NATIONAL COOPERATIVE
HIGHWAY RESEARCH PROGRAM REPORT 235

EFFECTIVENESS OF CHANGEABLE MESSAGE DISPLAYS IN ADVANCE OF HIGH-SPEED FREEWAY LANE CLOSURES

TRANSPORTATION RESEARCH BOARD
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AREAS OF INTEREST:
MAINTENANCE
CONSTRUCTION AND MAINTENANCE EQUIPMENT
TRANSPORTATION SAFETY
OPERATIONS AND TRAFFIC CONTROL
(HIGHWAY TRANSPORTATION)

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL
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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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FOREWORD

By Staff
Transportation
Research Board

Highway engineers responsible for the design and application of traffic control plans in construction and maintenance zones will be particularly interested in the findings of this research. The results should also be of assistance to sign manufacturers in their continuing effort to improve their product lines to better meet the needs of highway agencies. To determine the relative effectiveness of various types of changeable-message signs (CMS) and message displays in controlling traffic at lane closures, field studies were conducted at work zones in four states. Devices and messages representing the current state of the art were evaluated, and, therefore, the results should have immediate application.

NCHRP Project 3-21, "Motorist Response to Highway Guide Signing," developed various driver response measures that can be used to determine the effectiveness of different signs. Copies of the agency report are available on a loan basis from the NCHRP or may be purchased from University Microfilms International, 300 North Zeeb Road, Ann Arbor, Michigan 48106. Project 3-21(2), "Effectiveness of Changeable Message Displays in Advance of High-Speed Freeway Lane Closures," extended the original research by applying the response measures to a specific signing problem.

Various situations require closure of one or more traffic lanes as a result of planned or unplanned conditions (e.g., accidents, unexpected road obstructions, construction and maintenance activities). Although the *Manual on Uniform Traffic Control Devices* describes recommended traffic control treatments for typical lane closures, little information is provided on changeable-message signs. With the current trend toward more highway rehabilitation-type projects, many of which require lane closures, improved traffic control devices are needed for better guidance of the motorist and protection of the worker. Accident experience at lane-closure locations, especially on high-speed facilities, demonstrates this need.

The objective of the research reported herein was to determine effective advance-message presentation (e.g., display type, message content, placement distance) for lane closures on high-speed freeways. This report provides, as a result of field studies at selected lane-closure sites, an objective analysis of traffic performance in response to various changeable-message displays.

Field tests were conducted at work zones in Charleston, SC; Macon, GA; Boulder, CO; and Escondido, CA. Devices that were tested included 3-line and 1-line bulb matrix signs and a 2-line rotating drum sign; data were also collected for a base condition without a sign for comparison purposes. Data collection techniques included driver questionnaires and interviews and manual recording of traffic operational data (e.g., lane change location, speed). Both right- and left-lane closures were studied, but a suitable site with a center-lane closure could not be located. Similarly, information obtained for the unplanned condition (e.g., an accident) was quite limited because of the unpredictable and short duration nature

of the occurrences. The general findings from the field studies are reported herein; more detailed accounts of the results from each individual field site are included in Volume II of the agency report, "Effectiveness of Changeable Message Displays in Advance of High-Speed Freeway Lane Closures—Appendixes E–G." Copies of this material may be purchased upon written request to the NCHRP for $3.50.

NCHRP Project 3-21(2) was one of many studies being conducted in the late 1970s and early 1980s related to traffic control in work zones. These studies were sponsored by the FHWA and the NCHRP and provide information on arrowboards, traffic cones, tubes, barricades, and markings. As a result, considerable information is now available on the effectiveness of individual control devices; however, there remains a need for a comprehensive study of alternative combinations of devices.

CONTENTS

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The research reported herein was performed under NCHRP Project 3-21(2) by BioTechnology, Inc. The principal investigator, and author of the report, was Fred R. Hanscom, who is currently Director of the Transportation Research Corporation.

The cooperation of a number of state highway agencies and changeable message signing manufacturers is greatfully acknowledged. Special thanks are extended to the following state highway officials: Messrs. Robert F. Zimowski, California; William E. Taylor, Colorado; Donald Sinkville, Georgia; Vernon Dunlap, Ohio; Luther Fant and William DuBose, South Carolina; and Ken Kobetsky, West Virginia. Changeable message devices were provided by Energy Absorption Systems, Inc., of Chicago, Illinois; Traffic Control Device Systems Company (Skyline Products, Inc.), of Colorado Springs, Colorado; and Wink-o-matic, Inc., of Avon Lake, Ohio.

Other individuals who contributed significantly to the field studies were: Ron Curl, who assumed responsibility in every aspect of the field effort; and Robert Sharratt and Sharon Wood, who supervised the majority of the data collection.

EFFECTIVENESS OF CHANGEABLE MESSAGE DISPLAYS IN ADVANCE OF HIGH-SPEED FREEWAY LANE CLOSURES

SUMMARY

The closure of a freeway traffic lane for construction or maintenance activity poses a unique safety problem. Not only is there a disruption to the high-speed, continuous flow situation expected by motorists, but safety of working personnel is also at risk. Although the *Manual of Uniform Traffic Control Devices* describes traffic control treatments for lane closures, there is a need for improved methods of providing advanced information to the motorist.

Changeable message signing (CMS) devices were evaluated in this research project as a means to effectively provide improved advance warning of freeway lane closures. A sensitive evaluative method was based on traffic operational measures (lane change and speed profiles approaching the closure) and driver questionnaires (detection, comprehension, and subjective ratings). Various CMS format characteristics were tested under day and night conditions applied at both right- and left-lane closures using a variety of advance placement schemes.

Before-after studies (CMS versus no-CMS conditions) conducted in three states consistently demonstrated beneficial traffic operational effects resulting 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 kph). All tested CMS devices were nearly equal in their effectiveness. However, observational study, conducted in a fourth state, demonstrated that advance placement ¾ mile (1.2 km) from the closure produced improved results by comparison with a 2,000-ft (600-m) advance placement.

Varied CMS characteristics were compared. Five evaluated message combinations were: speed and closure advisories, speed and merge advisories, merge and closure advisories, closure advisory, and speed advisory. 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 traffic control device adequacy were highest during the presence of this message. Drivers reported that this message was the most helpful of all tested, that it was the easiest to read, that it met their information needs, and that 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 ¾ mile (1.2 km) in advance of the closure during the presence of a 3-line bulb matrix device.

However, no lane distribution differences were observed closer to the taper between this display type and the others tested: a 2-line rotating drum and a 1-line bulb matrix device.

Driver questionnaire data indicated a clear preference for CMS devices that displayed more information at a single glance. A 3-line device was rated as being more helpful and more likely to provide necessary information than either a 1- or 2-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 seeing the CMS did not differ between device types.

Although behavioral patterns for trucks were generally similar to those of the total vehicle sample, two minor differences were noted. Trucks slightly delayed their exit from the closed lane at one site (although they did not perform disproportionately more late exit maneuvers) and performed fewer late exits in response to a 2-line rotating drum CMS at another (a behavior not observed for the total traffic sample).

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 containing speed advisory messages verified the observed total traffic effect of reduced speed response to the appropriate CMS message.

Although 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 rate 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.

The study concludes that CMS application is warranted under certain conditions. Although standard traffic control device characteristics (most notably, a properly functioning and placed arrowboard) were seen to exert a consistently greater influence, operational improvement nevertheless resulted from CMS application. Suggested cost-efficient CMS uses are applications for (1) short-term closures characterized by decreased driver expectancy, (2) minimum traffic volumes of 900 vehicles per hour, 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 3-line presentation format with maximum of two message phases).
2. CMS devices should be located ¾ mile in advance of closure.
3. CMS devices are to be considered supplemental in nature to currently applied standard traffic control device schemes.
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.

CHAPTER ONE

INTRODUCTION AND RESEARCH APPROACH

STATEMENT OF THE PROBLEM

Various situations require the closure of one or more traffic lanes as a result of planned or unplanned conditions (e.g., accidents, unexpected road obstructions, construction, and maintenance activities). Although the *Manual on Uniform Traffic Control Devices* 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 to 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.

There exists a lack of empirical evidence regarding traffic operational effects of changeable message signing (CMS). However, in order to achieve a realistic determination of CMS effects at freeway lane closures, valid measures of effectiveness (e.g., insightful motorists' responses) must be applied to obtain a meaningful evaluation of any traffic control device. The key to incorporating this approach in a field CMS evaluation is the sensitivity of the applied measures. Conventional traffic engineering evaluations often tend to make assumptions regarding relationships between traffic performance and driver responses to the devices being evaluated. It was this lack of associative data that was responsible for the genesis of NCHRP Project 3-21.

OBJECTIVES AND APPROACH

The objective of this research was to determine the effectiveness of certain advance message displays (e.g., speed and merge, speed and closure advisories) for lane closures on high-speed freeways. Right- and left-lane closure situations were studied, and observations were made under day and night conditions. As a result of field studies at selected lane-closure sites, this research provided an objective analysis of traffic performance in response to various changeable message displays. Additionally, a sample (N = 489) of driver responses (detection, comprehension, and interpretation) was obtained. This applied methodology examined appropriate relationships between driver information processing and vehicle behavior required for validating operational measures of CMS effectiveness.

The product of this research, and operational evaluation of CMSs in advance of freeway lane closures, was approached through the following tasks. First, the identification of appropriate changeable message devices and display characteristics was accomplished via a literature review and inquiries to state officials to learn of existing, acceptable device applications. Second, the development of the data collection plan involved liaison procedures with selected state agencies who agreed to participate in the study. This task addressed conditions (e.g., CMS characteristics, locations, traffic conditions) applied in the field study. Finally, a field study was applied in four states to observe CMS effects. Recommendations for CMS application included placement, message content, CMS format, and cost-efficiency criteria.

The applied research approach included both planned and unplanned closure conditions. An extensive controlled field effort based on traffic operational and questionnaire measures was conducted for the planned condition, and an observational study of the unplanned condition examined agency deployment practice and applied traffic conditions.

CHAPTER TWO

FINDINGS

STATE OF THE ART

A considerable body of literature exists regarding the application of changeable message signs (CMS) in a variety of highway situations. Appendix A contains a summary of relevant literature. *NCHRP Synthesis of Highway Practice 61* thoroughly reviewed CMS application and revealed its use in traffic management and diversion, warning of adverse conditions, control at crossings, control during construction and maintenance, and special-use lane control.

However, only one reference was found specifically related to CMS application at construction zone lane closures. An unpublished evaluation of a 1-mile bulb matrix device conducted by the Pennsylvania Department of Transportation noted a significant reduction in average speeds from 56 mph (90 kph) to 47 mph (75 kph). A survey was made of the NCHRP 3-21(2) panel and certain researchers who might have further knowledge of relevant CMS use. Responses from the survey revealed plans for CMS application at construction zones during the summer of 1980 in the following states: Alabama, California, Georgia, Ohio, Oklahoma, South Carolina, Texas, and West Virginia. Sufficient information was available from a number of these states to com-

pile Table 1, which summarizes the state of the art in CMS characteristics applicable to work zone traffic control.

CMS devices were generally found to be applied as supplemental devices to standard work zone device schemes. CMS application was not seen to substitute for arrowboard use. While advance placement location of CMS devices was seen to vary between 1,500 and 2,500 ft in certain states, others left advance placement to the discretion of the project engineer.

FIELD STUDY PLAN

A brief description of the study plan is given in the following. Complete details are provided in Appendix B, "Study Procedure"; Appendix C, "Field Data Forms and Driver Questionnaire"; and Appendix D, "Site Diagrams and Tested CMS Conditions."

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; in-vehicle questionnaires were administered to test subjects to obtain sensitive measures of driver response. CMS application at "unplanned" (e.g., accident) lane closures were examined in a separate observational study.

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 planned (e.g., construction site) lane closures:

Table 1. CMS device characteristics.

State	CMS Type	Message Content	
Alabama	Bulb Matrix	Three-phase application: Two-Way Traffic Keep Right Do Not Pass	
California	Bulb Matrix	Delay Ahead (Time Estimated - 15, 30, 45 Min) Right/Left Lane(s) Closed Ahead Merge Right/Left One/Two Right/Left Lane(s) Open Pilot Car Ahead/Don't Pass	
	Fabric Panel	AHEAD CAUTION CLOSED CONGESTION CONGESTED CONNECTOR DETOUR DETOUR AHD. FWY CLOSED HEAVY LEFT	LEFT LANES MERGE RAMP RIGHT ROADWORK RT. LANE SLOW STOPPED TRAFFIC AHD. EXIT ALT. RTE USE
South Carolina and Ohio	Bulb Matrix	Keep Right/Left Do Not Pass Two-Way Traffic Reduce Speed Soft Shoulder Men Working on Road Center Lane Right/Left Lane Closed Ahead Caution-Vehicles Crossing Max Speed ** MPH Min Speed ** MPH One Lane Bridge Merge Ahead Closed Ahead	
West Virginia	Bulb Matrix	Men Working on Road Right Lane Closed Ahead Merge Left Shoulder Work Ahead Left Lane Closed Merge Right	

1. *Advance*—This point was selected in advance of sight distance to the CMS, approximately 1 mile (1.6 km) in advance of 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*—This location was either 2,000 ft (600 m) or ¾ mile (1.2 km) (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 CMS and taper, this point defined the lane change profile effect of 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 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 uniform 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. Table 2 summarizes the sampling procedures, and the data collection forms are contained in Appendix C.

In-Vehicle Driver Response

This technique provided human factors measures of driver detection, recognition, and comprehension as a further assessment of CMS effectiveness. Driving subjects were recruited via newspaper advertisements to participate in a "national driving study." Unobtrusive measures of their vehicle behaviors, compatible to those collected for the entire traffic sample, were matched to questionnaire responses to aid in the overall data analysis.

The driver questionnaire was completed by subjects immediately following their drives past our test sites. 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.

A questionnaire strategy involved first asking a series of general questions regarding observations of traffic control devices which 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 an indirect impact of the CMS. This provision of the survey afforded an internal response validation mechanism.

Following the general traffic control responses (e.g., device adequacy and overall sign helpfulness rating), questions pertained to CMS observation and recall of its message. Then more specific questions ascertained how helpful the CMS was and whether or not it afforded sufficient reading and reaction time, and the subject rated the ease or difficulty with which the CMS was read. Specific critical ratings by

Table 2. Traffic operations data collection procedure.

Data Collection Times

a.m. peak:	6:30 a.m.	–	8:30 a.m.
off-peak:	10:00 a.m.	–	11:30 a.m. and 1:30 p.m. – 3:00 p.m.
p.m. peak:	4:00 p.m.	–	6:30 p.m.
darkness:	9:30 p.m.	–	11:00 p.m.

Within-Hour Schedule

:00 –	:15 Speed Sampling	:30 –	:45 Speed Sampling
:15 –	:25 Volume Counting	:45 –	:55 Volume Counting
:25 –	:30 Break	:55 –	:00 Break

Speed Sampling

Use *random* selection procedure as follows:

1. Vehicle alternately selected between traffic lanes.
2. Random selection table applies to identify vehicle arrival within lane.
3. If no vehicle arrival was observed in designated lane within ten seconds, first vehicle to arrive was sampled.

Truck speeds were separately recorded by lane.

Within-hour speed sampling times were: :00 – :15 and :30 – :45.

Separate form for each 15-minute period.

Lane Distribution Counting

Vehicle counts recorded by traffic lane.

Within each lane, separate codes were noted for trucks and other vehicles.

1. Truck = tractor-trailer combinations.
2. Bus = intercity type (e.g., Greyhound).
3. These were coded as "trucks"; all other vehicles (including motorcycles and schoobuses) were "non-trucks."

Ten-minute sampling periods were applied, timed to the nearest second (using electronic watch).

Within-hour sampling times were: :15 – :25 and :45 – :50.

subjects then addressed various CMS design aspects: appropriateness of information provided, message length, and legibility characteristics (letter size and brightness). Finally, questions addressed the relative effect of the CMS with regard to other traffic control devices as well as a self-report of subject's behavioral response (e.g., changing lanes sooner/later). A highly significant aspect of the questionnaire procedure was that behavioral observations provided validation of the self-reported responses. Sufficient biographical data were also obtained to control for effects of familiarity, inherent driving behavior, etc.

Completed questionnaires void of missing data items were obtained for a sample of 489 drivers in South Carolina, Georgia, Colorado, and California. Age and sex distributions of the sample did not significantly differ between states. As noted in the procedure description, an attempt was made to control age and sex distributions so as to approximate normal exposure rates. The control criteria were to include substantial proportions of drivers younger than 20 and older than 60, and to obtain a nearly even male-female distribution.

Driver interviewing was conducted at all sites and under all CMS conditions used in the traffic operational CMS evaluation. The applied questionnaire forms and instructions given to the test subjects are included in Appendix C.

Tested CMS Conditions

The state-of-the-art review revealed general characteristics of available CMS devices applicable for construction zone traffic management. Three device types representing a variety of available characteristics were applied in this study. Three message capacities (1, 2, and 3 lines) were tested, representing two display types (bulb matrix and rotating drum). Table 3 gives CMS characteristics, while precise tested conditions are depicted in Table 4. Site diagrams describing deployment environments are contained in Appendix D.

Field Test Scenario

The study procedure had to accommodate a great variety of constraints. First, it was not possible to "stage" construction activity for the purpose of controlling necessary site conditions (e.g., highway geometry, traffic volume). Therefore, the study procedure could be applied only at existing construction sites. Second, it was not possible to test all of the 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 5) be based on a variety of data bases. Existing differences between data bases (e.g., varying traffic control device standards between states) dictated a 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 5. The effect of CMS device application was determined at sites initially containing standard (no CMS) traffic control device schemes via before–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: ¾-mile (1.2-km) advance placement; ¾-mile (1.2-km) and 2,000-ft (600-m) placements; and 2,000-ft (600-m) placement.

A variety of message conditions were tested in one state which routinely applied CMS devices. The following message types were permitted to be specified: speed and closure advisory, speed and merge advisory, merge and closure advisory, and closure advisory. It was possible to vary CMS display type for application at the same construction zone set-up location at only one site.

The foregoing scenario is somewhat deficient in terms of experimental control because of the aforementioned field study constraints. For example, the research team was limited to observing between-condition effects in South Carolina, where it was not possible to observe a baseline condition (this constraint was not anticipated at the time of site selection). Second, the majority of the baseline versus CMS condition comparisons were conducted in different states under varying baseline traffic control device conditions. Finally, and most significantly, varying traffic and geometric conditions (necessitated because of the transitory nature of the lane closures) created varying conditions within a given state.

Despite the foregoing disclaimer, this plan was quite effective in producing convincing evidence regarding CMS effectiveness. Replication of baseline versus CMS application in several states confirmed observed effects. Additionally, considerable experimental control afforded by the questionnaire procedure (e.g., grouping drivers not seeing the CMS to simulate a baseline condition) greatly contributed to the study capability.

In addition to the scenario applied to the planned condition, an observational study of CMS application for unplanned conditions (e.g., accidents, unexpected road obstructions, and maintenance activity) was accomplished via a survey of operations in two CalTrans districts.

FIELD STUDY RESULTS (PLANNED LANE CLOSURES)

Findings pertaining to CMS effectiveness for planned lane closures (i.e., construction activity) are discussed separately for three measures types: lane distribution, speed measurement, and in-vehicle driver responses. A more detailed discussion of site-specific findings is contained in Volume II of the agency report (a limited number of Volume II, "Effectiveness of Changeable Message Displays in Advance of High-Speed Freeway Lane Closures, Appendixes E–G," as submitted by the research agency to the sponsors, may be purchased upon written request to the NCHRP).

Lane Distribution Findings

The relative proportions of traffic in the through and closed lanes approaching construction zone lane closures were observed for a sample of more than 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 relative effects between certain CMS message alternatives (i.e., speed and closure, speed and merge, closure and merge advisories) and various placement configurations (i.e., one CMS at 2,000-ft (600-m) advance or ¾-mile (1.2-km) 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 on the approach to construction sites, and certain findings evolved regarding specific CMS characteristics. The results are now discussed for each of the CMS effects noted in the planned closure condition field test scenario.

Application

Consistent results between baseline 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 1 shows smoother profiles for left-lane closures following CMS application. Findings indicate significantly reduced proportions of vehicles remaining in the closed lane at all three approach points. Although the reduction in "late exits" (exit from closed lane within 100 ft (30 m) of closure) is not dramatic in this instance (1.2 versus 2.0 percent), it is nevertheless statistically significant.

Table 3. Characteristics of applied CMS devices.

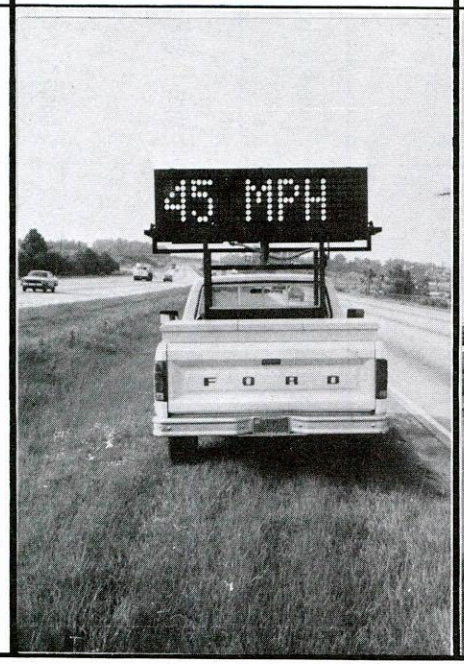
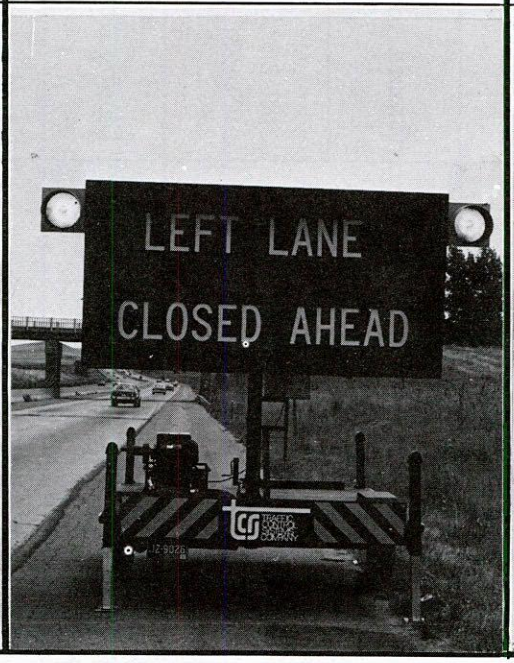
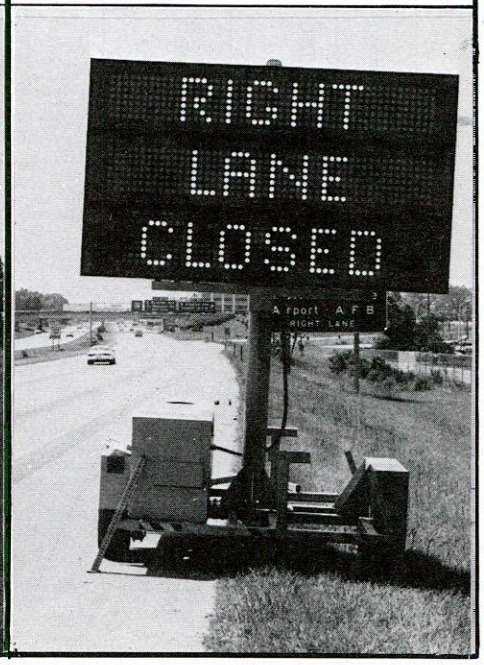
Display Type	Bulb Matrix	Rotating Drum	Bulb Matrix
Number of Lines	One	Two	Three
Characters per Line	Seven	Twelve	Nine
Letter Height	17″	12″	14″
Presentation Mode	Alternating; Two, Three and Four Phase	Continuous	Alternating; Two Phase
Message Face Dimensions	6′ - 5″ X 2′ - 0″	9′ - 7″ X 4′ - 6″	9′ - 10″ X 5′ - 10″
Message Mounting Height	8′ - 9″	8′ - 0″	9′ - 11″
Sign Color	Black	Black	Yellow
Flashing Beacon	No	Yes	No
Appearance			

Table 4. Tested CMS conditions.

Site	Display type/ Placement	Message Type	Display Format
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 15 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

1 foot = .3 m

1 mile = 1.6 km

Because of the greater criticality of lane-change maneuvers for the right-lane closure (traffic volumes are generally higher inthe right lane), more sites of this type were studied. Figure 2 shows lane distribution profiles of baseline CMS effects observed for 1- and 2-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 ¾ mile (1.2 km) of the closure. Table 6 contains combined lane distribution percentages for the two sites.

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

Table 5. CMS field test scenario.

CMS Effects	Test Conditions	Data Base
Application	Baseline V. One-line Device	Georgia
	Baseline V. Two-line Device	Colorado
	Baseline V. Three-line Device	California
Placement Location	2000 feet Advance	
	3/4 Mile and 2000 Feet	South Carolina
	3/4 Mile Advance	
Message Condition	Speed and Merge Advisories	
	Speed and Merge Advisories	South Carolina
	Merge and Closure Advisories	
	Closure Advisory	
Display Type	Two-line V. Three-line Device	California

1 foot = .3 m
1 mile = 1.6 km

Placement

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

1. *Single CMS use*—one device placed approximately 2,000 ft (600 m) in advance of the taper.

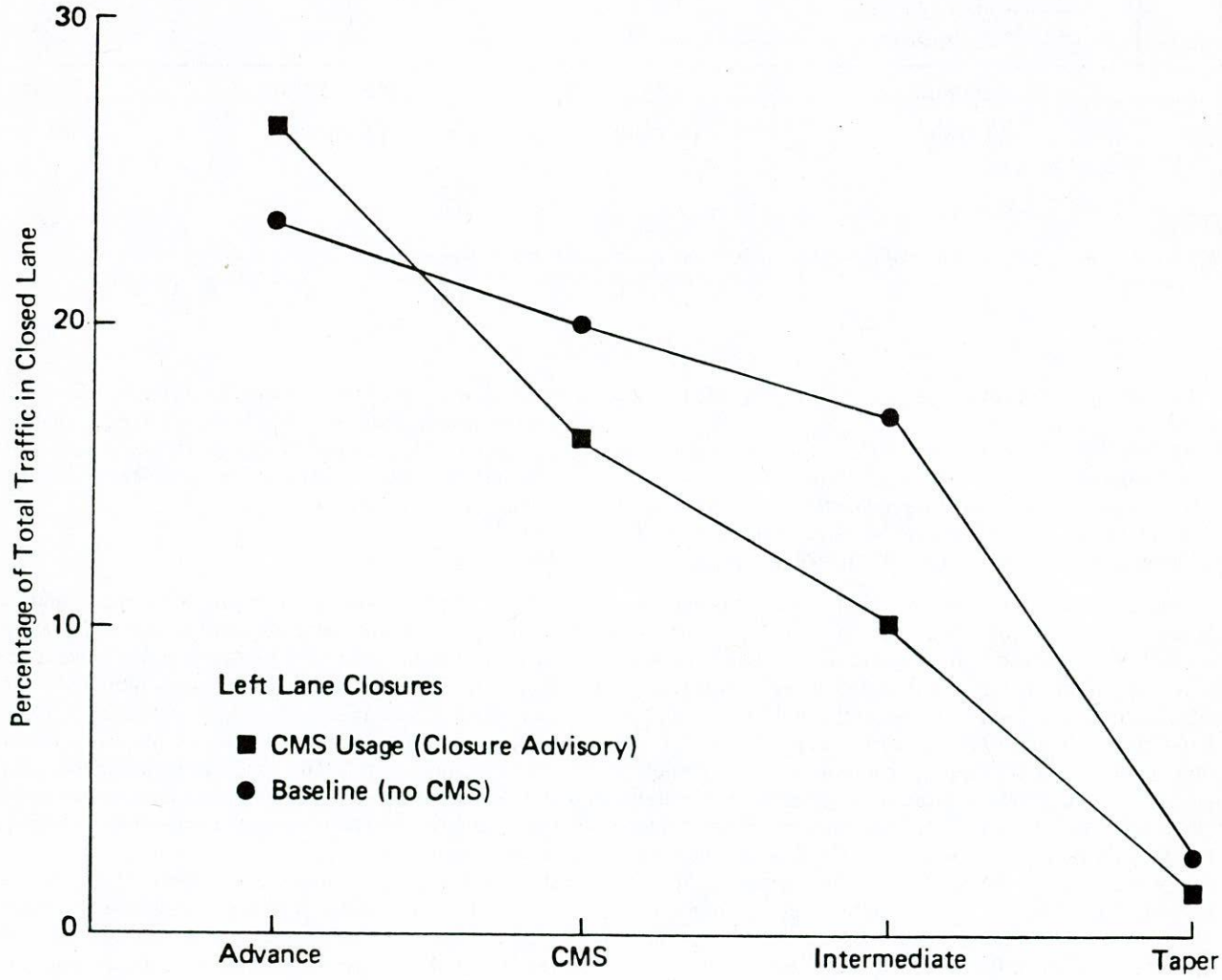


Figure 1. Lane distribution profiles for left lane baseline and CMS conditions (Georgia sample).

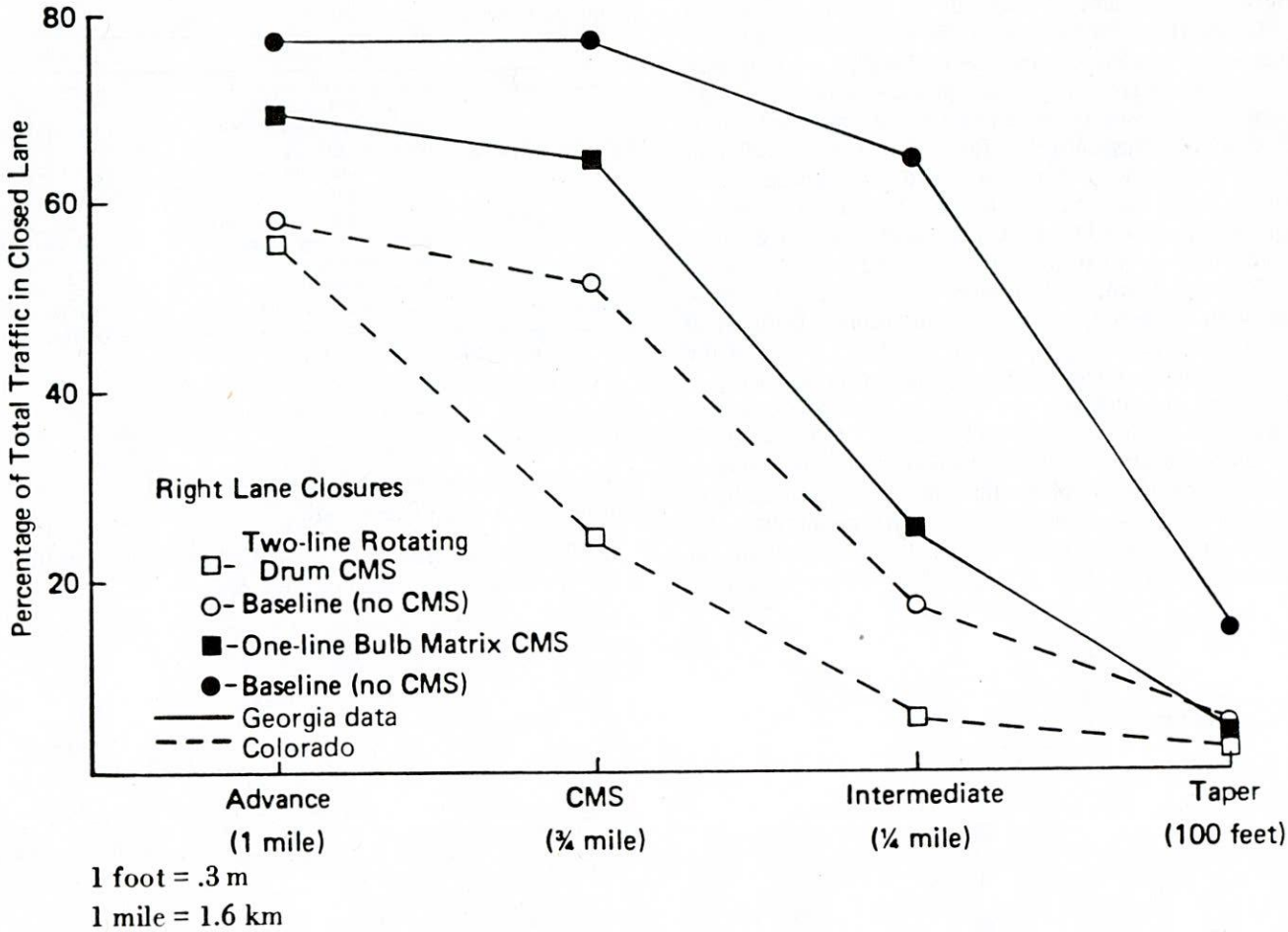


Figure 2. Lane distribution profiles for right lane baseline and CMS use conditions.

2. *Advance CMS use*—one device placed ¾ mile (1.2 km) in advance of the taper.

3. *Two CMS devices*—one device at each of the foregoing noted locations.

4. *Advance CMS with supplemental arrowboard*—one CMS placed ¾ mile (1.2 km) in advance of the taper and an additional arrowboard at the 2,000-ft (600-m) 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 a CMS at the ¾-mile (1.2-km) advance location. Data collected at the CMS location (2,000 ft (600 m) in advance of the taper) indicated a dramatic reduction in closed lane traffic proportion, from approximately 29 percent with one CMS, to an average of approximately 5 percent for the advance CMS schemes. No statistical differences were noted at the advance CMS conditions. A tendency was seen in the data, however, for the earliest preparatory lane changing to occur in the presence of a CMS at the ¾-mile (1.2-km) advance location and supplemental arrowboard at the 2,000-ft (600-m) location.

A word of caution is due regarding this finding. All but one day of testing for the ¾-mile (1.2-km) advance CMS testing was done at one construction location (CMS availability limited testing options), so a concern exists regarding the possibility of a site-specific effect. However, questionnaire findings (discussed later) confirmed the beneficial effect of ¾-mile (1.2-km) CMS location.

Message Condition

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 apsplication at subsequent sites. Table 7 contains lane distribution results for the tested conditions.

The majority of this data base was gathered using the two-state standard speed/closure and speed/merge advisory messages. Only limited data were available for the remaining two conditions as these represented deviations from the state standards. Figure 5 demonstrates improved lane distribution profiles to be associated with speed and merge advisory messages. Table 7 indicates that the closure advisory message resulted in the greatest amount of advance preparatory lane change activity and the lowest proportion of late exit behavior.

Table 6. Comparative lane distributions for three CMS message types used at left-lane closures.

	CMS Message Type: Speed and Closure Advisory		
	Open Lane %	Closed Lane %	Sample Size
Advance	84.9	15.1*	3,853
CMS Point	92.0	8.0*	3,847
Intermediate	97.6	2.4	3,623
Taper	99.6	.4*	2,577

No. Late Exits = 9* (.35% of sample)

	CMS Message Type: Speed and Merge Advisory		
	Open Lane %	Closed Lane %	Sample Size
Advance	77.6	22.4	3,599
CMS Point	90.1	9.9	3,581
Intermediate	97.3	2.7	3,647
Taper	99.3	.7	3,313

No. Late Exits = 23 (.69% of sample)

	CMS Message Type: Merge and Closure Advisory		
	Open Lane %	Closed Lane %	Sample Size
Advance	79.6	20.4	2,665
Taper	99.6	.4	2,635

No. Late Exits = 11 (.42% of sample)

*Indicates a significant reduction ($\alpha < .05$) compared to speed and merge advisory.

Display Type

Data gathered at the California site permitted a direct comparison between the 2-line rotating drum device and the 3-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 devices; and Table 8 depicts the percentages of vehicles in the closed and through lanes. A prominent difference in observed effects between the 2- and 3-line devices was a smaller proportion of vehicles present in the closed lane at the CMS point while the 3-line device was displayed. This difference between device types did not continue, however, into the intermediate and taper observation points. Although a larger proportion of vehicles (e.g., 18.1 versus 15.9 percent) remained in the closed lane at the late exit point during the presence of the 3-line CMS, this difference is not significant at the 0.01 level of significance.

An explanation of the reduced closed lane volume at the CMS point during the presence of the 3-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 2-line CMS. There was no possible sight-distance difference effect because both devices were deployed at the same loca-

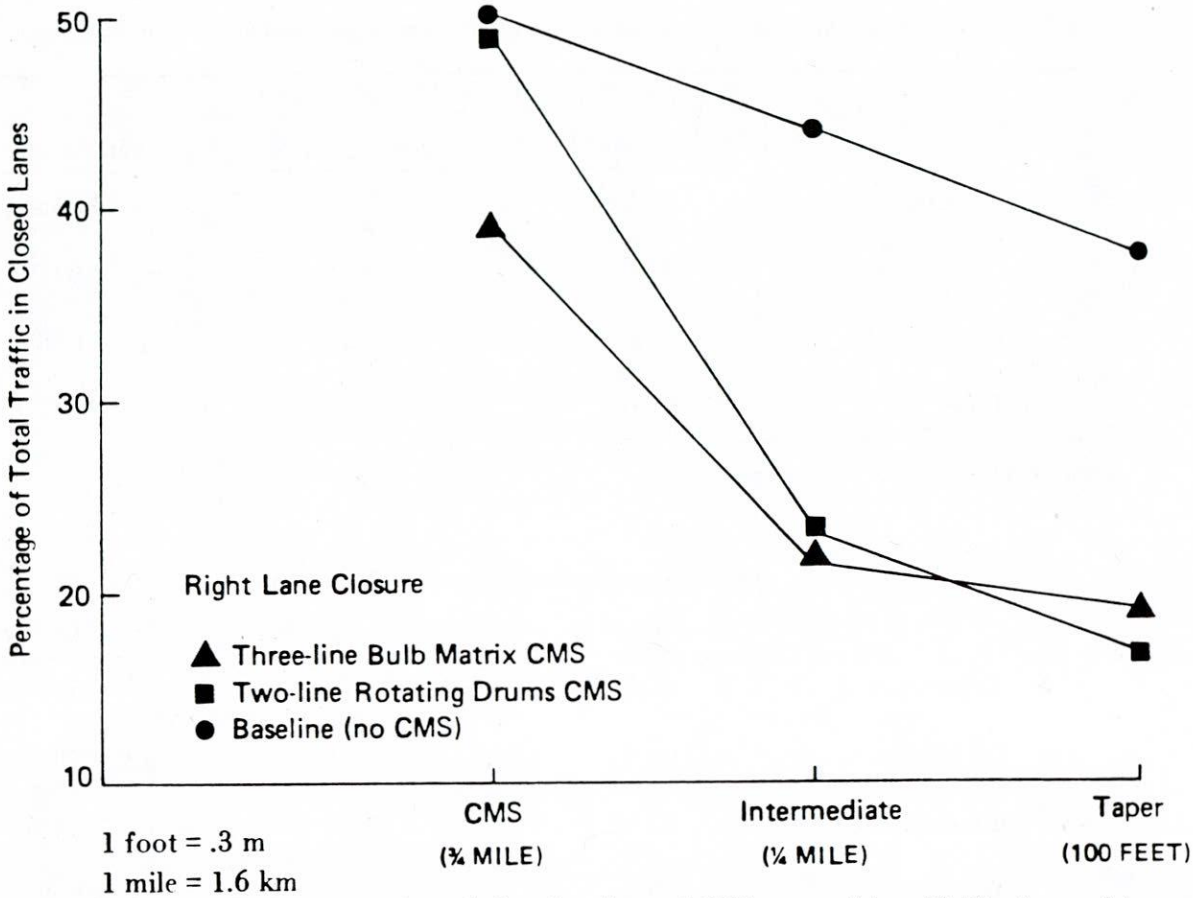


Figure 3. Lane distribution profiles for right lane baseline and CMS use conditions (California sample).

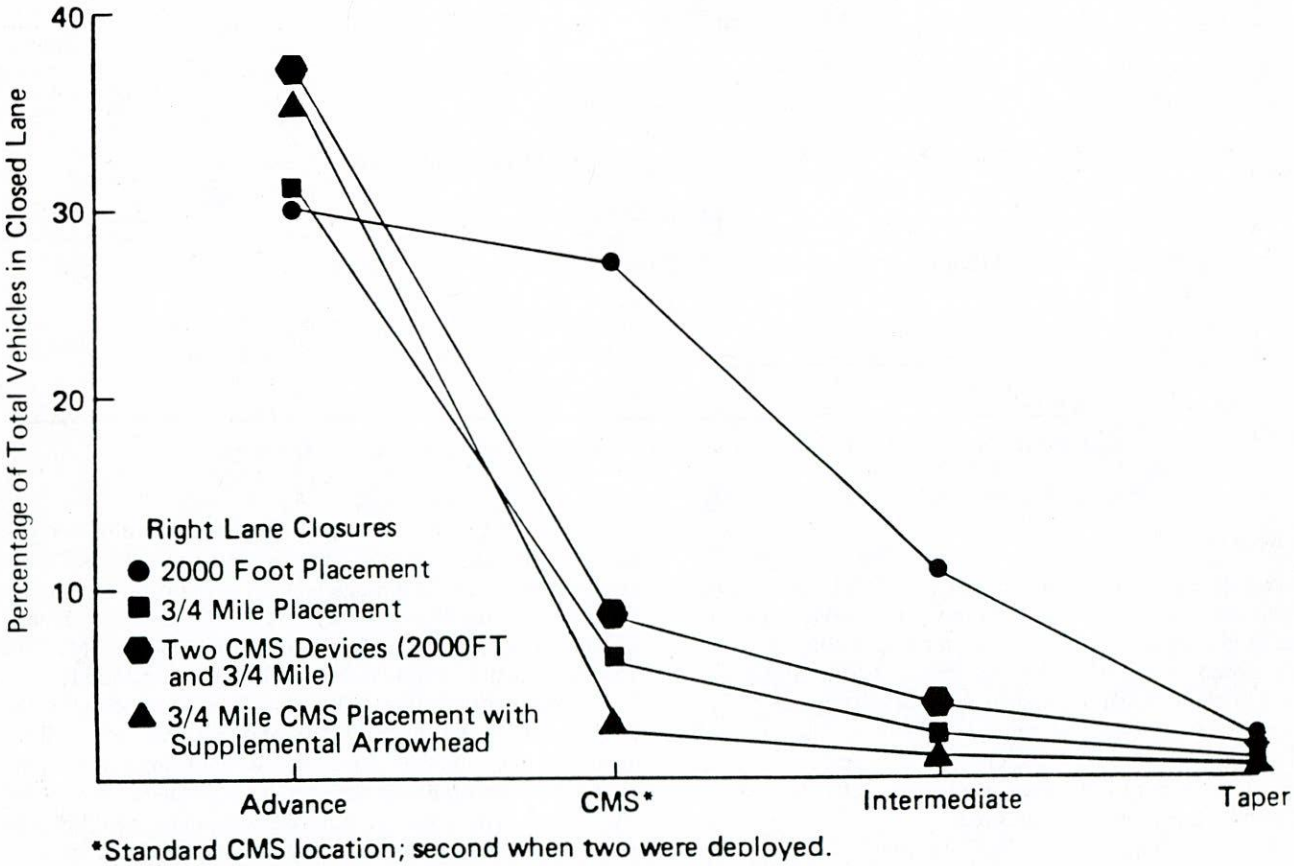


Figure 4. Lane distribution profiles for right lane closures and varied CMS placements.

Table 7. Comparative lane distributions between two CMS message types (both right- and left-lane closures, total sample).

	CMS Message Type: Speed and Closure Advisory		
	Open Lane %	Closed Lane %	Sample Size
Advance	72.8	27.2	11,241
CMS Point	88.8	11.2	11,994
Intermediate	95.4	4.6	11,767
Taper	99.2	.8	10,658

No. Late Exits = 83 (.78% of sample)

	CMS Message Type: Speed and Merge Advisory		
	Open Lane %	Closed Lane %	Sample Size
Advance	70.8	29.2	10,344
CMS Point	90.1	9.9	10,970
Intermediate	97.4	2.6	11,163
Taper	99.3	.7	10,605

No. Late Exits = 75 (.71% of sample)

	CMS Message Type: Merge and Closure Advisory		
	Open Lane %	Closed Lane %	Sample Size
Advance	79.6	20.4	2,601
Taper	99.6	.4	2,619

No. Late Exits = 11 (.42% of sample)

	CMS Message Type: Closure Advisory (3/4 location)		
	Open Lane %	Closed Lane %	Sample Size
Advance	63.7	36.3	2,387
CMS	97.8	2.2	2,414
Intermediate	98.8	1.2	2,426
Taper	99.6	.4	2,358

No. Late Exits = 9 (.38% of sample)

tion. The data strongly suggest that increased obtrusiveness of the sign itself did not serve to reduce closed lane occupancy closer to the taper. These results therefore imply equal effectiveness of the two CMS devices in conveying the lane-change message to motorists, despite the differing visibility of the devices themselves.

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 2-line device.

Summary

Findings based on lane distribution data can be summarized as follows. Consistent baseline versus CMS application results obtained in three states indicated improvements (smoother lane change profiles, larger proportions of advance preparatory lane change activity, and significantly fewer late exits) in the presence of CMS devices. However, findings regarding which specific CMS characteristics elicit greater improvements were not as clear. Conflicting findings were noted regarding message content. Greater proportions of lane-change activity tended to occur in the presence of merge advisory messages when used in combination with speed advisories; however, the closure advisory message resulted in fewer late exits when used alone. No clear difference between device types could be found to indicate which was superior at reducing late exits; however, more advanced preparatory lane change activity was noted in the presence of a large, obtrusive bulb matrix device. A clear tendency was found for ¾-mile (1.2-km), as opposed to 2,000-ft (600-m), advance CMS placement to result in improved lane distributions.

Two special studies were conducted to determine whether CMS effects on lane distribution varied between certain traffic conditions (i.e., peak versus off-peak conditions, and day versus night conditions). Findings indicated no differential effects between tested traffic conditions.

Speed Observation Findings

A sizable sample (N = 41,463) of vehicle speed observations was undertaken to determine the effect of CMS applica-

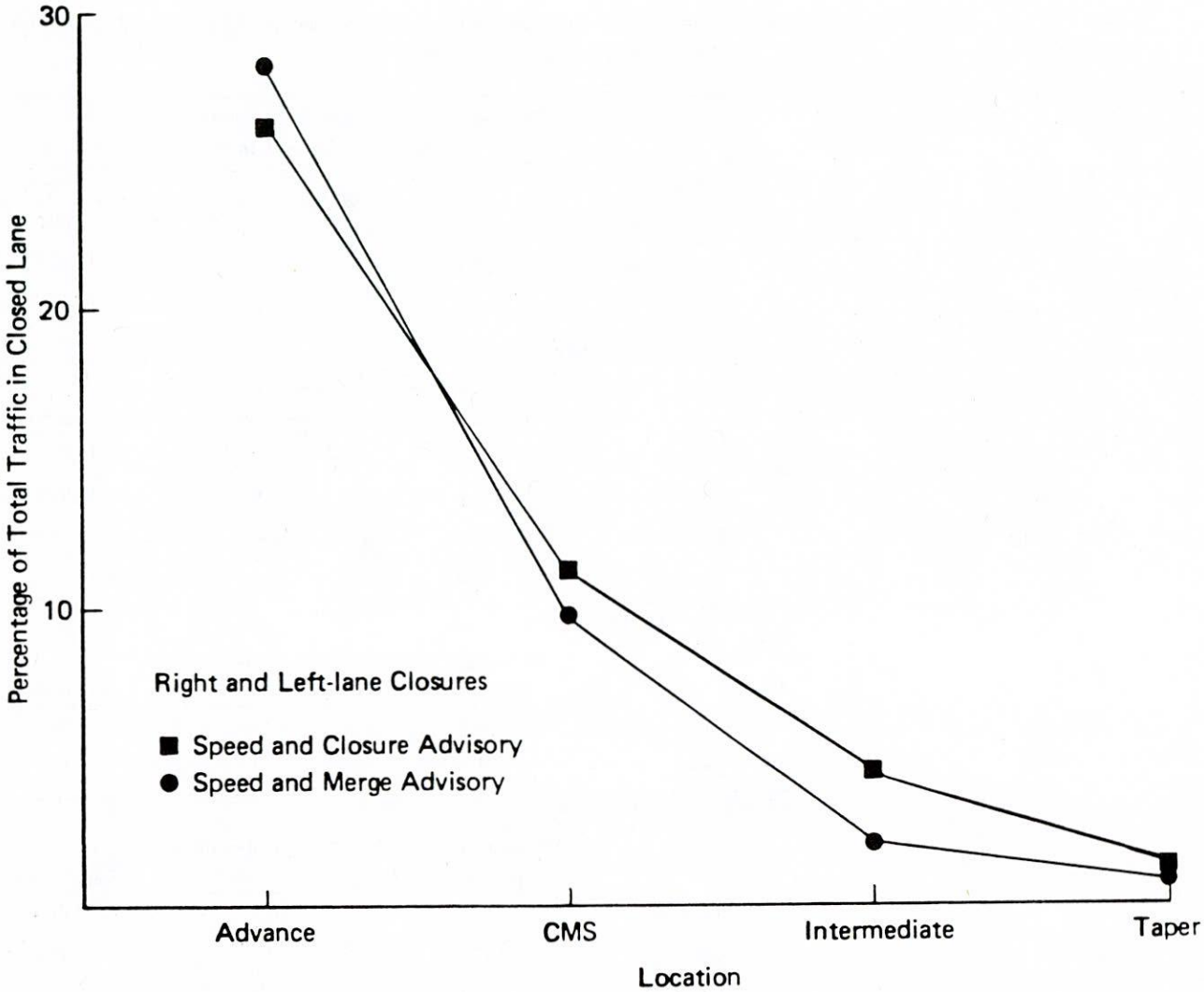


Figure 5. Lane distribution profiles for two CMS message conditions.

tion on the approach to 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 Carolina data collection effort was limited because of 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.

Because large sources of variance were shown to affect speed data, its interpretation was complex. The first two sites (South Carolina and Georgia) yielded large data bases; yet, as is generally the case with construction zone research, day-to-day changes resulting from construction work procedural modifications produced confounding effects. In order to overcome this limitation, a modified study procedure was applied in the latter two States favoring greater control for reduced (but statistically reliable) sample sizes.

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 exhibiting low preexisting speeds of approximately 47 mph (75 kph). No reduction was noted at the taper in the presence of a speed advisory CMS requesting reduced speeds of 45 mph (72 kph).

Extensive speed measurements during baseline versus CMS-application comparisons were made in Georgia using a 1-line bulb matrix CMS. Although no speed advisory message was displayed on the device, generally lower speeds (see Table 9) indicated a possible residual effect of motorists' increased awareness of the hazard. Because of the transient nature of construction activity, data collection points fre-

Table 8. Comparative lane distributions between two CMS conditions (California data).

	Two Line CMS		
	Open Lane %	Closed Lane %	Sample Size
CMS Point	**51.0**	**49.0**	**6,903**
Intermediate	**76.4**	**23.6**	**3,582**
Taper	**84.1**	**15.9**	**4,349**

No. Late Exits = †690 (15.86% of sample)

	Three Line CMS		
	Open Lane %	Closed Lane %	Sample Size
CMS Point	**60.7**	**39.3***	**4,702**
Intermediate	**78.1**	**21.9**	**3,349**
Taper	**81.9**	**18.1**	**3,049**

No Late Exits = 550 (18.07% of sample)

***Indicates significant reduction from 2-line CMS condtion (α = .001).**

Table 9. Speed behavior observed for baseline versus CMS application (Georgia data).

CMS Condition		Location: Advance	CMS Point	Inter-mediate	Begin Taper	Const. Area
Baseline (no CMS)	Sample Sizes	1282	1072	1406	1410	1200
	Mean Speed =	59.4	58.5	59.7	55.8	53.3
	Std. Dev. =	5.35	5.13	6.04	5.14	6.13
Closure Advisory (3/4 mile advance)	Sample Sizes	787	829	699	743	492
	Mean Speed =	58.1*	60.1	58.2*	55.4	50.4*
	Std. Dev. =	5.20	5.89	6.18	5.88	6.71

Total Sample = 9920

Note: *Device Type*: One-line bulb matrix

*Indicates significant reduction from baseline condition (α = .001)

1 mile = 1.6 km

quently changed. Data in the table are averaged across 5 days of data collection, and day-to-day speed variation was frequently seen to confound results. Therefore, 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 using this procedure, a sufficient number of observations were nevertheless obtained to support statistically reliable significance tests.

A sample of 393 speed observations was obtained to fill the four data cells noted in Table 10. Prior to displaying the CMS, observed speeds at the control location averaged 47.8 mph (76.5 kph), and concurrent speeds at the taper averaged 47.7 mph (76.3 kph). However, while the CMS was deployed, speeds at the control location dropped slightly to 47.3 mph (75.7 kph); and average speeds at the taper showed a slight increase to 47.8 mph (76.5 kph). Differences between speeds in all four cells are not statistically significant, indicating that conditions did not change before or after the CMS was deployed and that the CMS had no effect on speed behavior.

The same experimental procedure was applied at the California site which was characterized by higher speeds. This procedure was used to compare speed effects of all three CMS devices. 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 (72 kph).
2. Two-line rotating drum; single-phase message (all words continuously displayed); SLOW TO 45 MPH (72 kph).
3. Three-line bulb matrix; single-phase message (all words, flashing display); REDUCE SPEED, 45 MPH (72 kph).

Table 11 gives results. It may be noted that in the absence of a CMS, speeds at the taper averaged 63.7 mph (101.9 kph). 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 to 101.9 kph). 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 to 92.3 kph), indicating significant reductions of 6.0 to 7.5 mph (9.6 to 11.8 kph) below speeds observed when no CMS was present.

The applied experimental design permitted the computation of a "corrected" speed reduction, compensating for speed fluctuations observed at the control site. As an illustration of the speed correction procedure, the reader may note that speeds at the control site dropped 0.4 mph (0.6 kph) (62.5 to 62.1 mph (100.0 to 99.4 kph)) between data collection periods for the no-CMS and 1-line CMS conditions. Thus, the observed 7.4 mph (11.8 kph) (63.7 to 56.3 mph (102.0 to 90.1 kph) experimental site speed reduction, ostensibly elicited by the 1-line CMS, was corrected by subtracting 0.4 mph (0.6 kph) to show the true effect.

Further analysis was conducted to determine CMS effects on 85th percentile speeds. Results were consistent with those seen for mean speeds. The 85th percentile speed at the taper was reduced from 69.9 mph (111.8 kph) with no CMS to an average of 64.2 mph (102.7 kph) in the presence of CMS devices.

The result of this experimental procedure is 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 data gathered for a sizable vehicle sample (N =

Table 10. Results of controlled speed study of baseline versus CMS application (Colorado data).

	Speed (mph)	
	Control	Experimental
No CMS	47.8	47.7
Two-line rotating drum with "Slow to 45 mph" message	47.3	47.8

1 mile = 1.6 km

Table 11. Results of controlled speed study of CMS effects (California sample).

	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

1 mile = 1.6 km

30,790) proved to be more than adequate to statistically determine mean differences for a variety of CMS placement and message conditions. However, large amounts of unexplained speed variance, frequently observed even though all conditions (e.g., location, volume, CMS) were controlled, greatly hampered interpretation of these data. Additionally, geometric effects resulting from day-to-day relocation of construction activity were frequently seen to override CMS effects on speeds.

Figure 6 shows plots of average speeds for various tested CMS placement and message content conditions. One notable tendency from the data (shown in this figure) is that placement seemed to affect speeds at the intermediate and taper data collection locations. CMS deployments using a device at the ¾-mile (1.2-km) advance location resulted in lower mean speeds. No similar trend was noted for message content.

Although speed data alone were not conclusive regarding differential effects of various CMS configurations, questionnaire results (to be subsequently discussed) were insightful regarding CMS effect on speed for various message content conditions.

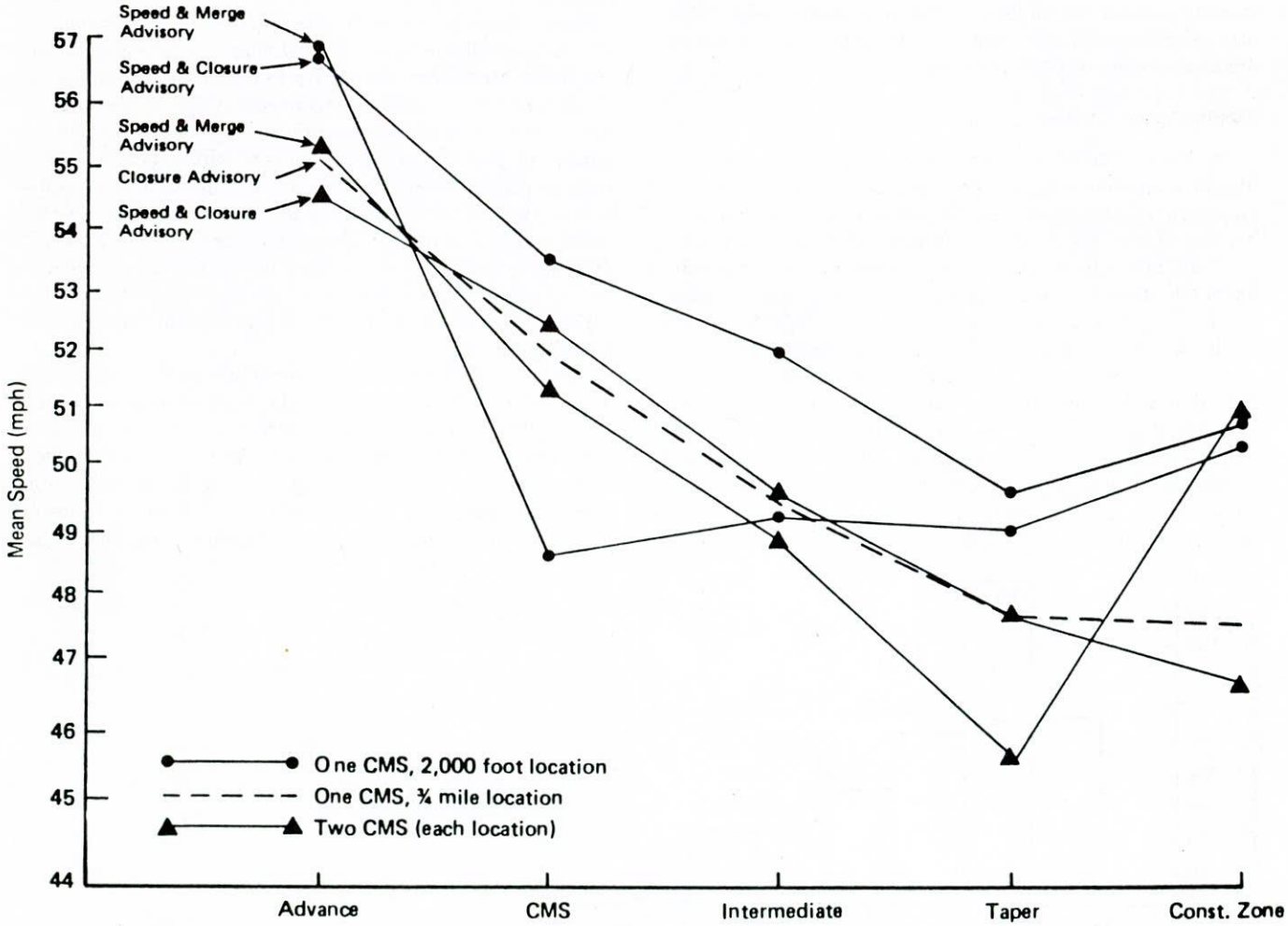
Display Type

Results previously given in Table 11 support the finding that no appreciable differential speed effects were obtained between the tested 1-, 2-, and 3-line formats. Although a greater speed reduction was associated with the rotating drum display than for either of the bulb matrix signs, this difference was not statistically significant.

Summary

In summary, findings based on a sample of 41,463 vehicles in four states demonstrated certain speed-reducing effects of CMS devices. Although CMS devices never elicited the requested 45-mph (72-kph) average speeds, significant speed reductions were frequently associated with their application.

Lower average speeds at the intermediate and taper locations were frequently noted in the Georgia data in the presence of a 1-line closure advisory sign. Although the Georgia sign did not specify a speed advisory message, the observed speed reduction may have been a residual effect of increased motorist awareness of the construction zone hazard. However, Georgia data did indicate that CMS speed-



1 foot = .3 m
1 mile = 1.6 km

Figure 6. Plots of average speed for various CMS conditions (South Carolina data).

reducing effects are susceptible to being overriden by geometric effects.

In Colorado, a 2-line rotating drum CMS bearing a SLOW TO 45 MPH (72 kph) message failed to elicit a significant change from the preexisting 47-mph (75-kph) average taper speeds at one location. However, California data produced convincing evidence that CMS devices (including the 2-line rotating drum sign) do produce speed reductions. All three tested CMS devices were associated with significant speed reductions of more than 7 mph (11 kph) from preexisting taper speeds averaging 64 mph (102 kph). Collectively, the Colorado and California results indicate speed reduction effects in higher speed locations where a greater need exists for speed countermeasures.

Speeds associated with a variety of CMS message and deployment configurations were tested in South Carolina. Although a great deal of confounding variability was seen in the data, promising results were nevertheless obtained through placing the CMS at the ¾-mile (1.2-km) advance location (that subsequently tested in Georgia, Colorado, and California) and use of two CMS devices.

On the basis of these results it was found that CMS devices were effective at reducing critical taper-entry speeds in situations characterized by generally high preexisting speeds. It must be pointed out, however, that other factors (e.g., highway geometrics) were often seen to obfuscate the speed-reducing effects of CMS devices.

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 subjects were controlled in order to ensure representativeness of the driving public. Distributions of ages and other appropriate demographic data describing the sample are shown in Figure 7 and Table 12. The questionnaire (contained in Appendix C) was administered at all sites during all tested CMS conditions.

A thorough question-by-question data analysis is contained in Volume II (see "Foreword" for availability) of this report. Many statistically significant differences were found to distinguish between CMS conditions. In certain instances, questionnaire findings were seen to refute or clarify traffic operational findings. In all cases of departure from traffic operational 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 operational data (e.g., CMS improvement over baseline condition).

Many cross-checks of findings within the questionnaire data were available because of similarities between certain questions. Moreover, the ability to match questionnaire responses with behavior data was used to validate certain findings. The questionnaire procedure was seen to confirm a number of findings in the traffic operations data base that were suspect because of geometric condition. The most notable of these situations related to the improved effect associated with the ¾-mile (1.2-km) advance CMS placement in relation to results based on the 2,000-ft (600-m) placement. Site-specific comparisons based on questionnaire data revealed improved reaction time available from the more advanced placement.

Tables 13 and 14 summarize questionnaire findings for day and night conditions, respectively. Arrows indicate that a differential effect of the noted CMS characteristics was generally evident at more than one site. Site-specific differences, such as the one previously noted, were frequently found (these are discussed in Volume II); yet findings reported herein are more general in nature. Questionnaire findings are

Table 12. Driver sample characteristics.

	OCCUPATION		
13%	HOMEMAKERS	10%	UNEMPLOYED
19%	STUDENTS	43%	SUBPROFESSIONAL
6%	RETIREES	9%	PROFESSIONAL
	EDUCATION		
9%	GRADESCHOOL	28%	UNDERGRAD. COLLEGE
45%	HIGH SCHOOL	18%	GRAD. COLLEGE
	DRIVING EXPERIENCE		
4%	LESS THAN ONE YEAR	15%	6–10 YEARS
8%	1–2 YEARS	56%	MORE THAN TEN YEARS
17%	3–5 YEARS		

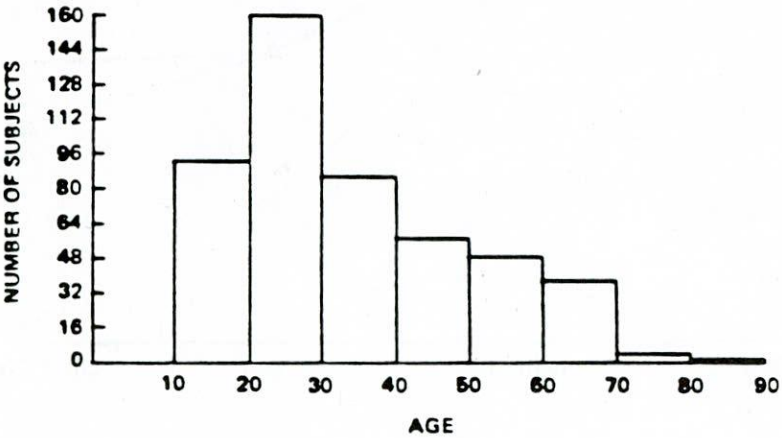


Figure 7. Histogram of subject age distribution.

discussed separately 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 changeable message sign. 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., 2-line rotating drum device based on Colorado), the increase was not statistically significant; however, high statistical significance was most frequently obtained.

Night data were collected for a small sample of interviewed subjects. Limitations on night data resulted from the fact that few state agencies closed lanes during hours of darkness for safety reasons. Day–night differences were noted for device adequacy and sign helpfulness ratings in that significantly lower ratings were obtained at night. Small sample sizes generally precluded any statistically significant differences between conditions based on these ratings; however, directional differences in scores tended to corroborate daytime findings.

Placement

Although mixed responses were obtained between CMS conditions employing one and two devices, differences more often favored the use of two devices. Obvious findings were that higher detection rates and fewer complaints of inadequate information provision 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 tradeoff between greater observation rate versus lower verbatim recall rate is interpreted to favor the use of two CMS devices.

As previously noted, questionnaire results tended to allay concerns that operational findings may not have accurately reflected a beneficial effect of advance CMS placement because of confounding geometric effects. Significant differences in questionnaire results were noted for two message conditions (speed/closure and speed/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 most often approved 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 behaviors 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 operational 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 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 2-line rotating drum sign. The 1-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 3-line bulb matrix device. Moreover, when the 3-line device was used alone, drivers more often reported seeing this device and rated it as being helpful.

The questionnaire item providing 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 15 gives the percentage of drivers who approved of

Table 13. Questionnaire results (daylight conditions, N = 462).

Questionnaire Items	Device Type					Message Content					
	One-line Bulb Matrix	Two-line Rotating Drum	Three-line Bulb Matrix	Three-line (2000-foot) and One-line (¾ mile)	Baseline (no CMS)	Speed & Closure	Speed & Merge	Merge & Closure	Speed & Closure (2 signs)	Speed & Merge (2 signs)	Closure Only
Overall Device Rating (1 = very poor to 5 = very good)	4.2	3.9↓	4.2	4.2	3.7	4.4↑	4.2	4.0↓	4.2	4.2	4.1
Overall Sign Rating (0= not helpful to 2 = extremely helpful)	1.7	1.6↓	1.7	1.7	1.5	1.8↑	1.7	1.5↓	1.7	1.7	1.6
Percentage of Drivers Seeing CMS	81%	79%	*77%	87%	–	85%	67%	80%	93%	78%	84%
Message Recall Correctness (0 = no recall to 1.0 perfect recall)	.64	.70	.59	.44↓	–	.62	.54	.59	.41↓	.50	.70↑
CMS Helpfulness Rating (0 = not helpful to 2 = extremely helpful)	1.5	1.6	1.8↑	1.9	–	1.8	1.5↓	1.8	1.9	1.8	1.5↓
Approval of CMS Information Amount	61%↓	76%	84%	89%	–	90%	79%	80%	92%	85%	65%↓
Non-approval of CMS Information Amount (Too much shown)	1%	0%	5%	0%	–	3%	4%	6%	0%	0%	2%
Non-approval of CMS Information Amount (Too little shown)	38%	22%	11%↑	11%↑	–	6%↑	17%	15%	8%	15%	33%↓
Available Time to Read CMS (1 = not enough to 4 = more than enough)	2.0↓	2.4	2.3	2.0↓	–	2.5↑	2.2	2.3	2.2	1.7↓	2.3
Ease of Reading (1 = much difficulty to 5 = much ease)	4.2	4.3	4.6	4.3	–	4.8↑	4.4	4.4	4.5	3.9	4.2
Self-report that CMS Affected Driving	77%	70%	*68%	80%	–	80%↑	55%	45%	85%	72%	76%
CMS Most Influential Factor	31%	38%	42%	47%	–	49%	28%	49%	59%	28%	38%

Legend

↑ Indicates differential effect between CMS conditions.

* Across-site differences tend to mask a direct comparison based on these numbers.

Table 14. Questionnaire results (night conditions, N = 27).

Questionnaire Items	Device Type			Message Content			
	Two-line Rotating Drum	Three-line Bulb Matrix	Baseline (no CMS)	Speed and Closure	Speed and Closure (2 signs)	Merge and Closure	Closure Only
Overall Device Rating (1 = very poor to 5 = very good)	3.4↓	4.4	3.4	4.4	3.8	4.4	3.4
Overall Sign Rating (0 = not helpful to 2 = extremely helpful)	1.6	1.6	1.4	1.8	1.2	1.6	1.6
Percentage of Drivers Seeing CMS	80%	100%	–	100%	50%	100%	80%
Message Recall Correctness (0= no recall to 1.0 = perfect recall)	.48	.68	–	.63%	–	.68	.48
CMS Helpfulness Rating (0 = not helpful to 2 = extremely helpful)	1.8	2.0	–	1.7	1.5	1.8	2.0
Approval of CMS Information Amount	75%	60%	–	90%	50%	60%	75%
Available Time to Read (1 = Not enough to 4 = more then enough)	2.0	2.6	–	2.6	1.5↓	4.6	2.0
Ease of Reading (1 = much difficulty to 5 = much ease)	4.8	4.6	–	4.7	3.0	4.6	4.8
Self-report that CMS Affected Driving	80%	100%	–	100%	50%	100%	80%

↓Indicates differential effect between CMS conditions.

Table 15. Driver approvals of specific CMS design elements.

CMS Characteristics	Percentage Approvals				
	Day			Night	
	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

↓Indicates existence and directionality of difference obtained between this and other CMS devices.

(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 1-line bulb matrix device. Additionally, lesser approval of letter brightness was noted for the 2-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. It may also be noted that significantly more drivers approved of the letter size associated with the 3-line sign.

Although these driver ratings are highly subjective, they apparently conveyed valid perceptual difference between devices. Drivers likely experienced a greater degree of difficulty with the 1-line device because its shorter display capability necessitated multiphase message presentation. These ratings indicate an obvious driver sensitivity to the smaller message capacity and consequently longer message presentation times. The lesser degree of approval for the rotating drum display likely stems from the fact that less brightness is afforded than with the bulb matrix display type. However, one observed difference related to letter size points out the subjective nature of the driver interview procedure. The letter size associated with the 3-line bulb matrix device is actually smaller than that for the 1-line bulb matrix, hence, theorectically, limiting the legibility. Yet, because of the ease of message assimilation associated with the larger format, the letters apparently appeared larger to the interviewed sample of drivers.

These design ratings were based on a substantial daytime sample of 273 respondents. A small sample of 9 nighttime respondents did not provide statistical reliability but did assist in establishing response tendencies.

Summary

A number of traffic control device rating scales (e.g., relative adequacy of overall device scheme) were used to differentiate between various conditions. These ratings most frequently demonstrated higher averages during the presence of any CMS device. An exception to this result was seen in the case of no difference between baseline (no CMS) and 2-line CMS application in Colorado. General device ratings consistently demonstrated an advantage to be associated with the use of the speed and closure CMS message.

Highway geometric and traffic conditions were frequently seen to affect driver observation of the CMS; however, when these factors were controlled, higher observation rates were obtained for the larger 3-line bulb matrix CMS than for the 2-line rotating drum device. (This observation rate difference was confirmed by observed preparatory lane change differences.) Although increased observation rates were observed for two-device CMS arrays, no distinction between device types could be based on nighttime data.

Drivers' ability to correctly recall CMS messages did not vary between CMS types; however, lower recall scores obtained when two CMS devices were used likely resulted from the increased message load. The message condition most frequently recalled correctly was the closure advisory message placed ¾ mile (1.2 km) in advance of the lane closure. This condition was tested on 1-, 2-, and 3-line CMS devices.

Interviewed drivers rated each CMS device on being helpful. The 3-line device was consistently rated higher than the 1- or 2-line devices, and some increase was noted when the 1-line was used as a supplemental device. Higher CMS helpfulness ratings were observed with greater amounts of information, with the speed and closure message (used singularly and on two CMS devices) being associated with the highest ratings.

Ratings pertaining to amount and specific deficiencies of displayed CMS information were highly insightful regarding motorists' message content requirements. A result consistent with that shown for the CMS helpfulness ratings was increasing driver approval of CMS information amounts as more information was provided. Day and night results indicated that the speed and closure advisory (with some improvement noted for the two-device array) message was superior to others tested in terms of fulfilling driver information needs. The single noteworthy CMS information deficiency noted by drivers was distance to the lane closure. It must be pointed out, however, that this information comprises the thrust of that provided via the conventional signs and, therefore, does not appear justified for inclusion on the CMS.

Two questionnaire measures used to distinguish the relative readability between CMS devices were (1) available time to read and react, and (2) the relative reading ease or difficulty. The response time measure indicated best performance ratings to be associated with the 3-line bulb matrix device and the speed and closure advisory message. Generally, degraded reading and response time ratings were associated with the 1- and 2-line devices. The ease/difficulty of reading score did not discriminate between CMS device types, but did show improved responses favoring the speed and closure advisory message.

Interviewed motorists were asked how the CMS device affected their driving on the approach to the construction area. Self-reported driving behaviors indicated earlier preparatory lane changes and lower approach speeds in the presence of the speed and closure message. Analysis of behaviors associated with questionnaires did validate these self-reported behavior responses. There was an increased tendency during presence of the speed and closure message for interviewed motorists to exit the closed lane prior to reaching the intermediate collection point and to exhibit lower average approach speeds (49.6 versus 53.4 mph (79.4 versus 85.4 kph)). This finding is highly significant in terms of establishing the general validity of basing findings on this survey technique.

A number of design preferences were found between CMS types. Drivers less frequently approved of the overall device size or message length in the presence of the 1-line bulb matrix device, and of letter brightness on the 2-line rotating drum device.

Validation of Questionnaire CMS Response

As noted in the previous section, one validation of subject questionnaire response was obtained on the basis of self-reported CMS responses. 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 via matching observed lane change behavior and comparing it to 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 presence of the speed/closure advisory sign to exit the closed lane prior to reaching the intermediate data collection point at an average of 49.6 mph (79.4 kph), while interviewed drivers during other CMS conditions tended to change lanes beyond the intermediate point and their speeds averaged 53.4 mph (85.4 kph).

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 Table 16 indicates a significant speed reduction for drivers seeing the speed advisory CMS, while no statistical difference was noted for the nonspeed advisory messages.

Further examination of the data was conducted to ensure that measured speed differences for this subset of drivers was not unduly influenced by inherent driver characteristics. Previous human factors research (Roberts, J.M. et al., "Driver Behavior and Self-Testing Attitudes," 55th Annual Meeting of the Transportation Research Board, Washington, D.C., January 1976) had demonstrated that drivers' speed selection is strongly influenced by factors such as age, sex, and certain measurable attitude traits. These factors were included in the questionnaire data base gathered in this project. Therefore, speed-reducing effects of the CMS were distinguishable from driver-inherent influences over speed selection.

The two groups of South Carolina drivers who reported seeing the CMS and who reported not seeing the CMS were compared on the basis of the following factors: age, sex, formal education, years of driving experience, whether or not they used seat belts, familiarity with site, and four attitude factors known to correlate with speed selection. (These latter four factors conveyed attitudes regarding ability to

Table 16. Speeds of interviewed motorists demonstrating CMS responsiveness.

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

*Significant reduction.

1 mile = 1.6 km

control their vehicle at high speeds, feeling safe driving at high speeds, liking to drive at high speeds, and enjoying passing at high speeds on two-lane roads.)

No statistically significant differences between the two groups were found on the basis of selected inherent factors. The 108 drivers who saw the CMS averaged 33 years of age and were comprised of a 46 to 54 percentage male–female ratio; the 32 drivers not observing the CMS averaged 31 years of age and consisted of a 56 to 44 percent male–female ratio. No differences were found on the basis of education, driving experience, seat-belt use, or attitude factors. The only difference between the two groups was that drivers who saw the CMS tended to be more familiar with the site. The difference was slight, driving past the site on the average of once per month for the less familiar and twice per month for the more familiar. As could be expected from this minor familiarity difference, the average number of reported times driven past the construction activity did not differ.

These findings, indicating speed differences associated with CMS messages while controlling for inherent driver characteristics, provide convincing evidence that CMS devices had an effect on driving speeds.

The nature of the observed speed differences must be considered in the interpretation of the findings. First, although observed speed reductions never averaged the 45 mph (72 kph) requested by the CMS devices, a significant reduction in speeds does indicate that an increased motorist awareness to reduce speed nevertheless did result. Second, the observed variability in speed data throughout this study has indicated that speed was highly influenced by many factors other than signing. Certain of these factors are addressed in the following discussion.

Factors Affecting Driver Speed

That considerable variability in speed data would likely occur was taken into account during the initial development of the applied questionnaire. As was evident from the previous discussion, appropriate questionnaire factors were useful in identifying sources of speed variance.

Among many factors seen to affect speed in this project was geographical region of the country. Regional differences were observed as follows: The Eastern (South Carolina and Georgia) sample drove significantly slower at 54.2 mph (86.7 kph) than did the Western (Colorado and California) sample at 56.5 mph (90.4 kph). Thus, speed data for these groups were treated separately in the analysis.

Although significantly different speeds were noted for driving samples exposed to differing CMS conditions, a disclaimer must carefully be made that CMS was a relatively minor influencing factor on driver speed selection.

Treatment of speed data for the questionnaire sample quantified the influence of inherent driver characteristics in their selection of vehicle speed. This step was necessary to determine the relative effectiveness of CMS devices in speed control. Past research has shown that certain driver-inherent characteristic influences over speed control can be measured via the "expressive self-testing profile" (Roberts, J.M. et al., "Expressive Self-Testing in Driving," *Human Engineering*, 1966, Vol. 25, pp. 54-63). These items were measured in the questionnaire and are shown in Figure 8. To demonstrate the effect of inherent factors in speed selection in these data, Table 17 gives results for drivers from the California sample. This sample was selected because minimal confounding effects due to geometry were found to affect selected speeds. The table gives regression correlations with speed on nine individual factors, the overall coefficient obtained via multiple linear regression, and the R^2 value. The R^2 value provides a direct indication of the amount of variation in the dependent variable (speed) that was explained in the regression against the set of independent measures (inherent factors). A highly significant (0.001 level) result was found: 48 percent of the speed variation was attributable to driver age, sex, and the seven cited attitude factors.

Further analysis, similar to that depicted in the previous table, demonstrated that drivers were less influenced (R^2 = 0.12) by inherent factors as they entered the taper at the construction area. More importantly, however, an even weaker influence (R^2 = 0.08) of CMS factors (e.g., CMS helpfulness rating) was found to be associated with speed selection. A point to be made from this analysis is that, although these factors are valid CMS effectiveness measures and are indeed appropriate for assessing CMS impact on speed selection, inherent factors may nevertheless exert an overriding effect.

It is quite likely that, had speed advisory signing been tested for the depicted driving sample, greater speed reductions and larger R^2 values depicting CMS influence would have been obtained for the preceding analysis. Speed variance induced by mobile construction zone locations at other sites rendered an application of the analysis impracticable.

The most noteworthy finding from this analysis of relative effects of various factors on driver speed selection is that driver-inherent characteristic effects were frequently demonstrated to outweigh CMS effects. It should be noted that this finding strengthens the association between speed reduction and CMS effects previously given in Table 16. In this situation, the CMS effect was seen to override inherent factors (shown not to be a causal factor of lower speed) to apparently result in the speed reduction.

Driver Information Needs in Work Zones

In order to provide a thorough assessment of driver response to construction zone traffic control devices, the questionnaire ascertained self-reported driver information needs. Information needs were asked early in the survey prior to any reference to the CMS device in order to gather responses that were as nearly unbiased as possible. A two-stage question requested the most important (primary) information needed from the construction zone devices and the second most important (secondary) information needed.

Because open-ended questions were used in order to obtain general responses, a wide variety of needs was indicated. A content analysis of these responses resulted in the categorization of 22 need types. A requirement that many of the noted categories be grouped together in the analytical process resulted from the ambiguous nature of many responses. For example, drivers would frequently indicate "merge right" as a need when the information really wanted was that the right lane was open. For this reason, results of the needs analysis collapsed the two categories, "open lane indication" and "merge direction."

Driver Attitude Profile

Please respond to these statements expressing your own feelings. Use the following scale:

1. Strongly Agree
2. Agree
3. Undecided
4. Disagree
5. Strongly Disagree

10: I have the ability to control my automobile at high speeds.
32
1 _____ 2 _____ 3 _____ 4 _____ 5 _____

11: Because of the sturdy construction of my vehicle, I feel safe driving at any speed.
33
1 _____ 2 _____ 3 _____ 4 _____ 5 _____

12: I like to drive at relatively high speeds.
34
1 _____ 2 _____ 3 _____ 4 _____ 5 _____

13: I like to pass cars when driving at relatively high speeds on two-lane roads.
35
1 _____ 2 _____ 3 _____ 4 _____ 5 _____

14. When avoiding a hazard, I steer around it rather than use my brakes.
36
1 _____ 2 _____ 3 _____ 4 _____ 5 _____

15: I believe traffic regulations are designed for unskilled drivers.
37
1 _____ 2 _____ 3 _____ 4 _____ 5 _____

16: From time to time, I enjoy finding myself in a situation that challenges my driving skills.
38
1 _____ 2 _____ 3 _____ 4 _____ 5 _____

Figure 8. Portion of questionnaire used to measure "Expressive Self-testing Profile."

Usable answers of primary information need were obtained for a sample of 486 responses. Tallied primary needs were indicated as:

	Percent
Closed lane indication	34
Open lane (merge direction)	28
Construction (distance) ahead	18
Speed information	10
Distance to lane closure or required merge point	4
Number of open lanes	2
Other	4

Other reported primary information needs were route diversion information, length of closure, prepare to stop, increased attention is required, and a warning of construction vehicles.

Speed was most often noted as the secondary information required. Types of speed information required were as follows:

	Percent
Safe driving speed	55
(Enforceable) speed limit	25
Speed reduction required	20

Limited analysis was conducted to associate behaviors with reported information needs. A hypothesis was tested to determine whether those drivers who reported speed-related information needs drove differently on the approach to the construction area. It was thought that this group might comprise a conservative subset with negative attitudes regarding high speed. However, the data did not conclusively bear out this assumption.

Site-specific and across-sites speed comparisons were made on the basis of whether drivers reported speed as a primary need only or as either a primary or secondary need. Tendencies were seen in most of the comparisons for drivers reporting speed information to drive somewhat more slowly. Although a significant difference existed for the California sample, showing that drivers reporting speed information

Table 17. Inherent factors influence on work zone approach speeds.

OVERALL (R^2 = .48)	r = .69
AGE	.37
SEX	.04
ATTITUDE FACTORS:	
VEHICLE CONTROL	.38
VEHICLE CONSTRUCTION	.49
LIKE FAST DRIVING	.44
TWO-LANE ROAD PASSING	.52
HAZARD AVOIDANCE PREFERENCE	.13
TRAFFIC REGULATION DESIGN	.22
ENJOY DRIVING CHALLENGES	.15

needs averaged 54.9 mph (87.8 kph) while those who did not drove faster (averaging 57.0 mph (91.2 kph)), nonsignificant speed differences were recorded at the South Carolina site.

Another finding that confirmed the lack of association between information needs and driving speeds was that information need distributions were not seen to differ (using the Spearman Rank Order test) between driving samples who traveled above or below 55 mph (88 kph).

Information needs were examined across two parameters related to CMS use. Information need differences were examined between driving groups exposed to right- and left-lane closures. However, distributions of primary information needs were essentially the same for drivers exposed to each closure type.

An effect of drivers' seeing CMS devices was shown to impact on reported information needs. In the presence of CMS, a shift in reported needs was noticed, with more drivers reporting closed lane indication requirements and fewer reporting the construction (distance) ahead category. This shift reflects retention of CMS information by interviewed motorists.

FIELD STUDY RESULTS (UNPLANNED LANE CLOSURES)

Although the major focus of NCHRP Project 3-21(2) was CMS application for lane closures involving the planned condition (highway construction), study was also made for the unplanned condition (e.g., accidents, unexpected road obstructions, and certain maintenance activity). Because of practical and logistical constraints, study of the unplanned condition was limited to a case study of CMS application in two California Department of Transportation (CalTrans) districts.

Two applications were observed for CMS devices at unplanned condition lane closures. The first involved a special standby unit (Major Incident Response Team) that deployed CMS devices for the purpose of diverting traffic past incidents, such as major traffic accidents. The second involved short-notice dispatching of mobile CMS devices to certain maintenance activity locations where traffic queuing was expected. Each of these applications is separately discussed.

Incident Response

CalTrans District 7 is staffed with an operational unit, the Major Incident Response Team, which stands by on a 24-hour per day, 7-day per week basis. The purpose of this team is to aid the California Highway Patrol in management of traffic affected by a major incident. Members of the team are assigned automobiles and special CMS trucks (see Fig. 9) to support their mobile, on-call response activity. A similar unit is employed in CalTrans District 8.

These teams deploy 1-line bulb matrix and fabric panel display type CMS devices containing message content depicted in Table 18. Figure 10 depicts typical message combinations deployed on CalTrans District 7 fabric panel CMS trucks.

End-of-Queue Operation

A similar CMS operation is used to control traffic in the vicinity of certain maintenance activity where queuing is expected. The purpose of this activity is to warn drivers of the queuing and thus reduce rear-end accidents at the end of the queue. The applied on-site traffic control strategy involves constantly repositioning the sign truck so as to maintain an advance placement of approximately 2,500 ft (750 m) upstream of the queue.

Observational study was made for a number of end-of-queue deployments within CalTrans District 7. The bulb matrix sign shown in Figure 11 displayed the message PREPARE TO STOP. In the event that the queue would temporarily dissipate, the message was changed to LEFT LANE CLOSED AHEAD

Figure 9. CalTrans District 7 Major Incident Response Team sign truck.

Table 18. CMS messages used by District 8.

Message Unit No. 1	Message Unit No. 3
1. Watch for Brake Lights	1. Shoulder Work Ahead
2. Slow Moving Traffic Ahead	2. Caution Sweeper Ahead
3. Slow Moving Vehicles Ahead	3. Ramp Closed Detour Ahead
4. Prepare to Stop	4. Slow Freeway Flooded Ahead
5. Slow Stopped Traffic Ahead	5. Caution Right Lanes Flooded
6. Freeway Closed Ahead	6. Caution Left Lanes Flooded
7. All Traffic Must Exit	7. Slow Dense Fog
8. Slow Wreck Ahead	8. Dense Fog Ahead
9. Use Detour Road	9. Test

Message Unit No. 2
1. Freeway Closed Detour →
2. Freeway Closed Detour ←
3. Caution Ramp Closed
4. Caution Detour Ahead
5. Merge Left ←
6. Merge Right →
7. Left Lanes Closed Ahead
8. Right Lanes Closed Ahead
9. CHP Pace Car Ahead

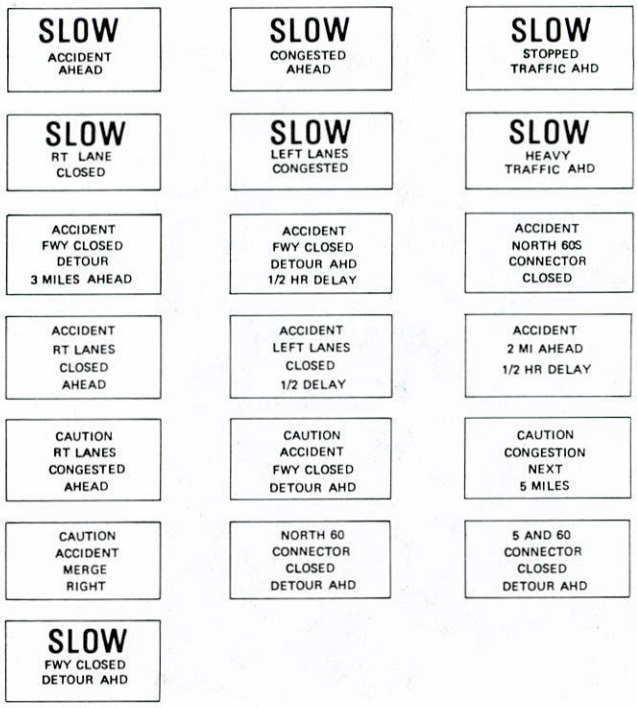


Figure 10. Typical message combinations deployed on CalTrans District 7 fabric panel trucks.

Figure 11. CalTrans District 7 end-of-queue operation sign truck.

and the truck was positioned approximately ½ mile (0.8 km) in advance of the closure.

Because of the nature of the observed traffic situation to which end-of-queue signing was applied, it was not possible to obtain meaningful operational response measures. The appropriate measure of sign effectiveness would be closure rates indicative of rear-end accident potential both with and without use of the sign. Such measures were not feasible given the methods associated with this project. However, the observational study did reveal the closed lane exiting behaviors on the approach to the lane closure.

Figure 12 shows traffic queuing on the approach to a closure observed in this special study. The upper photograph illustrates an approach to a right-lane closure. As can be seen, many vehicles were noted to occupy the closed lane on the approach. This situation was common to all those observed. The lower photograph illustrates the forced exit from the closed lanes because of the presence of the traffic cones actually closing the right lanes.

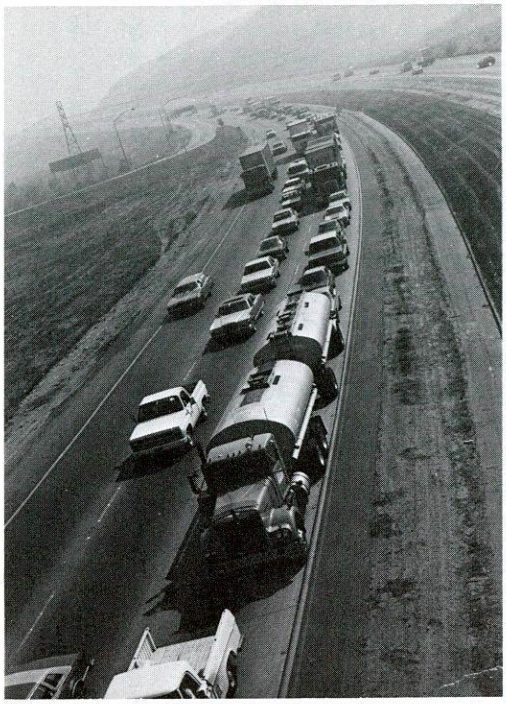


Figure 12. Traffic response observed for CalTrans District 7 end-of-queue operation.

CHAPTER THREE

INTERPRETATION, APPRAISAL, AND APPLICATION

The interpretation of the findings presented in the previous chapter is discussed in terms of the actual effect of CMS that was realized in view of observed confounding geometric effects. The findings are then appraised in terms of their potential applicability for future CMS application at construction zone lane closures. Finally, suggestions are made for highway agency application of these findings. Because of similarities in device use, this discussion is equally applicable

for CMS devices deployed at either planned or unplanned lane closures.

INTERPRETATION

Interpretation of the findings is discussed for the following CMS effects: application, placement, message condition, and display type.

CMS Applicatiwy

The findings pertaining to CMS application demonstrated significantly improved traffic operational effects in before–after study contrasting baseline (no CMS) and a variety of CMS schemes. Use of CMS devices was consistently seen to produce smoother transitions of approaching vehicles from lanes that were closed in the construction area. In cases where preexisting speeds appreciably exceeded those requested in speed advisory messages, significant speed reductions did result from CMS application. The findings based on traffic operational data were corroborated via driver questionnaire findings.

Although significant improvements were noted to occur as the result of CMS application, the data also demonstrated that these effects were susceptible to being overriden by geometric effects. Georgia data were confounded by the presence of grades that obfuscated speed-reduction effects of CMS; Colorado data indicated that exit location with respect to taper position can adversely affect lane distribution measures; South Carolina traffic conditions and sight distance difference resulted in lower CMS observation rates. Thus, interpretation of these findings must make note of these limitations associated with CMS application.

Traffic operational improvements observed to result from CMS application were generally confirmed by the findings in the questionnaire study. At all but one site, improvements were reported in ratings of traffic control device adequacy and sign helpfulness between baseline and CMS application conditions. No explanation was evident for the disparate Colorado questionnaire finding, as significant lane distribution improvements were observed at the site. Further, baseline versus CMS questionnaire comparisons using the Colorado (2-line, rotating drum) sign did demonstrate significant improvements with its use at the California site. Thus, the findings were interpreted to demonstrate favorable overall results by virtue of confirmatory findings obtained at all but the Colorado site.

CMS Placement

As in the case of general CMS application previously noted, traffic operational improvements observed with the ¾-mile (1.2-km) advance placement were susceptible to being masked by site-specific geometric effects.

That improved traffic operations resulted from the more advanced (¾-mile versus 2,000-ft (1.2-km versus 600-m)) placement is beyond refute. Average lane distribution profiles and critical speed data for a variety of CMS conditions tested in South Carolina demonstrated improved results when a CMS device was placed at the ¾-mile (1.2-km) point. Concerns that this effect may have resulted in part from site-specific geometrics in the South Carolina data base were allayed by the corroborating questionnaire findings that improved driver reaction time was reported with the ¾-mile (1.2-km) CMS placement. Confirmation of this latter finding was obtained with two message conditions gathered at different sites.

Insufficient evidence was found to dictate that simultaneous application of devices at both the 2,000-ft (600-m) and ¾-mile (1.2-km) locations is warranted.

Message Condition

Differences regarding which message condition produced the best results were not as clear cut. Conflicting evidence resulted from improved lane distributions being associated with speed and merge advisory messages, while preferences indicated in the questionnaire data base heavily favored the speed and closure advisory.

This conflict was resolved entirely on the basis of the questionnaire data and its associated vehicle behavior data. Improved lane distributions associated with the speed and merge advisory in the traffic operations data base likely resulted from the confounding effect of interchange proximity (with consequent vehicle exiting on the approach to the taper) to the lane closure. The in-vehicle study controlled for this effect by assigning drivers a uniform route, taking them past the construction area rather than exiting the highway prior to reaching the taper. Both questionnaire responses and associated vehicle performance were seen to favor the speed and closure advisory message.

The need for the closure advisory message was further substantiated in the questionnaire data base pertaining to driver information needs. Reported primary information needs for drivers not influenced by CMS information (data obtained during baseline condition and from drivers not seeing the CMS) heavily favored the closed-lane indication message over the merge-direction message.

One surprising finding from the questionnaire data base was seen to favor the speed and closure advisory. Although this message condition was longer than certain others (e.g., closure advisory), it was reported as being the most easy to read.

Display Type

As in the case of the CMS message condition, advantages associated with a particular display type were not as clear cut as the general advantages of CMS use. Two format comparisons (i.e., number of lines displayed and presentation mode) were available from the data.

Observed differences between the 1-, 2-, and 3-line tested devices resulted from the amount of information shown during a single presentation phase. Although each device type was successful at eliciting desired speed and lane-change responses in the traffic operational data base, questionnaire responses heavily favored presentation of greater information amounts in a single presentation phase. An ancillary effect found with the 3-line device was increased lane-change activity at one site, an effect apparently resulting from the obtrusiveness of the device. Thus, an interpretation of these findings is that the most favorable results were obtained with the 3-line format.

The bulb matrix display type CMS facilitates a multiphase message presentation, while the rotating drum was used for continuous message presentation. The potential advantage of

the continuous message presentation is improved message recall; however, this effect was not seen on the basis of within-site comparison between the 2- and 3-line device. Although less driver approval of letter brightness was associated with the rotating drum display, the sign was nevertheless quite legible. However, an interpretation of the collective findings slightly favors the bulb-matrix display using a 3-line format.

APPRAISAL OF RESULTS

As is likely to be expected with any research effort involving large amounts of data, certain conflicting evidence was noted in the findings. Moreover, certain issues noted earlier were difficult to resolve on the basis of the data. Finally, in numerous instances, obtained results were questioned because of external sources of variance.

The weakest point in the data base was the large amount of variance in the speed data that could not be explained. A highly controlled experimental procedure held constant known potential effects of time-of-day, traffic volume, geometric conditions, and traffic control device application; yet, significant speed differences were found to hamper the CMS evaluation. This problem had to be overcome by application of a statistical procedure to quantify the strength of the mean difference testing technique and discarding affected differences. The result was that much of the speed data were not usable in the CMS evaluation. Even using this approach, remaining speed data were frequently viewed as suspect because of confounding geometric effects.

Fortunately, large sample sizes of traffic operational data were available to permit a determination of CMS effects on a site-specific basis, thus eliminating the need to collapse across sites and to possibly jeopardize validity of the results. Thus, in many cases, findings could be corroborated by a corresponding difference obtained at another location.

Because of this speed variance problem, coupled with the fact that a highly portable data collection procedure allowed gathering of large samples during restricted time periods, a refined procedure was applied late in the study (Colorado and California) to support a valid speed determination of CMS effects. While this short-term measured speed effect did limit results to CMS "novelty" response, this approach nevertheless enjoys a high degree of face value because of the transient nature of construction activity.

The strongest point in the applied procedure was the application of questionnaire data and its ability to confirm, refute, and clarify suspect results in the traffic operational data base. Of particular note is the fact that a high degree of findings validation was obtained through the use of questionnaire data and associated vehicle behaviors. The two noted validation instances were speed reductions associated with drivers seeing the speed advisory message (this situation actually provided a baseline condition in the South Carolina data base), and the confirmation of driver self-reported performance responses to the speed and closure advisory message (this result tended to enhance the overall credibility of the questionnaire procedure).

In view of the internal validation provided the evaluative method as the result of the questionnaire procedure and the large samples of reliable data, an appraisal of results must conclude that findings regarding CMS use very likely convey their true effect. Thus, these findings can be interpreted to support a recommendation for CMS application.

APPLICATION OF FINDINGS

Three noted effects of CMS devices support their application to warn approaching motorists of highway lane closures at construction sites. These effects are:

1. Greater amounts of preparatory lane-change activity in advance of the closure.
2. Reduced occurrence of "late exit" behaviors (exiting from the closed lane within 100 ft (30 m) of the taper).
3. Reduced speeds at the beginning of the taper.

The foregoing effects were noted in comparison with "standard" traffic control device schemes following the application of CMS devices.

The following device specifications are suggested:

1. CMS placed approximately ¾ mile (1.2 km) in advance of the lane closure (it may be advisable to alter advance placement slightly to assure ample sight distance to CMS).
2. Shoulder placement; on the same side of highway as closed lane.
3. A two-phase, speed and closure advisory message displaying the wording: RIGHT (LEFT) LANE CLOSED AHEAD and SLOW TO 45 MPH. (72 kph).
4. CMS format should permit complete message (e.g., RIGHT LANE CLOSED AHEAD) for each phase to be read at once.

Although application of the CMS was seen to improve traffic conditions approaching lane closures, there were no indications throughout the conduct of this research that current MUTCD schemes are inadequate. Therefore, suggested application of CMS devices at lane closures may be considered a supplemental procedure for use in atypical situations (e.g., short sight distance to taper).

Cost considerations would logically dictate keeping the number of CMS devices owned by any highway agency to a minimum. Therefore, allocation of devices to specific worksites may be based on a number of criteria. Two suggested criteria are traffic volume and timing/duration of lane closures as follows:

1. *Minimum hourly volume*—Although CMS devices were seen to be equally effective under all tested volume conditions, a volume of 900 vph is viewed a reasonable lower limit for CMS application. Traffic flow below this level is considered sufficiently light so that smooth transitioning of traffic from the closed lane is likely to occur without CMS devices.
2. *Novelty effect requirement*—That a closed lane violates a driver's expectancy comprises a large portion of its hazard potential. Therefore, a highway agency may schedule one CMS device among a variety of construction projects so that its application would coincide with the initial closure. The obvious drawback of this strategy is that it entails removal of the CMS device, thus disrupting the continuity of information presentation. An alternative strategy is to assign CMS devices to transient projects rather than long-term projects characterized by familiar drivers accustomed to the closure.

CHAPTER FOUR

CONCLUSIONS AND SUGGESTED RESEARCH

CONCLUSIONS

The findings that changeable message signs tend to improve traffic flow on the approach to construction zone lane closures support their limited application as suggested in the previous chapter. 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 of 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.

The relative importance of the arrowboard to facilitate the smooth transition of traffic around a highway work area cannot be overemphasized. Numerous interviewed subjects indicated that its communication of the merge requirement message is much clearer than that of the CMS. A subjective conclusion of this study is that the effect of arrowboard placement and brightness has a considerably greater impact on construction zone safety than does the CMS device.

SUGGESTED RESEARCH

The construction zone safety problem remains a complex issue. An obvious underlying cause of accidents in construction areas relates not only to the development of new traffic control techniques but to the correct application of existing standards as well. Although recent improvements have been made in this regard (the Federal Highway Administration's research program, FCP Project IY ("Traffic Management in Construction and Maintenance Zones"), addressed the problem of adherence to MUTCD standards), numerous departures from standard practice were observed during the conduct of this project.

Specific areas of needed development for new device characteristics were noted during the conduct of the questionnaire study. The most urgent of these needs relates to nighttime visibility of temporary roadway alignment.

Questionnaires gathered during the conduct of NCHRP 3-21(2) suggested a number of promising innovative devices. Examples are:

1. New types of hand-held devices for use by flagmen. Many drivers suggested larger, reflective (or fluorescent), different-colored flags/paddles.
2. Use of arrows in barricade design. The California test site exhibited W1-6 arrow panels mounted on Type III barricades in tangent sections. The benefit of this repeated arrow presentation was evident in numerous questionnaires.
3. Multiple CMS application. A suggestion is speed information on 1-line bulb matrix devices at 1,000- to 2,000-ft (300- to 600-m) spacings throughout long closures.
4. Orange reflectorized lane marking. Nighttime questionnaires have revealed much difficulty in motorists' discerning path delineation of open lanes.
5. Audible signals. Potentially advantageous because of the increased attention-gaining effect.
6. Rumble strips. Attention-gaining effects similar to audible signals.
7. Combined use of symbols and words in changeable message signs.

Each of the foregoing specific concepts was suggested in more than one questionnaire and deemed noteworthy by the research team. General device concepts were evident from the survey consensus. Among these are: (1) increased use of symbols and arrows because of their potential ease of recognition and interpretation, and (2) use of flashing devices because of their attention-gaining characteristics. Moreover, numerous driver complaints of devices being confusing and distracting gave rise to the idea of seeking simpler device designs. There appeared to be a consensus among respondents that devices should be larger and simpler, should use fewer words and more symbology, and should incorporate flashing lights in the presentation of the most critical information. Thus, a continued developmental effort in the area of construction zone warning devices appears warranted.

APPENDIX A

RESULTS OF LITERATURE REVIEW

INTRODUCTION AND BACKGROUND

Beginning the late sixties and early seventies, the concept of the changeable message sign (CMS) for freeway traffic control has emerged as a valuable and important display tool for use by the highway systems engineer to effectively communicate to the driver. While the conventional or static sign conveys a message to the driver about a static situation, increasing hazard/incident occurrences such as adverse

weather, accidents, work areas, and special events require specific messages in the form of dynamic displays.

Two bodies of literature began appearing through the seventies that are relevant to the deployment of CMS displays. One provides information about the current state of the art of CMS use and may be divided into three categories: (1) descriptions of various proposed or operating CMS installations by a given transportation agency for their particular freeway problems, with or without evaluations; (2) principles of design of CMSs—messages, sizes, deployment recommendations, etc.; and (3) summaries of developing CMS hardware by manufacturers and regulating agencies.

A parallel, but not mutually exclusive, body of literature was also emerging during this time having to do with the design and evaluation of visual information displays that attend to the needs of the driver as he encounters a hazardous incident or complex visual environment. This design concept for visual information displays has emerged from the principles of positive guidance and more specifically, decision sight distance (DSD) (to be discussed later) as a means to promote optimum communicative properties of a display to interface with the drivers' perceptions. Here the CMS might be seen as one specific component in a total system to effectively warn the driver of a violation in his normal driving expectancies. Not only has the display design (structure, wording, format, placement) become critical, but the precise development of measurement techniques to monitor driver perceptions of the display has become crucial to the evaluative stages of CMS application.

A brief discussion of these two emerging bodies of literature follows.

DISCUSSION OF PERTINENT DOCUMENTS

The first set of documents relates to the CMS device itself. As mentioned earlier, its use and potential gained increased acceptance and experimentation through the last two decades (*A-1, A-2*). The CMS display enjoys a variety of applications ranging from reversible lane control to freeway conditions advisory to work zone/hazard. Many agencies use CMSs to provide advisory speed information to encourage motorists to reduce speeds approaching hazardous or incident conditions. A popular use is advisory speed coupled with a one-word warning of fog, ice, or snow (*A-3, A-4, A-5, A-6*). Some installations in Britain actually are experimenting with "pictogram" signals to effect appropriate speed reductions (*A-7*). Most of these reports contain summary information on CMS purpose for the locality, with limited quantitative evaluation of effectiveness (*A-8, A-9*). Extensive freeway control and surveillance projects, however, usually involve some survey evaluation.

Typically, CMS performance has been assessed by a comparison of traffic flow parameters such as speed, lane change, and diversion behavior before-and-after a CMS is operative. Then, drivers' license plate numbers are taken, and surveys mailed to these drivers to solicit public opinions regarding the new signs (*A-10, A-11, A-12*). In general, these two data sources are not related one to the other. Survey data consistently show that drivers "like" the new signs and very much appreciate the information given (*A-10, A-11*). In fact, the incident information even seems to serve some intangible benefit by reducing the drivers' uncertainty about conditions ahead, even if they cannot be avoided (*A-10*).

California DOT, in conjunction with the UCLA Institute of Transportation and Traffic Engineering, did considerable laboratory study of CMS messages with various wordings and formats using driving simulators and theater presentations of CMS displays to monitor driver reactions (*A-13*). A later series of many laboratory studies by the Texas Transportation Institute (*A-14*) produced human factors guidelines for development of sign messages in terms of content, format, redundancy, etc.

Field tests of these new design findings are as yet lacking, however. Although the driver may indicate in a paper survey that he "likes" the CMS display and appreciates the information given, there is no evidence to indicate what his behavior response would be in a real-world operational setting. A state-of-the-art summary, *NCHRP Synthesis 61* (*A-17*), surveys a great variety of CMS installations cross-country, and points to the data gap between actual driver behavior in the traffic stream and preference responses to the CMS concept in a nondriving mode.

A notable exception to the foregoing is the work being done by the Transport and Road Research Laboratory in Great Britain (*A-15, A-16*). Here, researchers have developed various "pictogram" messages for various roadway hazards ahead and presented these on several different CMS types (i.e., standard matrix, fiber optic, and roller type). Following laboratory investigations of recognition and meanings of the displays, subject drivers were driven in a test car to respond to the signs as placed on the actual roadway. Mean recognition distances were recorded. This type of evaluation begins to attack what has been called one of the technology voids in the development of changeable message signing (*A-17*).

Other areas of highway research have addressed the issue of the technology void between field operational measures and driver processing of displayed information. These works comprise the second emerging body of literature noted earlier. This shift in research emphasis to "driver intrusive" field performance evaluations of information displays has stemmed from awareness of highway safety and accident problems resulting from driver error. The concept of decision sight distance (DSD) for placement of hazard indicators defined as

> the distance at which a driver can detect a signal (hazard) in an environment of visual noise or clutter, recognize it (or its threat potential), select appropriate speed and path, and perform the required action safely and efficiently

arose as an attempt to realize the driver's needs as he negotiates a given roadway and is confronted with a diversity of visual information. NCHRP Project 3-21 (*A-18*) applied this concept to drivers' comprehension of highway guide signs. Here, drivers were extensively interviewed immediately following certain conflicts and erratic maneuvers committed at various complex interchanges they had just negotiated. It was found that certain erratic flow measures were resultant from the guide signing just seen, and some were not. Thus, statements could be made regarding sensitive measures to use for evaluating different signing presentations to reduce the dangerous maneuvers.

Studies in the area of work zone operations have also recognized a real safety problem as drivers seem unprepared to divert around such unexpected hazards. A recent analysis by the Virginia Research Council (*A-19*) attributed 79 per-

cent of vehicle accidents to driver error, yet did not identify the specific cause of the error. The report remains with the question, what are the most effective means of communicating to the driver the need for increased caution? Various reports have applied the decision sight distance concept for the design and placement of traffic control devices in work zones to approach an answer to this question (*A-20, A-21, A-22*). For example, in evaluating the role of the flashing arrowboard (*A-22*) as a high target value warning device for a lane closure, laboratory tests of arrow symbol design and meaning were followed by collection of flow parameters in the field. Placement was then governed by the DSD concept, and certain desirable behaviors such as early merging and shorter queues at the beginning of the lane closure were recorded. Driver intrusive measurement of channelizing devices begun in NCHRP Project 17-4 (*A-21*) also revealed which flow measures reflected driver responses to the devices and which did not.

Two bodies of literature have concurrently evolved to offer the opportunity for a realistic and meaningful field evaluation of the changeable message sign in a lane closure setting. Deployment of CMSs in the field followed by driver preference surveys have indicated enough interest in further use of these devices to demand an evaluation based on the driver-intrusive approach to valid assessment.

In summary, the preceding discussion has indicated awareness of CMS systems in use, how they were evaluated, and the growing importance of a new driver intrusive evaluation technique used in other areas to advance CMS evaluation for the future. The combination of these elements sets the stage for the evaluative work to be performed in this current research effort.

UPDATE OF CURRENT CMS USE AND LIAISONS WITH CMS MANUFACTURERS

Two other activities ensued as part of the literature review of documents related to CMSs: an update of current CMS installations to indicate the diversity of uses and applications, and a listing of manufacturers of CMSs with corresponding liaisons. Table A-1 gives CMS installations by locality and identifies the type of CMS used. Table A-2 presents major CMS manufacturers so that a working knowledge of the current hardware may be obtained. Several important documents were used to obtain this information (*A-23, A-24, A-25*), as well as many correspondences with appropriate officials through letter and telephone contacts.

Descriptive material regarding certain CMS devices known to be readily applicable at highway construction appears in Appendix B.

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Table A-1. Current CMS use.

Agency Maintaining Signs	Sign Location	Sign Type	Number of Signs	Number of Messages	Physical Characteristics of Signs	Interconnect to Signs	Surveillance and Control of Signs
California Department of Transportation	A 12-mile stretch of Santa Monica Freeway between Los Angeles and Santa Monica.	Lamp Matrix	35*	100 preprogrammed messages for all signs. Messages are reprogrammable.	Top of sign FREEWAY CONDITION (static message). Two variable lines of copy with 18-in. characters, 16 characters per line. Modular matrix.	Telephone	Detectors, police, and Caltrans patrols. Operator pushbutton control.
CalTrans Districts 7&8	As needed placement by Incident Response Teams	Lamp Matrix Fabric Panels	4 4	Lamp: 32 preprogrammed on 4 cassette Fabric: Many combinations from pre-printed words, letters, numbers.	Lamp: 17" high, one-line 5-letter words; 4 words in sequence. Fabric: 6'9" by 5'8" background 10" and 20" letters, black and red	None	Manually controlled on site.
City of Cincinnati, Ohio	Twelve signs on SB I 75, 6 signs on EB I 71, 1 on EB Ft. Washington Way.	Lamp Matrix	19	100 preprogrammed messages. Messages are reprogrammable. Number of preprogrammed messages per sign varies from 1 to 11.	Five 4-line signs (4 with 15-in. and 1 with 12-in. characters), 26 characters per line. 13 1-line signs (which are part of fixed overload signs) with 12-in. characters, 13 characters per line; 1 2-line sign with 15-in. characters, 26 characters per line.	Coax Cable	Detectors and CCTV. Automatic computer control with manual override.
Colorado Division of Highways	Two signs on I 70, 1 on US 36, 1 on I 25 in Denver area.	Lamp Matrix	4	50 preprogrammed messages for all signs. Messages are reprogrammable.	Two variable lines of copy with 12-in. characters, 20 characters per line.	Telephone	Detectors and State Highway Patrols. Automatic computer control with manual override.
City of Dallas, Texas	Skillman Ave. near North Central Expressway.	Drum	3	Combination of 13 fixed-in messages.	Top of sign SOUTHBOUND CENTRAL EXP. (static message). Four 4-sided drums, 12-in. characters.	Telephone	Detectors and CCTV. Operator pushbutton control.
Minnesota Department of Transportation	I 35 in Minneapolis.	Lamp Matrix	1	Nine fixed-in messages per line. Several possible combinations.	Three variable lines of copy with 16-in. characters, 18 characters per line.	Telephone	Detectors, CCTV, monitors CB and police radio. Automatic computer control with manual override.
New Jersey Turnpike Authority	Northern 36 miles of New Jersey Turnpike.	Drum, Neon, Neon/Lamp Matrix	89 97 103	Five messages on drum signs by combining 2 signs. Six messages on neon warning signs. Six messages on neon/lamp matrix speed control signs.	Drum: 3-line signs at ramps, 4-line signs on mainline. Neon: 4 lines. Neon/Lamp Matrix: 2 digits.	Buried Cable and Radio	Detectors and Highway Patrols. Automatic computer control with manual override for portion of system. Manual control for portion of system.
Pennsylvania Department of Transportation	I 279 near Pittsburgh.	Disk Matrix Drum	2 1	70 preprogrammed messages on disk signs. Messages reprogrammable. Three messages on drum sign.	Three variable lines of copy on disk signs with 18-in. characters, 20 characters per line. Drum signs: 12-in. characters, 6 characters per line.	Telephone	State police patrols. Plans for detector surveillance. Keyboard console for disk signs, pushbutton console for drum signs.

*Originally

Table A-2. CMS manufacturers of devices potentially applicable for use in NCHRP 3-21.

- American Sign and Indicator Corporation
  North 2310 Francher Way
  Spokane, Washington 99206
- Crouse-Hinds Company
  Syracuse, New York 13201
- Dietz Company
  225 Wilkinson Street
  Syracuse, New York 13201
- Display Technology Corporation (DISTEC)
  160 Main Street
  Los Altos, California 94022
- Energy Absorption Systems, Inc.
  One East Walker Drive
  Chicago, Illinois 60601
- Federal Sign
  Division Federal Signal Corporation
  5018 Chase Street
  Downers Grove, Illinois 60515
- Telespot Systems, Inc.
  521 Fifth Avenue
  New York, New York 10017
- Traffic Control Systems Company
  2903 Delta Drive
  Colorado Springs, Colorado 80910
- Varicon 3M
  Traffic Control Products Division
  3M Center
  St. Paul, Minnesota 55101
- Ve-Pad Traffic Controls, Inc.
  11313 North Broadway
  Rt. 2, Box 33
  Oklahoma City, Oklahoma 73114
- Winkomatic Signal Company
  659 Miller Road
  P.O. Box 155
  Avon Lake, Ohio 44012

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APPENDIX B

STUDY PROCEDURE

The conduct of this field study required a number of specific activities. Prerequisite activities prior to the actual data collection involved coordination with several highway agencies and the careful selection of sites and data collection procedures to ensure the overall success of the effort. Two types of data collection were conducted: traffic operations measurement and in-vehicle response measurement.

PREREQUISITE ACTIVITIES

Establish Agency Contacts

Survey of researchers' knowledge of CMS application and NCHRP 3-21 (2) panel members led to the identification of 10 candidate states likely to make application of CMS at freeway lane closures. Correspondence with traffic engineers in these states resulted in a list of five state agencies that exhibited highway and CMS conditions meeting project requirements. Finally, because of scheduling limitations, four states were designated as data collection sites. These were South Carolina, Georgia, Colorado, and California.

Among the information gathered in preselection visits to each state were names of state or contractor personnel who would be available to serve as liaison for the purpose of providing construction (and lane closure) scheduling information required for conducting data collection activity.

Determine Candidate Site Characteristics

Each state visited had construction activity planned during the period June 1 to September 31, 1980. Locations of each construction project were ascertained, and a site survey was performed to determine appropriate site characteristics (e.g., availability of suitable data collection observation points) and highway/traffic features. Lengths of planned construction projects varied from 5 to 12 miles (8 to 19 km). A preselection survey procedure involved driving the length of the project while taking a sufficient number of photographs to adequately illustrate appropriate features. Accompanying the pictures was a voice recording to provide supplemental information (i.e., location at which each picture was taken via matching mileposts with odometer readings). The result of this procedure essentially comprises photolog data of each candidate construction site. Sufficient descriptive data were collected during each preselection visit to support the subsequent selection of sites based on highway features (e.g., number of traveled lanes, sight distance), traffic volume and mix, and CMS characteristics.

Select Sites

Primary selection criteria for field test sites were lane closure condition, traffic characteristics, availability of questionnaire subjects, CMS availability, and duration of construction activity. States were selected that offered specific advantages in support of project objectives. South Carolina was the only state, evident from the survey, where planned construction activity involved an interior lane closure (center of three lanes). One CMS manufacturer offered the gratis use of a CMS device, limited to application within the State of Colorado. In addition, Colorado provided the greatest flexibility in terms of CMS availability (e.g., they agreed to the research team's use of any CMS type or message content). As data collection progressed and the research team was unable to obtain a baseline (no CMS) condition in South Carolina, additional data were collected in Georgia because of its close proximity. Ultimately, California afforded the best experimental condition in that a variety of CMS devices could be tested at one location.

Designate Changeable Message Signs

Selection of devices for testing was representative of the state of the art, and application was consistent with current practice. However, certain limiting constraints affected device selection. First, resource allocations associated with NCHRP Project 3-21(2) were earmarked for evaluative purposes, and the budget did not support the purchase or rental of devices. (This would be an expensive item, e.g., average CMS device cost exceeds $23,000). Second, because of the consequent dependency on state agency application of devices, one was by-and-large limited to equipment in current state inventories. The devices listed in Table B-1 were used in the field tests.

One objective of this project was to determine the effectiveness of specific device characteristics. A variety of devices were selected to include a wide range of changeable message sign characteristics. While it was not intended to conduct an exhaustive experimental treatment of performances associated with specific formats, a representative cross section of message presentation modes (1-, 2-, and 3-line devices) and two display techniques (bulb matrix and rotating drum) were included. Varied message phasing strategies were represented. Continuously displayed messages were presented on the 2-line, rotating drum device; a two-phase presentation was tested using the 3-line, bulb matrix device; and a three-phase presentation was used on the 1-line, bulb matrix device.

Designate Message Content

Guidance requirements of motorists approaching a work zone indicate that the following three types of information are appropriate for presentation using CMS:

1. Speed advisory—safe speed requirements for the construction zone (based on highway geometrics necessary to divert traffic around the work site).
2. Closure advisory—an indication of the modified lane configuration required to accommodate construction activity.
3. Merge direction—an imperative statement of merge activity required for traffic to negotiate the modified lane configuration.

Tables B-2, B-3, and B-4 depict selected presentation formats of the above information for 3-, 2-, and 1-line CMS devices, respectively.

Table B-1. Characteristics of tested CMS devices.

Device Characteristics / Manufacturer	CMS Type	No. of Lines	Maximum Characters Per Line	Message Presentation Mode
Winko-matic	Bulb Matrix	3	9	Continuous or Alternating
Energy Absorption	Bulb Matrix	1	7	Continuous, Alternating, and Sequential
Traffic Control Systems	Rotating Disk Drum	2	12	Continuous

Table B-2. Message combinations using 3-line bulb matrix format.

	LEFT CLOSURE	RIGHT CLOSURE
Speed Advisory	Max Speed 45 MPH	Max Speed 45 MPH
Closure Advisory	Left Lane Closed	Right Lane Closed
Merge Direction	Merge Right	Merge Left

Table B-3. Message combinations using 2-line rotating disk device.

	LEFT CLOSURE	RIGHT CLOSURE
Speed Advisory	MAX SPEED 45 MPH	MAX SPEED 45 MPH
Closure Advisory	LEFT LANE CLOSED AHEAD	RIGHT LANE CLOSED AHEAD
Merge Direction	LANE CLOSED MERGE RIGHT	LANE CLOSED MERGE LEFT

Table B-4. Message combinations using 1-line bulb matrix format.

	LEFT CLOSURE	RIGHT CLOSURE
Speed Advisory	SLOW 45 MPH	SLOW 45 MPH
Closure Advisory	LEFT LANE CLOSED AHEAD	RIGHT LANE CLOSED AHEAD
Merge Direction	MERGE RIGHT	MERGE LEFT

Designate Data Collection Procedures

Decisions regarding appropriate measures (what behaviors were observed) and methods (how behaviors were observed and recorded) were based on the need for portable, cost-effective, and sensitive data collection procedures. Measures of effectiveness were by-and-large evident on the basis of previous NCHRP research. NCHRP Project 17-4 had demonstrated that approach speeds and lane distributions were appropriate operational measures of traffic control device effectiveness on the approach to construction zone lane closures. NCHRP Project 3-21 had developed a set of evaluation measures including driver detection, recognition, and comprehension of signs.

Although previous operational evaluations of construction zone traffic control devices were based solely on operational measures, the need for a more sensitive technique was nevertheless apparent. Operational evaluations, while frequently attributing an observed behavioral effect to a specific cause (e.g., new traffic control device), fail to measure underlying causes such as driver motivational aspects of behavior. Moreover, the nature of the current study required sensitive driver input regarding issues such as CMS device design and the relative message impact of the CMS versus the arrowboard. For these reasons it was decided to conduct a questionnaire portion of the field study in addition to the traffic operational procedure.

Because of the requirement for portability, manual traffic observation techniques were chosen over a tapeswitch system such as the Traffic Evaluator System (TES). As construction operations frequently relocate several times within a day, the idea of collecting data via tapeswitches was untenable. Thus, a decision was made to rely on manual coding procedures with time-lapse photography as a backup.

Speed measurement via electronic stopwatch had been validated in NCHRP Project 3-21. This technique involved using electronic stopwatches with an accuracy of 1/100 sec. In preparation for the field study, an intercoder reliability test of the method was conducted. Table B-5 notes independent timings between two observers of 10 vehicles in a lane of freeway traffic. Vehicles were naturally timed in seconds, and the data were converted to mph; e.g., 2.50 sec over 200 ft (60 m) = 54.5 mph (87.2 kph) for presentation in the table. It can be noted for the sample of 10 vehicles that the mean differed by only 0.1 mph (0.16 kph) between the two observers. A Pearson-Product Coefficient, r = 0.96, also attests to the high reliability of this measurement technique. On the basis of these data and other evidence (NCHRP Project 3-21 Final Report), it was evident that this technique would yield individual speed measurements to an accuracy of 1 mph (1.6 kph).

Given this level of speed measurement precision, a determination was made of the required sample size for a specific level of statistical significance. Assuming a standard deviation of 5 mph (8 kph), which is slightly more conservative than the example shown in the table, a variance of 25 mph (40 kph) would be expected. In order to detect a 1-mph (1.6-kph) speed difference at the 0.01 level (Student's t = 2.58), the required sample size is given by N = (2.58) (2 × Expected variance), which is 129 vehicles in this case. Thus a minimum of 129 vehicles per data collection location for each condition was determined to be suitable. A data collection procedure was designed to yield this number of speed observations per hour in order to measure expected speed fluctuations.

Table B-5. Results of intercoder reliability determination.

Observer #1	Observer #2
54.5 mph	53.3 mph
47.3	48.0
52.9	51.7
52.2	53.5
57.1	57.5
61.4	62.3
53.5	52.7
53.9	52.7
50.7	51.3
53.3	55.0
AVG = 53.7 mph	AVG = 53.8 mph
STD DEV = 3.7 mph	STD DEV = 3.9 mph

Correlation between observers, r=.96

Manual observation was also designated as the method for gathering lane distribution data because of its low cost and high reliability. Ten-minute sampling intervals twice each data collection hour were sufficient to monitor volumes and lane distributions.

The method for gathering in-vehicle questionnaires involved considerable advance preparation. Newspaper ads were run to recruit subjects for a "national safety study." In addition, local personnel in states designated for data collection were hired to screen test subjects in order for the sample to comply with prerequisite age/sex distribution requirements.

The selected questionnaire administration procedure involved having test subjects drive their own vehicles past the construction area. In order to ensure nonbiased responses, the subjects were not aware of study objectives until they had completed the drive-through. Introductory instructions provided to subjects merely advised that this was a nationally sponsored driving safety study to gather data regarding normal driving habits and attitudes of motorists (not a total fabrication). The subjects were requested to drive normally over a prespecified route prior to completing the questionnaire.

Table B-6 summarizes the designated data collection procedures.

DATA COLLECTION PROCEDURE

Two separate procedures were applied. Manual coding of vehicle performance was used to gather traffic operational responses to the CMS alternatives; in-vehicle driver questionnaires were administered to driving test subjects.

Traffic Operations Measurement

Manual observations of vehicle speed and lane placement were obtained at the data collection points shown in Figure B-1. Uniform location of traffic measurements with respect to CMS and construction zone was maintained across sites. Rationale for location of data collection points is as follows. The first point, adjacent to the work zone, is a location where traffic operational safety is of obvious importance. In particular, flow smoothness is a measure of safety, and mean speeds determine motorists' conformance to advisory speed information posted on the CMS. The second point, 100 ft (30 m) from the beginning of taper, was the critical point for determining the incidence of critically late lane exits from the closed lane. The third point, midway between the CMS and taper, simply provided a central translation measure on both the lane change and speed reduction profiles. The fourth point, the CMS location, provided an indication of initial driver response to the CMS, as it was the first behavioral observation (speed following the measurement of "unaffected" or advance data. The final collection point, 2000 ft (600 m) upstream from the CMS, was just beyond sight distance of the sign. Measures observed there described "normal" flow behavior, characterized by non-CMS-related conditions. These data examined time of day, etc., and other uncontrolled effects.

Simultaneous manual coding was conducted at each of these observation points. An integrated procedure of traffic volume counting and speed measurement is outlined in Table B-7. Fairly short observation intervals (10-min traffic counts and 15-min speed sampling periods) were designated to ensure adequate coder vigilance. Each function was repeated at 30-min intervals.

An important aspect of the procedure is that vehicles were randomly selected for speed measurements. The speed data collection form (see Appendix C) included selection criteria

Table B-7. Traffic operations data collection procedure summary.

Data Collection Times

a.m. peak: 6:30 a.m. - 8:30 a.m.
off-peak: 10:00 a.m. - 11:30 a.m. and 1:30 p.m. - 3:00 p.m.
p.m. peak: 4:00 p.m. - 6:30 p.m.
darkness: 9:30 p.m. - 11:00 p.m.

Within-Hour Schedule

:00 - :15 Speed Sampling	:30 - :45 Speed Sampling
:15 - :25 Volume Counting	:45 - :55 Volume Counting
:25 - :30 Break	:55 - :00 Break

Speed Sampling

Use random selection procedure as follows:

1. Vehicle alternately selected between traffic lanes.
2. Random selection table applies to identify vehicle arrival within lane.
3. If no vehicle arrival was observed in designated lane within ten seconds, first vehicle to arrive was sampled.

Truck speeds were separately recorded by lane.

Within-hour speed sampling times were: :00 - :15 and :30 - :45.

Separate form for each 15-minute period.

Lane Distribution Counting

Vehicle counts recorded by traffic lane.
Within each lane, separate codes were noted for trucks and other vehicles.

1. Truck = tractor-trailer combinations.
2. Bus = intercity type (e.g., Greyhound).
3. These were coded as "trucks"; all other vehicles (including motorcycles and schoolbuses) were "nontrucks."

Ten-minute sampling periods were applied, timed to the nearest second (using electronic watch).

Within-hour sampling times were: :15 - :25 and :45 - :50.

Table B-6. Designated data collection procedures.

Measures	Collection Method	Procedure
Traffic Operations		
Speed Speed Variance	Stopwatch Timing	Precise manual timing between pavement markings. Random selection of vehicle arrivals, representative across lanes; separate code for trucks and non-trucks.
Lane Distribution	Manual Counts	Record lane volumes by vehicle type.
Intervehicle Driver Responses		
CMS Detection, Message Recall, Interpretation Overall Device Rating CMS Design Adequacy Driver Characteristic Effects on Speed Selection	Questionnaire	Subjects selected for "national safety study" on basis of age/sex distribution; drive own vehicle over test route; speeds and lane change behavior unobtrusively gathered from "chase car"; subjects complete survey form and interview by principal investigator following drive-through.

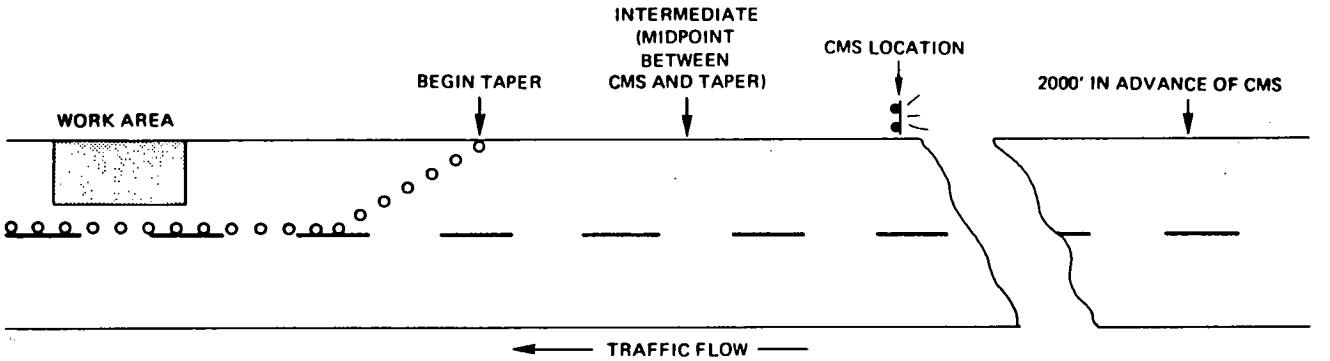

Figure B-1. Illustration of collection point locations for traffic operations data (1 ft = 0.3 m).

for choosing the first or second vehicle arrival using a random number table. Speed measurement was accomplished via precise timing (using an electronic stopwatch readable to 1/100 sec) of vehicles traveling between unobtrusive pavement markings spaced 2000-ft (600-m) apart. Systematic vehicle selection was necessary to avoid bias which could potentially affect results. The procedure applied in this study was to randomly select vehicles evenly distributed across lanes. As trucks represent a much smaller proportion of the traffic stream, preference was given to them in order to ensure an adequate sample.

Lane placement profiles were determined via recording traffic volume (and mix) by lane at each of the designated five locations. These data were collected using 6-bank (cars, trucks for each of three lanes) manual counting machines. The foregoing data were collected for each of the three following traffic conditions according to a prescribed schedule. Designated traffic conditions are peak hour (high volume), off-peak (low volume) flow during daylight hours, and one volume condition during hours of darkness.

The heavy reliance on manual data collection procedures necessitated scheduling in such a way as to maximize coding reliability. Human factors considerations warrant that short data collection periods be designated to ensure adequate vigilance on the part of observers. With these constraints in mind, daily data collection times noted in the table provide minimal within-hour times required to gather a statistically reliable data base.

Two hours of peak flow each day were designated in contrast to three hours of off-peak flow in order to approximately balance sample sizes. In addition to providing needed rest time for data coders, the selected data collection schedule clearly distinguished between hours of predictable peak and off-peak flow. Possible confounding effects which may be associated with quasi-peak conditions (e.g., lunchtime traffic flow in urban areas) were avoided.

Driver In-Vehicle Response Measurement

This technique provided human factors measures of driver detection, recognition, and comprehension required for a valid assessment of CMS effectiveness. The applied questionnaire is contained in Appendix C. From this set of questions, variables in the following areas were developed for use in the analysis.

1. Site and environment description—traffic condition, closure type, CMS condition, weather.
2. Driver characteristics—age, sex, familiarity with site, driving experience, formal education, driving attitude profile.
3. Scalar rating of devices—adequacy of warning devices, helpfulness of signs (overall and CMS).
4. Information required of warning devices—ranking of importance, whether or not this information was provided, best presentation mode.
5. Assessment of CMS effectiveness—driver comprehension of CMS message, helpfulness of device, rating of information provided, rating of time available to read CMS, rating of ease with which CMS was read, recommendations for changes in CMS design, self-report of CMS effects on driving past the construction site.

A sample of 489 questionnaires was obtained; age and sex distributions were controlled to ensure representativeness. Subjects were acquired via newspaper advertisements and paid $15 each to participate in a "national safety study." The applied procedure to obtain unbiased responses was as follows.

Respondents to the newspaper ads were selected to be test subjects on the basis of age and sex. Selection criteria were designated to yield the following sample characteristics: a 50-50 male/female ratio; 20 percent under 20 years of age; 60 percent between 21 and 59; and 20 percent aged 60 or older. Arrangements were made for test subjects to meet with an experimenter several miles from the construction site. General instructions regarding the route to be driven were provided, and all subjects drove their own vehicles. Once past the construction area, subjects based questionnaire responses on the drive which they had just completed. During the actual drive-through, subjects had no knowledge that the study related to construction areas or highway signing.

The initially planned procedure was to have an experimenter ride in the vehicle with the subject. However, pretest results indicated less bias in selected driving speed when subjects drove unaccompanied. Thus, the procedure was modified such that the driver of an unmarked "chase car," following sufficiently far back so as not to affect the subject's driving, unobtrusively recorded speed data via electronic stopwatch and preexisting special pavement markings.

Series of intercoder reliability studies were applied to validate this collection method.

Each subject drove to a designated exit location and completed the questionnaire. Upon returning the completed questionnaires to the original meeting place, each subject was interviewed by the principal investigator to ensure the validity of questionnaire responses.

APPENDIX C

FIELD DATA FORMS AND DRIVER QUESTIONNAIRE

This appendix contains those forms which supported the field study.

The first form, Speed Sampling Form, was completed in its entirety during each 30-min data collection interval. For 15 min during this interval, vehicles were sampled using the following procedure. The coder would start with the right lane and select the first vehicle to arrive. The first vehicle was chosen because the first number in the column headed "Randomization" is a 1. In the event that no vehicle would arrive in the right lane in approximately 10 sec (this 10-sec interval was approximated), the first vehicle to arrive in any lane would be timed and the time entered into the appropriate lane column.

To select the second vehicle, the coder would look to the center lane and time the second arriving vehicle (the next number in the random number table is a 2). Again the 10-sec rule would apply in case of a "no show." The third vehicle would be selected from the left lane, then back to the right for the fourth vehicle, and so on. Approximately 50 vehicles were timed, on the average, during a 15-min interval.

The second form was used to record manual counts of trucks and nontrucks, by lane, for the indicated time intervals. One form per day was used at each recording station.

Following is a set of instructions given to test subjects prior to their drive-through. The subjects naturally were not made aware of the study objectives.

Section I of the questionnaire was completed by an experimenter. In most cases, this was the driver of the unobtrusive "chase car" who made speed observations as the subject approached designated points on the construction zone approach. In a few instances (about 10 percent of the questionnaire sample), Section I was filled out by an in-vehicle experimenter who rode in the subject's car.

Section II was filled out by the subject prior to the drive-through. This procedure was necessary to screen illiterate subjects. In the event that a subject was unable to fill out a form, an experimenter rode with the subject and verbally administered Section III following the drive. Otherwise, Section III, in a sealed envelope, was given to the subject to be filled out on reaching his destination.

SPEED SAMPLING FORM

Observer: _____
Site: _____
Date: _____
Time: _____
Station: _____

Randomization	A	B	C	D	E	Comments
	Non-Trucks			Trucks		
	Shoulder Lane 1	Center Lane 2	Median Lane 3	All Lanes	L #	
1,2,2						1
2,1,1						2
1,2,1						3
1,1,2						4
1,1,2						5
2,2,1						6
1,2,1						7
2,1,1						8
2,1,1						9
2,2,1						10
2,2,1						11
2,2,2						12
1,1,2						13
2,1,1						14
1,2,2						15
2,2,1						16
1,2,1						17
2,2,2						18
1,1,2						19
1,1,1						20
1,1,2						21
1,1,1						22
2,1,1						23
1,2,1						24
2,1,1						25
1,2,1						26
1,1,2						27
1,2,2						28
2,1,2						29
1,2,1						30
2,1,2						31
TOTAL						

VOLUME COUNTS

Observer: _____
Site: _____
Date: _____
Station: _____

Time	F	G	H	I	J	K	Comments
	Left		Center		Right		
	Non-Truck	Trucks	Non-Truck	Trucks	Non-Truck	Trucks	
6:45-6:55							1
7:15-7:25							2
7:45-7:55							3
8:15-8:25							4
10:15-10:25							5
10:45-10:55							6
11:15-11:25							7
1:45-1:55							8
2:15-2:25							9
2:45-2:55							10
4:15-4:25							11
4:45-4:55							12
5:15-5:25							13
5:45-5:55							14
9:45-9:55							15
10:15-10:25							16
10:45-10:55							17
11:15-11:25							18

INSTRUCTIONS TO SUBJECT

The driving experiment which you have agreed to participate in is sponsored by the National Cooperative Highway Research Program and is related to highway safety. We would like you to drive your own automobile over a specified route in a normal fashion according to the way you usually drive. An experimenter will accompany you as a passenger, but will not influence your driving in any way. You are welcome to share with the experimenter any comments which you may have regarding the route and highway during the drive; however, do not permit this activity to affect your driving.

The only instructions which you are to be given regarding your route are as follows:

"Take __(name)__ street to Interstate __(number)__ and proceed __(direction)__ bound as if you were going to __(destination)__."

Are there any questions regarding this route? At some point you will be given further route directions in order to permit your return to this starting point in less than one hour from now.

Before you begin your drive, please fill-in the following questionnaire.

(The subject will be given SECTION 2 prior to the drive-thru and SECTION 3 immediately following.)

Date: _____

Time: _____

SECTION 1

(Experimenter Fill-In)

1: Questionnaire Number [1] _____

2: Site Number [2] _____

3: CMS Message Content [3]

_____ 1. None (Base Condition)
_____ 2. Speed Advisory
_____ 3. Closure Advisory
_____ 4. Merge Direction

4: CMS Type [4]

_____ 1. Bulb Matrix (3-line)
_____ 2. Bulb Matrix (1-line)
_____ 3. Rotating Disk

5: Lane Closure [5]

_____ 1. Right
_____ 2. Center
_____ 3. Left

6: Weather [6]

_____ 1. Fair
_____ 2. Cloudy
_____ 3. Raining

7: Pavement Condition [7]

_____ 1. Dry
_____ 2. Wet

8: Ambient Condition [8]

_____ 1. Daylight
_____ 2. Darkness

9: Traffic Condition [9]

_____ 1. Rush hour
_____ 2. Non-rush hour

10: Vehicle Trajectory

Speed	Lane (L, C, R)			
10 _____	_____	_____	_____	Station 1
11 _____	_____	_____	_____	Station 2
12 _____	_____	_____	_____	Station 3
13 _____	_____	_____	_____	Station 4
14 _____	_____	_____	_____	Station 5

Leave Blank _____

(15) (16) (17)

11: Was subject's lane change affected by other traffic?

18 _____ Yes (go to A) _____ No

A. Where would subject have preferred to change lanes?

19 Station _____

12: Subject was cued on the following questions.

_____ 77	_____ 81	_____ 85	_____ 89
_____ 78	_____ 82	_____ 86	_____ 90
_____ 79	_____ 83	_____ 87	_____ 91
_____ 80	_____ 84	_____ 88	_____ 92

13: Did subject wear seat belt?

20 _____ Yes _____ No

14: Comments:

21, 22

SECTION 2

(Pre Drive-Thru; Driver Fill-In)

Driver Biographical Data

1: Age 23

_____ Under 21 _____ 41-50
_____ 21-30 _____ 51-60
_____ 31-40 _____ over 60

2: Gender 24

_____ Male
_____ Female

3: Years Driving Experience 25

_____ less than 1 year _____ 6-10 years
_____ 1-2 years _____ more than 10 years
_____ 3-5 years

4: Last Formal Education Completed 26

_____ Grade School _____ College, Undergraduate
_____ High School _____ College, Graduate

5: What is your occupation? 27

_____

6: How old is the car you are driving today? 28

_____ less than 1 year _____ 3-4 years
_____ 1-2 years _____ more than 4 years

7: How long have you been driving the particular vehicle you'll be driving today? 29

_____ less than 1 year _____ 3-4 years
_____ 1-2 years _____ more than 4 years

8: How far from this location do you currently reside? 30

_____ less than 1 mile _____ 5-20 miles
_____ 1-5 miles _____ more than 20 miles

9: Do you usually wear seat belts when you drive? 31

_____ Yes
_____ No

Driver Attitude Profile

Please respond to these statements expressing your own feelings.
Use the following scale:

1. Strongly Agree
2. Agree
3. Undecided
4. Disagree
5. Strongly Disagree

10: I have the ability to control my automobile at high speeds.
32
1 _____ 2 _____ 3 _____ 4 _____ 5 _____

11: Because of the sturdy construction of my vehicle, I feel safe driving at any speed.
33
1 _____ 2 _____ 3 _____ 4 _____ 5 _____

12: I like to drive at relatively high speeds.
34
1 _____ 2 _____ 3 _____ 4 _____ 5 _____

13: I like to pass cars when driving at relatively high speeds on two-lane roads.
35
1 _____ 2 _____ 3 _____ 4 _____ 5 _____

14. When avoiding a hazard, I steer around it rather than use my brakes.
36
1 _____ 2 _____ 3 _____ 4 _____ 5 _____

15: I believe traffic regulations are designed for unskilled drivers.
37
1 _____ 2 _____ 3 _____ 4 _____ 5 _____

16: From time to time, I enjoy finding myself in a situation that challenges my driving skills.
38
1 _____ 2 _____ 3 _____ 4 _____ 5 _____

SECTION 3

(Post Drive-Thru; Driver Fill-In)

INSTRUCTION: Complete all information on each page before proceeding to next page.

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. 39

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

2. Note one feature about the warning devices which you liked. 40

3. Note one feature about the warning devices which you disliked. 41

4. On your approach to the construction area, what was the most important information you needed from the warning devices? 42

   Do you feel this information was adequately provided? 43

   Yes _____
   No _____
   Unsure_____

5. What was the second most important information you needed? 44

   Do you feel this information was adequately provided? 45

   Yes _____
   No _____
   Unsure_____

6. What type of sign (or other device) can best provide this information for you? 46

7. Please rate the signs as to how helpful you think they were. 47

Not at all helpful	Somewhat helpful	Extremely helpful
0	1	2

8. Please note one feature of the signs which you liked. 48

9. Please note one feature of the signs which you disliked. 49

10. Do you recall seeing a changeable message sign during your drive? 50

Yes _____ No _____

What was the sign's message? 51

(GO TO NEXT PAGE)

Did you see this sign? Yes__ No__

Please consider the sign in this picture while answering the following questions.

12. How helpful was this sign to you? 53

Not at all helpful	Somewhat helpful	Extremely helpful
0	1	2

13. How would you rate the information displayed on the sign? 54,55

_____ too much information;
I did not need to know that _____

_____ too little information
It would have been helpful to know _____

_____ the correct amount of information was shown.

14. Consider the length of the message, and rate the amount of time you had to read and react to the sign. 56

_____ More than enough time
_____ About the right amount of time
_____ Less time than I would have liked
_____ Not enough time at all.

15. Consider how the sign looked, and rate the ease or difficulty with which you could read it. 57

Much Difficulty	Some Difficulty	Borderline	Some Ease	Much Ease
1	2	3	4	5

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

58 Overall size: Larger _____, Smaller _____, Neither _____
59 Letter Size: Larger _____, Shorter _____, Neither _____
60 Letter Brightness: Brighter _____, Dimmer _____, Neither _____
61 Message Length: Longer _____, Shorter _____, Neither _____
Different Colors
62 Overall Sign: Color OK _____; other color (specify) _____
63 Message: Color OK _____; other color (specify) _____
64 Different Message:

17. Did this sign affect your driving as you approached the construction area? 65

_____ Yes (go to A & B); _____ No (go to jail)
_____ Not Sure (thanks for being honest)

A. I changed lanes 66
_____ earlier
_____ later
_____ neither

B. I changed speed 67
_____ sped up
_____ slowed down
_____ neither

18. What other factors affected your driving as you approached the construction area?

    A. Highway Signs (Yes _____, No _____) 68,69
        Which? _____
    B. Warning Devices (Yes _____, No _____) 70,71
        Barricades _____
        Cones _____
        Sequential Arrow _____
        Flagman _____
    C. View of Construction Activity (Yes_____, No_____) 72
    D. Other _____ 73

19. Of those factors mentioned in questions 17 and 18, which exerted the greatest influence on your driving? 74

20. About how often do you normally drive by the area which is currently under construction? 75

    _____never before
    _____once or twice before
    _____monthly
    _____weekly
    _____daily
    _____more often

21. About how often have you driven through this area since the construction activity has been underway? 76

APPENDIX D

SITE DIAGRAMS AND TESTED CMS CONDITION

Typical traffic control layouts used in each of the four test states are shown in Figures D-1 through D-4. Photographs of the applied devices are included in the appropriate site layout figures. Specific CMS placement alternatives and message conditions are given in Table D-1.

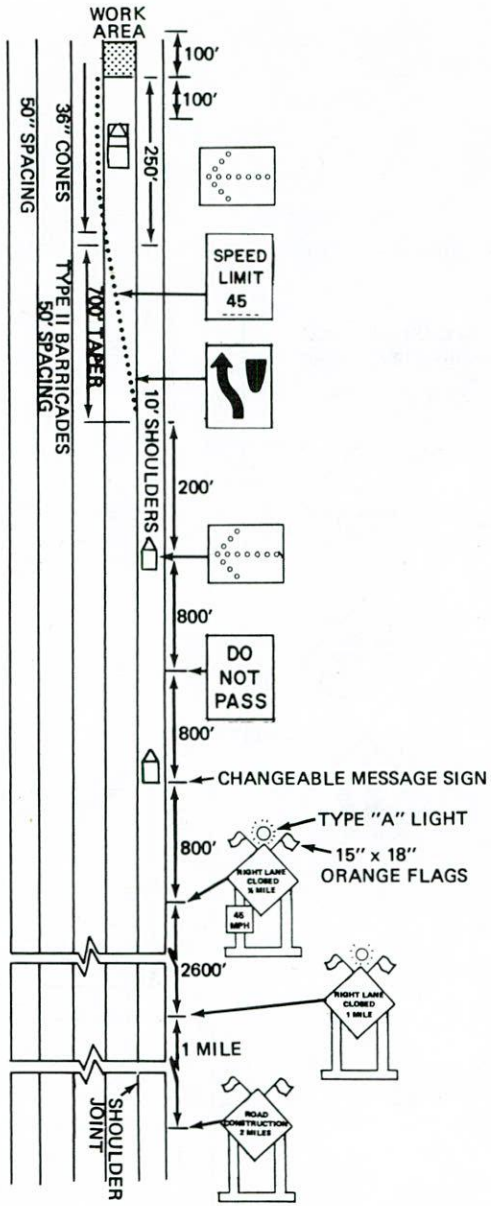

Figure D-1. Typical lane closure and traffic control device layout (South Carolina).

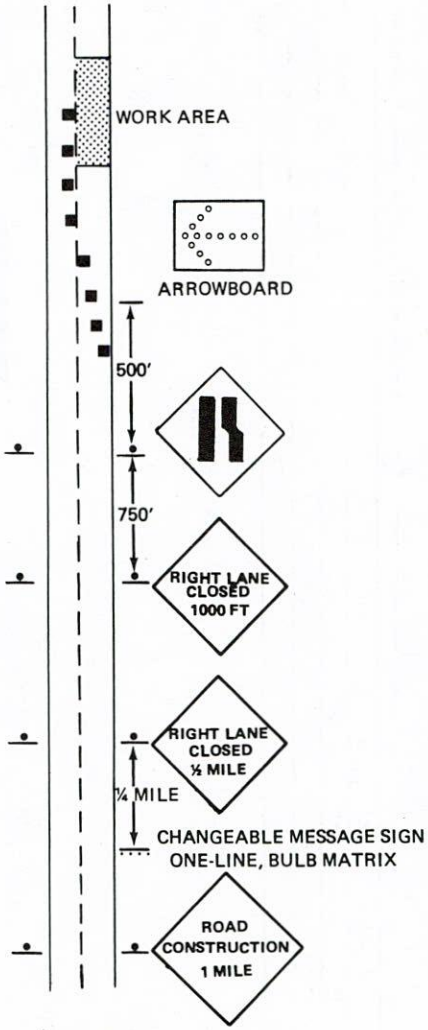

Figure D-2. Typical lane closure and traffic control device layout (Georgia).

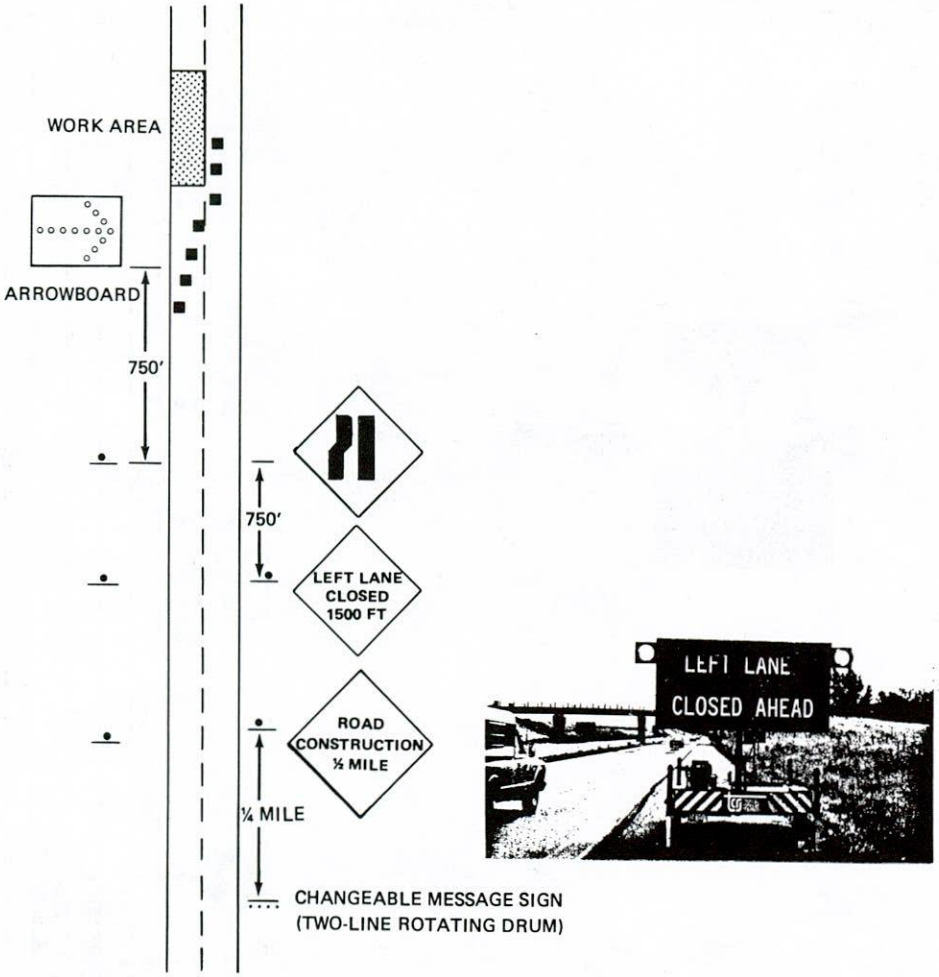

Figure D-3. Typical lane closure and traffic control device layout (Colorado).

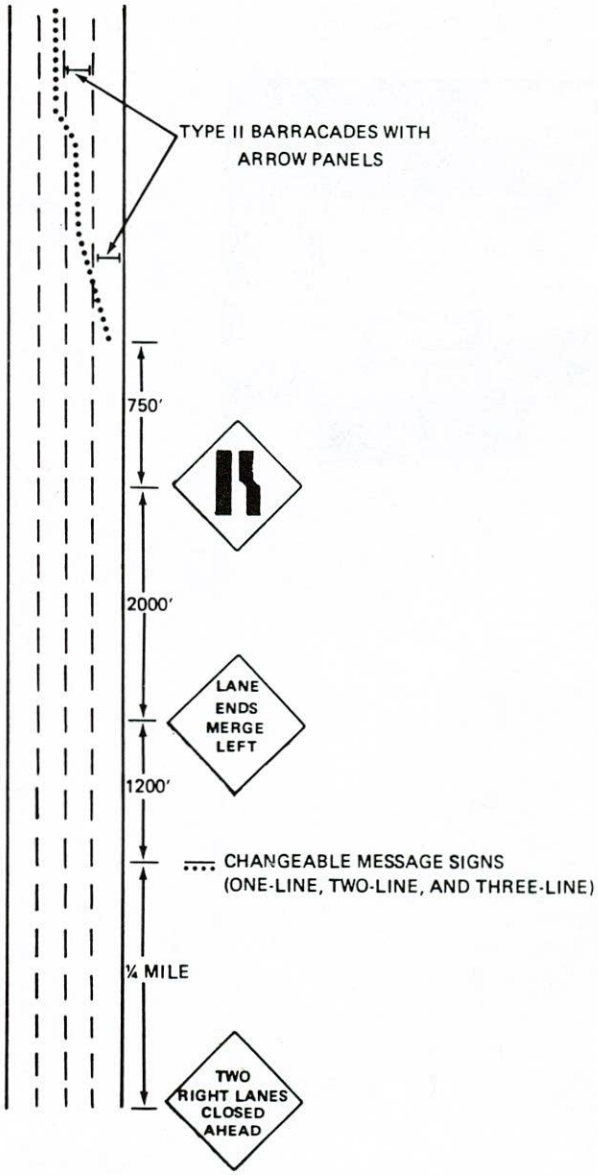

Figure D-4. Typical lane closure and traffic control device layout (California).

Table D-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	LEFT 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 / 15 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 ←

THE TRANSPORTATION RESEARCH BOARD is an agency of the National Research Council, which serves the National Academy of Sciences and the National Academy of Engineering. The Board's purpose is to stimulate research concerning the nature and performance of transportation systems, to disseminate information that the research produces, and to encourage the application of appropriate research findings. The Board's program is carried out by more than 250 committees, task forces, and panels composed of more than 3,100 administrators, engineers, social scientists, attorneys, educators, and others concerned with transportation; they serve without compensation. The program is supported by state transportation and highway departments, the modal administrations of the U.S. Department of Transportation, the Association of American Railroads, and other organizations and individuals interested in the development of transportation.

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TRANSPORTATION RESEARCH BOARD
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Washington, D.C. 20418

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