alternative Two	149
	Original	156
Total		454

5.3 Data Analysis

5.3.1 Results of Speed Data Analyses

Collected vehicle speed data were analyzed using similar approaches and procedures as in field experiment Phase I. Speed data under each of the five PCMS conditions were analyzed first using descriptive statistics. Then, the percentages of speed reduction were compared among different PCMS conditions. The statistical significance of the differences was determined using independent two-sample t-tests, and finally, regression models were built to illustrate the mean speed reduction profiles under three text-graphic PCMS conditions.

5.3.1.1 Descriptive Statistics

1. Text-graphic PCMS Alternative One

Table 5.3 shows the detailed statistics of speed data under text-graphic PCMS Alternative One. For a total of 540 valid speed data, the minimum speed varied between 24 mph and 50 mph, while the maximum speed stayed over 80 mph. Speed range (maximum speed minus minimum speed) fluctuated between 37 mph and 56 mph. The mean speed decreased gradually from 67 mph at Sensor 1 to 59 mph at Sensor 4, and then kept steady at Sensor 5, while median speeds were 1 mph higher that mean speeds at Sensors 1 to 4. The 85th percentile speeds were about 5 to 7 mph higher than mean speeds, declining from 72 mph to 66 mph. The standard deviation ranged between 5.1 and 7.7.

Table 5.3 Descriptive Statistics of Speed Data under Text-graphic PCMS Alternative One

No.	No. of Data	Min. Speed (mph)	Max. Speed (mph)	Range (mph)	Mean Speed (mph)	Median Speed (mph)	85th Percentile (mph)	Standard Deviation
Sensor 1	540	50	87	37	67	68	72	5.1
Sensor 2	540	46	86	40	64	65	70	5.8
Sensor 3	540	38	82	44	63	64	69	6.7
Sensor 4	540	24	80	56	59	60	66	6.9
Sensor 5	540	30	81	51	59	59	66	7.7

A box plot gives a more detailed view of the distribution of the speed data. As illustrated in Figure 5.10, from the top to the bottom, the five horizontal lines represent the largest observation (sample maximum), upper quartile (the 75th percentile), median, lower quartile (the 25th percentile), and the smallest observation (sample minimum), respectively. Dots represent observations that are considered outliers. The maximum speed at Sensor 1 and minimum speed at Sensor 4, marked by asterisks, were considered extreme outliers.

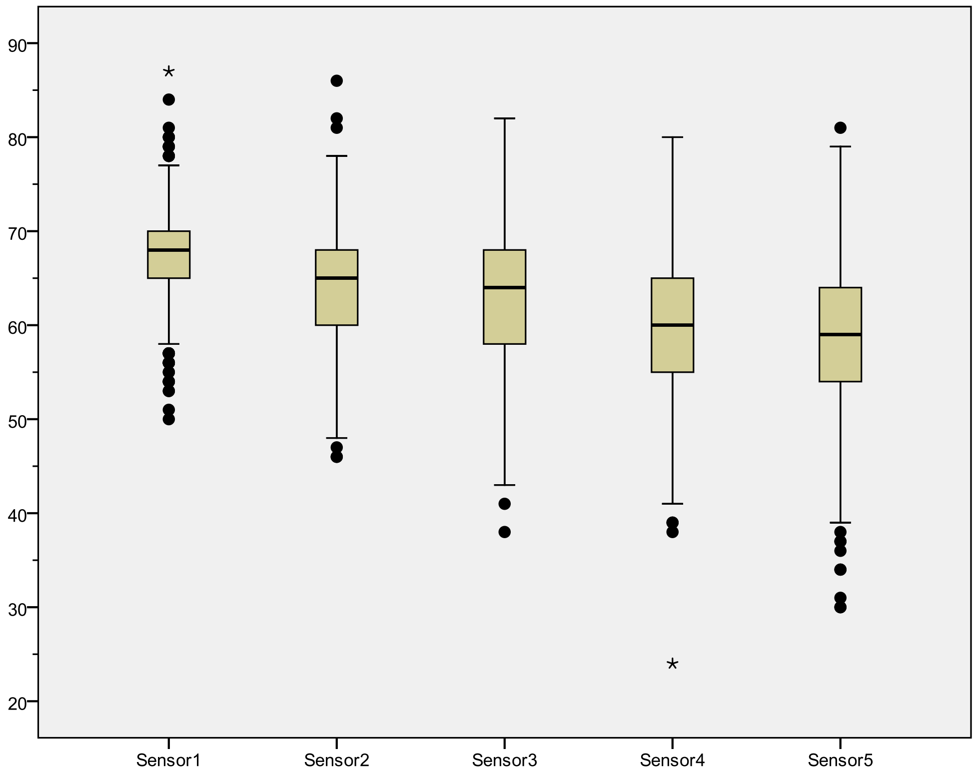

Figure 5.10 Box Plot of Speed Data under Text-graphic PCMS Alternative One

2. Text-graphic PCMS Alternative Two

Table 5.4 and Figure 5.11 display the statistics and box plot of speed data under text-graphic PCMS Alternative Two. For a total of 541 speed data, the minimum and maximum speed varied from 35 mph to 48 mph and from 75 mph to 81 mph, respectively, while the speed range changed between 33 mph and 44 mph. The mean speed reduced from 66 mph at Sensor 1 to 58 mph at Sensor 4, and then stayed the same at Sensor 5, while the median speeds were 1 mph higher than the mean speeds at Sensors 1 to 4. The 85th percentile speed decreased from 71 mph to 66 mph at Sensor 4, and then climbed by 1 mph at Sensor 5. The standard deviation ranged between 5.6 and 8.3.

Table 5.4 Descriptive Statistics of Speed Data under Text-graphic PCMS Alternative Two

No.	No. of Data	Min. Speed (mph)	Max. Speed (mph)	Range (mph)	Mean Speed (mph)	Median Speed (mph)	85th Percentile (mph)	Standard Deviation
Sensor 1	541	48	81	33	66	67	71	5.6
Sensor 2	541	35	79	44	63	64	69	6.2
Sensor 3	541	39	79	40	61	62	68	7.0
Sensor 4	541	36	75	39	58	59	66	6.9
Sensor 5	541	37	77	40	58	58	67	8.3

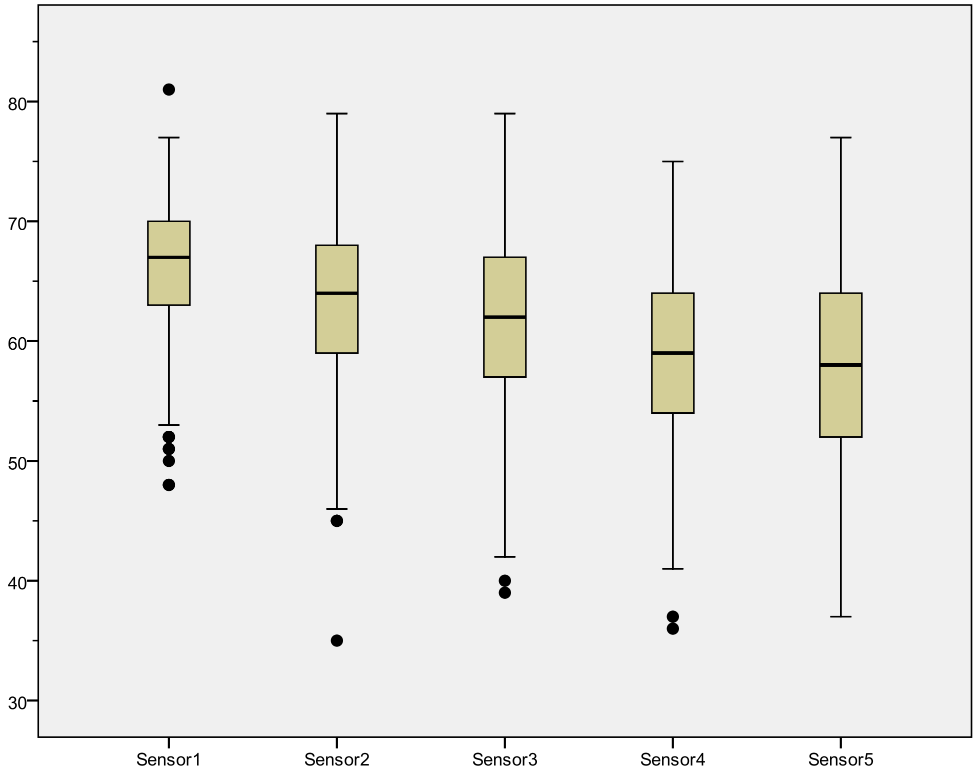

Figure 5.11 Box Plot of Speed Data under Text-graphic PCMS Alternative Two

3. Text-graphic PCMS Original

Table 5.5 and Figure 5.12 illustrate the statistics and box plot of speed data under text-graphic PCMS Original. For a total of 519 data, the minimum speed varied from 37 mph to 45 mph, and the maximum speed varied from 74 mph to 80 mph, while the speed range changed between 32 mph and 39 mph. The mean speed declined from 67 mph at Sensor 1 to 60 mph at Sensor 4, and again kept steady at Sensor 5, while the median speeds were 1 to 2 mph higher than the mean speeds at Sensors 1 to 3. The 85th percentile speed reduced from 72 mph to 66 mph at Sensor 4, and then increased slightly at Sensor 5. The standard deviation ranged between 5.2 and 6.8.

Table 5.5 Descriptive Statistics of Speed Data under Text-graphic PCMS Original

No.	No. of Data	Min. Speed (mph)	Max. Speed (mph)	Range (mph)	Mean Speed (mph)	Median Speed (mph)	85th Percentile (mph)	Standard Deviation
Sensor 1	519	45	80	35	67	68	72	5.2
Sensor 2	519	44	76	32	64	66	70	5.5
Sensor 3	519	37	76	39	63	64	69	6.3
Sensor 4	519	42	74	32	60	60	66	6.3
Sensor 5	519	38	77	39	60	60	67	6.8

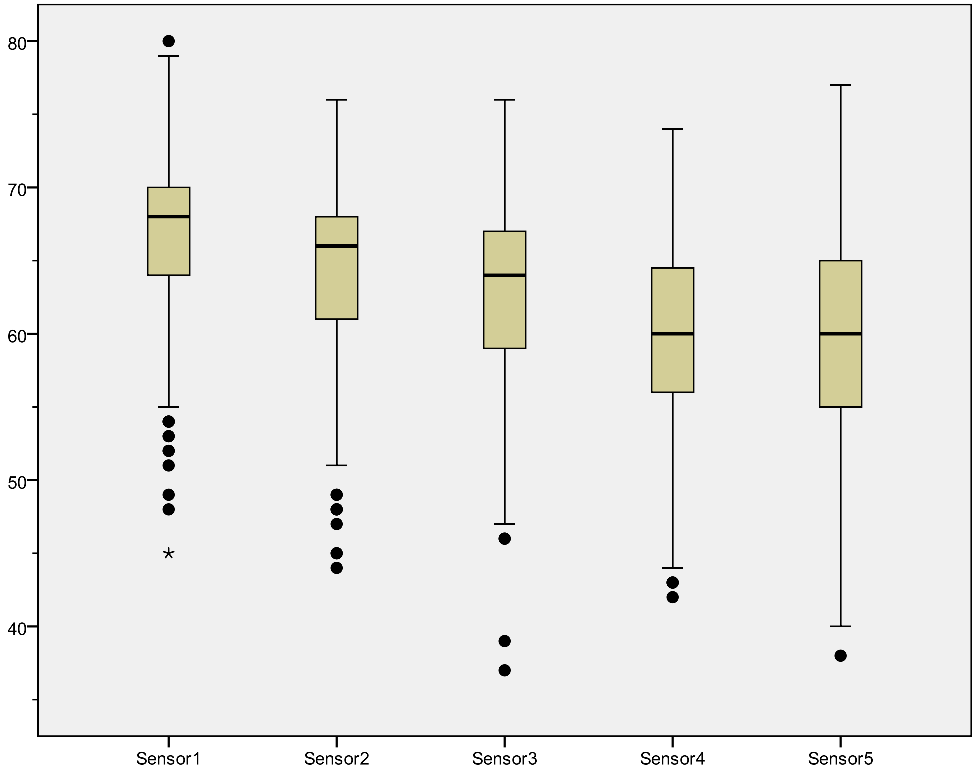

Figure 5.12 Box Plot of Speed Data under Text-graphic PCMS Original

4. Graphic PCMS Alternative One

In field experiment Phase II, speed data under text-graphic PCMSs and graphic PCMSs were collected at different locations. The location where speed data were collected under text-graphic PCMSs was straight and even, whereas the location where speed data were collected under graphic PCMSs had a slight downgrade between Sensor 1 and Sensor 2. Therefore, the statistics and box plots of speed data under graphic PCMSs have different profiles of speed reduction than those under text-graphic PCMSs.

Table 5.6 and Figure 5.13 show the statistics and box plot of speed data under graphic PCMS Alternative One. For a total of 536 data, the minimum and maximum speed varied from 34 mph to 45 mph and from 72 mph to 80 mph, respectively, while the speed range changed between 32 mph to 42 mph. The mean speed increased from 62 mph to 65 mph at Sensor 2, due to the downgrade, and then declined continuously to 53 mph at Sensor 5. Likewise, the median speed and 85th percentile speed increased from 63 mph and 67 mph to 66 mph and 71 mph at Sensor 2, and then dropped to 53 mph and 59 mph at Sensor 5, respectively. The standard deviation ranged between 5.3 and 6.9.

Table 5.6 Descriptive Statistics of Speed Data under Graphic PCMS Alternative One

No.	No. of Data	Min. Speed (mph)	Max. Speed (mph)	Range (mph)	Mean Speed (mph)	Median Speed (mph)	85th Percentile (mph)	Standard Deviation
Sensor 1	536	45	77	32	62	63	67	5.3
Sensor 2	536	41	80	39	65	66	71	6.3
Sensor 3	536	36	78	42	62	62	69	6.9
Sensor 4	536	39	74	35	57	58	64	6.3
Sensor 5	536	34	72	38	53	53	59	6.0

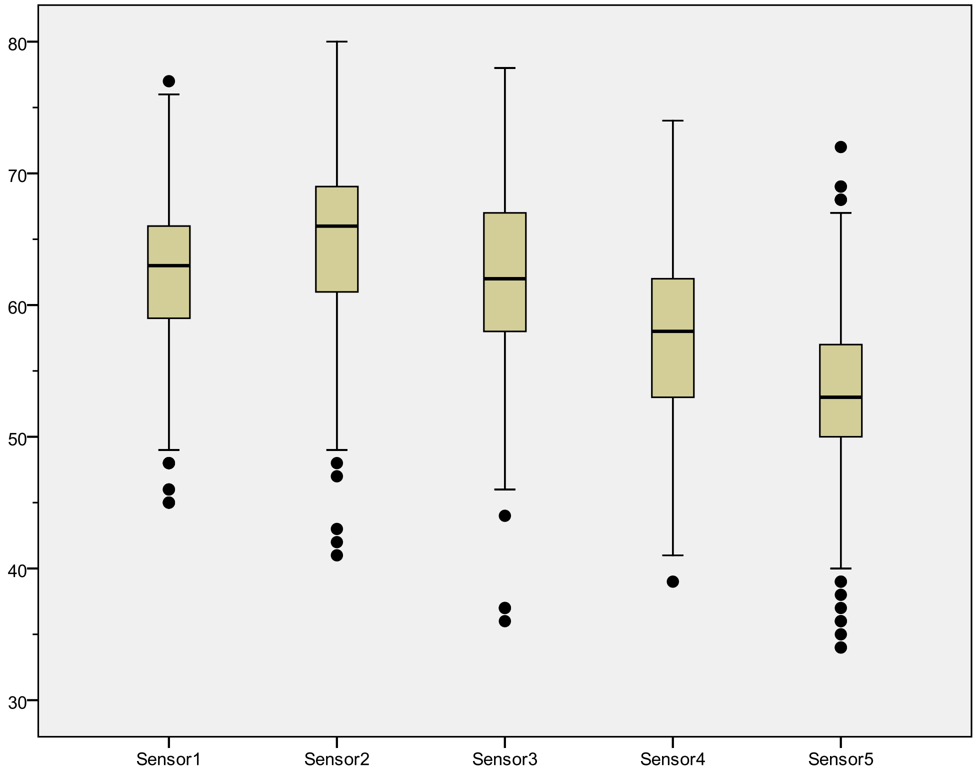

Figure 5.13 Box Plot of Speed Data under Graphic PCMS Alternative One

5. Graphic PCMS Alternative Two

Table 5.7 and Figure 5.14 present the statistics and box plot of speed data under graphic PCMS Alternative Two. For a total of 540 data, the minimum speed changed between 33 mph and 44 mph, the maximum speed varied from 73 mph to 88 mph, and the speed range was between 38 mph and 52 mph. The mean speed climbed from 62 mph at Sensor 1 to 64 mph at Sensor 2, again due to the downgrade, and then declined gradually to 53 mph at Sensor 5. The median speeds had 1 mph deviation from the mean speeds, and the 85th percentile speeds were about 5 to 7 mph higher than the mean speeds. The standard deviation ranged between 5.3 and 7.0.

Table 5.7 Descriptive Statistics of Speed Data under Graphic PCMS Alternative Two

No.	No. of Data	Min. Speed (mph)	Max. Speed (mph)	Range (mph)	Mean Speed (mph)	Median Speed (mph)	85th Percentile (mph)	Standard Deviation
Sensor 1	540	40	86	46	62	63	68	5.3
Sensor 2	540	44	88	44	64	65	71	6.3
Sensor 3	540	33	85	52	61	61	68	7.0
Sensor 4	540	38	82	44	57	56	64	6.5
Sensor 5	540	35	73	38	53	53	58	6.0

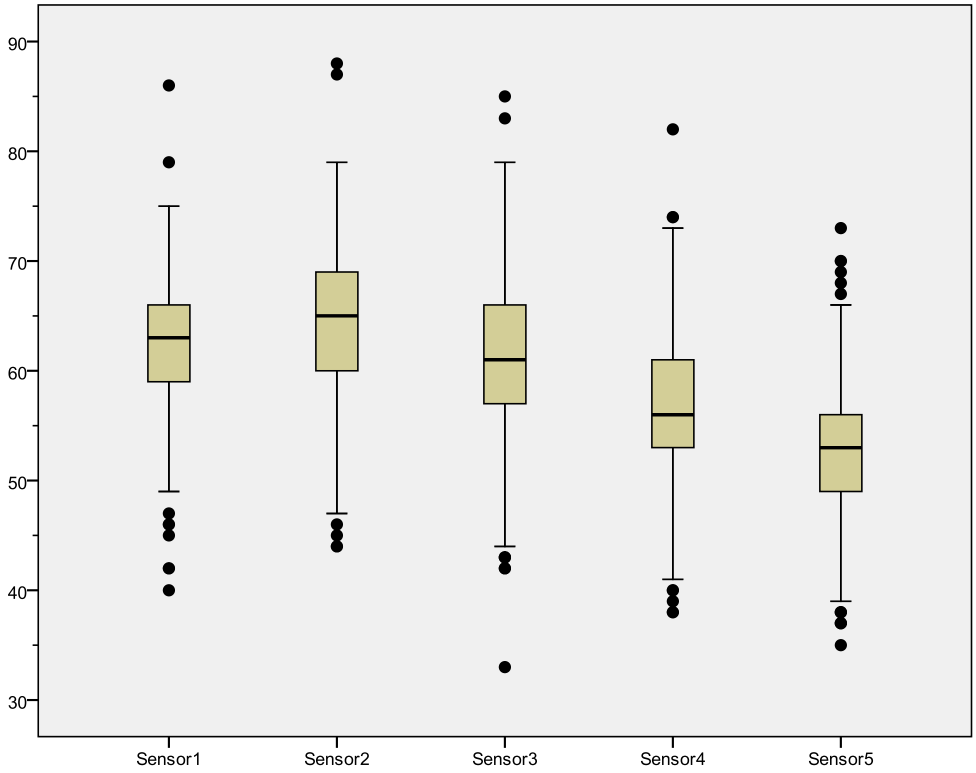

Figure 5.14 Box Plot of Speed Data under Graphic PCMS Alternative Two

5.3.1.2 Comparison Analyses

1. Mean Speed Reduction

Table 5.8 gives a summary of mean speed reduction under each PCMS condition in field experiment Phase II. Text-graphic PCMS Alternative One reduced mean vehicle speeds by 8 mph from 67 mph at Sensor 1 to 59 mph at Sensor 5, resulting in a 13% mean speed reduction. Text-graphic PCMS Alternative Two reduced mean vehicle speeds by 8 mph from 66 mph at Sensor 1 to 58 mph at Sensor 5, resulting in the same percentage of mean speed reduction as Alternative One. Text-graphic PCMS Original reduced mean vehicle speeds by 7 mph from 67 mph at Sensor 1 to 60 mph at Sensor 5, resulting in an 11% mean speed reduction. Figure 5.15 illustrates the mean speed reduction profiles under the three text-graphic PCMS conditions in field experiment Phase II.

Table 5.8 Summary of Mean Speed Reduction in Field Experiment Phase II

PCMS		Mean Speed (mph)					Speed Reduction	
Type	Graphic Displayed	S1	S2	S3	S4	S5	mph	%
Text-graphic	Alternative One	67	64	63	59	59	8	13%
	Alternative Two	66	63	61	58	58	8	13%
	Original	67	64	63	60	60	7	11%
Graphic	Alternative One	62	65	62	57	53	9	15%
	Alternative Two	62	64	61	57	53	9	15%

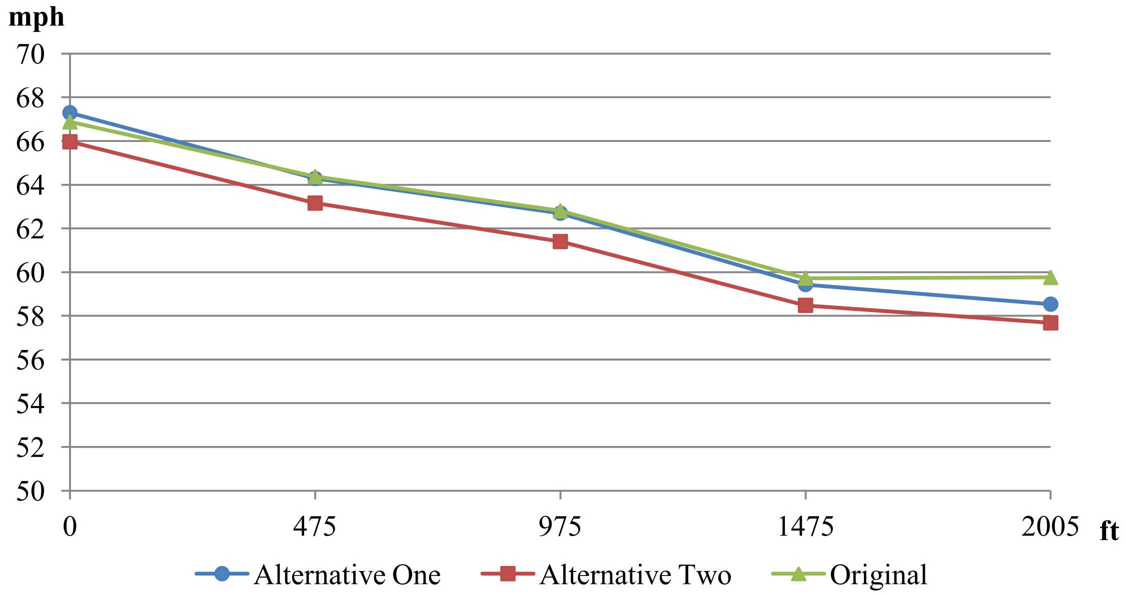

Figure 5.15 Mean Speed Reduction Profile under Text-graphic PCMSs in Field Experiment Phase II

The graphic PCMSs reduced mean vehicle speeds both by 9 mph from 62 mph at Sensor 1 to 53 mph at Sensor 5, resulting in the same percentage of mean speed reduction of 15%, as shown in Table 5.8. Figure 5.16 displays the mean speed reduction profiles under the two graphic PCMS conditions. Due to the downgrade of the experiment location, the speed reduction profiles under the two graphic PCMSs had upward trends from Sensor 1 to Sensor 2, which look differently than the speed reduction profiles under the three text-graphic PCMSs.

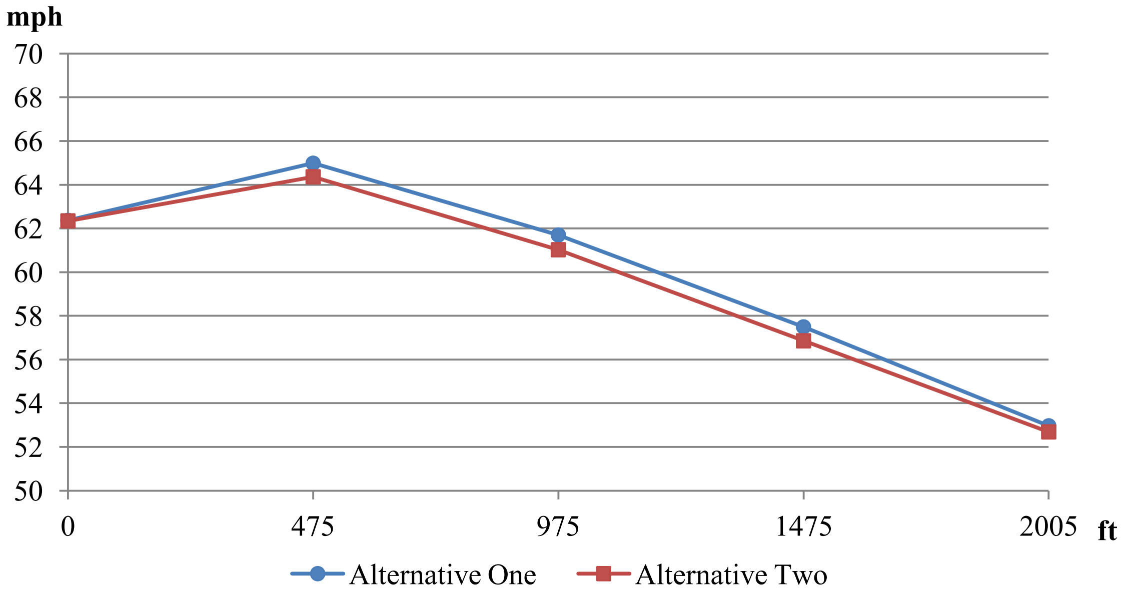

Figure 5.16 Mean Speed Reduction Profile under Graphic PCMSs in Field Experiment Phase II

Therefore, in terms of the percentage of mean speed reduction, text-graphic PCMSs Alternative One and Alternative Two had the same results of 13%, greater than 11% by text-graphic PCMS Original. Graphic PCMSs Alternative One and Alternative Two both resulted in the largest mean speed reduction of 15% among the five PCMSs in field experiment Phase II.

2. Equality of Mean Speeds

Independent two-sample t-tests were used to determine if the mean speeds at the same sensor location were statistically equal under different PCMS conditions. It was assumed that if the mean speeds were statistically equal at one sensor location, but not statistically equal at another sensor location under different PCMS conditions, the effectiveness of different PCMSs in reducing mean vehicle speeds would be different. In field experiment Phase II, one independent two-sample t-test was conducted to compare the mean vehicle speeds at each of the five sensors between every two text-graphic PCMSs and between the two graphic PCMSs. Therefore, 15 t-tests for vehicle speed data under text-graphic PCMSs and five t-tests for vehicle speed data under graphic PCMSs were conducted, making up a total of 20 independent 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:

$$H_0: \mu_1 = \mu_2$$

$$H_1: \mu_1 \neq \mu_2$$

where μ_1 = the mean speed at a sensor location under one PCMS condition; μ_2 = the mean speed at the same sensor location under another PCMS condition. In other words, the interpretation of the null hypothesis is that the mean speeds at a sensor location are statistically equal under the two compared PCMS conditions, and the alternative hypothesis is that the mean speeds at a sensor location are statistically unequal under 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 5.9 revealed the results of p-values of t-tests among the three text-graphic PCMSs and between the two graphic PCMSs. The results of t-tests between text-graphic PCMSs Alternative One and Alternative Two showed that the p-value at Sensor 5 was greater than 0.05, indicating that the mean vehicle speeds were statistically unequal at Sensors 1 to 4, but statistically equal at Sensor 5 under these two text-graphic PCMSs.

From Table 5.8 and Figure 5.15, it is clear that the mean speeds at Sensors 1 to 4 were higher under text-graphic PCMS Alternative One than Alternative Two. Therefore, text-graphic PCMS Alternative One was more effective in reducing mean vehicle speeds than text-graphic PCMS Alternative Two from 1,475 ft in the upstream of a work zone (location of Sensor 1) to the W20-4 sign (location of Sensor 5).

Table 5.9 P-Values of T-tests in Field Experiment Phase II

Location	Text-graphic PCMSs			Graphic PCMSs
	Alternative One vs. Alternative Two	Alternative One vs. Original	Alternative Two vs. Original	Alternative One vs. Alternative Two
Sensor 1	0.000	**0.188**	0.006	**0.948**
Sensor 2	0.002	**0.795**	0.001	**0.104**
Sensor 3	0.002	**0.793**	0.001	**0.111**
Sensor 4	0.023	**0.471**	0.002	**0.104**
Sensor 5	**0.079**	0.006	0.000	**0.448**

Likewise, the results of t-tests between text-graphic PCMSs Alternative One and Original showed that the p-values at Sensors 1 to 4 were greater than 0.05, indicating that the mean vehicle speeds were statistically equal at Sensors 1 to 4, but statistically unequal at Sensor 5 under these two PCMSs. From Table 5.8 and Figure 5.15, it is clear that the mean speed at Sensor 5 was lower under text-graphic PCMS Alternative One than text-graphic PCMS Original. Therefore, text-graphic PCMS Alternative One was more effective in reducing mean vehicle speeds than text-graphic PCMS Original from the beginning of a work zone (location of Sensor 4 and the W20-1 sign) to the W20-4 sign.

The results of t-tests between text-graphic PCMSs Alternative Two and Original showed that no p-value at the five sensors was greater than 0.05, indicating that the mean vehicle speeds were statistically unequal at all of the five sensors under these two PCMSs.

Therefore, the difference of effectiveness of text-graphic PCMS Alternative Two and text-graphic PCMS Original in reducing mean vehicle speeds could not be determined.

The results of t-tests between graphic PCMS Alternative One and Alternative Two showed that the p-values at all five sensors were greater than 0.05, indicating that the mean vehicle speeds were statistically equal at all of the five sensors under these two graphic PCMSs. Therefore, the effectiveness of graphic PCMSs Alternative One and Alternative Two in reducing mean vehicle speeds was statistically equal.

3. 85th Percentile Speed Reduction

Table 5.10 shows the summary of 85th percentile speed reduction in field experiment Phase II. The 85th percentile speed was reduced by 6 mph or 8% using text-graphic PCMS Alternative One, by 4 mph or 6% using text-graphic PCMS Alternative Two, and by 5 mph or 7% using text-graphic PCMS Original. The 85th percentile speed was reduced by 8 mph or 12% using graphic PCMS Alternative One and by 10 mph or 15% using graphic PCMS Alternative Two. The results indicated that using graphic PCMS Alternative Two reduced the 85th percentile speed more effectively than using the text-graphic PCMSs and graphic PCMS Alternative One.

Table 5.10 85th Percentile Speed Reduction in Field Experiment Phase II

PCMS		85th Percentile Speed (mph)					Speed Reduction	
Type	Graphic Displayed	S1	S2	S3	S4	S5	mph	%
Text-graphic	Alternative One	72	70	69	66	66	6	8%
	Alternative Two	71	69	68	66	67	4	6%
	Original	72	70	69	66	67	5	7%
Graphic	Alternative One	67	71	69	64	59	8	12%
	Alternative Two	68	71	68	64	58	10	15%

5.3.1.3 Regression Analyses

Based on the results of data analysis in field experiment Phase II, linear regression models were developed to illustrate the relationship between the mean vehicle speeds and the distance from Sensor 1 location to a vehicle under three text-graphic PCMSs.

The general function of a linear regression model is

$$y = a_0 + a_1 x$$

where y = the mean vehicle speed, x = the distance from Sensor 1 to a vehicle in the upstream of a work zone, as shown in Figure 5.8, a_0 = the mean speed at Sensor 1, which is the initial speed, and a_1 = the reduction rate of the mean speed in mph/ft.

A linear regression model (R^2 = 0.928) describing the mean vehicle speed profile in the upstream of a work zone under text-graphic PCMS Alternative One is

$$y = 66.52 - 0.00428\ x \tag{5.1}$$

A linear regression model (R^2 = 0.934) describing the mean vehicle speed profile in the upstream of a work zone under text-graphic PCMS Alternative Two is

$$y = 65.31 - 0.00427\ x \tag{5.2}$$

A linear regression model (R^2 = 0.923) describing the mean vehicle speed profile in the upstream of a work zone under text-graphic PCMS Original is

$$y = 66.32 - 0.00358\ x \tag{5.3}$$

Figure 5.17 illustrates the linear regression models of mean speed reduction under three text-graphic PCMSs. According to the linear regression models, text-graphic PCMS Alternative One resulted in the largest mean speed reduction rate of 0.00428 mph/ft, followed by a slightly smaller mean speed reduction rate of 0.00427 mph/ft under text-graphic PCMS Alternative Two. Text-graphic PCMS Original resulted in the smallest mean speed reduction rate of 0.00358 mph/ft. Using these linear regression models, the mean vehicle speed at any location from 1,475 ft in the upstream of a work zone to the location of the W20-4 sign under each text-graphic PCMS condition could be predicted.

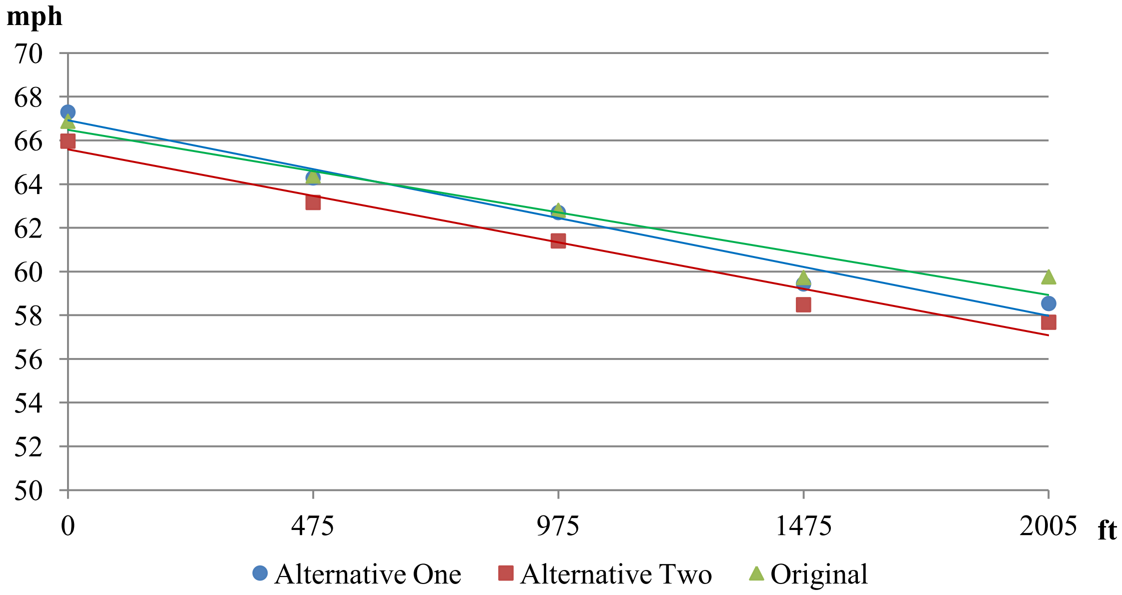

Figure 5.17 Linear Regression Models of Mean Speed Reduction under Text-graphic PCMSs

5.3.2 Results of Driver Survey Analyses

In field experiment Phase II, a total of 454 driver surveys were conducted under the three text-graphic PCMSs to identify drivers' perception of the two alternative work zone graphics, in comparison with the original work zone graphic.

5.3.2.1 Driver Survey Results

1. Text-graphic PCMS Alternative One

149 drivers participated in the surveys under text-graphic PCMS Alternative One. The results are described as follows.

Question 1: *Did you see a **graphic** displayed on the Portable Changeable Message Sign (PCMS) when you were approaching the work zone?* 139 drivers (93%) responded *Yes* and they answered the remaining survey questions. Drivers who did not see the PCMS ended their surveys after Question 1. The reasons why drivers did not see the PCMS could be that they turned onto the highway after the PCMS, their sights were interfered by sun glare, or they did not pay attention to the surroundings of the highway.

Question 2: *How did you interpret the meaning of this graphic?* All drivers (139 out of 139) selected *Work zone/Work zone ahead/Someone working*.

Question 3: *Did you think that the **graphic** drew your attention more to the work zone traffic conditions?* 89% of drivers (124 out of 139) selected *Yes* and 3% of drivers selected *No*; the remaining 8% answered *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 5.18, 11% of drivers preferred the text format; 32% of drivers chose the text-graphic format; 36% of drivers liked the graphic format; 14% of respondents thought there was no difference between the text format and the graphic format; the remaining 7% did not care about the message format.

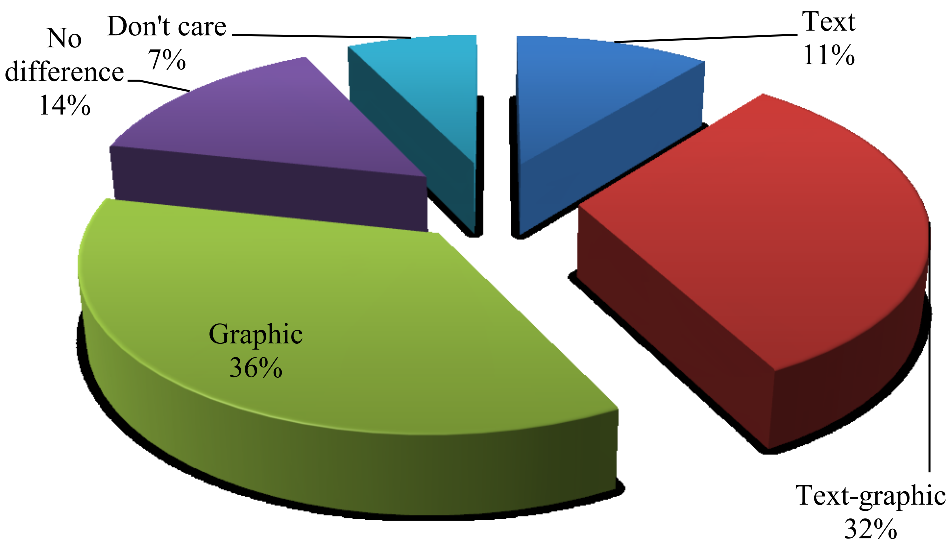

Figure 5.18 Drivers' Preferences to Message Format under Text-graphic PCMS Alternative One

2. Text-graphic PCMS Alternative Two

149 driver surveys were conducted under text-graphic PCMS Alternative Two. The 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?* 140 drivers (94%) responded *Yes* and continued the survey.

Question 2: *How did you interpret the meaning of this graphic?* All drivers (140 out of 140) selected *Work zone/Work zone ahead/Someone working*.

Question 3: *Did you think that the* ***graphic*** *drew your attention more to the work zone traffic conditions?* 83% of drivers (116 out of 140) selected *Yes* and 12% of drivers selected *No*; the remaining 5% answered *Don't know*.

Question 4: *Do you prefer the warning signs to be displayed in the graphical format or text format?* The results are illustrated in Figure 5.19. 8% of drivers preferred the text format; 36% of drivers chose the text-graphic format; 28% of drivers liked the graphic format; 14% of respondents thought there was no difference between the text format and the graphic format; another 14% did not care about the message format.

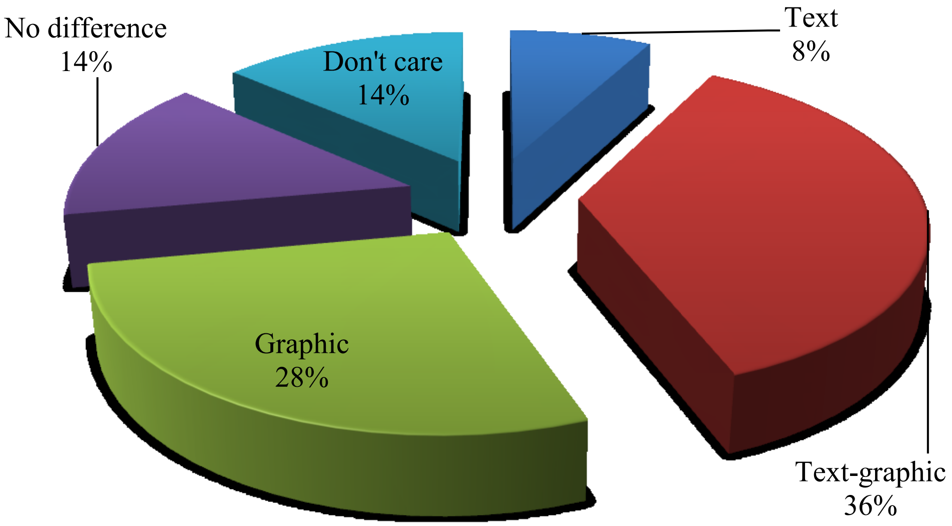

Figure 5.19 Drivers' Preferences to Message Format under Text-graphic PCMS Alternative Two

3. Text-graphic PCMS Original

156 drivers responded to the surveys under text-graphic PCMS Original. The driver survey results are described as follows.

Question 1: *Did you see a **graphic** displayed on the Portable Changeable Message Sign (PCMS) when you were approaching the work zone?* 150 drivers (96%) responded *Yes* and they continued the survey.

Question 2: *How did you interpret the meaning of this graphic?* 87% of drivers (130 out of 150) selected *Work zone/Work zone ahead/Someone working*; 9% of drivers, however, got confused about the original work zone graphic, and the other 5% did not understand the meaning of this graphic.

Question 3: *Did you think that the **graphic** drew your attention more to the work zone traffic conditions?* 72% of drivers (108 out of 150) selected *Yes* and 22% of drivers selected *No*; the remaining 6% answered *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 5.20, about a quarter of drivers preferred the text format (25%), the text-graphic format (27%), and the graphic format (26%), respectively. 15% of respondents thought there was no difference between the text format and the graphic format; 5% did not care about the message format and the remaining 2% chose *Don't know*.

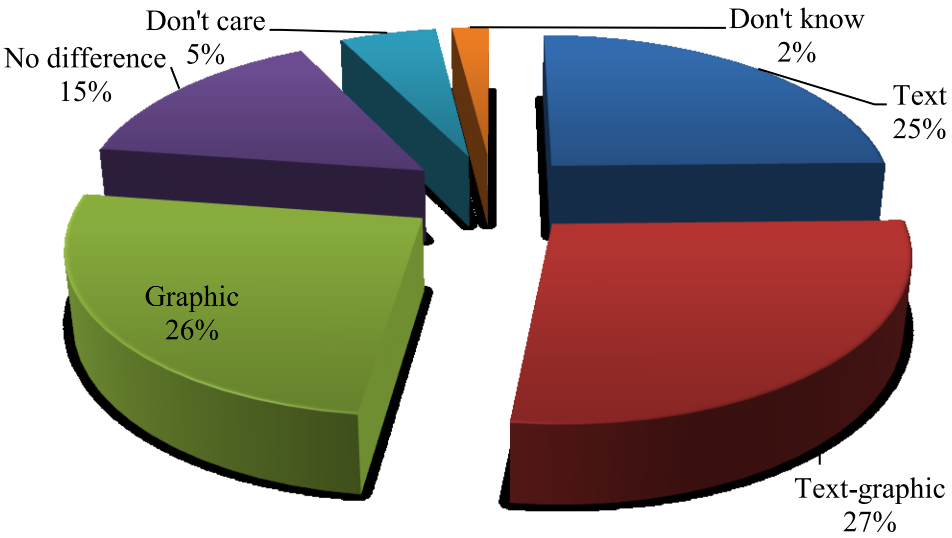

Figure 5.20 Drivers' Preferences to Message Format under Text-graphic PCMS Original

5.3.2.2 Comparison Analyses

Chi-square tests of independence were used to determine the independence of drivers' answers to each question under different text-graphic PCMS conditions. If drivers' answers to a question are statistically independent of different PCMSs, then different text-graphic PCMSs would have no impact on drivers' answers to the question, which means the distribution of drivers' answers would be statistically the same under the compared text-graphic PCMSs. If drivers' answers to a question are not statistically independent of different PCMSs, then different text-graphic PCMSs would have an impact on drivers' answers to the question, which means the distribution of drivers' answers would not be statistically the same under the compared text-graphic PCMSs.

In the Chi-square tests of independence, the null hypothesis (H_0) and the alternative hypothesis (H_1) were defined as:

H_0: Drivers' answers to a question are statistically independent

of different text-graphic PCMSs

H_1: Drivers' answers to a question are not statistically independent

of different text-graphic PCMSs

In other words, the interpretation of the null hypothesis is that the distribution of drivers' answers to a question is statistically equal under the compared text-graphic PCMSs, and the alternative hypothesis is that the distribution of drivers' answers to a question is statistically unequal under the compared text-graphic PCMSs. A 95% level of confidence was used in the Chi-square tests, and a p-value no greater than 0.05 would indicate that the null hypothesis could be confidently rejected.

1. Drivers' Recognition of Graphics on PCMSs

Table 5.11 shows the comparison of drivers' recognition of graphics on three text-graphic PCMSs. 93% (139 out of 149), 94% (140 out of 149), and 96% (150 out of 156) of drivers recognized the graphics on text-graphic PCMSs Alternative One, Alternative Two, and Original, respectively. The result of Chi-square test of independence is presented in Table 5.12. The p-value of 0.516 indicated that drivers' recognition of graphics was statistically independent of different text-graphic PCMSs, suggesting that the distribution of drivers' answers to their recognition of graphics were statistically the same under three text-graphic PCMSs. Therefore, there was no statistically significant difference among drivers' recognition of graphics under the three text-graphic PCMSs.

Table 5.11 Comparison of Drivers' Recognition of Graphics on Text-graphic PCMSs

Drivers' Recognition of Graphics on PCMSs		Text-graphic PCMSs			Total
		Alternative One	Alternative Two	Original	
Yes	Count	139	140	150	429
	Expected Count	140.8	140.8	147.4	429.0
	Percentage	93%	94%	96%	94%
No	Count	10	9	6	25
	Expected Count	8.2	8.2	8.6	25.0
	Percentage	7%	6%	4%	6%
Total	Count	149	149	156	454
	Expected Count	149.0	149.0	156.0	454.0
	Percentage	100%	100%	100%	100%

Table 5.12 Test of Independence on Drivers' Recognition of Text-graphic PCMSs

Drivers' Recognition of Graphics on PCMSs	Value	df	Asymp. Sig. (2-sided)
Pearson Chi-Square	1.324	2	.516
Likelihood Ratio	1.388	2	.499
Linear-by-Linear Association	1.210	1	.271
N of Valid Cases	454		

2. Drivers' Understanding of the Meaning of Graphics on PCMS

Table 5.13 displays the comparison of drivers' understanding of graphics under three text-graphic PCMSs. All drivers successfully interpreted two alternative work zone graphics, while 87% of drivers correctly understood the original work zone graphic. The result of Chi-square test in Table 5.14 showed a p-value of 0.000, suggesting a statistical difference of the answers to drivers' understanding of the three graphics on text-graphic PCMSs. Since drivers' understanding of the two alternative work zone graphics were the exactly same at 100%, the difference apparently came from the original work zone graphic, which was understood by 87% of drivers.

Table 5.13 Comparison of Drivers' Understanding of Graphics on Text-graphic PCMSs

Drivers' Understanding of Graphics on PCMS		Text-graphic PCMSs Alternative One	Alternative Two	Original	Total
Work Zone	Count	139	140	130	409
	Expected Count	132.5	133.5	143.0	409.0
	Percentage	100%	100%	87%	95%
Confused	Count	0	0	13	13
	Expected Count	4.2	4.2	4.5	13.0
	Percentage	0%	0%	9%	3%
Don't Know	Count	0	0	7	7
	Expected Count	2.3	2.3	2.4	7.0
	Percentage	0%	0%	5%	2%
Total	Count	139	140	150	429
	Expected Count	139.0	140.0	150.0	429.0
	Percentage	100%	100%	100%	100%

Table 5.14 Test of Independence on Drivers' Understanding of Graphics on Text-graphic PCMSs

Drivers' Understanding of Graphics on PCMS	Value	df	Asymp. Sig. (2-sided)
Pearson Chi-Square	39.019	4	.000
Likelihood Ratio	43.879	4	.000
Linear-by-Linear Association	26.106	1	.000
N of Valid Cases	429		

3. Effectiveness of PCMS in Drawing Drivers' Attention

Table 5.15 presents the comparison of the effectiveness of three text-graphic PCMSs in drawing drivers' attention. 89%, 83%, and 72% of drivers believed they paid more attention to the traffic conditions after seeing text-graphic PCMSs Alternative One, Alternative Two, and Original, respectively.

Table 5.15 Comparison of Effectiveness of Text-graphic PCMSs in Drawing Drivers' Attention

Effectiveness of PCMSs in Drawing Drivers' Attention		Text-graphic PCMSs			Total
		Alternative One	Alternative Two	Original	
Yes	Count	124	116	108	348
	Expected Count	112.8	113.6	121.7	348.0
	Percentage	89%	83%	72%	81%
No	Count	15	24	42	81
	Expected Count	26.2	26.4	28.3	81.0
	Percentage	11%	17%	28%	19%
Total	Count	139	140	150	429
	Expected Count	139.0	140.0	150.0	429.0
	Percentage	100%	100%	100%	100%

The p-value of 0.001 in Table 5.16 suggested that the effectiveness of PCMSs in drawing drivers' attention was not statistically independent of different text-graphic PCMSs, and that the distribution of drivers' answers to this question were not statistically the same. Further Chi-square tests were conducted to compare the effectiveness of PCMSs in drawing drivers' attention between each two different text-graphic PCMSs, the results of which are shown in Table 5.17, Table 5.18, and Table 5.19. When comparing the effectiveness in drawing drivers' attention between text-graphic PCMSs Alternative One and the Alternative Two, the p-value of 0.126 suggested that drivers' answers were statistically the same; when comparing text-graphic PCMS Alternative One or Alternative Two with text-graphic PCMS Original, the p-values of 0.000 or 0.028 suggested that drivers' answers under either of the two alternative text-graphic PCMSs were not statistically the same as the drivers' answers under text-graphic PCMS Original. Therefore, it was concluded that there was no statistically significant difference between the effectiveness of text-graphic PCMSs Alternative One and Alternative Two in drawing drivers' attention, and both were statistically more effective than text-graphic PCMS Original.

Table 5.16 Test of Independence on Effectiveness of Text-graphic PCMSs in Drawing Drivers' Attention

Effectiveness of PCMS in Drawing Drivers' Attention	Value	df	Asymp. Sig. (2-sided)
Pearson Chi-Square	14.359	2	.001
Likelihood Ratio	14.418	2	.001
Linear-by-Linear Association	14.014	1	.000
N of Valid Cases	429		

Table 5.17 Test of Independence on Effectiveness of Text-graphic PCMSs Alternative One and Alternative Two in Drawing Drivers' Attention

Alternative One vs. Alternative Two	Value	df	Asymp. Sig. (2-sided)
Pearson Chi-Square	2.340	1	.126
Likelihood Ratio	2.359	1	.125
Linear-by-Linear Association	2.332	1	.127
N of Valid Cases	279		

Table 5.18 Test of Independence on Effectiveness of Text-graphic PCMSs Alternative One and Original in Drawing Drivers' Attention

Alternative One vs. Original	Value	df	Asymp. Sig. (2-sided)
Pearson Chi-Square	13.494	1	.000
Likelihood Ratio	14.002	1	.000
Linear-by-Linear Association	13.447	1	.000
N of Valid Cases	289		

Table 5.19 Test of Independence on Effectiveness of Text-graphic PCMSs Alternative Two and Original in Drawing Drivers' Attention

Alternative Two vs. Original	Value	df	Asymp. Sig. (2-sided)
Pearson Chi-Square	4.856	1	.028
Likelihood Ratio	4.913	1	.027
Linear-by-Linear Association	4.839	1	.028
N of Valid Cases	290		

4. Drivers' Preferences to Message Format on PCMS

Table 5.20 details the comparison of drivers' preferences to message format under three text-graphic PCMSs. Text format was preferred by 11% and 8% of drivers under text-graphic PCMSs Alternative One and Alternative Two, respectively, and by 25% of drivers under text-graphic PCMS Original. Text-graphic format was chosen by 32%, 36%, and 27% of drivers under the three text-graphic PCMSs, respectively, while graphic format gained 36%, 28%, and 25% of drivers' selection under the three text-graphic PCMSs. About 15% of drivers did not believe any difference between text and graphic formats under each of the text-graphic PCMSs. The rest of drivers either did not care about the message format on PCMS or did not know which format to choose. Text-graphic and graphic formats were preferred by the majority of drivers over text format under text-graphic PCMSs Alternative One and Alternative Two, because the alternative work zone graphics were correctly understood by all drivers. Three formats were selected by a similar percentage of drivers (around a quarter) under text-graphic PCMS Original, mostly because the original work zone graphic had confused some drivers and made them believe that text was easier to understand than the original work zone graphic.

Table 5.20 Comparison of Driver's Preferences to Message Format under Text-graphic PCMSs

Drivers' Preferences to Message Format on PCMS		Text-graphic PCMSs			Total
		Alternative One	Alternative Two	Original	
Text	Count	15	11	37	63
	Expected Count	20.4	20.6	22.0	63.0
	Percentage	11%	8%	25%	15%
Text-graphic	Count	44	51	41	136
	Expected Count	44.1	44.4	47.6	136.0
	Percentage	32%	36%	27%	32%
Graphic	Count	50	39	38	127
	Expected Count	41.1	41.4	44.4	127.0
	Percentage	36%	28%	25%	30%
No Difference	Count	20	20	23	63
	Expected Count	20.4	20.6	22.0	63.0
	Percentage	14%	14%	15%	15%
Don't Care	Count	10	19	8	37
	Expected Count	12.0	12.1	12.9	37.0
	Percentage	7%	14%	5%	9%
Don't Know	Count	0	0	3	3
	Expected Count	1.0	1.0	1.0	3.0
	Percentage	0%	0%	2%	1%
Total	Count	139	140	150	429
	Expected Count	139.0	140.0	150.0	429.0
	Percentage	100%	100%	100%	100%

The p-value of 0.000 in Table 5.21 suggested that drivers' preferences to message format were not statistically independent of different text-graphic PCMSs, and that drivers' preferences to message format were not statistically the same under different text-graphic PCMSs. Further Chi-square tests were conducted to compare drivers' preferences to message format between each two different text-graphic PCMSs, and the results of which are shown in Table 5.22, Table 5.23, and Table 5.24. When comparing drivers' preferences to message format between text-graphic PCMSs Alternative One and Alternative Two, the p-value of 0.260 suggested that drivers' answers were statistically the same; when comparing text-graphic PCMSs Alternative One or Alternative Two with text-graphic PCMS Original, the p-values of 0.015 or 0.000 suggested that drivers' answers under either of the two alternative text-graphic PCMSs were not statistically the same as the drivers' answers under text-graphic PCMS Original. Therefore, it was concluded that 1) there was no statistically significant difference between drivers' preferences to message format under text-graphic PCMSs Alternative One and Alternative Two; and 2) drivers' preferences to message format under text-graphic PCMSs Alternative One and Alternative Two were statistically different than drivers' preferences to message format under text-graphic PCMS Original. In other words, text format was preferred by significantly fewer drivers under text-graphic PCMSs Alternative One and Alternative Two than under text-graphic PCMS Original; text-graphic and graphic formats were preferred by significantly more drivers under text-graphic PCMSs Alternative One and Alternative Two than under text-graphic PCMS Original.

Table 5.21 Test of Independence on Driver's Preferences to Message Format under Text-graphic PCMSs

Drivers' Preferences to Message Format on PCMS	Value	df	Asymp. Sig. (2-sided)
Pearson Chi-Square	32.750	10	.000
Likelihood Ratio	32.443	10	.000
Linear-by-Linear Association	.414	1	.520
N of Valid Cases	429		

Table 5.22 Test of Independence on Driver's Preferences to Message Format under Text-graphic PCMSs Alternative One and Alternative Two

Alternative One vs. Alternative Two	Value	df	Asymp. Sig. (2-sided)
Pearson Chi-Square	5.280	4	.260
Likelihood Ratio	5.333	4	.255
Linear-by-Linear Association	3.943	1	.047
N of Valid Cases	279		

Table 5.23 Test of Independence on Driver's Preferences to Message Format under Text-graphic PCMSs Alternative One and Original

Alternative One vs. Original	Value	df	Asymp. Sig. (2-sided)
Pearson Chi-Square	14.083	5	.015
Likelihood Ratio	15.527	5	.008
Linear-by-Linear Association	.490	1	.484
N of Valid Cases	289		

Table 5.24 Test of Independence on Driver's Preferences to Message Format under Text-graphic PCMSs Alternative Two and Original

Alternative Two vs. Original	Value	df	Asymp. Sig. (2-sided)
Pearson Chi-Square	22.556	5	.000
Likelihood Ratio	24.609	5	.000
Linear-by-Linear Association	1.871	1	.171
N of Valid Cases	290		

5.3.2.3 Independence Analyses

Chi-square tests of independence were used to determine the relationship between drivers' gender and age and their preferences to message format on PCMS. If drivers' gender and age are statistically independent of their preferences to message format, then drivers in all gender and age groups would have statistically the same preferences to message format on PCMS; otherwise, drivers in different gender and age groups would have different preferences to message format on PCMS.

In the Chi-square tests of independence, the null hypothesis (H_0) and the alternative hypothesis (H_1) were defined as:

H_0: *Drivers' gender or age is statistically independent*

of their preferences to message format.

H_1: *Drivers' gender or age is not statistically independent*

of their preferences to message format.

In other words, the interpretation of the null hypothesis is that drivers in all gender or age groups have statistically the same preferences to message format on PCMS, and the alternative hypothesis is that drivers in different gender or age groups have different preferences to message format on PCMS. A 95% level of confidence was used in the Chi-square tests, and a p-value no greater than 0.05 would indicate that the null hypothesis could be confidently rejected.

1. Drivers' Gender and Drivers' Preferences to Message Format

(1) Text-graphic PCMS Alternative One

78 male drivers (56%) and 61 female drivers (44%) took the survey under text-graphic PCMS Alternative One, and their preferences are detailed in Table 5.25. A similar percentage of male and female drivers chose the text format (10% to 12%) and *No difference* (14% to 15%). On the other side, about 13% more female drivers preferred the

text-graphic format, and 23% more male drivers liked the graphic format, which doubled the percentage of female drivers selecting this category. The p-value of Chi-square test of 0.041 in Table 5.26 revealed that drivers' gender was not statistically independent of their preferences to message format, suggesting that male and female drivers' preferences to text-graphic and graphic format were significantly different, and that more female drivers preferred the text-graphic format and more male drivers preferred the graphic format under text-graphic PCMS Alternative One.

Table 5.25 Drivers' Preferences to Message Format Associated with Drivers' Gender under Text-graphic PCMS Alternative One

Drivers' Preferences to Message Format under Alternative One		Gender		Total
		Male	Female	
Text	Count	8	7	15
	Expected Count	8.4	6.6	15.0
	Percentage	10%	12%	11%
Text-graphic	Count	20	24	44
	Expected Count	24.7	19.3	44.0
	Percentage	26%	39%	32%
Graphic	Count	36	14	50
	Expected Count	28.1	21.9	50.0
	Percentage	46%	23%	36%
No Difference	Count	11	9	20
	Expected Count	11.2	8.8	20.0
	Percentage	14%	15%	14%
Don't Care	Count	3	7	10
	Expected Count	5.6	4.4	10.0
	Percentage	4%	11%	7%
Total	Count	78	61	139
	Expected Count	78.0	61.0	139.0
	Percentage	100%	100%	100%

Table 5.26 Test of Independence on Drivers' Preferences to Message Format and Gender under Text-graphic PCMS Alternative One

Drivers' Preferences vs. Gender under Alternative One	Value	df	Asymp. Sig. (2-sided)
Pearson Chi-Square	9.980	4	.041
Likelihood Ratio	10.212	4	.037
Linear-by-Linear Association	7.518	1	.006
N of Valid Cases	139		

(2) Text-graphic PCMS Alternative Two

101 male drivers (72%) and 39 female drivers (28%) participated in the survey under text-graphic PCMS Alternative Two, the details of which are presented in Table 5.27. The preferences of male and female drivers to the text, text-graphic, and graphic format were similar measured in percentage. The percentage of male and female drivers who chose *No difference* and *Don't know* varied within a small range as well. The p-value of Chi-square test of 0.957 in Table 5.28 suggested that drivers' gender was statistically independent of their preferences to message format, and that male and female drivers' preferences to message format were statistically the same under text-graphic PCMS Alternative Two.

Table 5.27 Drivers' Preferences to Message Format Associated with Drivers' Gender under Text-graphic PCMS Alternative Two

Drivers' Preferences to Message Format under Alternative Two		Gender		Total
		Male	Female	
Text	Count	8	3	11
	Expected Count	7.9	3.1	11.0
	Percentage	8%	8%	8%
Text-graphic	Count	37	14	51
	Expected Count	36.8	14.2	51.0
	Percentage	37%	36%	36%
Graphic	Count	27	12	39
	Expected Count	28.1	10.9	39.0
	Percentage	27%	31%	28%
No Difference	Count	14	6	20
	Expected Count	14.4	5.6	20.0
	Percentage	14%	15%	14%
Don't Care	Count	15	4	19
	Expected Count	13.7	5.3	19.0
	Percentage	14.9%	10.3%	13.6%
Total	Count	101	39	140
	Expected Count	101.0	39.0	140.0
	Percentage	100%	100%	100%

Table 5.28 Test of Independence on Drivers' Preferences to Message Format and Gender under Text-graphic PCMS Alternative Two

Drivers' Preferences vs. Gender under Alternative Two	Value	df	Asymp. Sig. (2-sided)
Pearson Chi-Square	.654	4	.957
Likelihood Ratio	.676	4	.954
Linear-by-Linear Association	.367	1	.544
N of Valid Cases	140		

(3) Text-graphic PCMS Original

109 male drivers (73%) and 41 female drivers (27%) responded to the survey under text-graphic PCMS Original. Table 5.29 shows the details of male and female drivers' preferences to message format. Around 10% more female drivers liked the text format, about 7% more of male drivers chose the text-graphic format, and around 25% of male and female drivers preferred the graphic format. The difference of male and female drivers who selected other options varied within a small range of 4%. The p-value of Chi-square test of 0.730 in Table 5.30 again indicated that drivers' gender was statistically independent of their preferences to message format, and that male and female drivers' preferences to message format were statistically the same under text-graphic PCMS Original.

Table 5.29 Drivers' Preferences to Message Format Associated with Drivers' Gender under Text-graphic PCMS Original

Drivers' Preferences to Message Format under Original Graphic		Gender		Total
		Male	Female	
Text	Count	24	13	37
	Expected Count	26.9	10.1	37.0
	Percentage	22%	32%	25%
Text-graphic	Count	32	9	41
	Expected Count	29.8	11.2	41.0
	Percentage	29%	22%	27%
Graphic	Count	28	10	38
	Expected Count	27.6	10.4	38.0
	Percentage	26%	24%	25%
No Difference	Count	16	7	23
	Expected Count	16.7	6.3	23.0
	Percentage	15%	17%	15%
Don't Care	Count	7	1	8
	Expected Count	5.8	2.2	8.0
	Percentage	6%	2%	5%
Don't Know	Count	2	1	3
	Expected Count	2.2	.8	3.0
	Percentage	2%	2%	2%
Total	Count	109	41	150
	Expected Count	109.0	41.0	150.0
	Percentage	100%	100%	100%

Table 5.30 Test of Independence on Drivers' Preferences to Message Format and Gender under Text-graphic PCMS Original

Drivers' Preferences vs. Gender under Original Graphic	Value	df	Asymp. Sig. (2-sided)
Pearson Chi-Square	2.804	5	.730
Likelihood Ratio	2.919	5	.712
Linear-by-Linear Association	.215	1	.643
N of Valid Cases	150		

2. Drivers’ Age and Drivers’ Preferences to Message Format

(1) Text-graphic PCMS Alternative One

The age distribution of drivers who participated in surveys under text-graphic PCMS Alternative One is illustrated in Figure 5.21. The two largest age groups were 25−34 and 35−44, which accounted for 24% and 22%, respectively, followed by 45−54, 55−64, and over 65. Young drivers below 25 were less than 10% of all respondents in each of the two age groups.

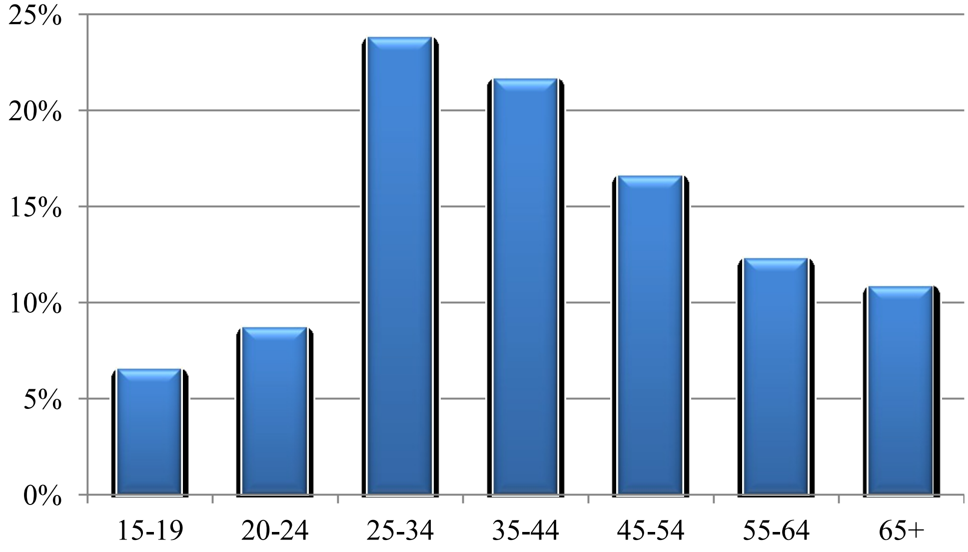

Figure 5.21 Distribution of Drivers’ Age under Text-graphic PCMS Alternative One

The detailed drivers’ preferences to message format associated with their age group under text-graphic PCMS Alternative One are presented in Table 5.31. Around 10% to 13% of drivers in all age groups preferred the text format except for drivers in 20−24. The percentage of drivers in favor of the text-graphic format varied between 20% and

44%; around 30% to 47% of drivers in different age groups chose the graphic format. The percentage of drivers seeing no difference in message formats varied between 0% and 33%. The p-value of Chi-square test of 0.763 in Table 5.32 suggested that the difference of percentages between each age group was not significant, and that drivers' preferences to message format were statistically independent of their age group. Therefore, drivers' age groups did not have significant impact on their preferences to message format under text-graphic PCMS Alternative One.

Table 5.31 Drivers' Preferences to Message Format Associated with Age Group under Text-graphic PCMS Alternative One

Drivers' Preferences under Alternative One		Age Group							Total
		<19	20-24	25-34	35-44	45-54	55-64	>65	
Text	Count	1	0	4	3	3	2	2	15
	Expected Count	1.0	1.3	3.6	3.2	2.5	1.8	1.6	15.0
	Percentage	11%	0%	12%	10%	13%	12%	13%	11%
Text-graphic	Count	4	3	10	9	8	7	3	44
	Expected Count	2.8	3.8	10.4	9.5	7.3	5.4	4.7	44.0
	Percentage	44%	25%	30%	30%	35%	41%	20%	32%
Graphic	Count	3	4	10	14	7	6	6	50
	Expected Count	3.2	4.3	11.9	10.8	8.3	6.1	5.4	50.0
	Percentage	33%	33%	30%	47%	30%	35%	40%	36%
No Difference	Count	1	4	8	1	4	0	2	20
	Expected Count	1.3	1.7	4.7	4.3	3.3	2.4	2.2	20.0
	Percentage	11%	33%	24%	3%	17%	0%	13%	14%
Don't Care	Count	0	1	1	3	1	2	2	10
	Expected Count	.6	.9	2.4	2.2	1.7	1.2	1.1	10.0
	Percentage	0%	8%	3%	10%	4%	12%	13%	7%
Total	Count	9	12	33	30	23	17	15	139
	Expected Count	9.0	12.0	33.0	30.0	23.0	17.0	15.0	139.0
	Percentage	100%	100%	100%	100%	100%	100%	100%	100%

Table 5.32 Test of Independence on Drivers' Preferences to Message Format and Age Group under Text-graphic PCMS Alternative One

Drivers' Preferences vs. Age Group under Alternative One	Value	df	Asymp. Sig. (2-sided)
Pearson Chi-Square	18.784	24	.763
Likelihood Ratio	23.059	24	.516
Linear-by-Linear Association	.132	1	.717
N of Valid Cases	139		

When combining the text-graphic format and the graphic format into the graphic-aided format, as shown in Figure 5.22, it can be observed that over 75% of drivers in 15−19, 35−44, and 55−64 preferred the graphic-aided format, while the percentage of drivers in other age groups were around 60%, though the difference was not significant.

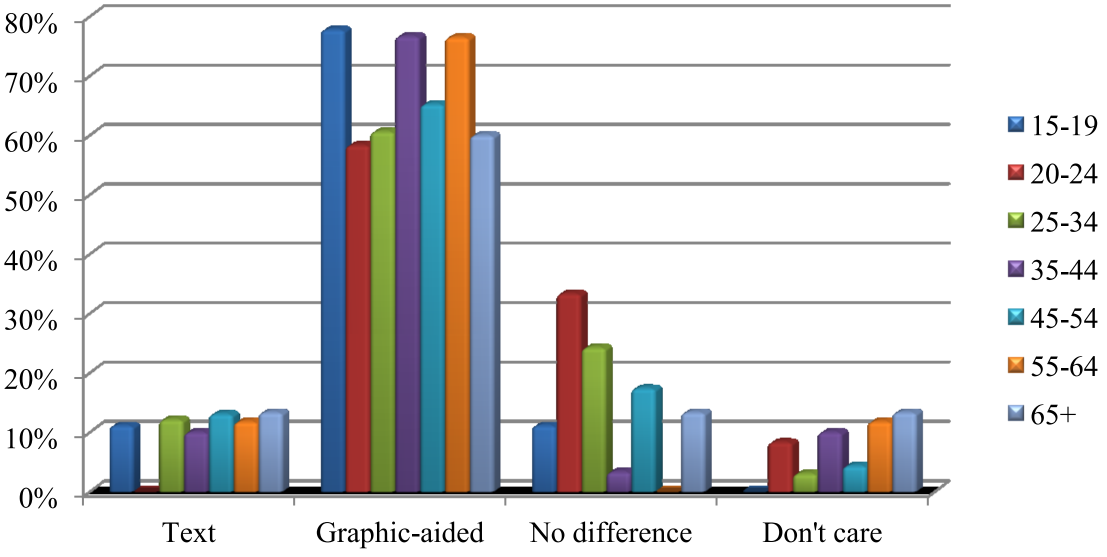

Figure 5.22 Drivers' Preferences to Message Format Associated with Age Group under Text-graphic PCMS Alternative One

(2) Text-graphic PCMS Alternative Two

As displayed in Figure 5.23, both of the age groups 45−54 and 55−64 had over 25% of drivers who responded to surveys under text-graphic PCMS Alternative Two, followed by 17% in the 25−34 age group and 12% in the 35−44 age group. The percentages of young (15−19, 20−24) and elderly drivers (over 65) were less than 10% in their age group.

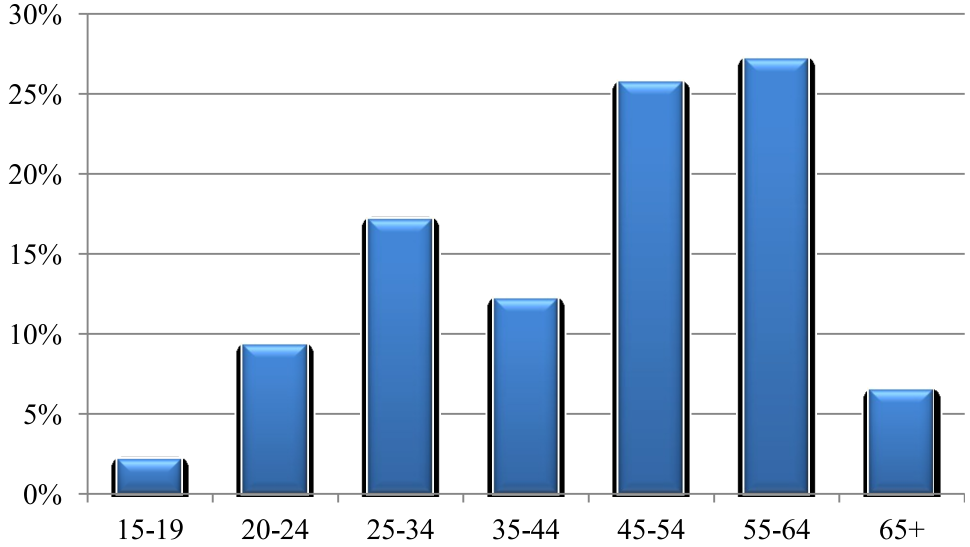

Figure 5.23 Distribution of Drivers' Age under Text-graphic PCMS Alternative Two

Table 5.33 details drivers' preferences to message format associated with their age group under text-graphic PCMS Alternative Two. Except for drivers younger than 19 and over 65, around 8% to 12% of drivers in each age group chose text format; over 30% of drivers in all age groups except for 20−24 preferred text-graphic format; between 21%

and 38% of drivers liked graphic format, except for drivers over 65. The percentage of drivers who selected *No different* and *Don't care* varied a lot in different age groups. The p-value of Chi-square test of 0.808 in Table 5.34 again indicated that the difference of percentages in drivers' preferences was not significant between age groups, suggesting that drivers' preferences to message format were statistically independent of their age group under text-graphic PCMS Alternative Two, and that their preferences were statistically the same among different age groups.

Table 5.33 Drivers' Preferences to Message Format Associated with Age Group under Text-graphic PCMS Alternative Two

Drivers' Preferences under Alternative Two		Age Group <19	20-24	25-34	35-44	45-54	55-64	>65	Total
Text	Count	0	1	2	2	3	3	0	11
	Expected Count	.2	1.0	1.9	1.3	2.8	3.0	.7	11.0
	Percentage	0%	8%	8%	12%	8%	8%	0%	8%
Text-graphic	Count	1	2	8	8	14	14	4	51
	Expected Count	1.1	4.7	8.7	6.2	13.1	13.8	3.3	51.0
	Percentage	33%	15%	33%	47%	39%	37%	44%	36%
Graphic	Count	1	5	5	5	10	13	0	39
	Expected Count	.8	3.6	6.7	4.7	10.0	10.6	2.5	39.0
	Percentage	33%	38%	21%	29%	28%	34%	0%	28%
No Difference	Count	1	3	4	0	6	3	3	20
	Expected Count	.4	1.9	3.4	2.4	5.1	5.4	1.3	20.0
	Percentage	33%	23%	17%	0%	17%	8%	33%	14%
Don't Care	Count	0	2	5	2	3	5	2	19
	Expected Count	.4	1.8	3.3	2.3	4.9	5.2	1.2	19.0
	Percentage	0%	15%	21%	12%	8%	13%	22%	14%
Total	Count	3	13	24	17	36	38	9	140
	Expected Count	3.0	13.0	24.0	17.0	36.0	38.0	9.0	140.0
	Percentage	100%	100%	100%	100%	100%	100%	100%	100%

Table 5.34 Test of Independence on Drivers' Preferences to Message Format and Age Group under Text-graphic PCMS Alternative Two

Drivers' Preferences vs. Age Group under Alternative Two	Value	df	Asymp. Sig. (2-sided)
Pearson Chi-Square	17.890	24	.808
Likelihood Ratio	23.617	24	.484
Linear-by-Linear Association	.037	1	.848
N of Valid Cases	140		

When combining the text-graphic format and the graphic format into the graphic-aided format, as illustrated in Figure 5.24, drivers in 15−19, 35−44, 45−54, and 55−64 in favor of graphic-aided format stood as the largest four age groups, the percentages of which were over 65%. The percentages of drivers in other age groups were less than 55%, though the difference was still not significant.

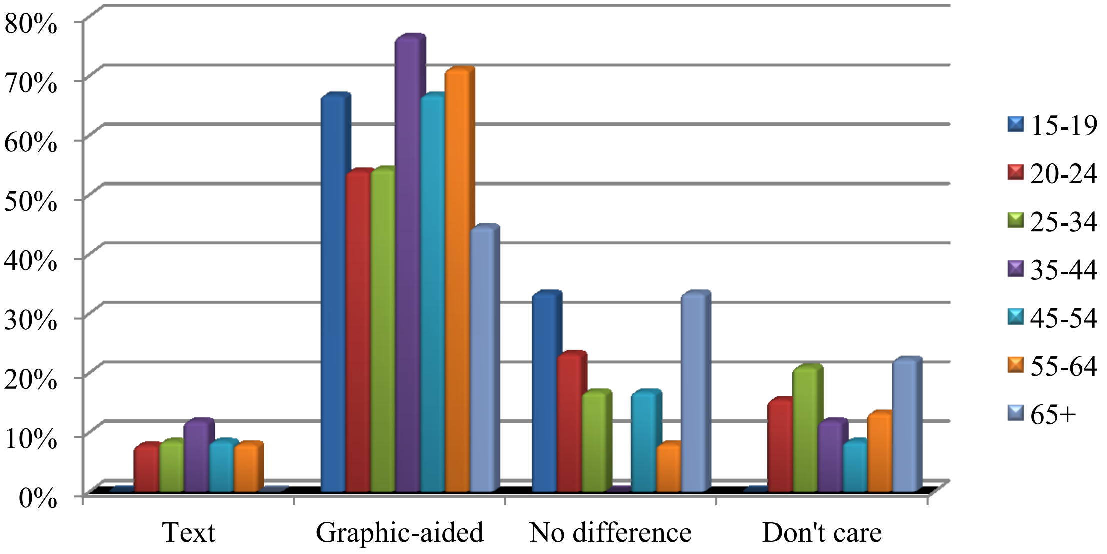

Figure 5.24 Drivers' Preferences to Message Format Associated with Age Group under Text-graphic PCMS Alternative Two

(3) Text-graphic PCMS Original

Under text-graphic PCMS Original, surveyed drivers in 45−54 and 55−64 accounted for the two largest age groups, at around 25%, followed by drivers in 25−34 and 35−44 age groups, as illustrated in Figure 5.25. The percentages of young drivers below 25 and elderly drivers over 65 were less than 10% in each age group.

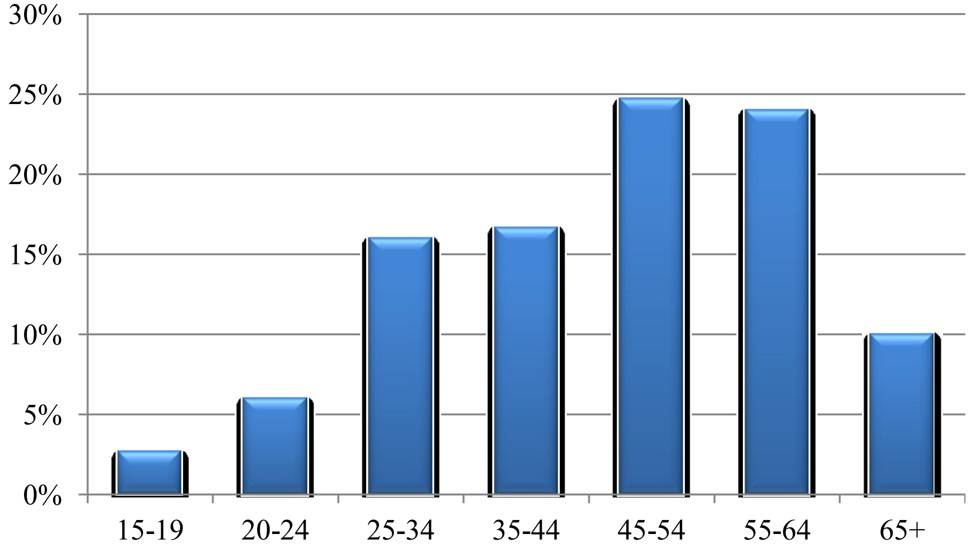

Figure 5.25 Distribution of Drivers' Age under Text-graphic PCMS Original

Drivers' preferences to message format associated with age groups under text-graphic PCMS Original are detailed in Table 5.35. Text format was preferred by over 20% of drivers in age groups younger than 65, but was selected only by 13% of elderly drivers over 65; about over a quarter of drivers in all age groups liked text-graphic format; around over a quarter of drivers in all age groups chose graphic format expect for drivers in 20−24 and 25−34 age groups. The percentage of drivers who believed there was no difference between message formats varied from 25% in young drivers to around 7% in elderly drivers. The p-value of Chi-square test of 0.675 in Table 5.36 again suggested that the difference of percentages was not significant between age groups, and that drivers' preferences to message format were statistically independent of their age group under text-graphic PCMS Original.

Table 5.35 Drivers' Preferences to Message Format Associated with Age Group under Text-graphic PCMS Original

Drivers' Preferences under Original Graphic		Age Group							Total
		<19	20-24	25-34	35-44	45-54	55-64	>65	
Text	Count	1	2	6	8	8	10	2	37
	Expected Count	1.0	2.2	5.9	6.2	9.1	8.9	3.7	37.0
	Percentage	25%	22%	25%	32%	22%	28%	13%	25%
Text-graphic	Count	1	3	9	6	9	9	4	41
	Expected Count	1.1	2.5	6.6	6.8	10.1	9.8	4.1	41.0
	Percentage	25%	33 %	38%	24%	24%	25%	27%	27%
Graphic	Count	1	1	2	6	11	13	4	38
	Expected Count	1.0	2.3	6.1	6.3	9.4	9.1	3.8	38.0
	Percentage	25%	11%	8%	24%	30%	36%	27%	25%
No Difference	Count	1	2	5	4	6	4	1	23
	Expected Count	.6	1.4	3.7	3.8	5.7	5.5	2.3	23.0
	Percentage	25%	22%	21%	16%	16%	11%	7%	15%
Don't Care	Count	0	1	2	1	1	0	3	8
	Expected Count	.2	.5	1.3	1.3	2.0	1.9	.8	8.0
	Percentage	0%	11%	8%	4%	3%	0%	20%	5%
Don't Know	Count	0	0	0	0	2	0	1	3
	Expected Count	.1	.2	.5	.5	.7	.7	.3	3.0
	Percentage	0%	0%	0%	0%	5%	0%	7%	2%
Total	Count	4	9	24	25	37	36	15	150
	Expected Count	4.0	9.0	24.0	25.0	37.0	36.0	15.0	150.0
	Percentage	100%	100%	100%	100%	100%	100%	100%	100%

Table 5.36 Test of Independence on Drivers' Preferences to Message Format and Age Group under Text-graphic PCMS Original

Drivers' Preferences vs. Age Group under Original Graphic	Value	df	Asymp. Sig. (2-sided)
Pearson Chi-Square	26.009	30	.675
Likelihood Ratio	27.290	30	.608
Linear-by-Linear Association	1.564	1	.211
N of Valid Cases	150		

Figure 5.26 illustrates the percentages of drivers' preferences after combining the text-graphic format and the graphic format into the graphic-aided format. Drivers in 55−64 stood as the largest age group in favor of graphic-aided format, which was over 60%, followed by 45−54 and over 65 age groups, which were over 50%. The percentage of drivers choosing the graphic-aided format in the remaining age groups varied between 44% and 50%, and the difference among all age groups was insignificant as well.

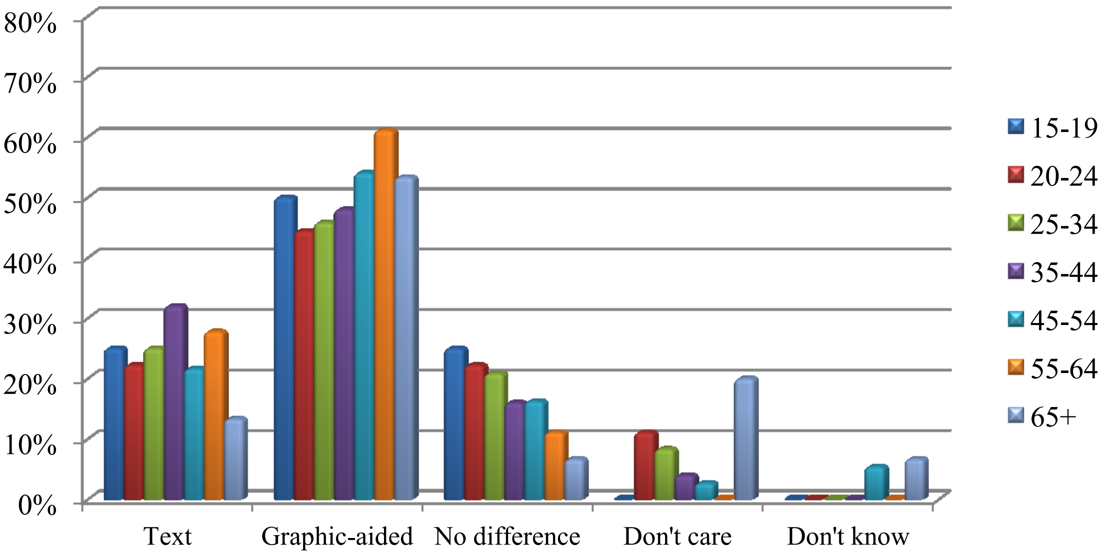

Figure 5.26 Drivers' Preferences to Message Format Associated with Age Group under Text-graphic PCMS Original

5.4 Summary of Field Experiment Phase II

Since the results of driver surveys in the field experiment Phase I showed that between 12% and 21% of drivers were confused about the work zone graphic on the text-graphic and the graphic PCMSs, which might have affected the mean speed reduction under these graphic-aided PCMS conditions, two alternative work zone graphics were designed to improve the drivers' recognition of the work zone sign. Field experiment Phase II was performed to determine the effectiveness of two alternative work zone graphics in reducing vehicle speeds in the upstream of a one-lane two-way rural highway work zone and compare their effectiveness with the effectiveness of the original work zone graphic used in field experiment Phase I.

Field experiment Phase II was conducted using the same experimental devices, a full-matrix PCMS and five speed measurement sensors, as employed in field experiment Phase I. The PCMS were programmed to display a text message WORKZONE AHEAD SLOWDOWN and four graphics, which were two alternative work zone graphics, as shown in Figure 5.1, the original work zone graphic as seen in Figure 5.2, and the flagger graphic. Using the text message and four graphics, five PCMS conditions were setup in field experiment Phase II, including:

- Text-graphic PCMS Alternative One: displaying text WORKZONE AHEAD SLOWDOWN and the alternative work zone graphic one (Figure 5.3),
- Text-graphic PCMS Alternative Two: displaying text WORKZONE AHEAD SLOWDOWN and the alternative work zone graphic two (Figure 5.4),

- Text-graphic PCMS Original: displaying text WORKZONE AHEAD SLOWDOWN and the original work zone graphic (Figure 5.5),
- Graphic PCMS Alternative One: displaying the alternative work zone graphic one and the flagger graphic (Figure 5.6), and
- Graphic PCMS Alternative Two: displaying the alternative work zone graphic two and the flagger graphic (Figure 5.7).

Field experiment Phase II was carried out in a rural highway work zone on US-75 between Burlington, KS and I-35 using the same experimental layout as described in field experiment Phase I. Drivers surveys were performed as well under three text-graphic PCMSs to determine drivers' acceptance of the two alternative work zone graphics and to compare with the original work zone graphic. A total of 2,676 valid vehicle speed data were collected, of which 540, 541, and 519 were collected under text-graphic PCMSs Alternative One, Alternative Two, and Original, respectively; 536 and 540 speed data were captured under graphic PCMSs Alternative One and Alternative Two, respectively. A total of 454 driver surveys were conducted under the text-graphic PCMSs, including 149 under Alternative One, 149 under Alternative Two, and 156 under Original.

Through the comparison of mean speed reduction, it was found that using text-graphic PCMSs Alternative One and Alternative Two resulted in 13% mean speed reduction, or 8 mph from Sensor 1 to Sensor 5; using text-graphic PCMS Original resulted in 11% mean speed reduction, or 7 mph from Sensor 1 to Sensor 5; and using graphic PCMSs Alternative One and Alternative Two resulted in 15% mean speed reduction, or 9 mph, from Sensor 1 to Sensor 5.

Independent two-sample t-tests were conducted to compare the effectiveness in reducing mean vehicle speeds among three text-graphic PCMSs and between two graphic PCMSs at each sensor location. The results revealed that text-graphic PCMS Alternative One was more effective in reducing mean vehicle speeds than text-graphic PCMSs Alternative Two from 1,475 ft in the upstream of a work zone (location of Sensor 1) to the W20-4 sign (location of Sensor 5), and more effective in reducing mean vehicle speeds than text-graphic PCMS Original from the beginning of a work zone (location of Sensor 4) to the W20-4 sign. Graphic PCMSs Alternative One and Alternative Two had statistically the same effectiveness in reducing mean vehicle speeds in the upstream of a work zone. The difference of effectiveness in reducing mean vehicle speeds between text-graphic PCMSs Alternative Two and Original could not be determined using t-tests based on the vehicle speed data obtained in field experiment Phase II.

Linear regression models were built to illustrate the relationship between the mean vehicle speeds and the distance from Sensor 1 location to a vehicle under three text-graphic PCMSs. The regression models showed that text-graphic PCMSs Alternative One, Alternative Two, and Original resulted in the speed reduction rates of 0.00428 mph/ft, 0.00427 mph/ft, and 0.00358 mph/ft, respectively, suggesting that using text-graphic PCMSs Alternative One and Alternative Two could reduce mean vehicle speeds more effectively than text-graphic PCMS Original.

Results of driver surveys showed that 93%, 94%, and 96% of drivers recognized the graphics on text-graphic PCMSs Alternative One, Alternative Two, and Original, respectively, and the results of Chi-square tests suggested that there was no statistical difference between drivers’ recognition of graphics on the three text-graphic PCMSs. All drivers successfully interpreted the meaning of the two alternative work zone graphics, while only 87% of drivers correctly understood the original work zone graphic. 89%, 83%, and 72% of drivers believed they paid more attention to the traffic conditions after seeing text-graphic PCMSs Alternative One, Alternative Two, Original, respectively. There was no statistical difference between the effectiveness of text-graphic PCMSs Alternative One and Alternative Two in drawing drivers’ attention, and both were statistically more effective than text-graphic PCMS Original.

Results of driver surveys also showed that the text format was preferred by 11%, 8%, and 25% of drivers under text-graphic PCMSs Alternative One, Alternative Two, and Original, respectively; the text-graphic format was chosen by 32%, 36%, and 27% of drivers under the three text-graphic PCMSs, respectively, while the graphic format gained 36%, 28%, and 25% of drivers’ selection under the three text-graphic PCMSs, respectively. The results of Chi-square tests suggested that there was no statistical difference between drivers’ preferences to message format under text-graphic PCMSs Alternative One and Alternative Two, and both were statistically different than drivers’ preferences to message format under text-graphic PCMS Original. In other words, the text format was preferred by significantly fewer drivers and the text-graphic and the graphic formats were preferred by significantly more drivers under text-graphic PCMSs Alternative One and Alternative Two, compared with under text-graphic PCMS Original.

The results of tests of independence revealed that under text-graphic PCMS Alternative One, male and female drivers’ preferences to the message format were significantly different, and that more female drivers preferred the text-graphic format, while more male drivers liked the graphic format. Under text-graphic PCMSs Alternative Two and Original, drivers' gender was statistically independent of their preferences to the message format; and male and female drivers' preferences to the message format were statistically the same. The results also suggested that drivers' age groups did not have significant impact on their preferences to message format under three text-graphic PCMSs, and that drivers' preferences to message format were statistically independent of their age group. A higher percentage of drivers in 15−19, 35−44, and 55−64 age groups preferred graphic-aided formats under text-graphic PCMSs Alternative One and Alternative Two, though the difference was not significant.

Chapter 6 Discussion, Conclusions and Recommendations

6.1 Summary

The aging highway system in the United States has led to an increasing number of highway work zones in the past decades. Work zones create an inevitable disruption on regular traffic flow and result in severe traffic delays and safety concerns. Although government agencies, industries, research organizations and individuals have devoted great efforts to improve highway work zone safety, the alarming numbers of fatalities and injuries each year indicate that additional improvements are needed.

To improve highway work zone safety, numerous traffic control devices have been developed and implemented, which have provided reasonably safe and efficient traffic flow during road construction and maintenance. Among these devices, the PCMS is an innovative traffic control device capable of displaying a variety of messages to inform motorists of unusual driving conditions. The traditional type of PCMS is a text-based device and has been in use for decades. Many recent studies, however, have pointed out that using text messages on a PCMS has several limitations, such as confusing drivers and delaying their responses during driving, being difficult to read for elderly drivers and non-English-speaking drivers, difficult to see under adverse viewing conditions, and having a short range of legibility.

The advancements in the sign technology have now allowed for the use of color and full-matrix PCMS and made it possible to display symbols and graphic features to drivers. Graphic-aided messages on PCMSs could offer potential advantages over text messages, because drivers can read and understand well-designed graphics quicker and farther upstream of the PCMS. 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 English language. Although these advantages have been realized for many years, the use of graphic-aided messages on PCMSs is still new in the United States. In addition, only a handful of simulation studies have been conducted in laboratory environments. Therefore, there is a need to conduct field experiments in the real-world driving conditions with ongoing traffic.

This study aimed to determine the effectiveness of graphic-aided PCMSs in reducing vehicle speeds and evaluate drivers' acceptance of the implementation of graphic-aided PCMS in the upstream of one-lane two-way rural highway work zones. To achieve these goals, a two-phase field experiment was designed and conducted to collect vehicle speed data and perform driver surveys, the details of which are presented in Chapters 4 and 5. A full-matrix PCMS was used to display text messages and graphics at 575 ft upstream of the beginning of a work zone, and five speed measurement sensors were employed to collection vehicle speed data at 1,475 ft, 1,000 ft, 500 ft, 0 ft upstream, and 530 ft downstream of the beginning of the work zone, respectively.

In field experiment Phase I, the PCMS was setup under three conditions, which were:

- A text PCMS: displaying text WORKZONE AHEAD SLOWDOWN and text FLAGGER AHD PREP TO STOP (Figure 4.4),

- Two text-graphic PCMSs: one displaying text WORKZONE AHEAD SLOWDOWN and the work zone graphic designed similar to the W21-1 sign (Figure 4.5); the other displaying text FLAGGER AHD PREP TO STOP and the flagger graphic designed similar to the W20-7 sign (Figure 4.6),
- A graphic PCMS: displaying the work zone graphic and the flagger graphic (Figure 4.7).

Field experiment Phase I was conducted in a rural highway work zone on K-13 between US-24 and K-16 from July 21st to August 4th, 2010 and in another work zone on US-36 between K-87 and Marysville, KS from September 20th to October 1st, 2010. A total of 1,115 valid vehicle speed data were collected, among which 345, 367, and 403 were collected under the text PCMS, the text-graphic PCMSs, and the graphic PCMS, respectively. A total of 524 driver surveys were performed, among which 149 were conducted under the text PCMS, 125 were conducted under the text-graphic PCMS with the work zone graphic, 124 were conducted under the text-graphic PCMS with the flagger graphic, and 126 were conducted under the graphic PCMS.

In field experiment Phase II, the PCMS was setup under five conditions, including:

- Text-graphic PCMS Alternative One: displaying text WORKZONE AHEAD SLOWDOWN and the alternative work zone graphic one (Figure 5.3),
- Text-graphic PCMS Alternative Two: displaying text WORKZONE AHEAD SLOWDOWN and the alternative work zone graphic two (Figure 5.4),
- Text-graphic PCMS Original: displaying text WORKZONE AHEAD SLOWDOWN and the original work zone graphic (Figure 5.5),

- Graphic PCMS Alternative One: displaying the alternative work zone graphic one and the flagger graphic (Figure 5.6), and
- Graphic PCMS Alternative Two: displaying the alternative work zone graphic two and the flagger graphic (Figure 5.7).

Field experiment Phase II was conducted in a rural highway work zone on US-75 between Burlington, KS and I-35 from July 14th to 27th, 2011. A total of 2,676 valid vehicle speed data were collected, of which 540, 541, and 519 were collected under text-graphic PCMSs Alternative One, Alternative Two, and Original, respectively; 536 and 540 speed data were captured under graphic PCMSs Alternative One and Alternative Two, respectively. A total of 454 driver surveys were conducted under text-graphic PCMSs, including 149 under Alternative One, 149 under Alternative Two, and 156 under Original.

6.2 Discussion

6.2.1 Problems in Field Experiments

The results of speed data analyses in field experiment Phase I showed that using the text PCMS, the text-graphic PCMSs, and the graphic PCMS resulted in a mean vehicle speed reduction of 13%, 10%, and 17%, respectively. These numbers indicated that using the graphic PCMS resulted in the largest percentage of mean speed reduction, while using the text-graphic PCMSs resulted in the smallest percentage of mean speed reduction. On the other side, the results of driver survey analyses revealed that 12% of drivers did not correctly understand the meaning of the work zone graphic on the text-graphic PCMS, and 21% of drivers did not successfully interpret this graphic on the graphic PCMS. In other words, between 12% and 21% of drivers got confused by the work zone graphic on the text-graphic and graphic PCMSs when approaching the work zone. The confusion made these drivers have to think first to understand the work zone graphic. This thinking-and-driving behavior could increase drivers' reaction time, delay their braking action, and make them fail to reduce speed when they were approaching the work zone. Therefore, drivers' confusion on the work zone graphic might have affected the mean speed reduction under the text-graphic and graphic PCMS conditions, and the results of speed data analyses in field experiment Phase I might not accurately reflect the effectiveness of graphic-aided PCMSs in reducing vehicle speeds because of the poor graphic design.

To address this problem, two alternative work zone graphics were designed in field experiment Phase II. Their effectiveness in reducing vehicle speeds in the upstream of a one-lane two-way rural highway work zone was measured, and the results were compared with those of the original work zone graphic used in field experiment Phase I.

The results of driver survey analyses in field experiment Phase II showed that under the text-graphic PCMSs, all drivers successfully interpreted the two alternative work zone graphics, while only 87% of drivers correctly understood the original work zone graphic. In other words, 13% of drivers did not understand the original work zone graphic on the text-graphic PCMS, which matched the results of driver surveys under the text-graphic PCMS with the work zone graphic in field experiment Phase I (12%).

Therefore, the results of speed data analyses in field experiment Phase II were able to reflect the effectiveness of the alternative text-graphic and graphic PCMSs in reducing mean vehicle speeds, and could be used to compare the effectiveness of the alternative work zone graphics and the original work zone graphic in reducing vehicle speeds. The results suggested that using text-graphic PCMSs Alternative One and Alternative Two resulted in a mean speed reduction of 13%, using text-graphic PCMS Original resulted in a mean speed reduction of 11%, and using graphic PCMSs Alternative One and Alternative Two resulted in a mean speed reduction of 15%. These results revealed that using the graphic PCMSs resulted in the largest percentage of mean speed reduction, while using text-graphic PCMS Original resulted in the smallest percentage of mean speed reduction.

6.2.2 Limitations of Study

6.2.2.1 Limitations of Data

A value of a vehicle speed at any given time depends on a variety of factors, such as roadway conditions, weather conditions, trip purpose, driver's emotion, and passengers' behavior. To determine the effectiveness of a graphic-aided PCMS in reducing vehicle speeds, the optimal experimental environment is in a driving condition where all factors that could affect the speed of a vehicle are excluded, which is not achievable in the real world. In the field experiments, influence of some of the above factors could not be determined, such as trip purpose, driver's emotion, and passengers' behavior. Other factors were optimized during the vehicle speed measurement process to reach the most accurate results, including the following:

1. Vehicle speeds were measured under favorable weather conditions in the daytime that allowed drivers to maintain a desired travel speed in a free flow condition.
2. Vehicle speeds were measured in the middle section of the rural highways away from adjacent towns, where speed limits were lowered to 55 mph, to avoid the speed reduction by post speed limits.
3. Vehicles turning to and from minor roadways had significantly low speeds when approaching the intersections. These vehicle speeds were sorted out and disregarded during the initial screening process.
4. Curves could reduce vehicle speeds by a certain amount and block drivers' sights depending on the surrounding environments. Due to the design of rural highways, the influence of curves on vehicle speeds could not be avoided in the field experiments.
5. The major factor that could considerably affect vehicle speeds is the rolling topography, which could create a great amount of upgrades and downgrades on the highways due to the design of rural highways. In field experiment Phase II, speed data under text-graphic PCMSs were measured on an even section of the highway, while speed data under graphic PCMSs were collected on a highway section where a slight downgrade existed between Sensor 1 and Sensor 2. Therefore, the mean vehicle speeds at Sensor 2 were higher than at

Sensor 1 under the two graphic PCMSs. The locations of field experiments were selected depending on the progress of road work. Since the construction project had a tight schedule, it was not allowed to wait until a favorable highway section became available for the field experiments.

6.2.2.2 Limitations of Methods

Methods of collecting data in this research project included using sensors to measure speeds and conducting driver surveys. Collected vehicle speed data and driver survey results, however, were not directly and correspondingly connected with each other, because collecting vehicle speeds and conducting driver surveys were performed individually and separately. In other words, drivers' age and gender could not be obtained when their vehicle speeds were measured, and the drivers' vehicle speeds were unknown when they participated in the surveys. The relationship between drivers' information and vehicle speeds could hardly be obtained in the field experiments, because measuring vehicle speeds required drivers to drive the vehicles while gathering drivers' information needed them to stop for the surveys.

In the field experiments, wheelbases were collected to categorize vehicles into passenger cars and commercial trucks; in the driver surveys, vehicles were grouped into seven categories (sedan, SUV, pick-up, van/minivan, truck, motorcycle, and bus). Because this research project did not aim to compare the effectiveness of graphic-aided PCMSs in reducing speeds between passenger cars and commercial trucks, these vehicle type data were not used in the statistical analyses. Therefore, the effectiveness of graphic-aided PCMSs in reducing speeds of different types of vehicles remained undetermined.

6.3 Conclusions

Conclusions were drawn based on the results of speed data analyses and driver survey analyses from the field experiments Phase I and Phase II, the details of which are presented in Chapters 4 and 5. The major findings of this study are:

1. Using a text PCMS resulted in a mean vehicle speed reduction of 13%, using a text-graphic PCMS resulted in a mean vehicle speed reduction between 11% and 13%, and using a graphic PCMS resulted in a mean vehicle speed reduction between 15% and 17%.
2. Using a text-graphic PCMS reduced mean vehicle speeds 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 a text PCMS from 1,000 ft in the upstream of the work zone to the W20-4 sign. Using a graphic PCMS reduced mean vehicle speeds more effectively than using a text PCMS from 1,475 ft in the upstream of the work zone to the W20-4 sign.
3. Using the text-graphic PCMS Alternative One reduced mean vehicle speeds more effectively than using the text-graphic PCMS Alternative Two from 1,475 ft in the upstream of a work zone to the W20-4 sign. Using the text-graphic PCMS Alternative One reduced mean vehicle speeds more effectively than using the text-graphic PCMS Original from the beginning of a work zone to the W20-4 sign. Therefore, work zone graphic Alternative One was the best work zone graphic to be displayed on a text-graphic PCMS.

4. Using graphic PCMS Alternative One and graphic PCMS Alternative had statistically the same effectiveness in reducing mean vehicle speeds from 1,475 ft in the upstream of a work zone to the W20-4 sign.
5. Linear and nonlinear regression models were developed and could be used to predict mean vehicle speeds at any location from 1,475 ft in the upstream of a work zone to the W20-4 sign under a text, a text-graphic, and a graphic PCMS conditions.
6. All drivers understood the flagger graphic displayed on graphic-aided PCMSs. 12% to 13% of drivers did not understand the original work zone graphic on a text-graphic PCMS; 21% of drivers did not understand the original work zone graphic displayed on a graphic PCMS. All drivers understood the two alternative work zone graphics displayed on text-graphic PCMSs.
7. 97% of drivers thought the text PCMS drew their attention more to the work zone traffic conditions when they only saw the text PCMS. 72% to 82% of drivers paid more attention to the work zone traffic conditions when they saw the text-graphic PCMS with the original work zone graphic. 83% to 89% of drivers believed the text-graphic PCMS with the alternative work zone graphics drew their attention more to the work zone traffic conditions. 87% of drivers thought the graphic PCMS drew their attention more to the work zone traffic conditions.
8. The majority of drivers (64%) liked the text format when only text messages were displayed on a PCMS, but preferred the graphic-aided formats (52% to

71%) when they saw graphics displayed on a PCMS. The graphic-aided formats were preferred by significantly more drivers over the text format when the alternative work zone graphics were displayed (64% to 68%) on text-graphic PCMSs, compared with the original work zone graphic (52%).

9. More female drivers preferred the text-graphic format and more male drivers liked the graphic format under text-graphic PCMS Alternative One; under text-graphic PCMSs Alternative Two and Original, drivers' gender was statistically independent of their preferences to message format, and male and female drivers' preferences to message format were statistically the same.
10. Drivers' age groups did not have significant impact on their preferences to message format under text-graphic PCMSs. Drivers' preferences to message format were statistically independent of their age group. A higher percentage of drivers in age groups of 15−19, 35−44, and 55−64 preferred the graphic-aided formats under text-graphic PCMSs with the alternative work zone graphics.

6.4 Recommendations

The following recommendations are suggested for implementing the results of this research project and for future research on graphic-aided PCMSs.

1. Using a graphic-aided PCMS was effective in reducing vehicle speeds in the upstream of work zones only if the graphic was able to convey a clear meaning to drivers. The results of the field experiments showed that a

graphic-aided PCMS with a confusing graphic, such as the original work zone graphic, could increase drivers' reaction time, delay their braking action, and thus increase the probability of vehicle crashes. The graphic-aided PCMSs with the redesigned alternative work zone graphics in field experiment Phase II, on the other side, were able to express a clear meaning to drivers, and therefore were more effective in reducing vehicle speeds. To maximize the benefits of using a graphic-aided PCMS in work zones, it is recommended that a graphic displayed on a PCMS must be well designed and understood in order to achieve its effectiveness.

2. This research project studied the effectiveness of graphic-aided PCMSs with two specific graphics, the work zone graphic and the flagger graphic, which were similar to the W21-1 and W20-7 signs specified by the MUTCD. Future research is needed to study additional graphics that could be potentially used in the graphic-aided PCMSs, such as reduced lanes, congestion, snow, and slippery road. The graphics used in Japan, Australia, and European countries might likely be modified to fit the traffic conditions in the U.S.
3. One of the major advantages of a graphic-aided PCMS is its good legibility in adverse viewing conditions, such as rain or fog. Field experiments in this study were conducted under favorable weather conditions, and the effectiveness of graphic-aided PCMSs in reducing vehicle speeds under adverse weather conditions was not determined. Therefore, there is a need to

compare the effectiveness of text PCMS and graphic-aided PCMS in reducing vehicle speeds under adverse weather conditions.

4. Another advantage of a graphic-aided PCMS is its legibility for non-English-speaking drivers. In this research project, drivers' native language was not recorded, and the relationship between drivers' preferences to message format and their native language remained unknown. Further driver surveys are recommended in places where more non-English-speaking drivers could participate in the study on drivers' preferences to message format on PCMS.
5. In the field experiments, measuring vehicle speeds and conducting driver surveys were performed individually and separately, which means drivers' age and gender could not be obtained when their vehicle speeds were measured, and drivers' vehicle speeds were unknown when they participated in the surveys. Therefore, the impact of driver's age and gender on the effectiveness of graphic-aided PCMSs in reducing vehicle speeds was not determined in this study. Future research is recommended to investigate the relationship between the effectiveness of graphic-aided PCMSs in reducing vehicle speeds and driver's age and gender.
6. Vehicle types were collected during the field experiments and driver surveys, but were not used in the statistical analyses, because this research project did not aim to determine the effectiveness of graphic-aided PCMSs in reducing speeds of different types of vehicles. Future research is recommended to

compare the difference of speed reduction between passenger cars and commercial trucks when a PCMS is deployed in a work zone.

7. The results of driver surveys showed that only 70% to 90% of drivers paid more attention to the work zone traffic conditions after seeing a graphic-aided PCMS. Therefore, in addition to the innovative work zone traffic control methods and devices, there is a need to develop an effective work zone safety education program to raise drivers' awareness of highway work zone risks.

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Appendix A Sample Questionnaires

Appendix A.1 A Sample Questionnaire under 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______________________

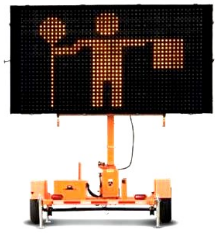
4: Did you think that the PCMS drew your attention more to the work zone traffic condition?

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_____

SAMPLE

Appendix A.2 A Sample Questionnaire under Text-graphic PCMS with the Work Zone Graphic

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**

SAMPLE

Appendix A.3 A Sample Questionnaire under Text-graphic PCMS with the Flagger Graphic

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

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

W20-7

Yes _____ No _____

<u>If the answer is YES, then, continue the survey. If the answer is NO, stop the survey.</u>

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 **<u>graphic</u>** 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**

SAMPLE

Appendix A.4 A Sample Questionnaire under 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	W20-7 Graphic
1) Work zone/Work zone ahead/Someone working	1) Flagger/Flagger ahead/Flagger present/Need to stop
2) Get confused	2) Get confused
3) Don't know	3) Don't know
4) Other______________________	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**

SAMPLE

Appendix A.5 A Sample Questionnaire under Text-graphic PCMS

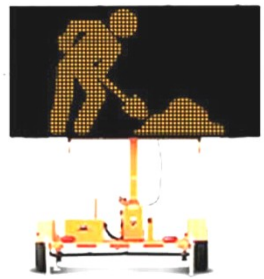
Alternative One

Date: 7/ **Time:** **S** **C**

1. Did you see a **graphic** displayed on the portable changeable message sign when you were approaching the work zone?

☐ Yes

☐ No



If you did NOT see the sign, please stop the survey here.

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

☐ Work zone/Work zone ahead/Someone working

☐ Get confused

☐ Don’t know

☐ Other___________

3. Did you think that the **graphic** drew your attention more to 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?

☐ Graphical format

☐ Text format

☐ Graphical and text format

☐ No difference

☐ Don’t care

☐ Don’t know

☐ Other__________

5. Could you please indicate your age range?

☐ 15−19 ☐ 20−24 ☐ 25−34 ☐ 35−44

☐ 45−54 ☐ 55−64 ☐ 65+

M **F** **S** **SUV** **P** **T** **V** **M** **B**

SAMPLE

Appendix A.6 A Sample Questionnaire under Text-graphic PCMS

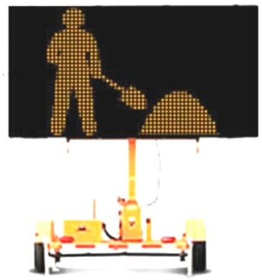
Alternative Two

Date: 7/ **Time:** **S** **C**

1. Did you see a **graphic** displayed on the portable changeable message sign when you were approaching the work zone?

☐ Yes

☐ No



If you did NOT see the sign, please stop the survey here.

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

☐ Work zone/Work zone ahead/Someone working

☐ Get confused

☐ Don't know

☐ Other___________

3. Did you think that the **graphic** drew your attention more to 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?

☐ Graphical format

☐ Text format

☐ Graphical and text format

☐ No difference

☐ Don't care

☐ Don't know

☐ Other__________

5. Could you please indicate your age range?

☐ 15−19 ☐ 20−24 ☐ 25−34 ☐ 35−44

☐ 45−54 ☐ 55−64 ☐ 65+

M **F** **S** **SUV** **P** **T** **V** **M** **B**

SAMPLE

Appendix A.7 A Sample Questionnaire under Text-graphic PCMS

Original

Date: 7/ Time: S C

---

1. Did you see a **<u>graphic</u>** displayed on the portable changeable message sign when you were approaching the work zone?

☐ Yes

☐ No

<u>If you did NOT see the sign, please stop the survey here.</u>

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

☐ Work zone/Work zone ahead/Someone working

☐ Get confused

☐ Don’t know

☐ Other___________

3. Did you think that the **<u>graphic</u>** drew your attention more to 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?

☐ Graphical format

☐ Text format

☐ Graphical and text format

☐ No difference

☐ Don’t care

☐ Don’t know

☐ Other__________

5. Could you please indicate your age range?

☐ 15−19 ☐ 20−24 ☐ 25−34 ☐ 35−44

☐ 45−54 ☐ 55−64 ☐ 65+

M F S SUV P T V M B

SAMPLE

Appendix B Sample of Vehicle Speed Data Sheet

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	7:38:21 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	7:44:09 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	7:45:44 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	8:13:18 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

SAMPLE

Appendix C Sample of Driver Survey Data Sheet

Appendix C.1 Driver Survey Data Sheet in Field Experiment Phase I

No.	Q1	Q2	Q3	Q4	Vehicle 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

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 Difference, 5=Don't Care, 6=Don't Know, 7=Other
Vehicle Type: 1=Sedan, 2=SUV, 3=Pickup, 4=Minivan, 5=Truck, 6=Motorcycle, 7=bus
Gender: 1=Male, 2=Female

SAMPLE

Appendix C.2 Driver Survey Data Sheet in Field Experiment Phase II

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

SAMPLE

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 Difference, 5=Don’t Care, 6=Don’t Know, 7=Other
Age: 1=15-19, 2=20-24, 3=25-34, 4=35-44, 5=45-54, 6=55-64, 7=65+
Gender: 1=Male, 2=Female