# USE OF DRIVING SIMULATOR TO EVALUATE THE EFFECT OF REPETITION ON VARIABLE MESSAGE SIGNS

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# ABSTRACT

Variable Message Signs are dynamic message displays that are used both to manage traffic incidents and to provide advisory messages to drivers. One of the more common methods of displaying long messages on a Variable Message Sign is to break the message into two segments (lines) and then present each segment in a different phase. We will refer to this as a Multiphasic (since there are several segments) Temporal (since the segments are presented at different times) Format. Biphasic Messages are defined as Multiphasic Temporal Messages with exactly two phases. Based on current research done on Multiphasic Variable Message Signs the duration of each phase is determined as follows: At least 1 second of exposure time for every word in a Multiphasic Variable Message Sign and at least 2 seconds of exposure time for every unit of information, whichever is larger. The objective of this paper is to determine if it is better to follow the above recommendations or, instead, reduce the exposure time by half and repeat the entire message twice. More specifically, let us assume that the driver, traveling at a certain speed, was able to view the Variable Message Sign for the minimum time based on the above recommendations. In this case, we want to determine whether it would be better to expose each phase for the recommended time or, instead expose each phase for exactly half the time recommended for that phase, but repeat the whole message twice? A number of factors can affect the performance of drivers seeing the two different formats (single or multiple presentations), including the presence of a partial obstruction of these signs by other vehicles, the order in which the phases are read by the driver, and the exposure time of the different phases of the message. The effect of these factors on performance was evaluated for Biphasic Variable Message Signs, which are the most common form of Multiphasic Variable Message Signs, using an Advanced Fixed Base Driving Simulator at the University of Massachusetts. Findings indicate equivalent or better overall driver performance across all the above conditions when the exposure times for each phase were reduced to half the recommended time but phases were repeated, when compared to each phase being displayed for the recommended exposure time but without repetition.

# INTRODUCTION

Variable Message Signs are used in a wide variety of applications ranging from providing information to the driver, to traffic management during traffic incidents. One of the key requirements for an effective Variable Message Sign is to convey the message in a manner that it is understood by the driver in the limited amount of time that he or she is exposed to the message. The need to optimize driver comprehension and reaction time for the message presented is exacerbated when they are used for traffic incident management, more so for incidents occurring in underground roadway systems, such as the Central Artery Tunnel (CA/T), currently under construction in Boston, MA. Two questions arise in this context: Where is it best to locate the Variable Messages Signs and how should messages that are too long to display entirely on a VMS be presented. While the first question is addressed primarily by the geometric layout of the tunnel (i.e. effect of horizontal and vertical curvature of the roads, tunnel walls, ceiling and moving traffic) the second question can be better answered by investigating the way in which information is processed by a driver. Moreover, in an underground roadway system, there is an enhanced effect of obstructions on Variable Message Signs. An obstruction here can occur both due to large vehicles, and the horizontal and vertical tunnel curvature due to which the walls and ceiling can potentially diminish the time available to the driver to view a message. As a result of this, drivers may fail to make the required maneuver. Or drivers may make the maneuvers much too late. Although prior research (1) has dealt with identifying the phase exposure time to maximize driver understandability of Variable Message Signs, the effect of possible message obstruction due to road geometry and other traffic on road has not been considered while identifying this phase exposure time. The objective of this paper is to determine if it is better to follow the existing recommendations or, instead, reduce each phase exposure time by half and repeat the entire message twice taking into account the effect of message obstruction.

In order to study effectively driver understandability of Variable Message Signs in an experiment, it is necessary to replicate three things- the dynamic messages themselves, psychomotor processes involved in vehicle control and cognitive processes involved in the processing of real time traffic behavior and information presented on traffic control devices. An effective method of incorporating the above features in an experiment to study the understandability of Variable Message Signs is with the use of a Driving Simulator. Below is a discussion of Driving Simulators in general as well as the Driving Simulator in the University of Massachusetts, Amherst, which was used to perform an experiment in order to optimize understandability of Variable Message Signs.

Driving Simulation is an example of man-in-the-loop simulation using computer generated graphics that are real time (2). A man-in-the-loop simulation essentially uses a person in the control loop of the simulation. The real time aspect of the simulator enables the dynamic model of the virtual simulated world to be continually evaluated and

modified based on the input from the operator. A Driving Simulator aims to create conditions which allow the operator to control the simulated vehicle in the same way that he would in a real world. The simulated environment holds the benefit of providing a safe and controlled testing environment.

One of the key issues in such application is the ability of the Driving Simulator to mimic reality. This is necessary in order to extrapolate the results of human behavior from a simulated world into the real world. This requires not only the development of improved software, but also hardware that can enable scene generation realistic enough so as not to resemble arcade games. Since the early eighties, there has been a rapid evolution of technology, both in terms of the hardware and the software used in Driving Simulators. Up until the late eighties, hardware was a major issue in terms of graphics generation. This was greatly alleviated in the nineties, with graphics oriented computer hardware becoming more readily available (3). Improved projection of images, high resolution images with anti-aliasing throughout, high refresh rates and high speed networking have also greatly enhanced visual simulation capabilities. Thus the benefits of the use of Driving Simulator are many- ranging from safe and controlled testing environment to realistic and customizable scenario creations for various experiments where it is necessary to simulate the driving task. Improvement of graphics software and hardware has contributed to the enhancement of realism of driving simulator. However cost remains a prohibitive factor in large scale implementation of the use of Driving Simulator for research. Moreover, as long as there do exist some differences between the real and simulated world, careful designing of experiments can help offset this difference. For instance, simulators can be used for comparative studies, (e.g. comparison of driver performance for two or more different Traffic Control Devices), rather than measurements on an absolute scale. Wherever possible, additional comparisons should be made with data generated in real world in similar experiments conducted in Driving Simulators. If the data match closely, it may be concluded that the simulation was close enough to warrant similar performances in real world. Even when the data does not match perfectly with the real world, the researcher can gather valuable trends from driver performance in the simulated world that are indicative of driver performance in real world. With the gradual increase in acceptance of Driving Simulators as a research tool, they have been used to study Human Factors issues in Transportation Engineering, both at the state and federal levels. Driving Simulators have been successfully used to evaluate a variety of issues, including younger driver behavior in risky scenarios (4), evaluation of traffic control systems and road signs (5,6), evaluation of different types of Protected/Permissive Left-Turn (PPLT) control displays (7) and evaluating the effectiveness of centerline rumble strips in reducing cross-over-the-centerline crashes (8).

One such simulator exists at the University of Massachusetts, Amherst. This is an advanced, fixed base driving simulator. The Driving Simulator at the University of Massachusetts has a body of 1995 Saturn Sedan, and is surrounded by three screens subtending approximately 150 degrees of visual angle. Each screen has a resolution of 1024 by 768. Image refresh rate is 90 Hz, i.e. the image on each screen is redrawn 90 times a second. Sound is generated through a Bose surround sound system. The computer powering the simulator is an SGI Infinite Reality computer which can display up to 8 separate channels. Assisting the main graphics engine are a computer dedicated to modeling effects of traffic and a computer dedicated to generate sound. The programming tool used to develop the simulations is Centric Softwares' Designers WorkBench. This simulator has been used to evaluate a variety of Human Factors issues in Transportation Engineering. Many of the studies have been used for comparison of different designs of Traffic Control Devices, rather than measurement in absolute terms. This yields the benefit of identification of a better design for a Traffic Control Device based on comparison, rather than attempting to predict driver behavior in more absolute terms.

# LITERATURE REVIEW

A review of the Variable Message Sign literature in areas related to the above issues was conducted and a summary of this review is presented. Ullman and Dudek (9) developed models that illustrate how horizontal and vertical curvatures as well as obstruction from large vehicles can limit the distance from which a Variable Message Sign can be viewed, depending on the characteristics of these obstructions. Their research has implications for proper placement and installation characteristics (mounting height, orientation etc.) from the standpoint of maximizing available reading time based on geometry. Their research also underscores the need to consider the effect of obstruction while designing Traffic Control Devices. Although their research identifies proper geometric placement of Variable Message Signs for maximizing the reading time, it does not address the issue of identifying the optimal phase exposure time in order to minimize the effect of obstruction.

Most messages contain more words than can be displayed on a single Variable Message Sign screen. This will be especially true of the VMS's in the CA/T since the signs will have room for only one line (12 - 24 characters long) of text. At least two possibilities exist for displaying messages more than one line long. The same screen can alternately display the different lines of text. We refer to this as multiphasic (since there are several segments) temporal (since the segments are presented at different times) formatting (*multiphasic temporal format*). The same screen can be used to scroll text from left to right (*multiphasic scroll format*).

To begin, consider a message which is broken into several different segments and then each segment is presented for some fixed duration on a screen. There are a number of factors that need to be considered when designing a VMS with multiphasic temporal formatting. First, we discuss the research bearing on the maximum number of phases. Miller, Smith, Newman and Demetsky (10) undertook research to develop operational guidelines for both portable and permanent VMS's. The researchers used three types of information gathering strategies: a literature search, surveys of Virginia Department of Transportation personnel, and discussions with drivers in the Commonwealth of Virginia. Miller et al. found that it is critical to consider the needs of both motorists and operators in order to maximize the effectiveness of VMS's. Operators need a set of guidelines rather than an extensive list of messages in order to take full advantage of the capabilities of VMS's. They recommend that VMS's should not use more than two screens (have more than two phases), and use of only one screen is preferred. This is so because motorists cited difficulties reading multiple screen messages when large vehicles blocked the line of sight, visibility conditions were poor, other distractions were present, or the sign was placed on the opposite shoulder. As a result of this recommendation, the messages used in the Experiment have been limited to the biphasic temporal format. Next, we discuss research determining the time that each word should be presented. There are a number of studies that bear on this issue. Dudek and Huchingson (11), based on the information provided by the British Road Research Laboratory [page 78 in (11)] and on a prior study done by Dudek et al (1), recommend that for two word messages presented on Variable Message Signs, the minimum exposure time is 2 seconds. For every additional word, exposure time should be increased by 1 second. Recommended presentation times are also given when a message is categorized into units. One unit of information is a single elemental idea that is being conveyed. Specifically, in a VMS, a unit of information is a data item given in a message, which can answer one of the following questions: (1) What happened? (2) Where did something happen? (3) What is the effect on traffic of a given event? (4) For whom is the advisory intended? (5) What driver action is advised? and (5) How long is the event supposed to last? For every unit of information, drivers require about two seconds of information processing time. Thus a minimum exposure time of one second per short word (four to eight characters) or two seconds per unit of information, whichever is largest is recommended.

Outside the traffic literature, there is research in more basic psychology which bears on the decision of how large a VMS to use when the message is displayed in a multiphasic temporal format. For example, Cocklin, Ward, Chen and Juola (12) investigated factors that influence the readability of rapidly presented text segments. They used what is referred to as a Rapid Serial Visual Presentation (RSVP) technique. The RSVP procedure consists of briefly presenting successive text segments to a fixed visual location so that the need for an individual to move his or her eyes while reading a sentence is eliminated. This multiple presentation of text segments is exactly what is being done with the multiphasic temporal format. Cocklin et al. conducted three experiments. The first experiment replicated earlier results indicating that RSVP reading results in levels of comprehension that are generally no worse than those obtained when text is read normally, with eve movements, at equivalent rates. In the second experiment they varied the window size (the amount of text visible on the screen in each phase). The results of the second experiment demonstrated that not all window size conditions are equivalent for text readability in the RSVP format. They found that comprehension behaved as an inverted U with increases in window size. Windows averaging about 12 character spaces were found to be optimal for reading comprehension. In the third experiment they tried to determine if a structured parsing scheme would further increase the reading efficiency for RSVP. The structured parsing scheme required the words to be chunked into small groups or 'idea units', averaging about 12 characters. They hypothesized that words are chunked together into small groups at an early processing stage in reading, such that the context in which a word appears is used to facilitate lexical access and interpretation of its meaning. The results of this experiment showed that an even greater advantage in comprehension level can be gained if successive windows are chosen to reflect phrase structure variables. In summary, their findings were that optimal RSVP conditions should include successive, non-overlapping text segments of about two to three words in length. When possible, segments of this average size should be chosen to represent integrated ideas or be short phrases from the text. Their results have implications for the design of Variable Message Signs. In particular, their results suggest that if a message of four units can be chunked into two semantically separate and complete ideas each requiring no

more than 12 characters to display, then it is better to present the four units as two phases of two words each in one 12 character VMS than it is to present the four units as one phase of a 24 character VMS. As a consequence of this literature, the Variable Message Signs used in the experiment used semantically separate ides as far as possible for each of the phases. Of course, the phases were related, but the message was grouped so that an integrated idea remained in a single phase. This is also the recommended practice for designing messages for Variable Message Signs in general.

Next, consider the presentation rate. Sometimes there may be only enough time to present a message once. However, at other times there may be more than the minimum time available. Dudek et al (1) performed a series of experiments related to presentation rate and timing issues for Variable Message Signs, which were compiled in a report for the Federal Highway Administration. Among other things, they addressed the question of whether a message should be displayed at a slow rate so that it is presented once while the driver is in the legibility zone, or whether the message should be displayed at a faster rate and exposed twice to the drivers. The authors used simulated traffic loading conditions to compare biphasic temporal messages with variable sequence rates both to determine the optimal sequence rate and to determine if the repetition of a message was better than no repetition of the message (assuming the same total exposure time in both instances). In this experiment, subjects drove a test vehicle between a sequence of traffic cones. Subjects were asked to maintain a speed of 45 mph. They were exposed to a message in a Variable Message Sign during the course of the drive. Their task was to repeat the message out loud immediately after the message had gone off. The authors found that in order to meet an 85<sup>th</sup> percentile recall criteria, the rate of presentation should be approximately 1 second per word. There were no significant differences between the repetition (with a rate of presentation of 0.5 second per word, but repeated) and no repetition (with a rate of presentation of 1 second per word) conditions on the measure of recall, suggesting that whatever advantages there were from repetition were offset by briefer exposure time. The recommended presentation time in this study for a two-phase message is, as mentioned earlier, 1 second per word. However this study did not evaluate the effect of possible obstructions to the Variable Messages. Moreover the driver understandability was based more on the ability to recapitulate the message rather than to perform an action based on the contents of the message. Presumably, if a portion of the message is obscured, it may be better to have a lower phase exposure time so that the message can be seen multiple times. But we do not know this for certain, as a lower exposure time in conjunction with the cognitive and psychomotor processes required in a driving task may result in insufficient exposure of message for driver understandability.

The multiphasic scroll format still appears on Variable Message Signs on some highways (Interstate 95 through New Jersey, for example), but is less frequently used than the multiphasic temporal format. Still, it is useful to consider research on this format. Dudek et al (1) conducted research on the multiphasic scroll format, comparing it to the multiphasic temporal format. In this experiment subjects were given a primary task similar to that of driving and a secondary task to simulate traffic load. Subjects were exposed to messages that were presented using either the multiphasic scroll or the multiphasic temporal format under no load and load conditions. The results of the study indicated better recollection of messages in the multiphasic temporal format. The difference in recollection was more pronounced in the task-loading group, but was still present, though to a lesser extent, in the no loading group. Thus it is anticipated that as the difficulty of driving task increases, the difference between the two formats would also increase.

The review of the literature on Variable Message Signs with multiphasic temporal formatting suggested the following. First, the use of a single phase is ideally preferred over the use of multiple phases. Drivers indicate that they prefer single phase messages when obstructions make it difficult to read a sign. However the Variable Message Sign may not always be able to accommodate sufficient words incorporate the entire message in a single phase, so multiple phases might be required. Second, drivers can understand well messages which are presented in two phases as long as the duration of each phase is sufficient. Messages longer than two phases should not be displayed. Memory limitations appear to play a role here. Third, further research is required to determine if repetition would help driver recall of messages in situations where the message is obscured and also to determine the optimal exposure time for phases with different units of information. More specifically, it is necessary to evaluate driver performance for no repetition and single repetition conditions under a wider range of factors, such as effect of the presence or absence of obstruction during part of the message, combined with viewing messages that are in sequence as well as out of sequence.

# EXPERIMENT

In this experiment, the focus was on biphasic temporal signs. Such messages consist of two pages. Each page is presented during a separate phase. As discussed earlier, Dudek et al. (1) reported that there were no significant differences between the repetition and no repetition conditions on the measure of recall of the message, suggesting that whatever advantages there were from repetition were offset by briefer exposure time. The recommended presentation time in this study for a two-phase message is 1 second per word. However this study does not extend immediately to situations in which either the drivers' view of the sign is obstructed by other vehicles or curves or crests in the road or in which the driver first sees the second phase as he or she enters the legibility zone. Either of the above differences could change the relative effectiveness of the number of presentations of a biphasic message in the legibility zone. This experiment was used to evaluate the effect of message repetition on drivers' understanding of the information being presented on a Variable Message Sign. In particular, a biphasic message was presented either once or twice for the same total time. For messages presented once, the exposure time was calculated based on one second per word. For messages presented twice, exposure time was calculated based on 0.5 second per word, but the message was repeated. A number of factors were varied systematically along with the number of presentations of the message (one or two), including the lane change direction specified in the message (left or right), the number of lane changes a driver would need to make in order to respond appropriately to the message (1 or 2), the presence of obstructions (Early- i.e., partial or complete obstruction of first phase. Late- i.e., partial or complete obstruction of second phase or None- i.e., No obstruction), the sequencing of the phases (in sequence or out of sequence- in sequence messages presumably resulting in better mental information parsing). The efficacy of a message was then measured both by the percentage of drivers responding appropriately (moving into the appropriate lane) and the time at which the drivers take their first corrective response to a message.

#### Method

#### **Participants**

A total of 48 subjects participated in the experiment. All were students or staff at the University of Massachusetts at Amherst and held valid Massachusetts driver's license.

#### Stimuli

A mid level Driving Simulator present at the Human Performance Laboratory at the University of Massachusetts, Amherst was used in this experiment. The driving simulator includes a fixed-base vehicle which is surrounded by three screens on which are projected a virtual world (**Figure 1**).



FIGURE 1 Driving Simulator at the University of Massachusetts, Amherst

Each participant was required to drive the Simulator for several trips through simulated underground tunnels. Each drive has a moderate amount of traffic. In order to ensure the commitment of the subjects to attentional demand during the fairly lengthy experiment, in conjunction with traffic, the concept of using Distracters was implemented. Distracters were one or two digit integers displayed in the middle of an opaque square positioned orthogonally to the line of sight of the driver during the course of the drives. The integers were written in black; the square was a flat white. The square was 3.05 m on a side, easily visible to the driver. The integers were 1.07 m high. The frequency of Distracter appearance was few and far between (approximately 10 distracters in every drive) with the intention of merely evaluating the alertness of the subject during the course of the experiment. Each trip through a tunnel consisted of straight and horizontally curving sections of five lane roadway. The basic structure of the roadway for any particular trip was either 'S' shaped or 'reverse S' (mirror image of S) shaped. The S shape essentially consisted of three straight links, each 1006 meters in length. For an S shaped link, the lowermost link was inclined towards the right, the middle link was inclined towards the left and the topmost link was again inclined towards the right resulting in an S shape. In order to reduce the turning radius between these links, adjacent links were joined using a horizontally curved section of roadway 457 meters long. Each drive began at the lowermost link and progressed from South to North. At the Northern end of each straight link, there was an exit either on the left side or right side of the road (but never both together) with the lane leading to the exit being an optional exit lane. A Variable Message Sign was at a distance of 550 meters before every exit. The VMS was fixed to the ceiling. The width of each virtual VMS was 12.5 meters and the height was 0.93 meters. Each virtual VMS could accommodate a single line of text, all in uppercase letters. Each of the exits also had advance signage informing the driver of an impending exit. A general layout in an S section is given in Figure 2.



FIGURE 2 Layout of 'S' section

As mentioned earlier, the reverse S design was simply a mirror image of the above mentioned layout. Based on the scenario allotted for a particular drive, drivers could be given an exit destination either on the first, second or third link. A total of 24 biphasic messages requiring action by the driver were used in the study. These messages are referred to as *experimental messages*. In addition to these there were also several *control messages* which did not require any action by the driver. Control messages were divided into two categories. One category of control messages was very similar to the experimental messages, the only difference being that the word TRUCKS or OVERHEIGHT VEHICLES was substituted for the word TRAFFIC. The other category of control messages contained messages which were completely unrelated to the experimental messages in their wordings (e.g. Phase 1: USE CAUTION/Phase 2: WHEN EXITING) and also did not require the driver having to take any action. They served much the same purpose as the previous set of control messages.

The control messages occurred in the two other links. The control messages were used in order to reduce learning effects and driver expectancy. The 24 *experimental messages* are listed in the **Table 1** below:

Message Group	Phase 1 [Phase ID) Message]	Phase 2 [Phase ID) Message]	Message Duration (sec) (P1,P2)
	1) ALL TRAFFIC	A-L) USE LT LANE	2,3
	1') ALL TRAFFIC	A-R) USE RT LANE	2,3
G1	2) ALL TRAFFIC	B-R) 2 RT LANES	2,3
	3) ALL TRAFFIC	B–L) 2 LT LANES	2,3
	4) ALL TRAFFIC	C-R) 3 RT LANES	2,3
	5) ALL TRAFFIC	C–L) 3 LT LANES	2,3

 TABLE 1 Experimental messages

	1) EXIT XX TRAFFIC	A-L) USE LT LANE	3,3
	1') EXIT XX TRAFFIC	A-R) USE RT LANE	3,3
G2	2) EXIT XX TRAFFIC	B-R) 2 RT LANES	3,3
	3) EXIT XX TRAFFIC	B–L) 2 LT LANES	3,3
	4) EXIT XX TRAFFIC	C-R) 3 RT LANES	3,3
	5) EXIT XX TRAFFIC	C–L) 3 LT LANES	3,3
	1) THRU TRAFFIC	A-L) LT LN CLSD	2,3
	1') THRU TRAFFIC	A-R) RT LN CLSD	2,3
G3	2) THRU TRAFFIC	B-R) 2 RT LNS CLSD	2,4
	3) THRU TRAFFIC	B-L) 2 LT LNS CLSD	2,4
	4) THRU TRAFFIC	C-R) 3 RT LNS CLSD	2,4
	5) THRU TRAFFIC	C-L) 3 LT LNS CLSD	2,4
	1) EXIT XX TRAFFIC	A-L) LT LN CLSD	3,3
	1') EXIT XX TRAFFIC	A-R) RT LN CLSD	3,3
G4	2) EXIT XX TRAFFIC	B-R) 2 RT LNS CLSD	3,4
	3) EXIT XX TRAFFIC	B-L) 2 LT LNS CLSD	3,4
	4) EXIT XX TRAFFIC	C-R) 3 RT LNS CLSD	3,4
	5) EXIT XX TRAFFIC	C-L) 3 LT LNS CLSD	3,4

Note that the experimental messages have been categorized into four different groups. These groups were created by bunching messages with very similar wording together in a single group. The timing of the individual phases in the 'No repetition condition' is also indicated in the table.

Also note that some of these messages can evoke only one lane change while others can evoke both one and two lane changes, by varying the starting lane of the driver. Further, some of the messages can evoke a lane change only to the left of the driver while others can evoke a lane change only to the right of the driver. **Table 2** identifies the messages which were used to yield different kinds of driver movements (i.e. 1 lane change to the left- 1L, 2 lane changes to the left- 2L, 1 lane change to the right- 1R and 2 lane changes to the right- 2R) based on driver understandability of the experimental signs.

	1L	2L	1R	2R
	Sequence	Sequence	Sequence	Sequence
1	G1-1	G1-1	G1-1'	G1-1'
2	G2-3	G2-3	G2-2	G2-2
3	G3-4	G3-4	G3-5	G3-5
4	G4-1'	G4-2	G4-1	G4-3
5	G1-3	G1-3	G1-2	G1-2
6	G2-5	G2-5	G2-4	G2-4
7	G3-1'	G3-2	G3-1	G3-3
8	G4-2	G4-4	G4-3	G4-5
9	G1-5	G1-5	G1-4	G1-4
10	G2-1	G2-1	G2-1'	G2-1'
11	G3-2	G3-4	G3-3	G3-5
12	G4-4	G4-2	G4-5	G4-3

# TABLE 2 Message allotment

#### Design

There are four levels of Number/Direction of Lane Change (1L, 2L, 1R, 2R), three levels of Obstruction (E--Early, L--Late, N—None) and two levels of Sequencing (In, Out). When these are combined, we have 4\*3\*2=24 different combinations. These combinations were arranged in pseudo-random order to minimize expectation. This order is presented in **Table 3**.

Drives	Msg Seq.	Obstruction	N/D Lanes (Number and Direction of lane change)
1	in	E	1L
2	out	L	2L
3	out	L	2R
4	in	N	1R
5	out	E	1L
6	out	N	1R
7	in	L	2R
8	in	L	2L
9	out	N	2L
10	in	E	1R
11	in	L	1L
12	out	N	2R
13	in	N	2L
14	out	L	1L
15	out	E	1R
16	in	N	2R
17	out	E	2L
18	out	E	2R
19	in	L	1R
20	in	N	1L
21	out	L	1R
22	out	N	1L
23	in	E	2L
24	in	E	2R

#### TABLE 3 Drive order

All combinations in Table 3 are drives performed by a single subject. For subsequent subjects, the order of presentation was simply rotated by one row downward, so that the combination in Drive 1 for subject 1 is the combination observed in Drive 2 by subject 2 and so on.

In order to achieve one complete rotation of combination, we would require 24 subjects. Repetition was counterbalanced across subjects. Thus 24 subjects were allotted the 'No Repetition' condition and 24 subjects were given the 'Single Repetition' condition. This adds up to 48, which was exactly the number of subjects for this experiment.

In addition to the above mentioned factors, other factors referred to as minor factors such as Tunnel Structure (S or reverse S), Message Groups (1 to 4), Sign Group (1 to 24), Critical Link Location (1, 2, 3), Distracter Group (1 to 6), and Control Message Allotment were varied. The main objective for counterbalancing these minor factors was to minimize the learning effects. However it was ensured that across the 'no repetition' and 'single repetition' conditions, all other factors remained identical.

#### Procedure

Participants were told that the study consisted of 24 drives. They were given a target destination and a starting lane (which could Left, Left-Center, Center, Right-Center or Right, depending on the given scenario) at the beginning of each drive. They were instructed that their job was to obey all instructions presented on Overhead Guide Signs and Variable Message Signs while trying to reach the specified destination. All participants were given practice trips through tunnel sections which enabled them to get used to the controls of the simulator. Participants were told that the purpose of the study is to test their ability to read, understand and take appropriate action based on information presented on all signs, including Overhead Guide Signs and Variable Message Signs, within a tunnel. Since there were static overhead guide signs as well as Variable Message Signs, they did not know specifically that it is only Variable Message Signs that are being evaluated. Thus, the drivers should not be paying undue attention to these signs, something that could make it more difficult to interpret the results. Drivers were also informed about the 'Cruise Control' feature that had been incorporated for the experiment which would enable them to maintain a speed of 45 mph during their drive. They were advised to use this feature.

**Managing Lane Position** Drivers were instructed to remain in their lane during the drive unless, based on information in any Variable Message Sign or Overhead Guide Sign, they were absolutely certain that a lane change was required. Thus, it was possible to control the lane in which they viewed the experimental message simply by starting the driver in a particular lane.

**Managing Exiting Traffic** Drivers were given a destination before each drive. Drivers can actually exit, as directed, or drive to the end of the tunnel, simply passing by the destination exit (pretending, say, that they missed their exit).

**Managing Thru Traffic** Some of the destinations were also mainline routes which simply ended after the driver passed all the exits. In other cases a mainline destination for the critical link was achieved by ensuring that if the destination was an exit, it was in a link after the critical link.

#### Dependent Variables

The efficacy of a message was measured both by the percentage of drivers responding appropriately (moving into the appropriate lane) and a measure of how soon a driver comprehends the message, which can be estimated by measuring the distance when the driver first begins to make a lane change as his or her first corrective response to a message.

#### Results

**Misses** Overall, 32.5% of the participants presented a biphasic message only once missed the instructions presented on the Variable Message Signs (**Figure 3**). And 11.3% of the participants presented a biphasic message twice missed the instructions presented on the Variable Message Signs. This difference was significant (t(982.8)=8.86, p<0.001). (We used the separate variance estimate of *t* since it is more conservative than the pooled variance estimate). Analyzing the results more finely and looking only at the relative effect of the different types of obstruction on performance, we find that the largest difference between the repetition and no repetition conditions occurred when there was an early obstruction 9.9% versus 40.6% with t(308.4)=7.27 and p<0.001, 12.4% versus 41.4% when the obstruction is late with t(323.4)=6.6, p<0.001.

Interestingly, the differences in the repetition and no repetition conditions were sizable only when an obstruction was present, either early or late. When there was no obstruction, both repetition and no repetition conditions were around 15% with no significant difference, which was quite similar to the results obtained by Dudek et al (1) who did similar comparisons without considering the effect of obstruction in their experiment.



FIGURE 3 Comparison of the percentage of misses

**Lane Change Location** We also measured how soon after the Variable Message Sign the driver first made a lane change (**Figure 4**). When the message was not repeated, drivers traveled almost twice as far beyond the variable message sign before making the lane change, as when the message was repeated (40.2 meters versus 23.6 meters). This difference was again very significant (t(732.8)=4.9, p<0.001). Analyzing the results more finely and looking only at the relative effect of the different types of obstruction on performance, we find that the largest difference between the repetition and no repetition conditions occurred when there was no obstruction (30.3 versus 4.4 meters with t(303.8)=5.2 and p<0.001), 66.2 versus 55.4 meters when the obstruction is early with t(215.9)=2.13, p=0.034; and 28.0 versus 10.9 when the obstruction is late with t(166.5)=2.63, p=0.009.



FIGURE 4 Comparison of Lane Change Distances

# DISCUSSION AND CONCLUSION

Drivers clearly seemed to benefit when a biphasic message was repeated in the legibility zone, both following the directions correctly more often and taking the appropriate action further upstream. Interestingly, drivers performed correctly more often in the repetition condition than the no repetition condition only when the first or second phase of the biphasic message was obscured. There was no statistically significant difference between seeing a biphasic message once and seeing it twice when there were no obstructions, consistent with what other investigators have reported. In all three conditions, drivers changed lanes sooner if the message was no obstruction. Here, in the repetition condition, drivers changed lanes almost a full 26 meters before than they did in the no repetition condition.

This experiment demonstrated that the timing of phase affects how soon a responsive action is taken by the driver. Even for the no obstruction condition, there was a very significant difference in the lane change distances between the no repetition and repetition condition, with drivers following the instructions much sooner in the repetition condition. While designing Variable Message Signs, traffic engineers and designers need to not only consider the location and orientation of Variable Message Signs from the geometrical standpoint, but also consider the phase exposure time, keeping in mind both the effect of obstruction and promptness of action taken by the driver.

Finally, several issues are relevant when designing an experiment using a driving simulator. The first issue pertains to the generalizability of the results on the simulator to the real world. It is generally found that drivers behave more cautiously in a simulator than they do in the real world (13,14). Thus, we might expect to make lane changes sooner on the open road than we do in the driving simulator. However, regardless of the absolute value of such comparisons between the two conditions, we would still expect drivers who see the repetition condition to perform better than drivers who see the no repetition condition, since the two conditions were compared with all other factors remaining constant. Second, an issue that arose during the experiment was ensuring that every subject was exposed to a Variable Message Sign for exactly the amount of time as designed in the experiment. If subjects had the ability to change the velocity of the vehicle, subjects traveling slower than the designed speed would be exposed for a longer period to the messages and vice versa, which could make it more difficult to interpret the results. In order to counter this problem, a cruise control feature was incorporated in the simulator, so that all subjects traveled at the designed

speed. Lastly, we discuss the issue of visibility in the simulator as compared to the real world. The image display in the simulation was in high resolution ( $1024 \times 768$ ). Research has shown (15) that the legibility distance for signs at this resolution is approximately 20 feet per inch (i.e., for every inch of letter height the sign is legible from 20 additional feet away) when compared to a legibility of around 43 feet per inch in real world. Since it was necessary to ensure that the signs would be perfectly legible from the maximum desired distance in the experiment the Variable Message Signs were resized accordingly. The font size used for the letters in the simulated VMS was 0.53 meters. At this font size, the messages were perfectly legible from the point the driver was first exposed to the Variable Message Sign.

In conclusion, it is recommended that for biphasic messages with up to four words or units of information (whichever is greater) calculating the phase time based on the addition of 0.5 seconds per word or unit of information is optimal from the viewpoint of driver performance, both when there are obstructions (leading to many more drivers following the directions on the message) and when there are no obstructions (leading drivers to make the required lane change much more upstream).

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