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Driver Responses to 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 temporary traffic control devices. Various studies showed that adding graphics to PCMS messages can provide advantages to traditional text messages, such as increasing legibility and improving the understanding of elderly drivers. This paper synthesizes the findings of a two-phase research project aimed to investigate driver responses to graphic-aided PCMSs. Different text and graphic-aided PCMSs representing roadwork and flagger were set up in the upstream of highway work zones, and speed data of over 2,700 vehicles were collected with a series of five speed sensors to determine vehicle speed reduction. Nearly 1,000 on-site driver surveys were performed to identify driver preference on the added graphics. The results discovered that graphic-aided PCMSs reduced mean vehicle speed between 13% and 17%, and reduced the speed of passenger cars and trucks significantly differently depending on their locations in work zone. The results indicated that all drivers correctly interpreted the flagger graphic and two work zone graphics, and suggested that 52% to 71% of drivers preferred to see graphics in PCMS messages. The findings also revealed that driver age did not have a significant impact on driver preference on PCMS message format.

KEYWORDS: Portable changeable message sign; Work zone; Driver survey; Vehicle type; Gender; Age.

1. BACKGROUND

A portable changeable message sign (PCMS) is a temporary traffic control device that has been applied in work zones for decades in the United States. As the U.S. highway system ages, the demand for highway rehabilitation is growing, and the rehabilitation expenditures of the National Highway System have been increasing by an average of 5.7% per year from 2002 to 2012 (FHWA, 2015b). As a result, a large number of PCMSs are being used in highway work zones to inform motorists of the construction activities.

Traditional PCMS can display only text messages. A few recent studies (Wang et al. 2007; Ullman et al. 2009) have discovered that adding graphics to PCMS messages can provide additional advantages to traditional text messages, such as increasing the range of legibility and helping elderly and non-English-speaking drivers to understand the messages. The advancing LED technology has now made full-matrix PCMS readily available, but its use in the highway construction industry is not popular and many of its advantages have not been utilized.

Some of the advantages of graphic messages over text messages were recognized as early as the 1970s by Dewar and Swanson (1972), Dewar and Ells (1974), Jacobs et al. (1975), and Ells and Dewar (1979) as being:

- More legible on a given size of sign and at shorter exposure durations;
- More easily recognizable under adverse viewing conditions;
- More quickly extracted by drivers when concentrating on driving; and
- More interpretable to drivers having difficulty understanding text.

In the recent decade, with the help of driving simulators, researchers have been studying driver behavior towards graphics on PCMSs in controlled laboratory environments. Wang et al. (2007) and Ullman et al. (2009) studied driver understanding of graphics added to text messages, including road work, accident, congestion, lane shift, and slippery road, using questionnaires and driving simulators. Wang et al. (2007) compared text only messages with graphic-aided messages and Ullman et al. (2009) compared text only messages with graphic only messages. Their results indicated that most participants understood and preferred the graphics, and that the graphics were responded to faster than text messages for elderly drivers and helped improve the understanding of non-English-speaking drivers. More recently, Chen et al. (2013) investigated driver understanding of different graphical information on message signs, including road closed, rain, snow, fog, and crosswind, through over 400 questionnaires in laboratory environments, and concluded that drivers of different gender and age had generally the same understanding of graphics.

Although the driving simulators and questionnaires employed in previous studies were able to simulate a variety of driving tasks while evaluating driver responses to graphics on PCMSs, such as lane keeping, speed controlling, and car following, it is unclear whether the results obtained from these simulation studies could still remain effective when it came to real-world driving. To overcome the limitations of simulation studies, this research aimed to investigate driver responses to graphic-aided PCMSs in the upstream of highway work zones by applying vehicle speed data and driver survey results that were collected under real-world highway work zone traffic conditions.

This paper synthesizes all findings of a two-phase research project. The results of vehicle speed analyses in both phases were presented in detail by Huang and Bai (2014) and were therefore only briefly introduced here. This paper primarily focused on the results of driver surveys in both phases as well as the impact of driver gender and age on speed reduction, which were not reported in previous publications. In this paper, a graphic-aided PCMS refers to a

PCMS that displays graphics, and a text PCMS refers to a PCMS that displays only text messages. 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. The findings presented in this paper address: 1) the effectiveness of text PCMS, text-graphic PCMS, and graphic PCMS in reducing mean vehicle speed in the upstream of highway work zones; 2) the difference of mean speed reduction between passenger cars and trucks resulted from using graphic-aided PCMS; 3) driver preference on PCMS message format when drivers saw text PCMS, text-graphic PCMS, and graphic PCMS; and 4) the impact of gender and age on driver preference on PCMS message format.

2. PHASE I STUDY

2.1 Methodology

2.1.1 Vehicle Speed

Field experiment phase I was conducted on Kansas Highway 13, a section of two-lane rural highway with a speed limit of 65 miles per hour (mph) and an annual average daily traffic (AADT) of around 1,200 vehicles per day (vpd), according to the traffic count from KDOT. Field observations lasted for a total of five working days from 6 am to 8 pm under favorable weather conditions. A full-matrix message board (model: Wanco WTMMB-SLL) was used to display PCMS messages, and vehicle speed was collected with five speed measurement sensors (model: JAMAR TRAX Apollyon). All experiment design and procedures were approved by the project sponsor Kansas Department of Transportation (KDOT), followed KDOT standards and policies, and were supervised by KDOT personnel to ensure research integrity.

A work zone graphic, a flagger graphic, and two text messages were designed and tested on four PCMSs, namely:

- A text-graphic PCMS displaying the text message WORKZONE AHEAD SLOWDOWN and the work zone graphic (see Figure 1)
- A text-graphic PCMS displaying the text message FLAGGER AHD PREP TO STOP (flagger ahead prepare to stop) and the flagger graphic (see Figure 2)
- A text PCMS displaying both text messages (see Figure 3)
- A graphic PCMS displaying both graphics (see Figure 4)

Each PCMS displayed the first text message or graphic for three seconds, then the second text message or graphic for another three seconds, and then switched back to the first message, and so forth. Each PCMS was presented continuously for two to three hours per day, distributed evenly in the daytime throughout the five working days to eliminate the impact of displaying order and time of day. Five speed measurement sensors were used to record vehicle speed along a distance of 2,005 ft. The layout of the PCMS and speed sensors (S1 through S5) is illustrated in Figure 5. Based on the findings of Bai et al. (2015) on the effective location of a PCMS in reducing work zone crashes, the PCMS was placed 575 ft upstream of the beginning of the work zone, which was marked by the W20-1 sign (diamond orange sign with text ROAD WORK AHEAD). The five speed sensors were installed approximately 500 ft apart with S4 at the location of W20-1 sign and S5 at the location of W20-4 sign (diamond orange sign with text ONE LANE ROAD AHEAD) to record the profile of vehicle speed reduction when approaching and entering the work zone. All devices were installed at the rear end of the work zone so as not to become obstacles when the work zone was moving forward.

<u>Insert Figure 1 here</u>

Insert Figure 2 here

Insert Figure 3 here

Insert Figure 4 here

Insert Figure 5 here

Vehicle speed data were recorded when a vehicle traveled over a pair of tubes, which were connected to a speed sensor located at each of the five sensor locations, as indicated in Figure 5. The five speed sensors recorded the speed of the same vehicle five to eight seconds apart between each two adjacent sensors, which was used to identify individual vehicles. Because of the time needed for initial equipment installation, re-installation after the work zone moved forward, and end-of-day removal, the actual recording duration of vehicle speed was only a small portion of the 14-hour working time. An extensive screening process was then performed to sort out vehicles with incomplete or apparent low speed (less than 20 mph), which typically included vehicles that turned into or out of the work zone as well as farm vehicles. Around a quarter of collected vehicle speed data were discarded after screening, and the speed data of a total of 1,115 vehicles were determined to be valid, among which 345 were under the text PCMS, 367 were under the text-graphic PCMSs, and 403 were under the graphic PCMS. Due to the fast work zone construction progress, vehicle speed data collected under two different text-graphic PCMS settings were not sufficient enough to analyze individually, and were therefore combined as one set of data for the text-graphic PCMS condition.

2.1.2 Driver Survey

Roadwork turned the highway section from a two-lane two-way roadway into a one-lane two-way work zone. Vehicles from one direction had to stop at a flagger location when vehicles from the other direction were traveling through the work zone under the lead of a pilot vehicle.

The pilot vehicle thus traveled back and forth between the two flagger locations of the work zone without impacting vehicle speed collection at the experiment sites in the upstream of the work zone. Driver surveys were performed at one flagger location, as indicated in Figure 5, at the rear end of the work zone as this flagger moved forward less frequently than the flagger at the front. Two graduate research assistants administrated the driver surveys by approaching stopped vehicles and asking drivers questions. Field observations revealed that the pilot vehicle took between 10 and 15 minutes to make a round trip in the work zone depending on work zone length, and a single survey took up to three minutes in most cases. Therefore, three to five surveys could be completed in each round before the graduate research assistants sighted the pilot vehicle and retreated from the vehicle queue so as not to interrupt work zone traffic and causing further delay.

Each driver was asked four questions from a questionnaire and the responses were recorded directly on the individual questionnaire. The questions for a driver specifically matched the messages displayed on the PCMS that the driver just saw when approaching the work zone. As a result, four different questionnaires were used for the four PCMS settings shown in Figures 1 through 4. For example, the following four questions were asked when the text-graphic PCMS with the work zone graphic, as illustrated in Figure 1, was displayed to the drivers.

1. Did you see a graphic displayed on the Portable Changeable Message Sign when you were approaching the work zone?

   □ Yes □ No

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

   □ Road work /Someone working □ Confused □ Don’t know □ Other, specify

3. Did you pay more attention to traffic conditions after seeing the graphic?

□ Yes □ No □ Don't know

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

   □ Text format □ Text plus graphic format □ Graphic format

   □ No difference □ Don't care □ Don't know □ Other

The questions asked when the text PCMS was displayed were slightly different because drivers did not see any graphics on the text PCMS. Therefore, in question 4, the pictures of the work zone graphic and the flagger graphic were included in the questionnaire to show the drivers how the graphic warning signs would look like compared with the text format they just saw. In addition, drivers' responses including No difference, Don't care, Don't know, and Other were considered as non-committal preferences of message format and were therefore combined into a single category Other in data analyses.

2.2 Results and Discussion

2.2.1 Vehicle Speed

The summary of the vehicle speed reduction in phase I is presented in Table 1. The text PCMS resulted in a mean vehicle speed reduction of 8 mph, or 13%, from 64 mph at S1 to 56 mph at S5. With the text-graphic PCMSs being displayed, mean vehicle speed decreased from 65 mph at S1 to 58 mph at S4, then climbed slightly to 59 mph at S5, resulting in a reduction of 6 mph or a reduction rate of 10%. Under the graphic PCMS, mean vehicle speed decreased almost linearly from 63 mph at S1 to 52 mph at S5, resulting in the largest reduction rate of 17%, or 11 mph. T-tests between each two PCMSs at each sensor location indicated that mean speed was not significantly different between text and graphic PCMSs only at S1 location and not significantly different between text and text-graphic PCMSs only at S2 location.

Insert Table 1 here

An MANOVA test was performed, where sensor location was assigned as the repeated measures with five levels and PCMS type was assigned as between-subjects factors, to determine if there was a significant difference between mean vehicle speed at different sensor locations. The test result of Wilks' Lambda in Table 2 suggested that there was a statistically significant difference in mean vehicle speed at all sensor locations, F (8, 2218) = 25.084, $p < .001$. Combining such test results with the mean speed reduction profile, it was concluded that the graphic and text-graphic PCMSs reduced mean vehicle speed more effectively than the text PCMS from S1 to S5 and from S1 to S2, respectively (Huang and Bai, 2014). While the comparison suggested that the combination of text and graphic messages resulted in the least vehicle speed reduction, speed reduction analyses did not reveal the reason of such results due to the fact that driver information was not collected. Therefore, to determine the reason of the different vehicle speed reduction, driver surveys were performed to collect driver information and their opinions towards different PCMSs.

Insert Table 2 here

2.2.2 Driver Survey

The minimum sample size of driver surveys was determined based on the table by Krejcie and Morgan (1970). The minimum sample size for a population of 1,200 AADT with a confidence level of 95% and a margin of error of 3.5% was 474. A total of 536 questionnaires were collected with 12 determined uninformative for the research purpose and discarded. In these 12 driver surveys, the drivers answered the first question as "did not see the PCMS" and therefore the following questions could not be asked. The reason for not seeing the PCMS might be that these drivers came from a minor road between the PCMS and the flagger, or that they were distracted when approaching the PCMS and thus did not see it. Among the 524 valid driver surveys, 149 were performed under the text PCMS, 125 were performed under the text-graphic PCMS with the work zone graphic, 124 were performed under the text-graphic PCMS with the flagger graphic, and 126 were performed under the graphic PCMS. In order to complete each survey within the shortest amount of time so as not to delay work zone traffic, drivers were not asked for any information other than the four questions above. As a result, the characteristics of survey participants in Phase I were not available.

After confirming that they saw the PCMS, drivers were asked to interpret the graphics on the PCMS, and the results are shown in Table 3. When the text-graphic PCMS with the work zone graphic (see Figure 1) was displayed, 88% of drivers correctly interpreted the work zone graphic. When the text-graphic PCMS with the flagger graphic (see Figure 2) was displayed, all drivers correctly interpreted the flagger graphic. When the graphic PCMS (see Figure 4) was displayed, the work zone graphic was interpreted correctly by 79% of drivers and the flagger graphic was still correctly interpreted by all drivers. In other words, 12% to 21% of drivers did not understand the meaning of the work zone graphic, and it could be inferred that using a text message along with the work zone graphic on the text-graphic PCMS helped 9% more drivers correctly interpret the graphic. In addition, the results also revealed that the work zone graphic had confused some drivers despite reading the messages on the text-graphic PCMS when approaching the work zone. These drivers might need to read the text message before they were able to understand the work zone graphic or see the flagger graphic on the graphic PCMS to relate it to roadwork. This confusion could be the reason that the text-graphic PCMS resulted in the least vehicle speed reduction.

<u>Insert Table 3 here</u>

Drivers were then asked if they paid more attention to traffic conditions after seeing the messages on the PCMS, and the results are presented in Table 3. 97% of drivers believed they paid more attention to traffic conditions after seeing the text PCMS. 82% and 90% of drivers thought they paid more attention to traffic conditions after they saw the text-graphic PCMS with the work zone graphic and with the flagger graphic, respectively. After viewing the graphic PCMS, 87% of drivers indicated that they paid more attention to traffic conditions. Although the work zone graphic on the graphic PCMS was interpreted correctly by the least drivers (79%) according to Table 4, the graphic PCMS still had 87% of drivers pay more attention to traffic conditions. It was likely that the well-understood flagger graphic on the graphic PCMS helped to result in this relatively high percentage.

Insert Table 4 here

Drivers were finally asked about their preferred message format on PCMS, and their preferences are shown in Table 5. The *text format* was preferred by 64% of drivers when the text PCMS was displayed to them. When the text message was displayed along with a graphic on the text-graphic PCMS, the percentage dropped to 24% for the work zone graphic and to only 3% for the flagger graphic. 12% of drivers still preferred the text format when the graphic PCMS was displayed to them. In contrast, the *graphic format* was chosen by only 5% of drivers when they had only seen the text PCMS. This was most likely because under the current KDOT practice, most drivers had never seen messages in graphic format displayed on a PCMS and thus were not able to effectively compare it with the text format. When drivers were exposed to the text-graphic PCMS, the percentage rose to 26% preferring the work zone graphic alone and 52% preferring the flagger graphic alone. When the graphic PCMS was displayed, the percentage of drivers who preferred the graphic format kept relatively high at 45%. The *text-graphic format* had more even percentages of driver preferences: 16% under the text PCMS, 26% under the text-graphic PCMS with the work zone graphic, 19% under the text-graphic PCMS with the flagger graphic, and 21% under the graphic PCMS.

<u>Insert Table 5 here</u>

When combining the text-graphic and graphic formats into the graphic-aided format, the above results in Table 5 suggested that when a graphic-aided PCMS was displayed to the drivers, 52% to 71% of them preferred the graphic-aided format. This finding generally agreed with the results of the simulator study by Wang et al. (2007), who concluded that 94% out of the 127 survey participants preferred graphics to text messages when graphic-aided PCMSs are available to them. The results in Table 3 also mainly agreed with the outcomes of the laboratory study by Ullman et al. (2009), who concluded that the symbol representation of roadwork was well understood by 80% to 90% out of 962 participants, compared with 79% to 88% in this study.

79% to 88% of understanding rate for the work zone graphic, however, was not considered optimal in the design of this research. The advantages of using graphics on PCMS, as expressed by many drivers who talked more after completing the survey, were that the large graphics were able to "catch their eyes" from a distance away and that they were able to understand it at their first sight "without thinking", such as the flagger graphic. But for the work zone graphic, when some drivers did not understand it at their first sight, the advantage did not exist. Furthermore, driver confusion while driving would increase their reaction time and delay the braking action, and might have affected the mean vehicle speed reduction when the work zone graphic was displayed. To improve driver understanding of the work zone graphic and better test the relationship between message format and vehicle speed, phase II study was carried out.

3. PHASE II STUDY

3.1 Methodology

3.1.1 Vehicle Speed

Field experiment phase II was conducted on U.S. Highway 75, a section of two-lane rural highway with a speed limit of 65 mph and an AADT of around 4,000 vpd, according to KDOT's traffic count. Field observations lasted for a total of six working days from 6 am to 8 pm, and the roadway and weather conditions were similar to those in Phase I. Vehicle type, driver gender, and driver age were collected in phase II to better test the relationship between message format and vehicle speed, which had been identified as a weakness of phase I. These were the vehicle and driver factors that would most influentially impact vehicle speed reduction and could be quickly and easily identified without interrupting work zone traffic. Vehicles were categorized into passenger cars and trucks to compare their speed reduction. Driver gender and age were recorded to evaluate their impact on driver preference on PCMS message format.

Two alternative work zone graphics were designed and programed in the PCMS. These two alternatives were tested along with the original work zone graphic used in phase I on three text-graphic PCMSs, including:

- Original: displaying the text message WORKZONE AHEAD SLOWDOWN and the original work zone graphic (see Figure 1)
- Alternative One: displaying the text message WORKZONE AHEAD SLOWDOWN and work zone graphic alternative one (see Figure 6)
- Alternative Two: displaying the text message WORKZONE AHEAD SLOWDOWN and work zone graphic alternative two (see Figure 7)

Each PCMS was presented continuously for two to three hours per day, distributed evenly in the daytime throughout the six working days. The two alternative work zone graphics were not tested on graphic PCMS because using the text-graphic PCMS alone was able to determine if the alternative graphics could improve driver understanding.

Insert Figure 6 here

Insert Figure 7 here

Collecting and processing vehicle speed data was generally the same as in phase I. Vehicle types were identified in phase II to compare the difference of mean speed reduction between passenger cars and trucks. Since vehicles were not categorized by visual observation during speed data collection, vehicle speed data were sorted additionally to identify vehicle type by its number of axles and wheelbase. The general sorting rule was that if the average number of axles recorded by five speed sensors was larger than two or the average wheelbase recorded by five speed sensors was longer than 200 inches (16 feet 8 inches), the vehicle was categorized as a truck. After an extensive screening and sorting, the speed data of a total of 1,600 vehicles were determined to be valid, among which 519 were under the Original, including 387 passenger cars and 132 trucks, 540 were under the Alternative One, including 410 passenger cars and 130 trucks, and 541 were under the Alternative Two, including 399 passenger cars and 142 trucks.

2.1.2 Driver Survey

Driver surveys were performed in phase II for each of the three text-graphic PCMSs. The surveys were administrated using the same approach as in phase I. The same four questions were asked and the responses were recorded on individual questionnaires, as described in the previous section. In addition, in order to evaluate the impact of driver age and gender on driver preference on PCMS message format, drivers were asked to choose their age from the following seven age groups based on the age categories in FHWA’s Highway Statistics: *Less than 19*, *19 to 24*, *25 to 34*, *35 to 44*, *45 to 54*, *55 to 64*, and *Over 64*, and their gender was also recorded on the questionnaire.

3.2 Results and Discussion

3.2.1 Vehicle Speed

The descriptive statistics of vehicle speed in phase II are presented in Table 6 and the summary of mean vehicle speed reduction is presented in Table 7. Unlike the speed reduction comparison in phase I, the results of speed reduction from the three text-graphic PCMSs did not vary much. When considering all vehicles, the Original PCMS resulted in a 10.6% of mean vehicle speed reduction, matching the results in phase I shown in Table 1. The Alternative One PCMS helped reduce mean vehicle speed by 13.0% and the Alternative Two PCMS helped reduce mean vehicle speed slightly less, by 12.6%, both exceeding the Original by at least 2%. T-tests between each two PCMSs at each sensor location indicated that while mean speed was significantly different at all sensor locations between Alternative Two and Original PCMSs, mean speed was not significantly different from S1 through S4 locations between Alternative One and Original PCMSs (Huang and Bai, 2014). Combining such test results with the mean speed reduction profile, it was concluded that the Alternative One PCMS reduced mean vehicle speed more effectively than the Original PCMS from S4 to S5 (Huang and Bai, 2014).

<u>Insert Table 6 here</u>

<u>Insert Table 7 here</u>

When splitting vehicle speed data by passenger cars and trucks, the results are shown in Table 7. While the Original PCMS resulted in almost the same mean speed reduction rates for both passenger cars and trucks from S1 to S5, the Alternative One and Alternative Two PCMSs helped reduce mean vehicle speed slightly better for passenger cars than trucks, at 1.2% difference and 0.6% difference, respectively. An MANOVA test was performed, where sensor location was assigned as the repeated measures with five levels whereas PCMS type and vehicle type assigned as between-subjects factors, to determine if there was a significant difference between mean vehicle speed at all sensor locations and different vehicle types. The test result of Wilks' Lambda in Table 8 suggested that there was a statistically significant difference in mean vehicle speed at all sensor locations based on different vehicle types, F (4, 1591) = 19.63, p < .001.

Insert Table 8 here

Pairwise t-tests were further performed to determine if the mean vehicle speed was significantly different between passenger cars and trucks at each sensor location. The alpha values were adjusted to α=.01 based on Bonferroni Correction to avoid inflated Type I errors in repeated t-tests. The p-values of t-tests in Table 7 indicated that mean speed was not significantly different at S3 and S4 locations under all PCMSs and also at S5 location under the Alternative One and Alternative Two PCMSs. Combining with the mean speed reduction profile presented in Figure 8, such results suggested that all three PCMSs reduced mean vehicle speed of passenger cars more effectively than trucks from S1 to S3, and the Original PCMS reduced mean vehicle speed of trucks more effectively than passenger cars from S3 to S5. Although trucks were traveling 2 to 3 mph slower than the passenger cars when they saw the PCMS, they did not reduce speed as much as the passenger cars did. This could be simply due to the fact that trucks needed longer distance to reduce the same amount of speed compared to passenger cars because of their larger weight.

Insert Figure 8 here

3.2.2 Driver Survey

The minimum sample size of driver surveys for a population of 4,000 AADT with a confidence level of 95% and a margin of error of 4.5% was 424. A total of 454 questionnaires were collected, among which 25 were determined to be uninformative for the research purpose because the drivers stated that they "did not see the PCMS" and thus the following three questions could not be asked. In the remaining 429 questionnaires, 150 were performed under the Original PCMS, 139 were performed under the Alternative One PCMS, and 140 were performed under the Alternative Two PCMS.

Drivers who confirmed seeing the PCMS were asked to interpret the graphics on the PCMS first, and the results are shown in Table 9. 87% of drivers who saw the Original PCMS correctly understand the original work zone graphic, and this percentage matched the results from phase I, which was 88% from Table 2. All drivers who saw the Alternative One and Alternative Two PCMS correctly understand the two alternative work zone graphics.

Insert Table 9 here

Drivers were then asked if they paid more attention to traffic conditions after seeing the messages on the PCMS, and the results are presented in Table 10. 72% of drivers who saw the Original PCMS indicated that they paid more attention to traffic conditions while 22% of drivers did not. When the Alternative One and Alternative Two PCMS was displayed, 89% and 83% of drivers who saw it believed they paid more attention to traffic conditions, 17% and 11% higher than the Original PCMS, respectively. The results indicated that the Original PCMS with the original work zone graphic attracted drives' attention least effectively, which aligned with the results from phase I in Table 4.

Insert Table 10 here

Drivers were finally asked about their preferred message format on PCMS, and their preferences are shown in Table 11. When the *Original PCMS* was displayed, the text, text-graphic, and graphic format was preferred by roughly a quarter of the drivers who saw it, which was highly consistent with the results from phase I in Table 5. Driver preferences were similar under the *Alternative One PCMS* and *Alternative Two PCMS*. The percentage for the text format dropped to 8% to 11%, and the percentages for the text-graphic format and the graphic format climbed to 32% to 36% and 28% to 36%, respectively. The results again indicated that when the work zone graphic displayed on PCMS was correctly understood, more drivers (64% to 68% in phase II) preferred to see the graphic either combined with text or alone on PCMS.

Insert Table 11 here

3.2.2.1 Impact of Driver Gender

Driver gender and age information were recorded during the surveys in phase II to evaluate their impact on driver preference on PCMS message format. Chi-Square tests of independence were used to determine the relationship between driver gender and age and their preference on PCMS message format separately for each of the three graphics displayed on the PCMSs. The null hypotheses assume that drivers of both genders or in all age groups have statistically the same preference on PCMS message format, and the alternative hypotheses assume that drivers of different genders or in different age groups have different preferences to PCMS message format. A 95% level of confidence was used in the Chi-Square tests.

The driver surveys included 109 males (73%) and 41 females (27%) under the Original PCMS, 78 males (56%) and 61 females (44%) under the Alternative One PCMS, and 101 males (72%) and 39 females (28%) under the Alternative Two PCMS. The number of licensed Kansas male and female drivers was approximately equal (49% vs 51%) in 2015 according to Highway Statistics (FHWA, 2015a), so male drivers were over-represented in the study sample. Male and female drivers' preference on message format under each of the three PCMSs in phase II are detailed in Table 12 and their comparison is illustrated in Figure 9. The comparison showed that male and female drivers' preference on message format was generally similar under the Original and Alternative Two PCMSs, but varied under the Alternative One PCMS.

<u>Insert Table 12 here</u>

<u>Insert Figure 9 here</u>

The results of Chi-Square test of independence on driver preferences and gender under each of the three PCMSs are presented in Table 13. Driver responses including No difference, Don't care, Don't know, and Other were considered as non-committal preferences and had been omitted in the Chi-Square test of independence since this study did not aim to compare these four categories of responses and the number of responses in each category were relatively low. The test results suggested that there was a significant relationship between driver gender and their preferred message format under the Alternative One PCMS (p-value =.030) but not under the Original PCMS (p-value =.419) or Alternative Two PCMSs (p-value =.936). The comparison in Figure 8 revealed that under the Alternative One PCMS, male drivers were more likely to prefer the graphic format, whereas female drivers were more likely to prefer the text-graphic format.

<u>Insert Table 13 here</u>

3.2.2.2 Impact of Driver Age

Driver age distribution under each PCMS message format is presented in Table 14 as compared to licensed Kansas drivers. Although Highway Statistics showed very similar percentages (15% to 18%) of Kansas drivers in each age group from 25 to over 64 (FHWA, 2015a), the age distribution of drivers under each PCMS message format varied. Chi-Square tests of goodness of fit had p-values of .022, .113, and less than .001, respectively for the three PCMS message formats, suggesting that driver age distribution under Alternative One was not different to driver population statistics, but the Original and Alternative Two samples tended to be over-represented in older age categories (45-64) compared to Kansas drivers.

Insert Table 14 here

Drivers' preference on PCMS message format in different age groups under each of the three PCMSs in phase II are detailed in Table 15 and their comparison is illustrated in Figure 10. Due to the small frequency of several preference categories, the seven age groups were combined into three for the Chi-Square test: less than 34, 35 to 54, and over 55. In addition, the test again omitted driver responses which were considered as non-committal preferences. The results of the Chi-Square test of independence in Table 16 indicated that there was no significant relationship between driver age and their preferred message format under any of the three PCMSs (all p-values >.237). Since over 20% of cells had expected frequencies less than 5 under Alternative Two, which might have indicated the test to be invalid, a Fisher's Exact Test with the Freeman-Halton extension was further performed for this 3x3 table and resulted in a p-value of .942. The test results on driver age were consistent with the findings by Chen et al. (2013) that drivers of different age had generally the same understanding of graphics for road conditions.

Insert Table 15 here

Insert Figure 10 here

Insert Table 16 here

4. CONCLUSIONS

PCMS, as a temporary traffic control device, has been increasingly employed in work zones due to the growing number of highway rehabilitation projects in the United States. A few recent simulation studies showed that graphics on PCMSs were understood and preferred by most respondents and improved the understanding of elderly and non-English-speaking drivers. Although the advantages of graphic-aided PCMS have been recognized in simulator environments, whether these results still hold in real-world driving conditions remains a question. To overcome the limitations of simulation studies, this research aimed to investigate driver responses to graphic-aided PCMSs in the upstream of highway work zones by applying vehicle speed data and driver survey results that were collected under real-world highway work zone traffic conditions.

The research was carried out in two phases. In phase I, a work zone graphic and a flagger graphic were designed and tested, and the results of driver surveys suggested that the work zone graphic was not an optimal design and should be improved. As a result, phase II was carried out. Two alternative work zone graphics were designed and, along with the original work zone graphic in phase I, were tested. In addition, vehicles were categorized into passenger cars and trucks to compare their speed reduction, and driver gender and age were recorded to evaluate their impact on driver preference on PCMS message format.

The results of the two-phase field experiments showed that while the original text-graphic PCMS reduced mean vehicle speed by 10%, graphic-aided PCMSs with redesigned graphics reduced mean vehicle speed between 13% and 17%, compared with 13% mean vehicle speed reduction by text PCMS. Statistical analyses suggested that in phase I, the graphic and text-graphic PCMSs reduced mean vehicle speed more effectively than the text PCMS from S1 to S5 and from S1 to S2, respectively, and in phase II, the Alternative One PCMS reduced mean vehicle speed more effectively than the Original PCMS from S4 to S5. Overall, the Alternative One and Alternative Two PCMSs helped reduce mean vehicle speed slightly better for passenger cars than trucks. All three PCMSs reduced mean vehicle speed of passenger cars more effectively than trucks from S1 to S3, and the Original PCMS reduced mean vehicle speed of trucks more effectively than passenger cars from S3 to S5.

The results of driver surveys indicated that all drivers correctly interpreted the flagger graphic and two redesigned work zone graphics, and suggested that 52% to 71% of drivers preferred to see graphics in PCMS messages. The findings also revealed that while driver age did not have a significant impact on driver preference on PCMS message format, male and female drivers had significantly different preference on message format under the Alternative One PCMS. Since the conclusion on driver gender was inconsistent with previous studies, additional research is needed to clarify the impact of driver gender on their preference on message format.

Several limitations of this study have been identified in research design and field experiment: 1) the results of phase I study were potentially affected by the poorly-designed work zone graphic; 2) phase II study was conducted in an approach not allowing direction comparison between the different PCMS message formats displayed in both phases; 3) all survey responses were self-reported data which might be affected by drivers' views about the purpose of the study. Nonetheless, this paper provides valuable information from pilot field experiments and driver surveys for future research of a comprehensive evaluation of implementing graphic-aided PCMSs in highway work zones.

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Figure 1. Text-graphic PCMS with the Work Zone Graphic (from Huang and Bai (2014) Figure 3, license obtained)

Figure 2. Text-graphic PCMS with the Flagger Graphic (from Huang and Bai (2014) Figure 4, license obtained)

Figure 3. Text PCMS (from Huang and Bai (2014) Figure 2, license obtained)

Figure 4. Graphic PCMS (from Huang and Bai (2014) Figure 5, license obtained)

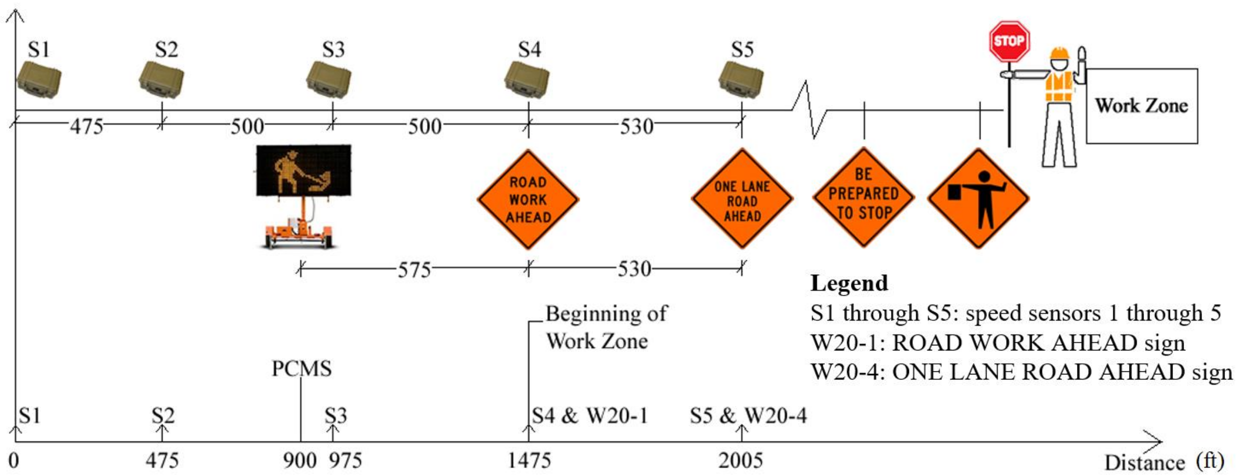

Figure 5. Field Experimental Layout (from Huang and Bai (2014) Figure 6, license obtained)

Figure 6. Text-graphic PCMS with Work Zone Graphic Alternative One (from Huang and Bai (2014) Figure 9, license obtained)

Figure 7. Text-graphic PCMS with Work Zone Graphic Alternative Two (from Huang and Bai (2014) Figure 10, license obtained)

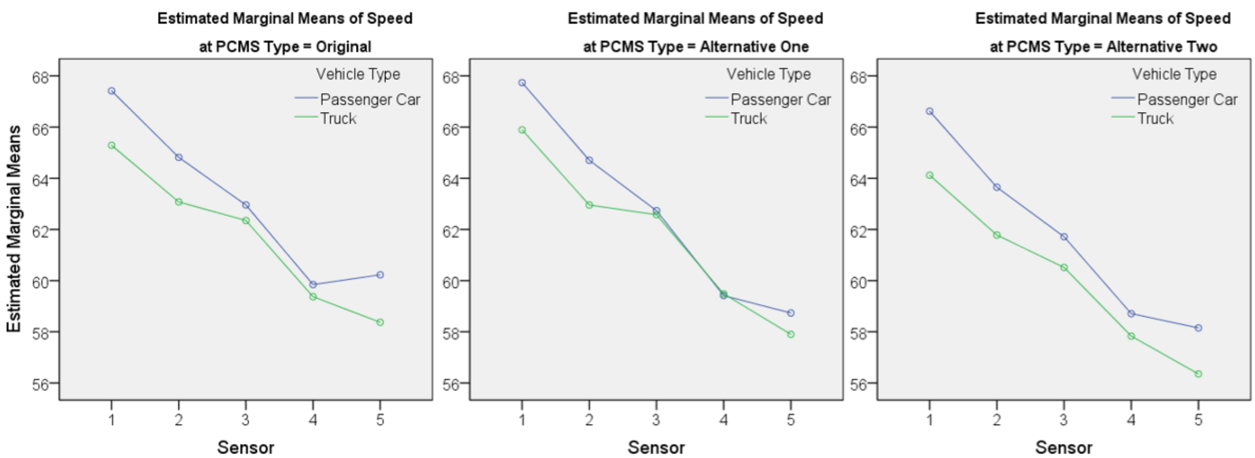

Figure 8. Comparison of Mean Vehicle Reduction Profile between Passenger Cars and Trucks in Phase II

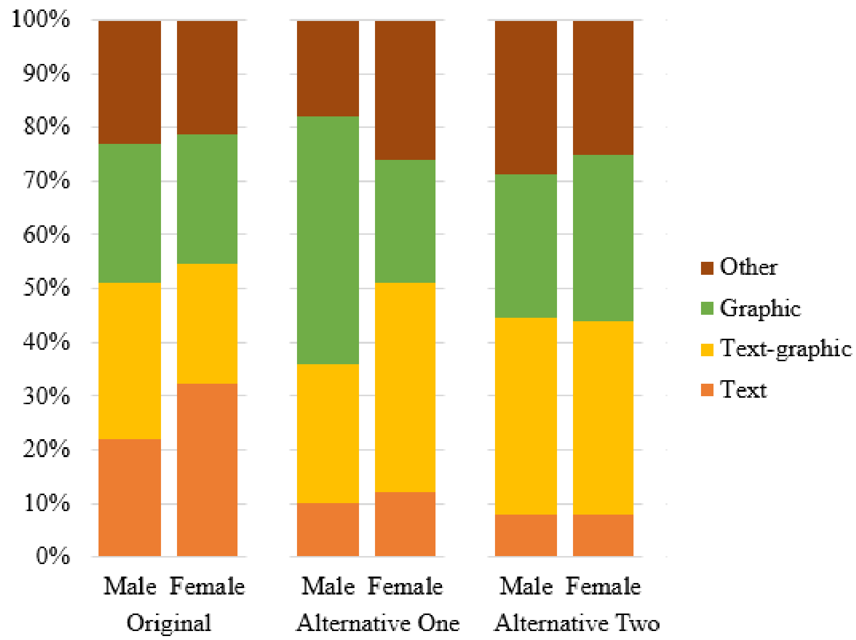

Figure 9. Comparison of the Impact of Driver Gender on Preference on PCMS Message Format

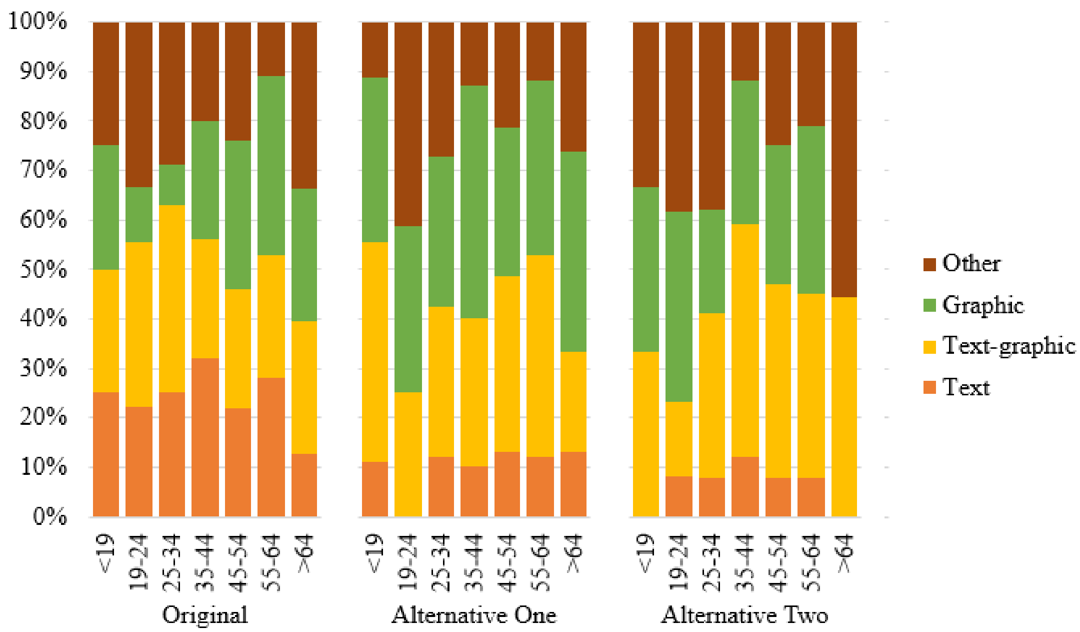

Figure 10. Comparison of the Impact of Driver Age on Preference on PCMS Message Format

Table 1. Summary of Vehicle Speed Reduction in Phase I

PCMS	Speed Sensor	Min. (mph)	Max. (mph)	Range (mph)	Median (mph)	Mean (mph)	Standard Deviation	Mean Speed Reduction (mph)	(%)
Text PCMS: 345 Vehicles	S1	45	83	38	64	64	7.0		
	S2	37	83	46	62	62	8.7		
	S3	28	83	55	59	59	8.5		
	S4	31	78	47	57	57	7.9		
	S5	21	78	57	56	56	8.6	8	13
Text-graphic PCMS: 367 Vehicles	S1	45	84	39	66	65	5.5		
	S2	42	76	34	63	63	5.6		
	S3	38	77	39	61	61	6.8		
	S4	30	75	45	59	58	7.5		
	S5	31	76	45	60	59	7.6	6	10
Graphic PCMS: 403 Vehicles	S1	42	77	35	64	63	6.3		
	S2	41	76	35	62	61	7.0		
	S3	33	76	43	58	58	7.5		
	S4	34	74	40	55	55	7.4		
	S5	29	75	46	53	52	8.1	11	17

Table 2. Results of MANOVA Test[a] between Mean Vehicle Speed and Different Sensor Locations in Phase I

Effect		Value	F	Hypothesis df	Error df	Sig.
Sensor	Pillai's Trace	.602	420.035[b]	4.000	1109.000	.000
	Wilks' Lambda	.398	420.035[b]	4.000	1109.000	.000
	Hotelling's Trace	1.515	420.035[b]	4.000	1109.000	.000
	Roy's Largest Root	1.515	420.035[b]	4.000	1109.000	.000
Sensor * PCMS	Pillai's Trace	.162	24.459	8.000	2220.000	.000
	Wilks' Lambda	.841	25.084[b]	8.000	2218.000	.000
	Hotelling's Trace	.186	25.709	8.000	2216.000	.000
	Roy's Largest Root	.164	45.585[c]	4.000	1110.000	.000

a. Design: Intercept + PCMS
 Within Subjects Design: Sensor
b. Exact statistic
c. The statistic is an upper bound on F that yields a lower bound on the significance level.

Table 3. Driver Understanding of Graphics on PCMS in Phase I

Survey Response \ Displayed PCMS		Text-graphic PCMS				Graphic PCMS			
		Work zone		Flagger		Work zone		Flagger	
		N	%	N	%	N	%	N	%
Work zone graphic	Work zone	110	88	-	-	99	79	-	-
	Confused	14	11	-	-	20	16	-	-
	Don't know	0	0	-	-	7	5	-	-
	Other	1	1	-	-	0	0	-	-
Flagger graphic	Flagger	-	-	124	100	-	-	126	100
	Confused	-	-	0	0	-	-	0	0
	Don't know	-	-	0	0	-	-	0	0
	Other	-	-	0	0	-	-	0	0
Total		125	100	124	100	126	100	126	100

Table 4. Driver Paying More Attention after Seeing PCMS in Phase I

Response \ PCMS	Text PCMS		Text-graphic PCMS with				Graphic PCMS	
			Work zone graphic		Flagger graphic			
	N	%	N	%	N	%	N	%
Yes	144	97	103	82	112	90	109	87
No	5	3	20	16	9	7	17	13
Don't know	0	0	2	2	3	3	0	0
Total	149	100	125	100	124	100	126	100

Table 5. Driver Preference on PCMS Message Format in Phase I

Survey Response \ Displayed PCMS	Text PCMS		Text-graphic PCMS with				Graphic PCMS	
			Work zone graphic		Flagger graphic			
	N	%	N	%	N	%	N	%
Text	96	64	30	24	4	3	15	12
Graphic-aided	30	21	65	52	88	71	84	66
Text-graphic	23	16	32	26	24	19	27	21
Graphic	7	5	33	26	64	52	57	45
Other	23	15	30	24	32	26	27	22
Total	149	100	125	100	124	100	126	100

Table 6. Descriptive Statistics of Vehicle Speed in Phase II

PCMS	Speed Sensor	Min. (mph)	Max. (mph)	Range (mph)	Median (mph)	Mean (mph)	Standard Deviation
Original PCMS: 519 Vehicles	S1	45	80	35	68	67	5.2
	S2	44	76	32	66	64	5.5
	S3	37	76	39	64	63	6.3
	S4	42	74	32	60	60	6.3
	S5	38	77	39	60	60	6.8
Alternative One PCMS: 540 Vehicles	S1	50	87	37	68	67	5.1
	S2	46	86	40	65	64	5.8
	S3	38	82	44	64	63	6.7
	S4	24	80	56	60	59	6.9
	S5	30	81	51	59	59	7.7
Alternative Two PCMS: 541 Vehicles	S1	48	81	33	67	66	5.6
	S2	35	79	44	64	63	6.2
	S3	39	79	40	62	61	7.0
	S4	36	75	39	59	58	6.9
	S5	37	77	40	58	58	8.3

Table 7. Summary of Mean Vehicle Speed Reduction in Phase II

PCMS	Vehicle Type	N of Vehicles	Mean Speed (mph)					Speed Reduction from S1 to S5	
			S1	S2	S3	S4	S5	mph	%
Original		519	67	64	63	60	60	7	10.6
	Passenger Car	387	67	65	63	60	60	7	10.7
	Truck	132	65	63	62	59	58	7	10.6
T-test P-value (α=.01)			.000	.002	.340	.456	.007		
Alternative One		540	67	64	63	59	59	8	13.0
	Passenger Car	410	68	65	63	59	59	9	13.3
	Truck	130	66	63	63	59	58	8	12.1
T-test P-value (α=.01)			.000	.003	.817	.920	.282		
Alternative Two		541	66	63	61	58	58	8	12.6
	Passenger Car	399	67	64	62	59	58	9	12.7
	Truck	142	64	62	61	58	56	8	12.1
T-test P-value (α=.01)			.000	.002	.080	.191	.026		

Table 8. Results of MANOVA Test[a] between Mean Vehicle Speed at Different Sensor Locations and Vehicle Type in Phase II

Effect		Value	F	Hypothesis df	Error df	Sig.
Sensor	Pillai's Trace	.632	683.485[b]	4.000	1591.000	.000
	Wilks' Lambda	.368	683.485[b]	4.000	1591.000	.000
	Hotelling's Trace	1.718	683.485[b]	4.000	1591.000	.000
	Roy's Largest Root	1.718	683.485[b]	4.000	1591.000	.000
Sensor * Vehicle_Type	Pillai's Trace	.047	19.631[b]	4.000	1591.000	.000
	Wilks' Lambda	.953	19.631[b]	4.000	1591.000	.000
	Hotelling's Trace	.049	19.631[b]	4.000	1591.000	.000
	Roy's Largest Root	.049	19.631[b]	4.000	1591.000	.000
Sensor * PCMS	Pillai's Trace	.016	3.286	8.000	3184.000	.001
	Wilks' Lambda	.984	3.286[b]	8.000	3182.000	.001
	Hotelling's Trace	.017	3.287	8.000	3180.000	.001
	Roy's Largest Root	.012	4.601[c]	4.000	1592.000	.001
Sensor * Vehicle_Type * PCMS	Pillai's Trace	.005	1.002	8.000	3184.000	.432
	Wilks' Lambda	.995	1.002[b]	8.000	3182.000	.432
	Hotelling's Trace	.005	1.002	8.000	3180.000	.432
	Roy's Largest Root	.004	1.686[c]	4.000	1592.000	.151

a. Design: Intercept + Vehicle_Type + PCMS + Vehicle_Type * PCMS
Within Subjects Design: Sensor
b. Exact statistic
c. The statistic is an upper bound on F that yields a lower bound on the significance level.

Table 9. Driver Understanding of Graphics on PCMS in Phase II

Survey Response \ Displayed PCMS	Text-graphic PCMS Original		Alternative One		Alternative Two	
	N	%	N	%	N	%
Work zone	130	87	139	100	140	100
Confused	13	9	0	0	0	0
Don’t know	7	4	0	0	0	0
Other	0	0	0	0	0	0
Total	150	100	139	100	140	100

Table 10. Driver Paying More Attention after Seeing PCMS in Phase II

Survey Response \ Displayed PCMS	Text-graphic PCMS Original		Alternative One		Alternative Two	
	N	%	N	%	N	%
Yes	108	72	124	89	116	83
No	33	22	4	3	17	12
Don’t know	9	6	11	8	7	5
Total	150	100	139	100	140	100

Table 11. Driver Preference on PCMS Message Format in Phase II

Survey Response \ Displayed PCMS	Text-graphic PCMS Original		Alternative One		Alternative Two	
	N	%	N	%	N	%
Text	37	25	15	11	11	8
Graphic-aided	79	52	94	68	90	64
Text-graphic	41	27	44	32	51	36
Graphic	38	25	50	36	39	28
Other	34	21	30	21	39	28
Total	150	100	139	100	140	100

Table 12. Impact of Driver Gender on Preference on PCMS Message Format

Displayed PCMS / Survey Response	Driver Gender: Original				Alternative One				Alternative Two			
	Male		Female		Male		Female		Male		Female	
	N	%	N	%	N	%	N	%	N	%	N	%
Text	24	22	13	32	8	10	7	12	8	8	3	8
Graphic-aided	60	55	19	46	56	72	38	62	64	64	26	67
Text-graphic	32	29	9	22	20	26	24	39	37	37	14	36
Graphic	28	26	10	24	36	46	14	23	27	27	12	31
Other	25	23	9	21	14	18	16	26	29	29	10	25
Total	109	100	41	100	78	100	61	100	101	100	39	100

Table 13. Results of Chi-Square Test of Independence on Driver Preferences and Gender

Layer Variable	Chi-Square Value	Degrees of Freedom	P-value	No. of Valid Cases	Phi Coefficient
Original	1.738[a]	2	.419	116	.122
Alternative One	7.011[b]	2	.030	109	.254
Alternative Two	0.131[c]	2	.936	101	.036
Total	1.722[d]	2	.423	326	.073

a. 0 cells (.0%) have expected frequencies less than 5. The minimum expected cell frequency is 10.21.
b. 0 cells (.0%) have expected frequencies less than 5. The minimum expected cell frequency is 6.19.
c. 1 cells (16.7%) have expected frequencies less than 5. The minimum expected cell frequency is 3.16.
d. 0 cells (.0%) have expected frequencies less than 5. The minimum expected cell frequency is 20.48.

Table 14. Driver Age Distribution under Each PCMS Message Format

PCMS	Driver Age: <19	19-24	25-34	35-44	45-54	55-64	>64	Chi-Square: Value	Sig.
Original	3%	6%	16%	17%	25%	24%	10%	14.773[a]	.022
Alternative One	6%	9%	24%	22%	17%	12%	11%	10.299[b]	.113
Alternative Two	2%	9%	17%	12%	26%	27%	6%	24.304[c]	.000
Kansas Drivers	7%	9%	17%	15%	16%	17%	18%	-	-

a. 0 cells (.0%) have expected frequencies less than 5. The minimum expected cell frequency is 7.1.
b. 0 cells (.0%) have expected frequencies less than 5. The minimum expected cell frequency is 7.1.
c. 0 cells (.0%) have expected frequencies less than 5. The minimum expected cell frequency is 7.0.

Table 15. Impact of Driver Age on Preference on PCMS Message Format

Survey Response	Driver Age													
	<19		19-24		25-34		35-44		45-54		55-64		>64	
Original	N	%	N	%	N	%	N	%	N	%	N	%	N	%
Text	1	25	2	22	6	25	8	32	8	22	10	28	2	13
Graphic-aided	2	50	4	44	11	46	12	48	20	54	22	61	8	54
Text-graphic	1	25	3	33	9	38	6	24	9	24	9	25	4	27
Graphic	1	25	1	11	2	8	6	24	11	30	13	36	4	27
Other	1	25	3	33	7	29	5	20	9	24	4	11	5	34
Total	4	100	9	100	24	100	25	100	37	100	36	100	15	100
Alternative One	N	%	N	%	N	%	N	%	N	%	N	%	N	%
Text	1	11	0	0	4	12	3	10	3	13	2	12	2	13
Graphic-aided	7	77	7	58	20	60	23	77	15	65	13	76	9	60
Text-graphic	4	44	3	25	10	30	9	30	8	35	7	41	3	20
Graphic	3	33	4	33	10	30	14	47	7	30	6	35	6	40
Other	1	11	5	41	9	27	4	13	5	21	2	12	4	26
Total	9	100	12	100	33	100	30	100	23	100	17	100	15	100
Alternative Two	N	%	N	%	N	%	N	%	N	%	N	%	N	%
Text	0	0	1	8	2	8	2	12	3	8	3	8	0	0
Graphic-aided	2	66	7	53	13	54	13	76	24	67	27	71	4	44
Text-graphic	1	33	2	15	8	33	8	47	14	39	14	37	4	44
Graphic	1	33	5	38	5	21	5	29	10	28	13	34	0	0
Other	1	33	5	38	9	38	2	12	9	25	8	21	5	55
Total	3	100	13	100	24	100	17	100	36	100	38	100	9	100

Table 16. Results of Chi-Square Test of Independence on Driver Preferences and Age (<34, 35-54, >55)

PCMS	Chi-Square Value	Degrees of Freedom	P-value	No. of Valid Cases	Phi Coefficient
Original	5.537[a]	4	.237	116	.218
Alternative One	0.309[b]	4	.989	109	.053
Alternative Two	0.761[c]	4	.944	101	.087
Total	0.929[d]	4	.920	326	.053

a. 0 cells (.0%) have expected frequencies less than 5. The minimum expected cell frequency is 8.29.
b. 1 cells (11.1%) have expected frequencies less than 5. The minimum expected cell frequency is 3.58.
c. 3 cells (33.3%) have expected frequencies less than 5. The minimum expected cell frequency is 2.72.
d. 0 cells (.0%) have expected frequencies less than 5. The minimum expected cell frequency is 17.39.