Field Experiments for Comparing the Effectiveness of Graphics Displayed in a Portable Changeable Message Sign in Highway Work Zones

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Abstract

The traditional message format on a portable changeable message sign (PCMS) is text-based, which has been found to have several limitations in recent studies. The use of graphic-aided messages on PCMSs has many advantages over text-based PCMSs based on a number of previous laboratory simulation experiments. To validate the effectiveness of graphic-aided PCMSs, a field experiment was conducted at a highway work zone in the summer of 2010. The results of data analysis indicated that between 12% and 21% of drivers got confused when the work zone graphic was displayed on the graphic-aided PCMS. Therefore, there was a need to improve the work zone graphic representation on the PCMS. Two alternative graphics were designed after the 2010 field experiment. The objective of this research project was to compare the effectiveness of two alternative work zone graphics displayed on a graphic-aided PCMS in reducing vehicle speeds in the upstream of a one-lane two-way highway work zone. Field experiments were conducted to collect vehicle speed data. In addition, driver surveys were performed to evaluate drivers' acceptance on the implementation of a graphic-aided PCMS in work zones. The results of speed data analysis suggested that using alternative work zone graphics on the graphic-aided PCMSs could reduce mean vehicle speeds more effectively than using the original work zone graphic. The results of driver surveys revealed that all drivers successfully interpreted the two alternative work zone graphics in the work zone. Thus, authors concluded that the quality of graphic design had a significant impact on drivers' understanding and acceptance of the graphic-aided PCMS in highway work zones.

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Chapter 1 Introduction

A portable changeable message sign (PCMS) is an innovative traffic control device capable of displaying one or more alternative messages to inform motorists of unusual driving conditions (FHWA, 2009). It can capture motorists' attention, display information that is difficult to accomplish with static signing, and can be used to supplement other required signing. The traditional type of 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 (Nsour, 1997; Wang et al., 2007; Ullman et al. 2009).

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 laboratory studies only provided a relative performance measure on sign reading in optimal circumstances (Wang and Cao, 2005).

To overcome the limitations of simulation experiments in laboratory environments, the authors conducted a field experiment in the summer of 2010 that aimed to determine the effectiveness of graphic-aided PCMSs with a work zone graphic (similar to the W21-1 sign specified by the Manual on Uniform Traffic Control Devices) and a flagger graphic (similar to the W20-7 sign) on reducing vehicle speeds in highway work zones. The results of data analysis indicated that between 12% and 21% of drivers got confused when the work zone graphic was displayed on the graphic-aided PCMSs. Some drivers 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. Therefore, there was a need to improve the work zone graphic representation on the PCMS. Two alternative work zone graphics were designed after the 2010 field experiment and their effectiveness needed to be determined using field experiments.

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

Chapter 2 Research Objectives

The primary goals of this research project were to compare the effectiveness of two alternative work zone graphics displayed on graphic-aided PCMSs in reducing vehicle speeds and drivers' acceptance on the implementation of graphic-aided PCMS in the upstream of a one-lane two-way rural highway work zone. The goals will be 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-graphic PCMS and graphic PCMS in reducing vehicle speeds;
2. To conduct field experiments in the upstream of a highway work zone using PCMSs and to collect vehicle speed data using speed measurement sensors;
3. To compare the effectiveness of different graphic-aided PCMSs in reducing vehicle speeds; and
4. To determine drivers' acceptance on the implementation of graphic-aided PCMS in the upstream of a highway work zone.

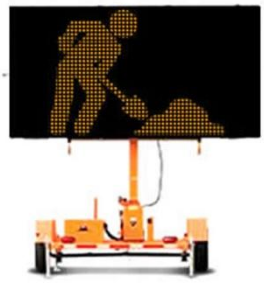
Objectives 3 was achieved by conducting field experiments, collecting vehicle speed data, and analyzing speed data using statistical methods; objective 4 was accomplished by conducting driver surveys along with the field experiments, and analyzing survey results using mathematical approaches.

Chapter 3 Field Experiment Design

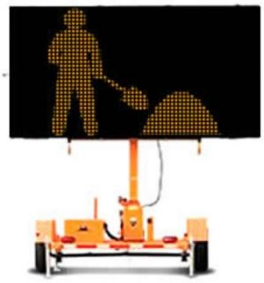
3.1 Experiment Devices and Installation

Vehicle speed data were collected and analyzed to compare the effectiveness of different work zone graphics displayed on graphic-aided PCMSs in reducing vehicle speeds. Driver surveys were conducted to evaluate drivers' opinions on the implementation of graphic-aided PCMS in highway work zones. A full-matrix PCMS was utilized to display text messages and graphics, and five speed sensors were used to collection vehicle speed data. In addition, questionnaires were developed for driver surveys.

The PCMS was programmed to display two alternative work zone graphics, as shown in Figure 3.1, as well as the original work zone graphic and the flagger graphic used in the summer of 2010, as shown in Figure 3.2.



Alternative Work Zone Graphic One



Alternative Work Zone Graphic Two

Figure 3.1 Alternative Work Zone Graphics

Figure 3.2 Original Work Zone Graphic and Flagger Graphic

Three work zone graphics were first used 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. The two alternative work zone graphics were then used on two graphic PCMSs to compare the effectiveness in reducing vehicle speeds between each other. Each PCMS condition included two phases, switching every three seconds. Therefore, in the field experiment, 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 (Figure 3.3),
- Text-graphic PCMS Alternative Two: displaying text WORKZONE AHEAD SLOWDOWN and alternative work zone graphic two (Figure 3.4),
- Text-graphic PCMS Original: displaying text WORKZONE AHEAD SLOWDOWN and the original work zone graphic (Figure 3.5),
- Graphic PCMS Alternative One: displaying alternative work zone graphic one and the flagger graphic (Figure 3.6), and
- Graphic PCMS Alternative Two: displaying alternative work zone graphic two and the flagger graphic (Figure 3.7).

Figure 3.3 Text-graphic PCMS Alternative One

Figure 3.4 Text-graphic PCMS Alternative Two

Figure 3.5 Text-graphic PCMS Original

Figure 3.6 Graphic PCMS Alternative One

Figure 3.7 Graphic PCMS Alternative Two

Five speed measurement sensors were used to record 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 feet spacing, perpendicular to the flow of traffic, as shown in Figure 3.8. Each tube was secured by four 2 in $\times$2 in and one 2 in $\times$1 in mastic tapes (rubberized asphalt) on the pavement, as shown in Figure 3.9.

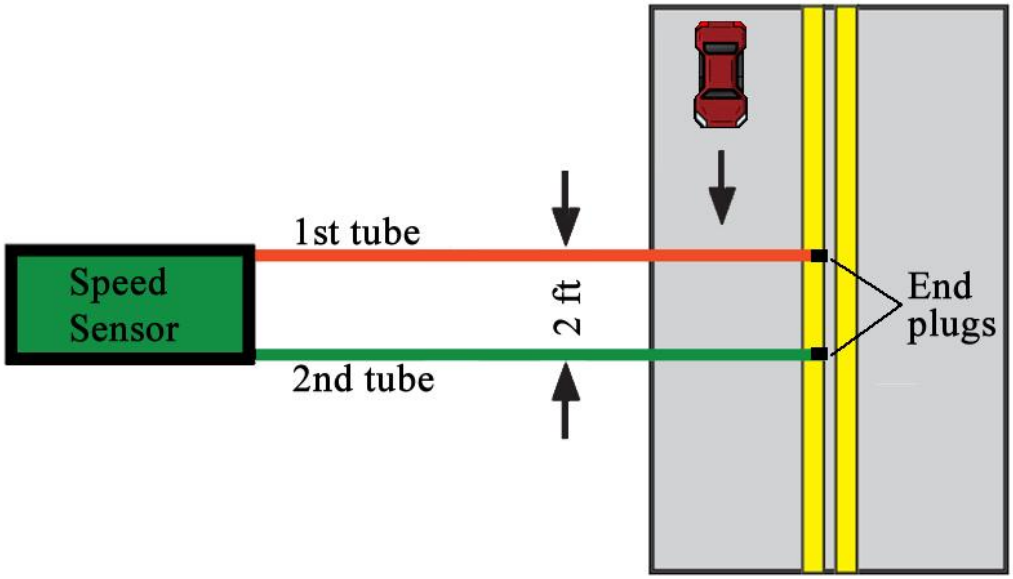


Figure 3.8 Road Tubes Configuration

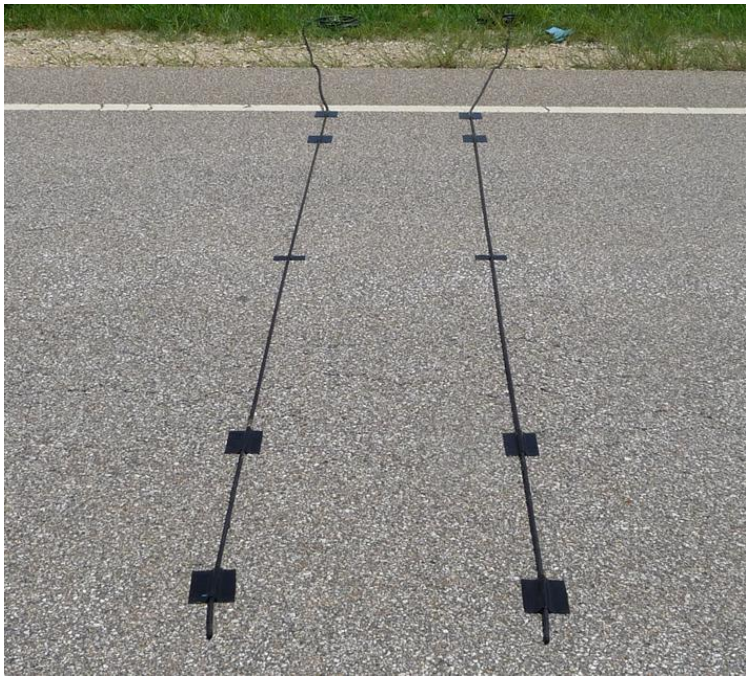


Figure 3.9 Installation of Road Tubes

3.2 Field Experiment Layout

As illustrated in Figure 3.10, 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, right after the PCMS (75 ft) to collect vehicle speeds when passing the PCMS; Sensor 2 (S2) was installed 500 ft away upstream from S3, and Sensor 1 (S1) was installed 475 ft away upstream from S2 to gather vehicle speeds when drivers were approaching the PCMS. Sensor 5 (S5), as a complement of the above four sensors, was installed at the same location of 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. The location of Sensor 1 was defined as the original coordinate.

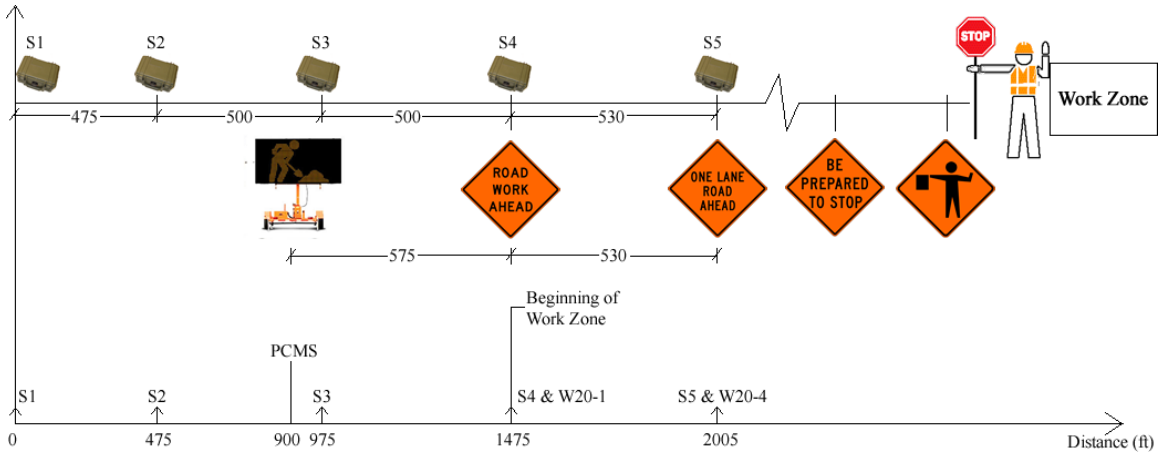


Figure 3.10 Field Experiment Layout

3.3 Work Zone Location and Conditions

A highway work zone located on US-75 between Burlington, KS and I-35, as shown in Figure 3.11, was selected for the field experiment. 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 Kansas Department of Transportation (DOT) Traffic Flow Map, the annual average daily traffic (AADT) for the selected section of US-75 was 3,680 vehicles per day (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). The field experiment was conducted from July 14th to 27th, 2011.

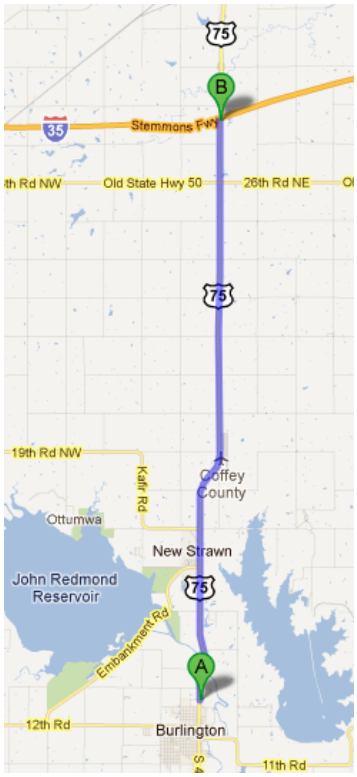


Figure 3.11 Selected Work Zone on US-75 between Burlington, KS and I-35

The construction project was a paving operation to rehabilitate the roadway surface. The construction process required one traffic lane to be closed for pavement hot-in-place recycling while the other lane 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 passing

vehicles had to stop before the flagger and wait for the pilot car. The work zone was moved forward once to twice per day depending on the project progress.

3.4 Driver Survey Questionnaires

Driver surveys were conducted to determine drivers' acceptance on the two alternative work zone graphics in comparison with the original work zone graphic. Four multiple-choice questions were asked in each questionnaire in an effort to determine the drivers' acceptance of the graphic-aided PCMS and evaluate their opinions on its implementation in a work zone. A fifth question was also asked for 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 to identify the relationship between age category and drivers' preferences to message format. Samples of the questionnaires are attached in Appendixes A.1, A.2 and A.3. A questionnaire used for the text-graphic PCMS with the original 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 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 to have no effectiveness in drawing more of his/her attention to the work zone conditions. The last survey question was:

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

This question was designed to evaluate drivers' opinions on the implementation of the graphic-aided PCMS. The possible options included: *1) Graphical format*, *2) Graphical and text format*, *3) Text format*, *4) No difference*, *5) Don't care, 6) Don't know*, and *7) Other*. "*No difference*" could be chosen if the driver believed that the 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.

Chapter 4 Data Collection

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 3.10. Driver surveys were conducted at the flagger locations where all vehicles had to stop and wait for the pilot car.

4.1 Vehicle Speed Data

A total of 2,676 valid vehicle speed data were collected during the field experiment, as shown in Table 4.1. Among these speed data, 540, 541, and 519 were collected under text-graphic PCMSs which were the alternative one (Figure 3.3), the alternative two (Figure 3.4), and the original (Figure 3.5), respectively; 536 and 540 speed data were captured under graphic PCMSs which were the alternative one (Figure 3.6) and alternative two (Figure 3.7), respectively.

Table 4.1 Summary of Vehicle Speed Data

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

4.2 Driver Survey Data

A total of 454 driver surveys were conducted during the field experiment, as shown in Table 4.2. All driver surveys were conducted under text-graphic PCMSs, including 149 under the text-graphic PCMS alternative one (Figure 3.3), 149 under the text-graphic PCMS alternative two (Figure 3.4), and 156 under the text-graphic PCMS original (Figure 3.5).

Table 4.2 Summary of Driver Survey Data

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

Chapter 5 Data Analysis

5.1 Results of Speed Data Analyses

Speed data of 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 significance of the differences was finally determined using independent two-sample t-tests.

5.1.1 Descriptive Statistics

5.1.1.1 Text-graphic PCMS Alternative One

Table 5.1 shows the detailed statistics of speed data of 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. Median speeds were 1 mph higher that mean speeds from Sensors 1 to 4. The 85^{th} 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 5.1 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

5.1.1.2 Text-graphic PCMS Alternative Two

Table 5.2 displays the statistics of speed data of 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 from Sensors 1 to 4. The 85th percentile speed decreased from 71 mph at Sensor 1 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 5.2 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

5.1.1.3 Text-graphic PCMS Original

Table 5.3 illustrates the statistics of speed data of 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 from Sensors 1 to 3.The 85th percentile speed reduced from 72 mph at Sensor 1 to 66 mph at Sensor 4, and then increased slightly at Sensor 5. The standard deviation ranged between 5.2 and 6.8.

Table 5.3 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

5.1.1.4 Graphic PCMS Alternative One

In the field experiment, 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 of speed data under graphic PCMSs have different profiles of speed reduction than those under text-graphic PCMSs.

Table 5.4 shows the statistics of speed data of 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 at Sensor 1 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 at Sensor 1 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 5.4 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

5.1.1.5 Graphic PCMS Alternative Two

Table 5.5 presents the statistics of speed data of 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 5.5 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

5.1.2 Comparison Analyses

5.1.2.2 Mean Speed Reduction

Table 5.6 gives a summary of mean speed reduction of each PCMS condition in the field experiment. The 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. The 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. The 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 5.1 illustrates the mean speed reduction profiles under the three text-graphic PCMS conditions in the field experiment.

Table 5.6 Summary of Mean Speed Reduction

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%

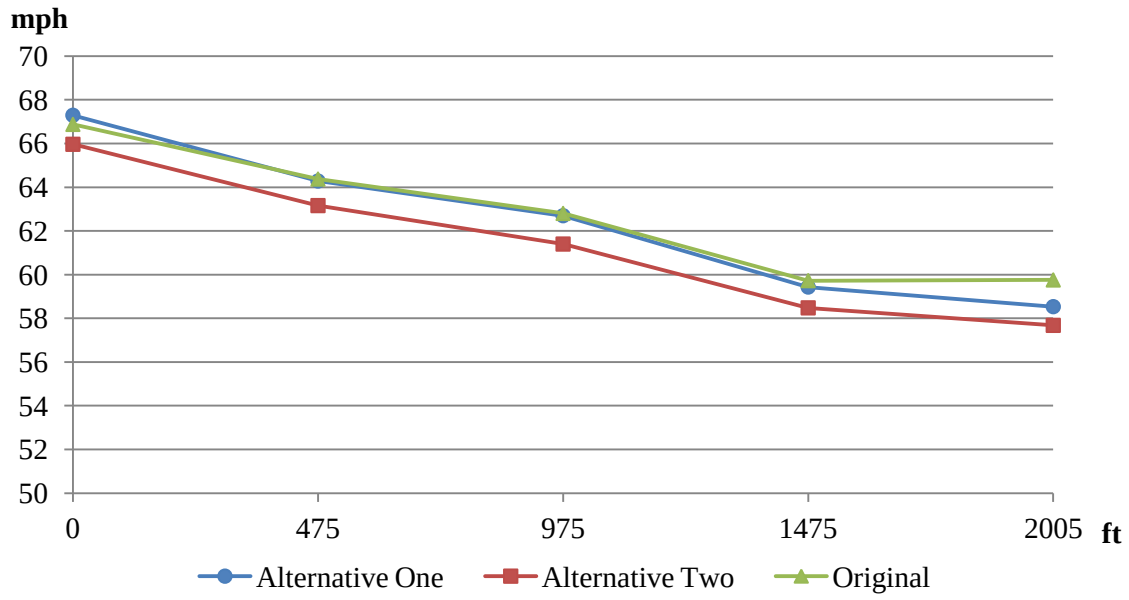


Figure 5.1 Mean Speed Reduction Profile under Text-graphic PCMSs

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 5.6. Figure 5.2 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 different than the speed reduction profiles under the three text-graphic PCMSs.

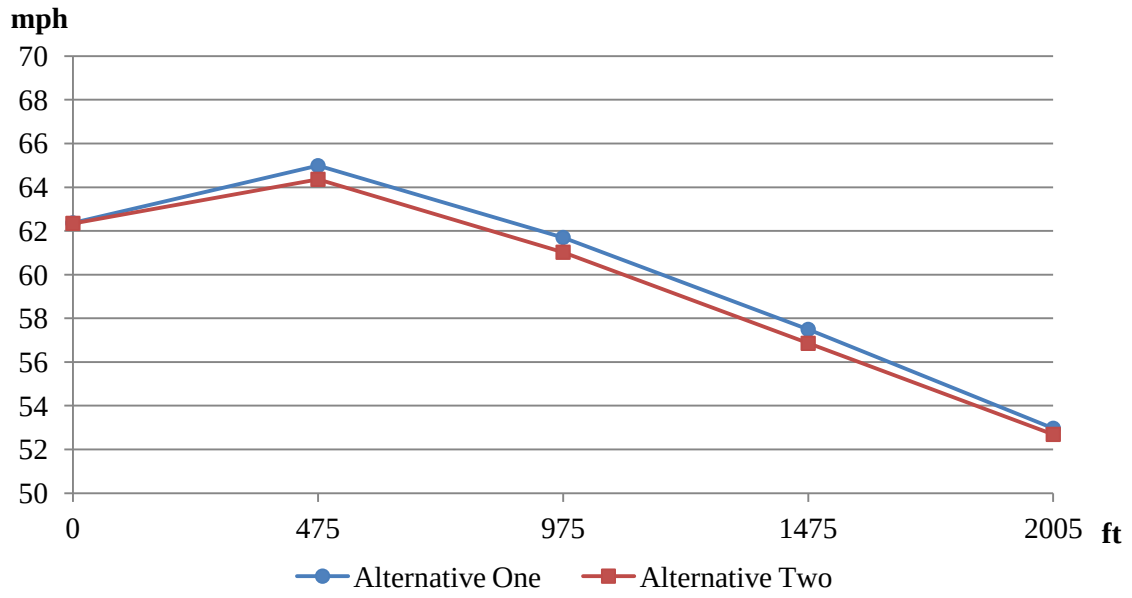


Figure 5.2 Mean Speed Reduction Profile under Graphic PCMSs

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

5.1.2.2 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 the data analysis, one independent two-sample t-test was conducted to compare the mean vehicle speeds at each of the five sensor locations between every two text-graphic PCMSs and between two graphic PCMSs. Therefore, 15 t-tests for vehicle speed data under text-graphic PCMS conditions and five t-tests for vehicle

speed data under graphic PCMS conditions 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 5.7 revealed the results of p-values of t-tests between 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 from Sensors 1 to 4, but statistically equal at Sensor 5 under these two text-graphic PCMS conditions. From Table 5.6, it is clear that the mean speeds from Sensors 1 to 4 were higher under the text-graphic PCMS Alternative One condition than the Alternative Two condition. Therefore, the text-graphic PCMS Alternative One was more effective in reducing mean vehicle speeds than the 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 5.7 P-Values of Independent Two-sample T-tests

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 from Sensors 1 to 4 were greater than 0.05, indicating that the mean vehicle speeds were statistically equal from Sensors 1 to 4, but statistically unequal at Sensor 5 under these two text-graphic PCMS conditions. From Table 5.6, it is clear that the mean speed at Sensor 5 was lower under the text-graphic PCMS Alternative One condition than the Original condition. Therefore, text-graphic PCMS Alternative One was more effective in reducing mean vehicle speeds than text-graphic PCMS Original from the W20-1 location to the W20-4 location (530 ft) in the upstream of a work zone.

The results of t-tests between text-graphic PCMSs Alternative Two and Original showed that none p-value at the five sensor locations was greater than 0.05, indicating that the mean vehicle speeds were statistically unequal at all of the five sensor locations using these two text-graphic PCMSs. Therefore, which condition is more effective in reducing mean vehicle speeds, the Alternative Two or the Original, could not be determined.

The results of t-tests between graphic PCMSs Alternative One and Alternative Two showed that the p-values at all five sensor locations were greater than 0.05, indicating that the mean vehicle speeds were statistically equal at all of the five sensor locations under these two

graphic PCMS conditions. Therefore, the effectiveness of graphic PCMSs Alternative One and Alternative Two in reducing mean vehicle speeds was statistically the same.

5.2 Results of Driver Survey Analyses

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

5.2.1 Driver Survey Results

5.2.1.1 Text-graphic PCMS Alternative One

149 drivers participated in the surveys under text-graphic PCMS Alternative One condition. 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 answered the remaining questions of the survey. Drivers who did not see the PCMS ended their surveys after Question 1. The reasons why drivers did not see the PCMS might be that they entered the highway after the location of 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 5.3, 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.

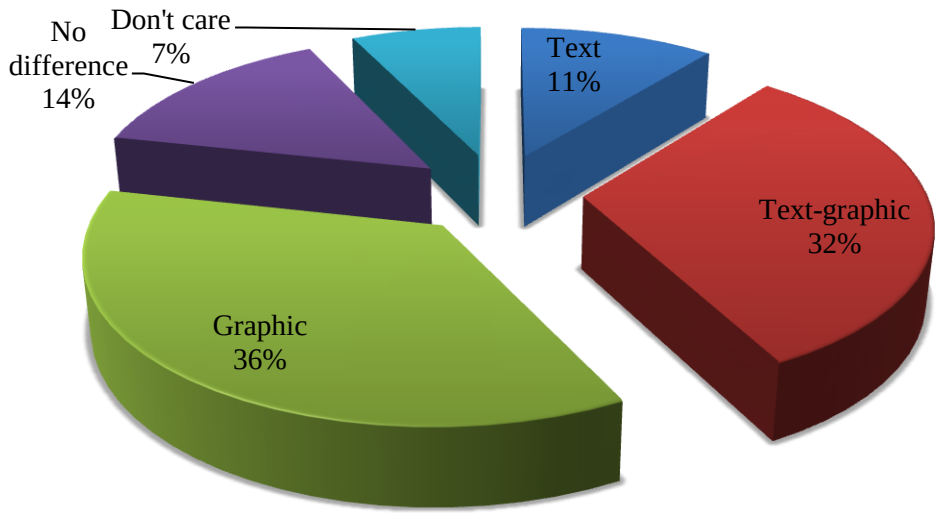


Figure 5.3 Drivers' Preferences on Message Format of Text-graphic PCMS Alternative One

5.2.1.2 Text-graphic PCMS Alternative Two

149 driver surveys were conducted under text-graphic PCMS Alternative Two condition. 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*, 12% of drivers selected *No*, and 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 5.4. 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; and another 14% did not care about the message format.

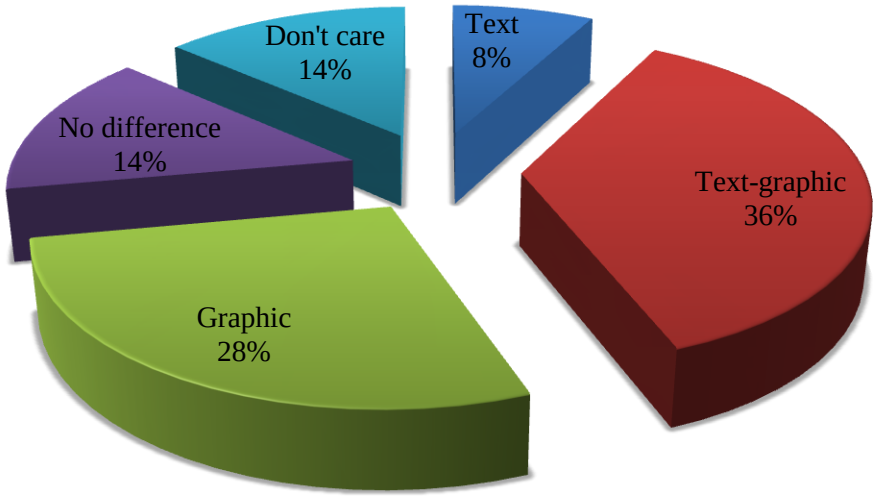


Figure 5.4 Drivers' Preferences on Message Format of Text-graphic PCMS Alternative Two

5.2.1.3 Text-graphic PCMS Original

156 drivers responded to the surveys under text-graphic PCMS Original condition. 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 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*, 22% of drivers selected *No*, and 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 5.5, about a quarter of drivers preferred the text format (25%), the text-graphic format (27%), and the graphic format (26%). 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*.

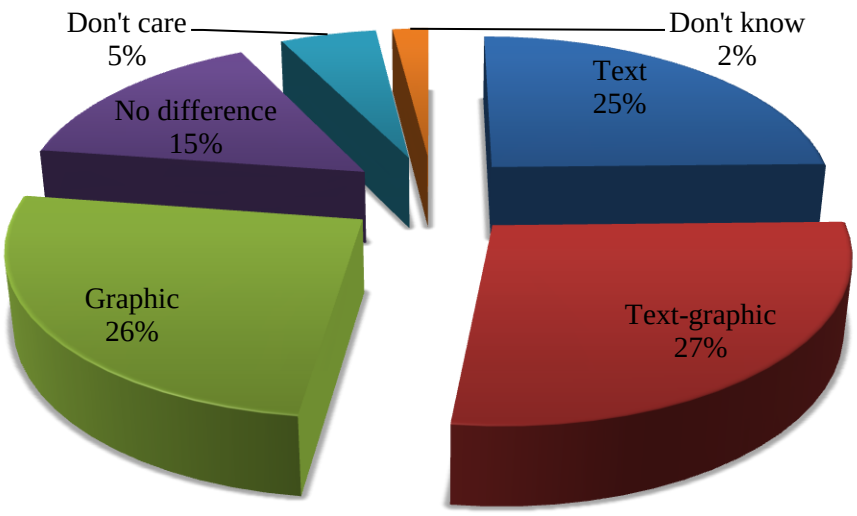


Figure 5.5 Drivers' Preferences on Message Format of Text-graphic PCMS Original

5.2.2 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 under different text-graphic PCMS conditions are statistically independent*

H_1: *Drivers' answers to a question under different text-graphic PCMS conditions are not statistically independent*

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.

5.2.2.1 Drivers' Recognition of Graphics on PCMSs

Table 5.8 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 5.9. The p-value of 0.516 indicated that drivers' recognition of graphics under different text-graphic PCMS conditions were statistically independent, suggesting that the distribution of drivers' answers to their recognition of graphics were statistically the same under three text-graphic PCMS conditions. Therefore, there was no statistically significant difference among drivers' recognition of graphics under the three text-graphic PCMS conditions.

Table 5.8 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 5.9 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		

5.2.2.2 Drivers' Understanding of the Meaning of Graphics on PCMS

Table 5.10 displays the comparison of drivers' understanding of graphic meanings under three text-graphic PCMS conditions. All drivers successfully interpreted two alternative work zone graphic meanings, while 87% of drivers correctly understood the original work zone graphic meaning. The result of Chi-square test in Table 5.11 showed a p-value of 0.000, suggesting a statistical difference in the answers of drivers' understanding of graphic meanings among three text-graphic PCMS conditions.

Table 5.10 Comparison of Drivers' Understanding of Graphic Meanings on Text-graphic PCMSs

Drivers' Understanding of Graphics on PCMS		Text-graphic PCMSs			Total
		Alternative One	Alternative Two	Original	
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 5.11 Test of Independence on Drivers' Understanding of Graphic Meanings 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		

5.2.2.3 Effectiveness of PCMS in Drawing Drivers' Attention

Table 5.12 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. The p-value of 0.001 in Table 5.13 suggested that the effectiveness of

PCMSs in drawing drivers' attention under different text-graphic PCMS conditions were not statistically independent, and that the distribution of drivers' answers to the related question were not statistically the same.

Table 5.12 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%

Table 5.13 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		

5.2.2.4 Drivers' Preferences to Message Format on PCMS

Table 5.14 details the comparison of drivers' preferences to message format under three text-graphic PCMS conditions. 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 PCMS conditions, respectively; while graphic format gained 36%, 28%, and 25% of drivers' selection under the three text-graphic PCMS conditions. About 15% of drivers did not see any difference between text and graphic formats under each of the text-graphic PCMS conditions. 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 (text, text-graphic, and graphic) 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 texts might be easier to understand than the original work zone graphic.

The p-value of 0.00 in Table 5.15 suggested that drivers' preferences to message format under different text-graphic PCMS conditions were not statistically independent, and that drivers' preferences to message format were not statistically the same under different text-graphic PCMS conditions.

Table 5.14 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%

Table 5.15 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		

Chapter 6 Conclusions and Recommendations

6.1 Conclusions

The data analysis results of field experiments in summer 2010 indicated that between 12% and 21% of drivers were confused by the work zone graphic displayed on a graphic-aided PCMS. To improve the work zone graphic representation on the PCMS, two alternative graphics were developed. This research project aimed to compare the effectiveness of two alternative work zone graphics with the original work zone graphic displayed on a PCMS in term of reducing vehicle speeds and drivers' acceptance in the upstream of a one-lane two-way rural highway work zone.

Field experiments were conducted using a full-matrix PCMS and five speed measurement sensors. 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 3.1, the original work zone graphic and the flagger graphic, as seen in Figure 3.2. Using the text message and four graphics, five PCMS conditions were setup including:

- Text-graphic PCMS Alternative One: displaying text WORKZONE AHEAD SLOWDOWN and alternative work zone graphic one (Figure 3.3),
- Text-graphic PCMS Alternative Two: displaying text WORKZONE AHEAD SLOWDOWN and alternative work zone graphic two (Figure 3.4),
- Text-graphic PCMS Original: displaying text WORKZONE AHEAD SLOWDOWN and the original work zone graphic (Figure 3.5),

- Graphic PCMS Alternative One: displaying alternative work zone graphic one and the flagger graphic (Figure 3.6), and
- Graphic PCMS Alternative Two: displaying alternative work zone graphic two and the flagger graphic (Figure 3.7).

The field experiment was conducted in a rural highway work zone on US-75 between Burlington, KS and I-35 using the experiment layout as illustrated in Figure 3.10. Driver surveys were performed under three text-graphic PCMSs to determine drivers' acceptance on the two alternative work zone graphics in comparison 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 text-graphic PCMSs, including 149 under the Alternative One, 149 under the Alternative Two, and 156 under the 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 between 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 and Original from 1,475 ft in the upstream of a work zone (location of Sensor 1) to the W20-4 sign

(location of Sensor 5). The comparison 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 the field experiment. Graphic PCMSs Alternative One and Alternative Two had the same effectiveness in reducing mean vehicle speeds in the upstream of a work zone.

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. The results of Chi-square tests suggested that there was no statistical difference between drivers' recognition of graphics under the three text-graphic PCMS conditions. All drivers successfully interpreted the two alternative work zone graphics, while 87% of drivers correctly recognized 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.

Results of driver surveys also showed that text format was preferred by 11%, 8%, and 25% of drivers under text-graphic PCMSs Alternative One, Alternative Two, and Original, respectively. Text-graphic format was chosen by 32%, 36%, and 27% of drivers under the three text-graphic PCMSs, respectively. Graphic format gained 36%, 28%, and 25% of drivers' selection under the three text-graphic PCMSs, respectively.

6.2 Recommendations

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

1. This research project studied the effectiveness of graphic-aided PCMS with two specific graphics, a work zone graphic and a flagger graphic. Future research is needed to study additional graphics that could be potentially applied to the graphic-aided PCMSs, such as graphics of reduced lanes, congestion, snow, and slippery road.
2. Vehicle types were collected during the field experiments and driver surveys, but were not utilized for statistical analyses, because this research project did not aim to determine the effectiveness of graphic-aided PCMS in reducing speeds of different types of vehicles. Future research is recommended to compare the difference of effectiveness in reducing vehicle speeds between passenger cars and commercial trucks.
3. 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 signs and devices, there is a need to develop a work zone safety education program to raise drivers' awareness of highway work zone risks.

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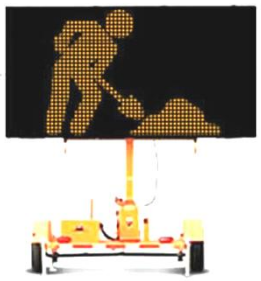
Appendix A Sample Questionnaires

Appendix A.1 A Sample Questionnaire under Text-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 ☐ No difference

☐ Text format ☐ Don't care

☐ Graphical and text format ☐ Don't know

☐ Other_____

5. Could you please indicate your age range?

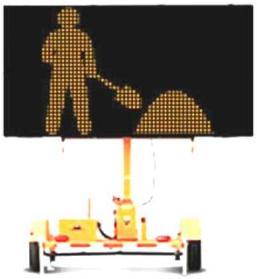
☐ 15−19 ☐ 20−24 ☐ 25−34 ☐ 35−44

☐ 45−54 ☐ 55−64 ☐ 65+

Appendix A.2 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 ☐ No difference

☐ Text format ☐ Don't care

☐ Graphical and text format ☐ 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+

Appendix A.3 A Sample Questionnaire under Text-graphic PCMS Original

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 ☐ No difference

☐ Text format ☐ Don't care

☐ Graphical and text format ☐ 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+