Effectiveness of Changeable Message Signing at Freeway Construction Site Lane Closures

FRED R. HANSCOM

The effectiveness of changeable message signing (CMS) devices in advance of freeway construction and maintenance zone lane closures was evaluated. Operational traffic behavior and driver interview data were gathered in four states. Before-and-after studies of baseline (no CMS) versus CMS application consistently demonstrated increased advanced preparatory lane-change activity, smoother lane-change profiles, significantly fewer late exits (within 100 ft of closure), and reduced speeds at the lane-closure point to be associated with CMS use. The most preferable CMS location was found to be 0.75 mile (1.2 km) in advance of the lane closures. Of three tested device types (one-line bulb matrix, two-line rotating drum, and three-line bulb matrix), the large, obtrusive three-line bulb matrix tended to produce more advance lane-change behavior; however, no difference in the hazardous late exit maneuvers was observed between types. All three were equally effective in eliciting speed reductions at the entrance to the lane closure. Driver interview data tended to favor the three-line device due to its greater information display capacity. Message combinations of speed, lane closure, and merge advisories were tested on the devices. Although lane-change behavior of the total traffic stream did not significantly differ between message conditions, interviewed motorists favored the speed and lane-closure message combination as being most helpful, providing most response time, and meeting information needs. The study recommends CMS applications as a supplement to standard device schemes but not as a substitution for the arrowboard. Suggested cost-efficient CMS applications involve (a) short-term closures characterized by decreased driver expectancy, (b) traffic volumes of 900 vehicles/h or greater, and (c) limited sight distance to the closure.

Highway construction activity or other types of incidents (e.g., accidents, unexpected road obstructions, and maintenance activities) frequently require the closure of one or more traffic lanes. Although the Manual on Uniform Traffic Control Devices (1) describes recommended treatments for typical lane closures, there is a need for improved methods of providing advance information to the motorist. The need for this research is emphasized by the current trend for highway rehabilitation projects, many of which require lane closures. Accident experience at lane-closure locations, especially on high-speed facilities, demonstrates the need for better guidance for the motorist and protection of the worker.

OBJECTIVES AND APPROACH

The objective of this research was to determine the effectiveness of changeable message signing (CMS) applications at lane closures on high-speed freeways. Right- and left-lane closure situations were studied and observations were made under day and night conditions. By using field studies at selected lane-closure sites, this research examined traffic performance effects of various changeable message displays. In addition, a sample (N = 489) of driver responses (detection, comprehension, and interpretation) was obtained. This applied methodology examined appropriate relations between driver information processing and vehicle behavior required for validating operational measures of CMS effectiveness.

FIELD-STUDY METHODS

Two separate procedures were applied to study CMS effects at planned lane closures. Manual coding of vehicle performance was applied to gather traffic operational responses to the CMS alternatives, and in-vehicle questionnaires were administered to test subjects to obtain sensitive measures of driver response.

Traffic-Operations Measurement

Manual observations of vehicle speed and lane distributions (proportions of traffic in the closed and through lanes) were obtained at the following data-collection points on the approach to freeway lane closures:

1. Advance--The advance point was selected in advance of the sight distance to the CMS, approximately 1 mile (1.6 km) before the lane closure. The purpose of collecting data at this point was to determine behavior of traffic not influenced by the CMS.
2. CMS Point--The CMS location was either 2000 ft (600 m) or 0.75 mile (1.2 km) (the two tested CMS placements) in advance of the taper. Data were gathered here to determine the advance effect of the CMS.
3. Intermediate--Midway between the CMS and taper, the intermediate point defined the lane-change profile effect of the CMS.
4. Taper--The most critical collection point was 100 ft (30 m) in advance of the first taper channelizing device. Data gathered here revealed the level of hazardous late exit behavior.

This uniformity of data-collection points between CMS test locations permitted limited combining of data for the purpose of comparing CMS effects. Time of day for data collection was also controlled in order to eliminate its possible confounding effect.

Both speed and lane-distribution data were sampled within 30-min data-collection intervals. This incremental observation procedure permitted the monitoring of interactive effects of speed and volume changes as conditions fluctuated throughout the data-collection day.

In-Vehicle Driver Response

A driver questionnaire was completed by subjects who participated in a controlled field study staged at construction sites observed in the traffic-operations study. These subjects were not aware that they were participating in a study specifically related to highway construction zone signing until they had completed a considerable portion of the questionnaire. Lane-change behavior and driving speeds were unobtrusively recorded and subsequently matched to questionnaire responses.

The applied questionnaire strategy involved first asking a series of general questions regarding observations of traffic-control devices that the drivers had passed. Although answers to these questions were provided prior to the subjects being directly asked about their CMS observations, the answers nevertheless reflected a direct impact of the CMS. This provision of the survey afforded an internal response-validation mechanism.

Completed questionnaires void of missing data items were obtained for a sample of 489 drivers. Age and sex distributions of the sample did not significantly differ between states. Age and sex distributions were controlled so as to approximate normal exposure rates. The sample included substantial proportions of drivers younger than 20 and older than 60 while maintaining a nearly even male-female distribution.

Tested CMS Conditions

A review of current use revealed general characteristics of available CMS devices applicable for construction zone traffic management. Three device types that represent a variety of available characteristics were applied in this study. Three message capacities (one, two, and three lines) were tested, which represent two display types (bulb matrix and rotating drum). Figure 1 summarizes tested conditions (note: 1 ft = 0.3 m, and 1 mile = 1.6 km).

Field-Test Scenario

The study procedure had to accommodate a variety of constraints. First, it was not possible to stage construction activity for the purpose of controlling necessary site conditions (e.g., highway geometry and traffic volume). Therefore, the study procedure could be applied only at existing construction sites. Second, it was not possible to test all CMS devices at one site. The research team was dependent on CMS manufacturers and state agencies for providing the devices and, therefore, constrained to specific locations and data-collection times. Finally, at one site it was not possible to test a baseline (no CMS) condition because of possible liability consequences to the state agency.

These locational and CMS device constraints required that the applied field-test scenario (see Table 1) use a variety of data bases. Existing differences between data bases (e.g., varying traffic-control-device standards between states) dictated complete reliance on within-site data analysis. Therefore, in the interest of statistical validity of the analysis, adequate sample sizes were gathered at each site.

Analysis of the data addressed the four CMS effect issues identified in Table 1. The effect of CMS device application was determined at sites that initially contained standard (no CMS) traffic-control-device schemes via a before-and-after study of each tested CMS device. Placement conditions (including use of more than one CMS) were tested as the result of the simultaneous availability of two devices at one site. Three placement alternatives that varied CMS location with respect to the lane closure were as follows.

1. 0.75-mile advance placement,
2. 0.75-mile and 2000-ft placements, and
3. 2000-ft placement.

A variety of message conditions were tested in one state that routinely applied CMS devices. The following message types were permitted to be specified:

1. Speed and closure advisory,
2. Speed and merge advisory,
3. Merge and closure advisory, and
4. Closure advisory.

FIELD-STUDY RESULTS

Results are separately discussed for the three applied field measure types: traffic distribution across lanes, speed measurements, and in-vehicle responses.

Lane-Distribution Results

The relative proportions of traffic in the through and closed lanes that approach construction zone lane closures were observed for a sample of more then 196 500 vehicles. Data gathered in three states (Georgia, Colorado, and California) were used to compare these lane distributions between baseline (no CMS) conditions and various CMS applications. A fourth data set, gathered in South Carolina, was used to determine the relative effects between certain CMS message alternatives (i.e., speed and closure, speed and merge, and closure and merge advisories) and various placement configurations (i.e., one CMS at 2000-ft or 0.75-mile advance placement, and two CMS devices, one at each advance location).

A number of findings evolved from this analysis. CMS application was consistently shown to improve lane-distribution profiles (e.g., increased advance preparatory lane changing) on the approach to construction sites, and certain findings evolved regarding specific CMS characteristics. Findings are now discussed for each of the CMS effects noted in the field-test scenario (previously summarized in Table 1).

Application

Consistent results between baseline (no CMS) and CMS conditions based on data collected in Georgia, Colorado, and California demonstrated improved lane-distribution profiles following the application of CMS at both right- and left-lane closures.

Figure 2 shows lane-distribution profiles of baseline CMS effects observed for one- and two-line CMS devices in Georgia and Colorado, respectively. Because distinctly different baseline profiles were noted, it would be inappropriate to combine these data across sites for illustrative purposes. Higher volumes noted for the Colorado sites likely explained the increased early exiting from the closed lane. As can be seen from the figure, application of CMS devices was associated with decreased closed-lane proportions of traffic at all three data-collection points within 0.75 mile of the closure.

Two CMS conditions were compared with baseline conditions at one site, the results of which are shown in Figure 3. Dramatic reductions in the proportions of vehicles that remain in closed lanes were observed for both conditions. Differences observed between specific CMS conditions of placement, message type, and format are discussed next.

Placement

Four CMS placement schemes were tested in the South Carolina data base. These were as follows:

1. Single CMS use--One device placed approximately 2000 ft in advance of the taper,
2. Advance CMS use--One device placed 0.75 mile in advance of the taper,
3. Two CMS devices--One device at each of the above noted locations, and
4. Advance CMS with supplemental arrowboard--One CMS placed 0.75 mile in advance of the taper and an additional arrowboard at the 2000-ft location.

Figure 4 depicts an apparent effect of CMS placement on lane-distribution profiles. Significantly smaller proportions of traffic were observed in the right (closed) lane for the three noted conditions that included as CMS at the 0.75-mile advance location. Data collected at the CMS location (2000 ft

Figure 1. Tested CMS conditions.

Site	CMS Format/ Placement	Message Type	Display
South Carolina	Three-line bulb matrix (2000 feet from taper)	Speed and Closure Advisory	MAX SPEED 45 MPH ⇄ RIGHT LANE CLOSED
		Speed and Merge Advisory	MAX SPEED 45 MPH ⇄ MERGE LEFT
		Merge and Closure Advisory	RIGHT LANE CLOSED ⇄ MERGE LEFT
	Supplemental One-line bulb matrix (3/4 mile advance)	Closure Advisory	RIGHT / LANE / CLOSED / AHEAD
		Speed and Merge Advisory	MERGE / LEFT / SLOW TO / 45 MPH
Georgia	One-line bulb matrix (3/4 mile advance)	Closure Advisory	LANE / CLOSED / AHEAD
Colorado	Two-line rotating drum (3/4 mile advance)	Closure Advisory	RIGHT LANE CLOSED AHEAD
California	One-line bulb matrix	Speed Advisory	SLOW TO / 18 MPH
	Two-line rotating drum	Speed Advisory	SLOW TO 45 MPH
		Closure Advisory	RIGHT LANES CLOSED AHEAD
	Three line bulb matrix (All 3/4 mile advance)	Speed and Closure Advisory	RIGHT LANES CLOSED ⇄ MAX SPEED 45 MPH

Table 1. CMS field-test scenario.

CMS Effect	Test Condition	Data Base
Application	Baseline versus one-line device	Georgia
	Baseline versus two-line device	Colorado
	Baseline versus three-line device	California
Placement location	2000-ft advance	South Carolina
	0.75 mile and 2000 ft	
	0.75-mile advance	
Message condition	Speed and merge advisories	South Carolina
	Speed and closure advisories	
	Merge and closure advisories	
	Closure advisory	
Format	Two-line versus three-line device	California

Note: 1 ft = 0.3 m; 1 mile = 1.6 km.

in advance of the taper) indicated a dramatic reduction in the proportion of closed-lane traffic for the advance CMS schemes. No statistical differences were noted between the advance CMS conditions. However, a tendency was seen in the data for the earliest preparatory lane changing to occur in the presence of a CMS at the 0.75-mile advance location and supplemental arrowboard at the 2000-ft location.

Message Condition

The four tested message conditions were speed and closure advisory, speed and merge advisory, merge and closure advisory, and closure advisory. All four conditions were tested at the South Carolina site and the results obtained were used as a basis for message application at subsequent sites.

The majority of this data base was gathered by using the two state standard speed and closure and speed and merge advisory messages. Only limited data were available for the remaining two conditions, as these represented deviations from state standards. Improved lane-distribution profiles were associated with the use of speed and merge advisory messages.

Display Type

Data gathered at the California site permitted a direct comparison between the two-line rotating-drum device and the three-line bulb-matrix sign because both devices could be separately tested at one lane closure. Figure 3, previously presented to show baseline versus CMS application, also plots the comparative effect of the CMS display types. A prominent difference in observed effects between the two- and three-line devices was a smaller proportion of vehicles present in the closed lane at the CMS point while the three-line device was displayed. This difference between device types did not continue, however, into the intermediate and taper observation points.

An explanation of the lower closed-lane volume at the CMS point during the presence of the three-line device likely resides in the fact that the device itself is large and highly visible at a substantially greater lead distance than is the two-line CMS. There was no possible sight-distance difference effect because both devices were deployed at the same location. The data strongly suggest, however, that increased obtrusiveness of the sign itself did not serve to reduce closed-lane occupancy closer to the taper.

Although no difference in late exit behavior was noted between the two devices for the total vehicle sample, a different effect was observed for the truck population. Fewer trucks were observed to perform late exits during the presence of the two-line device.

Speed Observation Findings

A sample of 41 463 vehicle speed observations revealed an effect of CMS application at the construction site lane closures. Data-collection points on the approach were the same as those previously discussed for lane-distribution results. A large data base (N = 30 790) was initially collected in South Carolina to examine relative effects associated with specific CMS conditions. A number of message and placement variations were compared. The South Caroline data-collection effort was limited due to state CMS use requirements and consequent liability concerns that precluded testing a baseline. Baseline conditions were subsequently compared with CMS application effects in Georgia, Colorado, and California.

Unlike the lane-distribution results, substantive conflicting findings were noted between sites. However, a number of distinct tendencies were found in the data to support the finding that certain speed effects did result from CMS use.

CMS Application

Comparison between baseline and CMS conditions revealed speed reductions to be associated with speed advisory messages under most circumstances. The only exception was one site that exhibited low preexisting speeds of approximately 47 mph (75 km/h). No reduction was noted at the taper in the presence of a speed advisory CMS that requested reduced speeds of 45 mph (72 km/h).

Extensive speed measurements during baseline versus CMS-application comparisons were made in Georgia by using a one-line bulb-matrix CMS. Although no speed advisory message was displayed on the device, generally lower speeds indicated a

Figure 2. Lane distribution profiles for right-lane baseline and CMS use conditions (Colorado and Georgia samples).

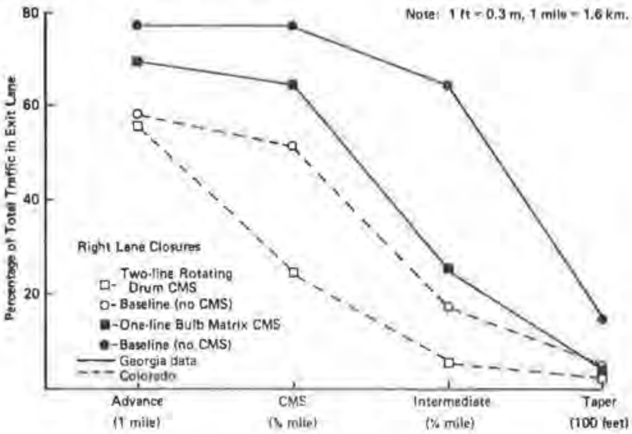
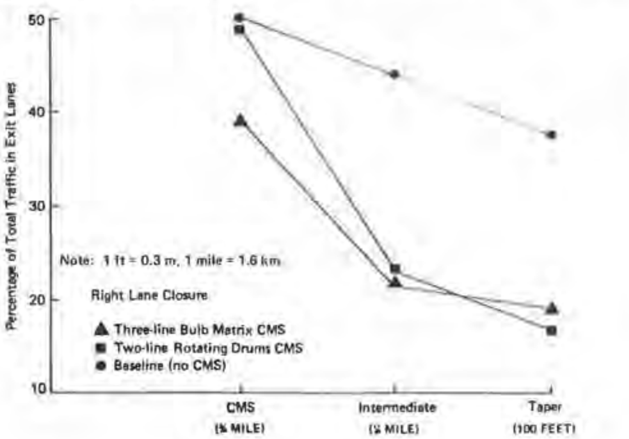


Figure 3. Lane distribution profiles for right-lane baseline and CMS use conditions (California sample).



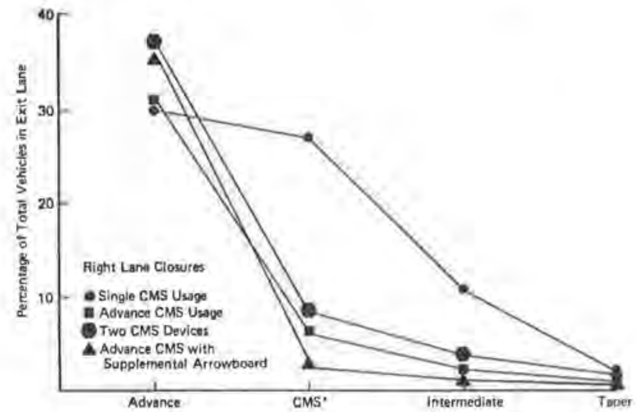
possible residual effect of motorists' increased awareness of the hazard. Because of the transient nature of construction activity, a more controlled experimental approach was applied at subsequent sites.

A modified procedure applied in Colorado and California entailed concurrent baseline and CMS-condition data collection within a period of a few hours. The advantage was that effects of geometry (previously noted on many occasions to obfuscate effects of the CMS) were eliminated by conducting both the before and after studies while construction crews were working at one point. Although sample sizes were obviously restricted by using this procedure, a sufficient number of observations were nevertheless obtained to support statistically reliable significance tests.

This procedure was used to compare the speed effects of all three CMS devices at one California site. The devices and displayed messages were as follows:

1. One-line bulb matrix; two-phase message (two words flashed at a time); "Slow to 45 mph";
2. Two-line rotating drum; single-phase message (all words continuously displayed); "Slow to 45 mph"; and
3. Three-line bulb matrix; single-phase message (all words, flashing display); "Reduce Speed, 45 mph".

Figure 4. Lane distribution for right-lane closures with advance CMS deployment.



*Standard CMS location; second when two were deployed.

The table below gives the results of the comparison (1 mile = 1.6 km):

Device	Speed (mph) Control	Experimental	Corrected Reduction
No CMS	62.5	63.7	N/A
One-line bulb matrix	62.1	56.3	7.0
Two-line rotating drum	63.0	56.6	7.6
Three-line bulb matrix	63.7	57.7	7.2

Note that in the absence of a CMS, speeds at the taper averaged 63.7 mph (101.9 km/h). Minor speed changes (day-to-day effects, etc.) were noted at the control location as average speeds varied from 62.1 to 63.7 mph (99.4-101.9 km/h). The table notes that reduced speeds were observed at the taper during the presence of each CMS device. These reduced speeds ranged from 56.3 to 57.7 mph (90.1-92.3 km/h), which indicates significant reductions of 6.0 to 7.5 mph (9.6-11.8 km/h) below speeds observed when no CMS was present.

The applied experimental design permitted the computation of a corrected speed reduction, which compensates for speed fluctuations observed at the control site. As an illustration of the speed-correction procedure, note that speeds at the control site dropped 0.4 mph (0.6 km/h) [62.5 to 62.1 mph (100.0 to 99.4 km/h)] between data-collection periods for the no-CMS and one-line CMS conditions. Thus, the observed 7.4 mph (11.8 km/h) [63.7 to 56.3 mph (102.0 to 90.1 km/h)] experimental site speed reduction, ostensibly elicited by the one-line CMS, was corrected by subtracting 0.4 mph to show the true effect.

The result of this experimental procedure indicated that each CMS device had a significant speed-reducing effect. Statistical tests indicated no difference between effects of the three devices.

Placement and Message Condition

Speed measurements gathered for a sizable vehicle sample (N = 30 790) proved to be more than adequate to statistically determine mean differences for a variety of CMS placement and message conditions. One notable tendency from the data was that placement seemed to affect speeds at the intermediate and taper data-collection locations. CMS deployments that use a device at the 0.75-mile advance location resulted in lower mean speeds. No similar trend was noted for message content.

Display Type

Results previously given in the above table support the finding that no appreciable differential speed effects were obtained between the tested one-, two-, and three-line formats. Although greater speed reduction was associated with the rotating-drum display than for either of the bulb-matrix signs, this difference was not statistically significant.

Questionnaire Findings

The human factors portion of the study involved application of a questionnaire to 489 subjects in order to gather measures of driver detection, recognition, and comprehension of the CMS devices. Characteristics of the subjects were controlled in order to ensure representativeness of the driving public.

Many statistically significant differences were found to distinguish between CMS conditions. In certain instances, questionnaire findings were seen to refute or clarify traffic-operation findings. In all cases of departure from traffic-operation results, findings based on questionnaire data were deemed highly credible because of the controlled nature of this experimental method. Questionnaire findings did not tend to refute the more convincing findings based on traffic-operation data (e.g., CMS improvement over baseline condition). Questionnaire findings are separately discussed, which reveal effects of CMS application, placement, message condition, and format.

Application

Certain questions were designed to determine whether or not drivers sensed general device improvement during the application of CMS devices. Two questions at the outset of the questionnaire requested drivers to provide a general rating of the overall adequacy of the traffic-control devices and to rate the signs as to how helpful they were. Each question was posed prior to any questionnaire reference to the CMS. These two questions were provided as follows:

1. In this driving test, you have just passed a highway area which is under construction. Please rate the overall adequacy of the construction warning devices (signs, barricades, etc.) according to the following scale.

Very poor	Poor	Borderline	Good	Very good
1	2	3	4	5

2. Please rate the signs as to how helpful you think they were.

Not at all helpful	Somewhat helpful	Extremely helpful
0	1	2

Comparisons between baseline and CMS-application conditions at all sites demonstrated an increase in the warning-device adequacy and sign helpfulness rating during the presence of any CMS device. In one isolated instance (e.g., two-line rotating-drum device based in Colorado) the increase was not statistically significant; however, high statistical significance was most frequently obtained.

Placement

Although mixed responses were obtained between CMS conditions that employ one and two devices, results more often favored the use of two devices. Higher detection rates and fewer complaints about providing inadequate information were associated with the use of two devices. In view of the fact that two-device arrays contained considerably greater amounts of information, lower average message recall scores were associated with their use. The trade-off between greater observation rate versus lower verbatim recall rate is interpreted to favor the use of two CMS devices.

Differences in questionnaire scores were noted between two message conditions (speed and closure and speed and merge), present with and without the use of supplementary advance devices. In each case a significant improvement in reported read and react time was noted in the presence of the advance device.

Message Condition

Questionnaire results heavily favored the use of speed and closure advisory messages. General device adequacy and sign helpfulness ratings, noted earlier to distinguish between baseline and CMS-application conditions, were also sensitive to CMS message differences. Higher ratings based on these two scores were associated with use of the speed and closure message than with others tested. However, in this case no increase was noted for the addition of the supplementary advance CMS.

Both with and without use of the supplemental CMS, the amount of information shown in the CMS array was approved most often during the presence of speed and closure advisories. Drivers reported that the speed and closure message was the easiest to read and that they most frequently modify their driving during its presence. This latter finding was validated by comparing vehicle behavior that had been matched for questionnaire responses. The validation procedure demonstrated that motorists interviewed during the presence of the speed and closure message made earlier preparatory lane changes and entered the taper area at lower speeds than those interviewed during the presence of other message conditions.

Another questionnaire finding, which refutes advantages shown in the traffic-operation data to be apparently associated with the speed and merge advisory, was that CMS devices were more often rated as being less helpful while this message was displayed. Moreover, low-CMS helpfulness ratings were indicated, and the amount of information shown was criticized as being inadequate for the Lane Closed Ahead message in the absence of specifying which lane was closed. The closure advisory message was most often correctly recalled.

Display Type

A number of differences were found between CMS display types. Lower overall device adequacy and sign helpfulness ratings were associated with the two-line rotating-drum sign. The one-line bulb-matrix sign drew less driver approval of the amount of information shown; moreover, drivers reported less available time to read and react to it both when used alone and in combination with the three-line bulb-matrix device. Moreover, when the three-line device was used alone, drivers more often reported seeing this device and rated it as being helpful.

The questionnaire item that provided the greatest distinction between CMS device types was the following question:

16. What changes would you want to see made to this sign?

Overall size:	Letter brightness:
______Larger	______Brighter
______Smaller	______Dimmer
______Neither	______Neither
Letter size:	Message length:
______Larger	______Longer
______Shorter	______Shorter
______Neither	______Neither

Table 2 summarizes the percentage of drivers who approved of (wanted no change in) overall CMS size, letter size, letter brightness, and message length for each of the tested devices under both day and night conditions. Certain significant differences were noted in these percentages. Lowest approvals of overall device size and message length (71 and 68 percent, respectively) were seen for the one-line bulb-matrix device. In addition, lesser approval of letter brightness was noted for the two-line rotating-drum sign both for day and night conditions. This latter comparison rated the difference between the bulb-matrix and rotating-drum CMS formats. Note also that significantly more drivers approved of the letter size associated with the three-line sign.

Validation of Questionnaire CMS Response

Two validations of subject questionnaire response were obtained on the basis of matched vehicle performance. South Carolina drivers interviewed during the presence of the speed and closure advisory message indicated that they responded to the CMS by slowing down and making earlier preparatory lane changes. Their self-reports were validated by matching observed lane-change behavior and comparing it with lane-change and speed behavior observed during other sign conditions. A positive validation was based on significant differences in average behaviors between the groups of drivers. This comparison indicated a significant tendency for drivers interviewed during the presence of the speed and closure advisory sign to exit the closed lane prior to reaching the intermediate data-collection point at an average speed of 49.6 mph (79.4 km/h), while interviewed drivers during other CMS conditions tended to change lanes beyond the intermediate point and their speeds averaged 53.4 mph (85.4 km/h).

Another statistical check on questionnaire validity, as well as CMS effectiveness, examined speed differences for drivers who saw the CMS versus those who did not see the CMS. Driving groups exposed to two different CMS conditions (one containing speed advisory information and not containing any speed message) were each taken from large homogeneous data bases (South Carolina and California). All of the South Carolina sample (N = 140) were exposed to a CMS speed advisory while the California group (N = 96) were exposed to merge or closure advisories. Of the total sample, 161 drivers saw the CMS and 75 did not. The matrix depicted in the table below indicates a significant speed reduction for drivers who saw the speed advisory CMS while no statistical difference was noted for the nonspeed advisory messages (note: 1 mile = 1.6 km; * = significant reduction):

	Average Speeds (mph)	
Item	Saw CMS	Did Not See CMS
Speed advisory	50.0*	52.0
No speed advisory	57.7	58.0

Table 2. Percentage of driver approvals of specific CMS design elements.

	Day			Night	
CMS Characteristic	One-Line Bulb Matrix	Two-Line Rotating Drum	Three-Line Bulb Matrix	Two-Line Rotating Drum	Three-Line Bulb Matrix
Overall size	71↓	81	88	100	80
Letter size	70	70	90↑	100	100
Letter brightness	77	54↓	76	50	80
Message length	68↓	83	82	75	80

Note: ↓ indicates existence and directionality of difference obtained between this and other CMS devices

SUMMARY

Before-and-after studies (CMS versus no-CMS conditions) conducted in three states consistently demonstrated beneficial traffic-operation effects that resulted from CMS application. Increased advance preparatory lane-change activity, smoother lane-change profiles, and significantly fewer late exits [exit from closed lane within 100 ft (30 m) of closure] were observed in each state. Reduced average traffic speeds approaching the taper were observed at locations characterized by preexisting speeds in excess of 48 mph (77 km/h). All tested CMS devices were nearly equal in their effectiveness. However, an observational study conducted in a fourth state demonstrated that advance placement 0.75 mile from the closure produced improved results by comparison with a 2000-ft advance placement.

Effectiveness differences between message conditions were not clearly discernible on the basis of lane-change behavior for the total traffic sample. However, driver interviews consistently favored the speed and closure (e.g., Right Lane Closed; Slow to 45 mph) message combination. Driver ratings of the adequacy of traffic-control devices were highest during the presence of this message. Drivers reported that this message was the most helpful of all tested, it was the easiest to read, it met their information needs, and they were most likely to change lanes early and reduce speed when the speed and closure message was displayed. Vehicle performance exhibited by interviewed drivers confirmed the validity of this latter claim.

A single traffic behavioral difference was observed between various CMS display types. More preparatory lane-change behavior was observed 0.75 mile in advance of the closure during the presence of a three-line bulb-matrix device. However, no lane-distribution differences were observed closer to the taper between this display type and the others tested, i.e., a two-line rotating-drum and a one-line bulb-matrix device.

Driver questionnaire data indicated a clear preference for CMS devices that displayed more information at a single glance. A three-line device was rated as being more helpful and more likely to provide necessary information than either a one- or two-line device. Sign letter brightness associated with the bulb-matrix format was favored by motorists over that of the rotating-drum format. Reported rates for drivers who saw the CMS did not differ between device types.

Vehicle performance data were coupled with driver interview responses to validate findings of the CMS evaluation. As previously noted, interviewed drivers reported more slowing and earlier lane changes in response to the speed and closure advisory, and they actually differed in those respects

from interviewed drivers exposed to other message conditions. Also, separate analyses of drivers seeing versus those not seeing CMS devices that contained speed advisory messages verified the observed total traffic effect of reduced speed response to the appropriate CMS message.

While improved traffic behavior was convincingly demonstrated to occur with CMS use, it was repeatedly shown that beneficial effects can be overridden by such factors as roadway geometry. For example, CMS observation by drivers was shown to be affected by traffic volume and sight distance to the device. Effects of grade and interchange proximity were seen to obfuscate speed and lane-change responses otherwise elicited by CMS devices.

CONCLUSIONS

Numerous substantiated results that CMSs tend to improve traffic flow on the approach to construction zone lane closures support their limited application. The associated smoother lane-change profiles can potentially reduce side-swipe and rear-end accidents on the construction zone approach, and the reduced speeds may increase safety for construction zone workers.

Yet, that beneficial effects of CMS were often seen to be overridden by specific highway geometric conditions points out the need for their judicious application (as is the case with traffic-control devices in general). Furthermore, any conclusion regarding the effect of CMS devices must emphasize that these devices are to be considered supplemental in nature to standard traffic-control schemes currently in use rather than a substitution for any specific device.

Suggested cost-efficient CMS applications are as follows:

1. Short-term closures characterized by decreased driver expectancy,
2. Minimum traffic volumes of 900 vehicles/h, and
3. Limited sight distances to the closure.

Four specific guidelines for CMS application resulted from this research:

1. Device format should permit maximum amount of information display at a glance (i.e., use three-line presentation format with a maximum of two message phases),
2. CMS devices should be located 0.75 mile in advance of closure,
3. CMS devices are to be considered supplemental in nature to currently applied standard traffic-control device schemes, and
4. CMS devices are not to be considered as an alternative to the arrowboard; arrowboard placement and brightness have a considerably greater impact on operational safety than does CMS use.

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Reading Time and Accuracy of Response to Simulated Urban Freeway Guide Signs

ROGER W. McNEES AND CARROLL J. MESSER

The results and methodology used in a laboratory study to determine motorists' time required to read urban freeway guide signs and the accuracy with which they read the signs are presented. The study was performed by using licensed drivers as subjects. The subjects, ranging in age from 18 to 79 years, were taken along a hypothetical urban freeway route where 2-, 3-, 4-, and 5-panel signs were used. A sign bridge typically has between one and four sign panels that have a green background and a white border around each panel. Each panel contains one or two route designations, one or more destination cities, and additional action messages. Each panel contained either 2, 4, 6, 8, or 10 units of information. The results of this study indicate that the optimum accuracy level was about 6 units of information/panel. When the information level was less than 16 units, 100 percent of the subjects could read the signs acceptably; when the level was between 16-30 units, 51 percent could read the sign acceptably; and when the level was between 31-50 units, only 33 percent could read the sign acceptably. It is apparent that route-selection accuracy decreases as the number of route choices increases. On a large sign (3 or more panels), the information content should not exceed 16 units of information/sign bridge. The time required to read a sign also increases with the number of route choices and total information on the sign.

Extensive research in the area of sign reading began in the late 1930s and continues even today. These efforts have mainly been concerned with the physical dimensions of the lettering, types of sign, illumination and reflectorization, recognition and effectiveness, message content, and placement in relation to the driver's cone of vision and line of sight. These research efforts have led to the development of standards that apply to alphabets and numerals used on the signs. The Federal Highway Administration (FHWA) has a standard alphabet that dictates the letter series to be used in the design of exit-direction signs. The standard alphabet used on overhead exit-direction signs is the series E(M) alphabet. These letters are designed in such a way that they can be seen by a person with 20-20 vision at a distance equal to 60 ft/in of letter height.