DRIVER UNDERSTANDING OF MESSAGES DISPLAYED ON SEQUENTIAL PORTABLE CHANGEABLE MESSAGE SIGNS IN WORK ZONES

by

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November 2006
Word Count: 5138 words + 9 Figures/Tables = 7388 words total Abstract: 171 words

ABSTRACT

In this paper, researchers present the results of a Texas Transportation Institute (TTI) driving simulator study of the ability of motorists to capture and process information on two portable changeable message signs (PCMSs) used in sequence (i.e., one PCMS following another along the edge of the roadway such that each PCMS contains part of a single message) to convey information about upcoming traffic situations. The study results indicate the need to keep overall messages at or below the four-unit maximum recommended in existing guidelines. Researchers found that presenting five units of information on sequential PCMSs resulted in low comprehension rates, below what would be acceptable for highway applications. However, by keeping the message length to four units, it does appear that the use of sequential PCMSs will result in comprehension rates comparable to those obtained by presenting the same information at a single location on a large dynamic message sign (DMS). Comprehension may be enhanced by repeating one of the lines of the message on both PCMSs used in sequence.

INTRODUCTION

Portable changeable message signs (PCMSs) have become an integral part of work zone traffic control, advising motorists of unexpected traffic and routing situations. When used properly, these signs can command additional attention over that achievable through static work zone signing. Furthermore, PCMSs can present a wide variety of information to motorists, making them a highly versatile tool for traffic control designers and work crews. PCMSs have been used in a variety of applications in both construction and maintenance work zones. Some of these applications are to (*1-9*):

- warn of a new detour or a change in a detour,
- warn of a ramp closure,
- identify the presence of a lane drop where a continuous lane once existed,
- emphasize the existence of reduced speed limits,
- warn of downstream traffic queues,
- warn of the presence of downstream flaggers or work crews,
- notify motorists of adverse environmental conditions,
- warn of changes in alignment or surface conditions,
- notify motorists to turn to a highway advisory radio (HAR) station for more details, and
- alert motorists of future changes which will be made to current traffic conditions (i.e., that road work will occur at a future date).

Whereas PCMSs can be highly effective tools when used properly, improper use of PCMSs can destroy their credibility with the public. Also, in a worst-case scenario, improper PCMS usage can contribute to motorist confusion, which can ultimately degrade the safety of motorists and workers as well as the operational efficiency of the overall traffic control plan.

To be effective, a PCMS must communicate a meaningful message that can be read and comprehended by motorists within a very short time period. Fundamental human factors principles that take into consideration motorist vision, information processing, and cognitive capabilities govern proper PCMS use. These human factors principles have been identified through extensive research and field validation (*1-19*). One part of these principles is the idea of message load. Message load refers to the number of informational “units” contained in a message. A unit of information refers to each separate data item given in a message that a driver could recall and use as a basis for decision making. Each unit of information is typically the answer to a simple question a driver might have (e.g., What is the problem? - “Road Work” would be one informational unit). Typically, a unit of information is one to three words. Other specific factors that enhance understanding of PCMS messages include:

- simplicity of words,
- brevity,
- standardized order of words,
- standardized order of message lines, and
- use of understood abbreviations when needed.

Recent studies of driver understanding of traffic control devices through several work zones on high-speed roadways further suggest that misapplications of PCMSs in work zones are quite common and that these misapplications often contribute to driver confusion and anxiety about their appropriate travel paths (*20*). More specifically, one of the issues raised during an observational study of PCMS use and interviews with transportation engineers was the difficulty in conveying important information within the two-phase limitation the Manual on Uniform Traffic Control Devices (MUTCD) imposes on PCMS usage (*21*). When information needs dictate the need of more than two phases, the MUTCD recommends that two PCMSs be used in sequence to convey the information (i.e., one PCMS following another along the edge of a roadway such that each PCMS contains part of a single message). However, only limited research has been performed to evaluate whether such a practice would result in adequate driver interpretation and comprehension of messages that are split onto two PCMSs. Questions remained as to whether drivers, viewing two PCMSs in sequence, would relate the separate pieces of information on the two signs into a cohesive message.

In previous work using New Jersey drivers, Huchingson and Dudek investigated differences between stand-alone messages (which repeat a particular unit of information on each phase of a message) and distributed messages (which do not repeat any units of information) using laptop surveys (*22*). They found that subjects had similar comprehension and recall rates of information for both types of display formats. However, these rates were often below the 85 percent correct level desired for good message design, especially when more than two phases were presented to drivers. They also found that presenting information that does not apply at the time the message is displayed can confuse some drivers into thinking that it currently applies. Unfortunately, the use of laptop computer surveys to investigate these issues proved somewhat problematic for the subjects, limiting the extent of the researchers' findings.

Although not a direct investigation of the ramifications of using PCMSs in sequence, the Huchingson and Dudek study suggests that drivers may have some difficulties in adequately processing multiple phases of information. The findings also suggest that both stand-alone and distributed information formats should be researched as viable message design approaches in sequential PCMS applications. Consequently, the study reported in this paper was designed and conducted using the TTI Driving Simulator to test this practice on a sample of participants.

STUDY OBJECTIVE

The objective of this study was to assess whether drivers are able to effectively "piece" the information from two PCMSs displayed in sequence upstream of a particular traffic situation into a single cohesive message. A secondary objective was to determine whether utilizing redundancy between the two PCMSs (i.e., using an identical key information element in one phase of both PCMSs) improved the driver's ability to link the messages together and fully comprehend its intended meaning.

STUDY METHODOLOGY

Overview

Based on a previous preliminary research experiment, researchers determined that traditional methods of evaluating PCMS message effectiveness, such as pen-and-paper evaluations or the laptop based laboratory studies, would not be sufficient for evaluating if and how well a driver is able to link information together from two PCMSs in sequence (*23*). Therefore, researchers opted to study this question indirectly by immersing participants in a more realistic driving environment in a driving simulator in which PCMSs were placed in sequence at strategic points along the travel route. Using carefully worded exploratory questions about conditions referred to in the PCMS messages, researchers hoped to assess whether the subject drivers had truly compiled information from both PCMSs into a single cohesive message and could properly interpret and process that information. To establish a baseline of expected performance, researchers also included larger signs replicating the information and display characteristics of full-size permanent dynamic message signs (DMSs) in the study environment at other locations along the travel route. By counterbalancing the information presented on the two sequential PCMSs and the larger DMSs, researchers were able to compare the sequential PCMS responses to those obtained as the participant traveled past the full-size DMS messages. To avoid having the participants focus exclusively on the PCMSs and DMSs, researchers designed the overall study protocol to query participants about all types of traffic control devices presented in the driving environment.

Description of the TTI Driving Simulator

The driving simulator at TTI is produced by DriveSafety™ and runs through a 1995 Saturn SL mid-sized sedan. The driving simulator is illustrated in Figure 1. It is instrumented as an actual operating vehicle and provides an interactive driving experience. The system includes a 150-degree wraparound visual field with high-resolution (1024 × 768 pixels) projectors for each of the three integrated screens. Research participants control the accelerator and brake pedals and the steering wheel exactly as they would when driving in the real world. The simulator is fixed-based and provides no kinetic motion cues such as tire vibrations or vehicle pitching during braking. A subwoofer speaker located behind the driver's seat provides simulated road and engine sounds. For the present study, researchers created the custom driving environments using the HyperDrive™ Authoring Suite software.

As the participant "controls" the vehicle, the driving simulator's integrated computer calculates several performance measures such as vehicle velocity, acceleration, steering, braking, and lane position in real time. An intercom system in the vehicle allows the experimenter and participant to easily communicate during the study.


FIGURE 1 TTI's Driving Environment Simulator.

PCMS Messages Tested

To evaluate the impacts of using sequential PCMS, researchers tested two types of messages that could be shown either on a single large DMS or on two PCMS in sequence. In the first message type, researchers presented four units of information total on both a single large DMS or on the two PCMS. However, one of the units of information was repeated on both PCMS as a way to "link" the two signs together from the perspective of the motorist, similar to the study of the stand-alone messages by Huchingson and Dudek described above (see Table 1). In the second type of messages, no units of information were repeated on the two PCMS (see Table 2). It should be noted that the messages in this table contain 5 units of information, which exceeds the recommended maximum levels for highway speeds of 55 mph or greater (*1*). Also, in the messages contained in Table 2, the messages formatted for the full-size DMS contain two phases. Figure 2 contains examples of how the PCMS and DMS were represented within the driving world. With the messages that did not have repeating units of information, the messages created were in relation to an event occurring on a cross-highway, and for the messages that did have a repeating component the messages related to events on the same road as the driver.

As shown in Tables 1 and 2, two messages were developed for each message type tested. Each study participant saw the messages from one group in each of Tables 1 and 2. This was done to reduce any learning effects due to multiple presentation of the same message in different formats. The order in which participants received each group of messages was counterbalanced to further reduce any learning effects that might be present

TABLE 1 Messages with Repeating Information (Redundancy).

Group 1:				
Message 1				
PCMS 1			PCMS 2	
Phase 1	Phase 2		Phase 1	Phase 2
ROADWORK PAST MAIN	**RIGHT 2 LANES CLOSED**		**RIGHT 2 LANES CLOSED**	**BE PREPARED TO STOP**
Message 2				
DMS Phase 1				
ACCIDENT AT KENT LEFT LANE CLOSED EXPECT DELAYS				
Group 2:				
Message 3				
PCMS 1			PCMS 2	
Phase 1	Phase 2		Phase 1	Phase 2
ACCIDENT AT KENT	**LEFT LANE CLOSED**		**LEFT LANE CLOSED**	**EXPECT DELAYS**
Message 4				
DMS Phase 1				
ROADWORK PAST MAIN RIGHT 2 LANES CLOSED BE PREPARED TO STOP				

TABLE 2 Messages with Non-repeating Information.

<table>
<tr><td colspan="5">Group 1:</td></tr>
<tr><td colspan="5">Message 5</td></tr>
<tr><td colspan="2">PCMS 1</td><td></td><td colspan="2">PCMS 2</td></tr>
<tr><td>Phase 1</td><td>Phase 2</td><td></td><td>Phase 1</td><td>Phase 2</td></tr>
<tr><td>ROADWORK
ON
I-40 EAST</td><td>2 LANES
CLOSED</td><td></td><td>OAKDALE
TRAFFIC</td><td>USE
OTHER
ROUTES</td></tr>
<tr><td colspan="5">Message 6</td></tr>
<tr><td colspan="2">DMS Phase 1</td><td></td><td colspan="2">DMS Phase 2</td></tr>
<tr><td colspan="2">ACCIDENT
ON US 87 S
LEFT LANE CLOSED</td><td></td><td colspan="2">DOWNTOWN TRAFFIC
EXPECT DELAYS</td></tr>
<tr><td colspan="5">Group 2:</td></tr>
<tr><td colspan="5">Message 7</td></tr>
<tr><td colspan="2">PCMS 1</td><td></td><td colspan="2">PCMS 2</td></tr>
<tr><td>Phase 1</td><td>Phase 2</td><td></td><td>Phase 1</td><td>Phase 2</td></tr>
<tr><td>ACCIDENT
ON
US 87 S</td><td>LEFT
LANE
CLOSED</td><td></td><td>DOWNTOWN
TRAFFIC</td><td>EXPECT
DELAYS</td></tr>
<tr><td colspan="5">Message 8</td></tr>
<tr><td colspan="2">DMS Phase 1</td><td></td><td colspan="2">DMS Phase 2</td></tr>
<tr><td colspan="2">ROADWORK
ON I-40 EAST
2 LANES CLOSED</td><td></td><td colspan="2">OAKDALE TRAFFIC
USE OTHER ROUTES</td></tr>
</table>

Note: All message contain 5 units of information

a) Representation of a Full-Size DMS

b) Representation of Sequential PCMSs

FIGURE 2 Examples of DMS and PCMS in the Driving World.

Experimental Design

Four simulator driving environments or “worlds” were created for this study. Each world consisted of identical roadways and landscapes as well as 10 sign stimuli, 6 of which were static signs that were the same graphics and location for all of the worlds. As noted above, the purpose of these six signs was to keep the participants’ attention on all signs along the roadway, not just the PCMSs and DMSs. The remaining four stimuli consisted of the DMSs and PCMSs.

Researchers designed the four worlds in a circular pathway. This layout allowed for multiple starting points within each world. Figure 3 shows the layout of the worlds and the location of both the fixed sign stimuli and the DMSs and PCMSs (Sites 1-4). Table 3 illustrates how the DMS and PCMS messages corresponded to the four sign location sites in the worlds.

TABLE 3 DMS and PCMS Sign Locations Corresponding to the Simulator Map.

Group/Simulator World	Site 1 Signs	Site 2 Signs	Site 3 Signs	Site 4 Signs
W	Message 5: 2 PCMSs	Message 6: 1 DMS	Message 2: 1 DMS	Message 1: 2 PCMSs
X	Message 8: 1 DMS	Message 7: 2 PCMSs	Message 1: 2 PCMSs	Message 2: 1 DMS
Y	Message 6: 1 DMS	Message 5: 2 PCMSs	Message 4: 1 DMS	Message 3: 2 PCMSs
Z	Message 7: 2 PCMSs	Message 8: 1 DMS	Message 3: 2 PCMSs	Message 4: 1 DMS

The simulated DMSs provided 8 to 10 seconds of legible reading time for each message, while the simulated PCMS each provided 4 to5 seconds of legible reading time (8 to 10 seconds total as well). This was done in order to keep total available reading times comparable between the two types of signs, and to comply with existing human factors guidelines which state that drivers need 2 seconds of viewing time per unit of information provided (*1*).

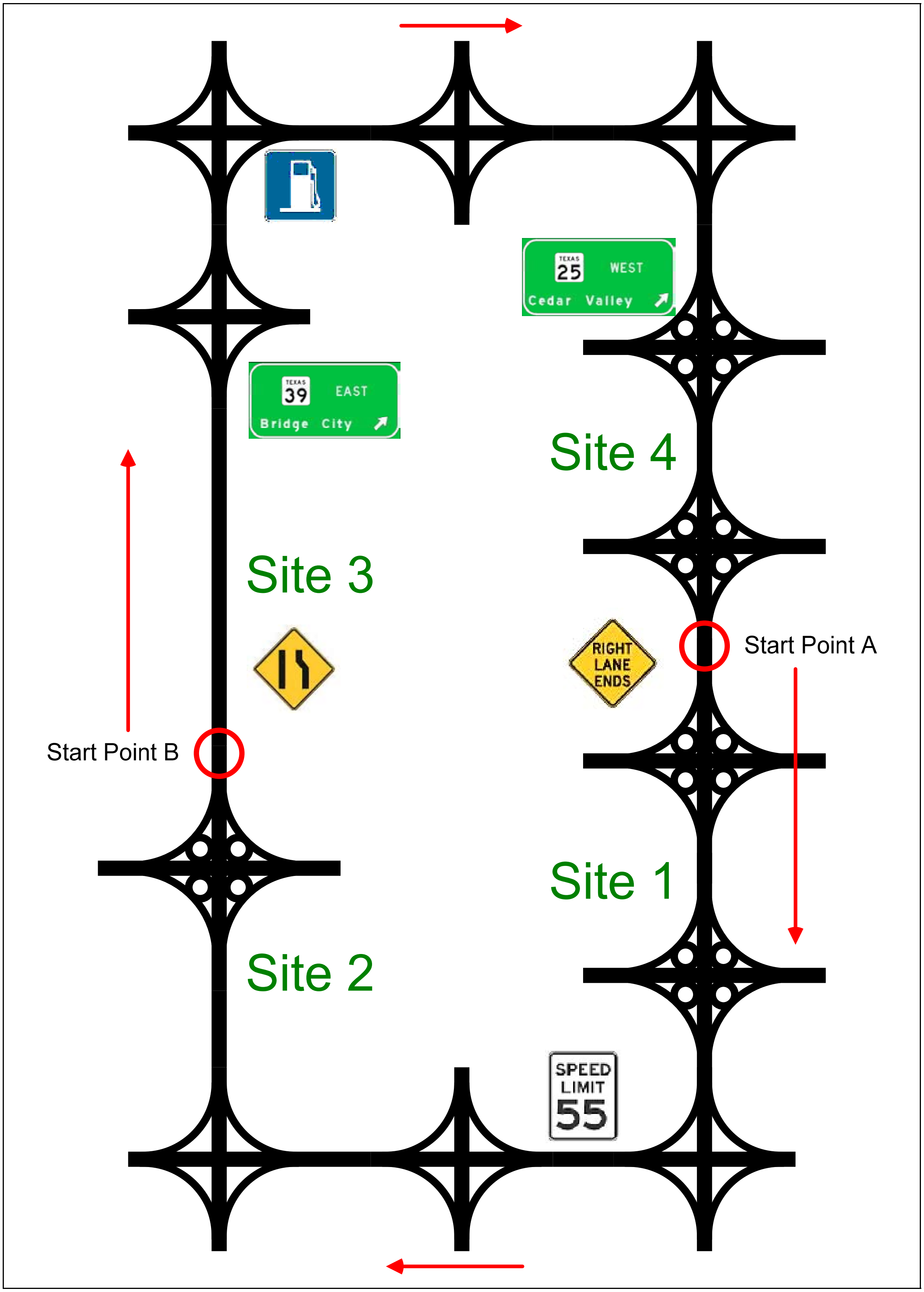

FIGURE 3 Schematic Map of Travel Route in Simulator.

The creation of four separate worlds gave flexibility to test more variations in the PCMS and DMS messages and also allowed for increased counterbalancing. There were two different starting points within each world, to further balance the order of the test signs.

Participant Recruitment

Thirty-two participants were recruited for this study based on a demographic sample of the driving population in Texas with relation to age, education, and gender as shown in Table 4.

TABLE 4 Participant Demographics.

Age	High School Diploma or Less (50%)		Some College or more (50%)		Total
	M	F	M	F	
18-39 (47%)	4	4	4	3	15
40-54 (29%)	2	2	2	3	9
55+ (24%)	2	2	2	2	8
Total	8	8	8	8	32

Upon initial contact, the participants went through a process of pre-screening and scheduling for the study. The pre-screening not only ensured that the subjects met the demographic requirements for the study, but also identified them as unlikely to experience Simulator Induced Discomfort (SID). Only 1 of 33 participants did not complete the experiment due to discomfort.

Study Procedures

Practice Session
Before beginning the experiment, the participants drove a practice session to become familiar with the test vehicle and simulator. The practice session consisted of roadways, signs, landscaping, buildings, etc. similar to those in the experimental worlds. The practice began with the test vehicle parked in front of three types of signs illustrating different features the participant would encounter during the experiment (i.e. a static guide sign, a PCMS, and a DMS). Before beginning the practice session, the participants listened to recorded instructions describing the simulator driving experience and explaining the example signs displayed.

Experimental Session
As with the practice session, before beginning the experimental session, the participants listened to recorded instructions. The recorded experimental instructions were as follows:

> *We are now ready to begin the driving study. When the driving scene begins, the simulator vehicle will be stopped on the side of the roadway, just like in the practice*

session. Place the vehicle in 'drive,' drive onto the roadway, and proceed through the driving environment.
As you begin the study, you will be traveling on an Interstate. As you are traveling, the study administrator will give you driving directions through a speaker system in the simulator vehicle. A microphone in the vehicle will pick up your voice if you have any questions. We ask that you drive 55 mph while you are on the freeway; however, do not feel that you need to obsess over your speed. Remember, you are to drive in a normal fashion and obey all traffic laws.
As mentioned earlier, when you are traveling this route, you will see different signs along the roadway. The study administrator will ask you questions about the signs that you encounter.
At the end of the experiment the study administrator will ask you to bring the vehicle to a complete stop and place it in 'park.' The experiment will take approximately 20 minutes. If you have any questions regarding your task feel free to ask the study administrator.

During the participants' session, the study administrator asked the appropriate questions over an intercom system and recorded the participants' responses after passing each of the stimuli signs. Along with the data collected from the verbal responses, the simulator program recorded speed, lane position, and brake and accelerator response during the drive.

RESULTS

As discussed in the protocol, each participant saw two of the four messages tested in this study, one each from the two different formatting options (four units of information with redundancy of one of the information units between the sequential PCMSs versus five units of information with no redundancy in information between sequential PCMSs). The results of the study are presented below for each of the formatting options.

Messages with Repeating Information (Redundancy)

Table 5 illustrates the overall correct percentage results for each of the questions submitted to the participants for the sequential PCMSs and DMS messages shown in Table 1. The response rates shown in Table 5 represent the combination of both messages used in this portion of the study (recall that researchers utilized a counterbalanced experimental design of both message types to account for learning effects and other potential biases). The information presented in Table 5 is subdivided to illustrate how participants were able to comprehend and recall information from either the first PCMS in sequence or the second, in contrast to the DMS when all information was presented at one location. It should be noted again that redundancy was used for a single informational unit between the two sequential PCMSs for this message group.

TABLE 5 Participant Correct Response Rate: Messages with Redundancy.

Information Presented	Percent of Participants Correctly Recalling and Comprehending the Information		Level of Significance (p-value)
	Sequential PCMS Format	Single, Two-Phase DMS Format	
Information on 1st PCMS:			
What is the Problem?	94	94	1.000
Where is the Problem?	72	72	1.000
What Lanes are Affected? [a]	88	81	0.439
TOTAL 1st PCMS	84	82	0.831
Information on 2nd PCMS:			
What Lanes are Affected? [a]	88	81	0.439
How is Traffic Affected?	59	59	1.000
TOTAL 2nd PCMS	73	70	0.790
OVERALL MESSAGE COMPREHENSION	78	77	0.924

[a] information presented in both PCMS messages

Using this message format, correct response rates were very similar between the sequential PCMSs and the single-phase DMS. Ninety-four percent of the participants correctly recalled the problem displayed on the sign, regardless of whether it was on the first PCMS in sequence or the large DMS. Similarly, 88 percent of the participants recalled the lanes that were closed from the PCMSs, compared to 81 percent of the participants seeing the information on the large DMS. Of course, the lanes closed information was presented twice in the PCMS sequence (once on each sign), and was displayed continuously on the large DMS. Overall, the participants recalled 84 percent of the information on the first PCMS in sequence and 82 percent of the same information from the large DMS. As shown in the last column of Table 6, none of the differences between the PCMS and DMS were highly significant based on a test of proportions.

Researchers noted that participants did not recall and interpret the information describing how traffic was affected very well in either the PCMS or DMS presentation formats (59 percent correct comprehension). This was because many of the participants indicated that the affect on traffic was that “lanes were closed” rather than “delays expected” or “need to be prepared to stop.” The consistency of these mistakes suggests that the reason for the lower performance was due more to the wording or administration of the question rather than to the PCMS or DMS message itself.

Messages with Non-repeating Information

The second portion of the driving simulator study also tested sequential PCMSs versus identical information presented on a large DMS. However, the information load in this case was 5 units of information in each message without redundancy of any of the informational units between the sequential PCMSs. Also, it should be noted that due to the higher number of informational units, the DMS message contained two phases for this message group. Table 6 provides the percentage of correct comprehension for the message group displayed in Table 2.

As illustrated in Table 6, participants were less likely to correctly recall the information from the first PCMS in sequence than they were to recall that same type of information from the large DMS. Where 84 percent of the participants were able to identify the problem on the large DMS, only about 63 percent could do so from the information presented on the first PCMS. Likewise, more participants recalled the location of the problem from the large DMS than from the first PCMS (59 percent versus 31 percent, respectively). The differences in comprehension rates appear to be highly significant (p-values of 0.057 and 0.024, respectively). The percent of subjects who correctly recalled which lanes were to be affected were similar from the first PCMS and the DMS (69 percent versus 75 percent, respectively).

TABLE 6 Participant Correct Response Rate: 5 Units of Information, No Redundancy.

	Percent of Participants Correctly Recalling and Comprehending the Information		
Information Presented	Sequential PCMS Format	Single, Two-Phase DMS Format	Level of Significance (p-value)
Information on 1st PCMS:			
What is the Problem?	63	84	0.057
Where is the Problem Located?	31	59	0.024
What and How are Lanes Affected?	69	75	0.593
TOTAL 1st PCMS	54	73	0.114
Information on 2nd PCMS:			
Who is the Intended Audience for Message?	53	47	0.631
What is the Effect of Problem/Desired Action?	53	50	0.810
TOTAL 2nd PCMS	53	48	0.689
OVERALL MESSAGE COMPREHENSION	54	63	0.465

Further examination of Table 6 results suggests that the differences in comprehension rates were indeed due to the sequential nature in which the PCMS information was presented, since participant recall of the information presented on the second PCMS was similar to that obtained when viewing the same information on a two-phase DMS. Specifically, participant recall of the intended audience for the message was 53 percent when viewed on the second PCMS and 47 percent from the DMS. Similarly, subject recall of the effect of the problem on traffic or the action the audience should take was 53 percent from the PCMS message and 50 percent from the DMS. As indicated by the large p-values in Table 6, none of these differences are highly significant.

Examining participant recall of information on each PCMS overall, researchers found that participants recalled only 54 percent of the information presented in the first PCMS versus 73 percent of that same information when presented on the two-phase DMS, a difference of nearly 20 percent (corresponding to a moderately significant p-value of 0.114). For the second PCMS, the comprehension and recall rates of information were much closer to that of the two-phase DMS at 54 percent versus 63 percent, respectively, with the much less significant p-value of 0.689.

Overall, this message group had a much lower level of comprehension for the messages than with the previous group. It is important to again note that these messages contained five units of information, which is more than the maximum four units of information recommended based on previous research *(1)*. The results of this study provide further evidence of the importance of complying with these guidelines. Even for the large DMS, overall comprehension rates were lower than the 85 percent correct responses that are desired for message design purposes. It is clear from this portion of the study that attempting to provide more than four units of information to motorists via PCMS, even if physically possible by using two signs in sequence, will not yield satisfactory information transmission to the motoring public. In fact, it could be argued that such a practice would actually be detrimental to the overall long-term credibility and target value of PCMS operations and should be avoided.

SUMMARY OF FINDINGS

In this paper, the design and results of a driving simulator study to evaluate the ability of motorists to correctly recall and comprehend messages placed on two PCMSs located in sequence on the side of the road are described. Researchers tested messages with both four- and five-units of information. The benefits of replicating one of the information units on both PCMSs were also evaluated. Comprehension and recall rates of the information placed on PCMSs in sequence were compared to the same information placed on large DMS in either one or two phases.

For messages that contained four units of information, it appears that the use of sequential PCMSs will result in comprehension rates comparable to those obtained by presenting the same information on a large single-phase DMS. The format of the sequential PCMSs tested in this study included replication of one of the units on both PCMSs. However, given the fact that participants were able to recall the information from the first PCMS that was not replicated (i.e., the problem), such replication may not be required as long as the overall length of the message is kept below the recommended maximum.

Furthermore, the results of the study indicate that presenting five units of information on sequential PCMSs will result in substantially lower comprehension rates than if the information is presented at one location on a large two-phase DMS. Also, the overall comprehension rates the PCMSs and the DMS are below what would be acceptable for highway applications. The results strongly indicate the need to keep overall messages below the four-unit maximum recommended in existing guidelines.

ACKNOWLEDGMENTS

This project was conducted in cooperation with TxDOT and FHWA.). However, the contents of this paper reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of FHWA or TxDOT. The authors would like to thank several TxDOT staff members for their insights and guidance in this research: Ismael Soto, Paul Frerich, Susan Feudo, Howard Holland, Dale Barron, Charles Kratz, and Wade Odell,. The authors gratefully acknowledge the assistance of numerous other TxDOT employees who provided assistance during the data collection activities of this project. Similarly, the researchers appreciate the contributions of Susan Chrysler, Nada Trout, Steven Schrock, and Melisa Finley of TTI during various phases of the project.

REFERENCES

1. Dudek, C.L. *Dynamic Message Sign Message Design and Display Manual*. Report No. FHWA/TX-04/0-4023-P1. Texas Transportation Institute, College Station, TX, March 2004.
2. Dudek, C.L. *Guidelines on the Use of Changeable Message Signs*. Report No. FHWA-TS-90-043. FHWA, U.S. Department of Transportation, Washington, DC, May 1991.
3. Dudek, C.L. Changeable Message Signs. *NCHRP Synthesis of Highway Practice 237*. TRB, National Research Council, Washington, DC, 1997.
4. Dudek, C.L. Changeable Message Signs. *NCHRP Synthesis of Highway Practice 61*. TRB, National Research Council, Washington, DC, 1979.
5. Dudek, C.L., R.D. Huchingson, et al. *Human Factors Requirements for Real-Time Motorist Information Displays, Vol. 1 -- Design Guide*. Report FHWA-RD-78-5. FHWA, U.S. Department of Transportation, Washington, DC, September 1978.
6. Dudek, C.L., R.D. Huchingson, R.D. Williams, and R.J. Koppa. *Human Factors Design of Dynamic Visual and Auditory Displays for Metropolitan Traffic Management, Vol. 2 -- Dynamic Visual Displays*. Report No. FHWA-RD-81/040. FHWA, U.S. Department of Transportation, Washington, DC, January 1981.
7. Dudek, C.L., and R.D. Huchingson. *Manual on Real-Time Motorist Information Displays*. Report FHWA-IP-86-16. FHWA, U.S. Department of Transportation, Washington, DC, August 1986.
8. Dudek, C.L. *Guidelines on the Use and Operation of Changeable Message Signs*. Report No. FHWA/TX-93/1232-9. Texas Transportation Institute, College Station, TX, 1992.
9. *Manual on Uniform Traffic Control Devices*. FHWA, U.S. Department of Transportation, Washington, DC, 2003.
10. Dudek, C.L. *Guidelines on the Selection and Design of Messages for Changeable Message Signs*. Report No. FHWA/TX-93/1232-10. Texas Transportation Institute, College Station, TX, 1992.
11. Dudek, C.L., G.D. Weaver, D.R. Hatcher, and S.H. Richards. Field Evaluation of Messages for Real-Time Diversion of Freeway Traffic for Special Events. In *Transportation Research Record 682*. TRB, National Research Council, Washington, DC, 1978.
12. Dudek, C.L. *Portable Changeable Message Signs at Work Zones*. Report No. FHWA/TX-85/07+292-4. Texas Transportation Institute, College Station, TX, July 1984.
13. Turner, J.M., J.D. Carvell, and C.L. Dudek. Real-Time Diversion of Freeway Traffic During Maintenance Operations. In *Transportation Research Record 683*. TRB, National Research Council, Washington, DC, 1978.
14. Dudek, C.L., W.R. Stockton, and D.R. Hatcher. Real-Time Freeway-to-Freeway Diversion: The San Antonio Experience. In *Transportation Research Record 841*. TRB, National Research Council, Washington, DC, 1982.
15. Richards, S.H., R.C. Wunderlich, and C.L. Dudek. Field Evaluation of Work Zone Speed Control Techniques. In *Transportation Research Record 1035*. TRB, National Research Council, Washington, DC, 1985.
16. Hanscomb, F.R. *Effectiveness of Changeable Message Displays in Advance of High-Speed Freeway Lane Closures.* NCHRP Report 235. TRB, National Research Council, Washington, DC, September 1981.

17. Garber, N.J., and S.T. Patel. Control of Vehicle Speeds in Temporary Traffic Control Zones (Work Zones) Using Changeable Message Signs with Radar. In *Transportation Research Record 1509*. TRB, National Research Council, Washington, DC, 1995.
18. Durkop, B.R., and C.L. Dudek. *Texas Driver Understanding of Abbreviations for Dynamic Message Signs*. Report No. FHWA/TX-00/1882-1. Texas Transportation Institute, College Station, TX, February 2000.
19. Dudek, C., N. Trout, S. Booth, and G. Ullman. *Improved Dynamic Message Sign Messages and Operations*. Report No. FHWA/TX-01/1882-2. Texas Transportation Institute, College Station, TX, October 2000.
20. Helmuth, J.L. *Visual Complexity in Highway Work Zones: An Exploratory Study*. Master of Science Thesis, Department of Civil Engineering, Texas A&M University, College Station, TX, May 2002.
21. Ullman, G., B. Ullman, C. Dudek, A. Williams. *Advanced Notification Messages and Use of Sequential Portable Changeable Message Signs in Work Zones*. Report No. FHWA/TX-05/0-4748-1. Texas Transportation Institute, College Station, TX, July 2005.
22. Huchingson, R.D. and C.L. Dudek. Preliminary Results of Human Factors Studies in New Jersey: Response Time to Key Information: Stand-Alone vs Distributed Messages, Two-Frame and Three-Frame Messages. Technical Memorandum 7296-5-12 Prepared for the New Jersey Department of Transportation. Texas Transportation Institute, College Station, TX, 1998.
23. Story, B. Evaluation of the Effectiveness of Dual Portable Changeable Message Signs (PCMS) in the Display of a Single Message. In *Compendium of Student Papers: 2004 Undergraduate Transportation Engineering Fellows Program.* Southwest Region University Transportation Center, Texas A&M University, August 2004.