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NATIONAL COOPERATIVE
HIGHWAY RESEARCH PROGRAM REPORT **337**

SERVICE VEHICLE LIGHTING AND TRAFFIC CONTROL SYSTEMS FOR SHORT-TERM AND MOVING OPERATIONS

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL

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SERVICE VEHICLE LIGHTING AND TRAFFIC CONTROL SYSTEMS FOR SHORT-TERM AND MOVING OPERATIONS

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AREAS OF INTEREST

- Maintenance
- Construction and Maintenance Equipment
- Transportation Safety
- Human Factors
- 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

This report will be of special interest to traffic and construction engineers responsible for the development of traffic control plans for short-term and moving work zone operations. The research analyzed a variety of service vehicle lighting and marking schemes and traffic control practices to warn motorists of the hazards related to workers and equipment on or near the roadway. The findings of the research on the relative effectiveness of various service vehicle lighting and marking schemes and advance warning practices may provide the basis for the modification of federal, state, and local standards for work zone traffic control. In addition, private agencies which conduct periodic maintenance of their infrastructure in the highway right-of-way may find it beneficial to evaluate their equipment and procedural manuals in the context of the findings presented here. The continuing safety problems associated with workers and equipment in or near the roadway makes it important for agencies to consider the findings of this research.

A wide variety of service vehicle lighting and marking schemes and advance warning practices are used to delineate equipment used on or near the roadway. These schemes include the use of flashing beacons, strobe lights, arrowboards, and light bars in conjunction with various patterns, sizes, colors, and reflectorization of markings. Under NCHRP Project 17-6A, the Transportation Research Corporation undertook a study to develop guidelines for warning systems on service vehicles and for traffic control in short-term, intermittently moving, and continously moving work zones. While basic traffic and safety requirements were the primary focus of this research, operational efficiency and cost effectiveness of each treatment were considered in formulating the guidelines.

This research identified various service vehicle marking and lighting schemes that are in common use and structured a series of tests to determine the relative effectiveness of those schemes. The research included laboratory, closed field, and operational field tests of various types of short-term and moving work zone situations. The test data were used to study driver information needs, the effects of lighting intensity, pattern influences, and other factors. The research found differences in the manner in which various lighting schemes conveyed closure information to the motorist. It also assessed the influence of supplementary devices such as flags and signs in providing information to the motorist. The cost effectiveness of the various lighting and marking schemes was analyzed to develop recommendations for devices.

The findings of the research are summarized in this report together with an appendix which is intended as a user's guide for determining the most appropriate traffic controls to be used in various work zone situations. The user's guide provides a means to assess the traffic, facility type, work duration, roadway position, and other factors in deciding the proper traffic controls. This decision tool can be useful to persons responsible for providing traffic control in work zones to systematically consider the situational and work operations factors in selecting an appropriate traffic control scheme.

When reviewing the research findings in either the report or the appendix, readers must recognize that these recommendations require judicious application. Lighting and marking schemes used on agency equipment must function across a wide range of duty conditions, and it was not possible under the scope of this research to consider all conditions. For example, the effectiveness of devices under nighttime conditions or reduced visibility (e.g., fog, blowing snow) were not investigated. The findings presented herein represent an advancement in the understanding of means to provide motorist information, but further research is needed before definitive recommendations can be made for changes to current standards.

This document is an abridged version of the contractor's final report. The agency-prepared report contains other appendixes that, in addition to the guidelines, provide further details of the state-of-the-art review, assessment driver information needs, laboratory and closed-field experiments, field studies, and cost-effectiveness analysis. The agency final report is available on a loan basis, on written request to the National Cooperative Highway Research Program, Transportation Research Board, 2101 Constitution Avenue, N.W., Washington, D.C. 20418. It must be emphasized that the report and user's guide should be reviewed carefully prior to incorporation into state and local manuals used by service personnel in the planning and operation of short-term and moving work zones. The recommendations in the report have not been accepted by any agency or body as standards, and additional research questions still exist.

CONTENTS

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SERVICE VEHICLE LIGHTING AND TRAFFIC CONTROL SYSTEMS FOR SHORT TERM AND MOVING OPERATIONS

SUMMARY

This report has resulted from continuing research directed toward development of guidelines for traffic control and service vehicle warning lights for short-term (15 min or less) and moving work zone operations. The goal of the research was to provide guidance for the use of recommended treatments that have demonstrated effectiveness in the research, or show promise, for typical situations that are representative of a large number of possible maintenance situations. In addition, the guidelines were to be tailored to meet the needs of state and local agencies, as well as utility companies, in an operationally efficient and cost-effective manner.

This report documents the results of a two-phase effort. Phase I (NCHRP Project 17-6) included preparatory work consisting of a literature review, identification of short-term and moving situations, and the development of traffic control alternatives based on driver information requirements.

Key project activities undertaken in the second phase (NCHRP Project 17-6A) were carried out through laboratory and field studies. A survey of warning light device manufacturers and state highway and maintenance engineers provided information on current warning light applications, traffic control practices, available devices, and problems with applicable work zone operations. Specific types of work activities were determined for short-term lane closure and continuous-moving maintenance operations.

An analysis of driver information requirements permitted classifying all of these activities into 11 categories, which, in turn, were arranged in a decision-aid flow chart for use in categorizing any short-term or moving maintenance operation. A comparison of information requirements with state survey responses identified driver response problems with these types of work zones. One of the most prevalent problems noted was that drivers do not move out of the way of the work zone quickly enough to avoid a crash or panic avoidance maneuver.

Next, a laboratory study was conducted of rear-end truck markings and signing intended to deter drivers from cutting through convoys. Slides, depicting various rear-end marking treatments mounted on a dump truck, and taken at close (100 ft)

and far (300 ft) distances, were shown tachistoscopically to subjects. The marking that was most quickly and correctly responded to consisted of black diagonal stripes (minimum 8 in. width) on a background of orange (preferably reflectorized). A border of alternating orange and white reflectorized blocks (2 in. by 8 in.) around the diagonal striping was effective and demonstrated an accident reduction effect. A LANE BLOCKED AHEAD sign for advance signing was well understood by subjects. Three other sign messages—FOLLOW CONVOY, USE NEXT EXIT, and DO NOT CUT THROUGH CONVOY—were moderately well understood.

Closed-field testing was carried out on strobe, rotating, flashing, arrowboard, and light bar vehicle lighting systems. Variables included light intensity, flash rate, number of lights, mounting position, service vehicle speed, approach vehicle speed, and day versus night. Subjects rode in a test van as it followed simulated maintenance activity, at 300 ft at 35 mph, or 750 ft at 55 mph, with the service vehicle's speed at 3 to 4, 16 to 17, or 27 to 28 mph, with one of the lighting conditions. Subjects estimated the lead vehicle speed and how rapidly they were approaching the lead vehicle. This response provided a measure of the expected safety effect associated with the tested lighting systems.

Generally, the more slowly the lead vehicle traveled, the less accurate was the subject's perception of speed and closure rate. Subjects usually thought the lead vehicle was going faster than actual speed. Thus, the error was in the direction of increased hazard, i.e., subjects actually approaching faster than they sensed.

No effect on driver response was shown for certain light characteristics: flash rate (60 to 120), number of lights, mounting position, medium versus high intensity. Arrows and flashing lights (as opposed to rotating) were the most successful in reducing perceptual inaccuracies. The results of these tests, namely that information transmission was important, as is device conspicuity, were confirmed in the operational field tests.

A subset of lights from the closed field were tested with simulated maintenance activities on Maryland, New York, and Louisiana highways. Also tested in actual highway settings were the Ohio light (double-faced, side-mounted, amber beacons) and various applications of supplemental flags, shadow vehicle, and varied temporary ground-mounted sign characteristics (mounting heights, number of signs, and distance to work zone). Studied settings were lane closures on multilane roads and shoulders. The work zone either moved or was a short-term stop. As free floating cars approached the work zone, time from initiation of lane change to reaching the work activity was recorded.

Field tests of short-term closure operations revealed that one lighting system (two rotating beacons plus flashing light) was notably superior to other tested lighting systems (i.e., light bar, double flash strobe, and four-way with single flasher combination). Although the light bar often produced an improvement in terms of mean lane change times, associated occurrences of critically close lane changes suggested that drivers confused light bars with those on moving vehicles such as tow trucks. A number of applications for temporary ground-mounted signing proved beneficial. These were:

Placement—1,500, 1,000, and 500 ft in advance of taper. No advantage was found for additional signs at either 1-mile or ½-mile placement.
Flags—two supplemental orange flags placed on sign array are recommended.
Mounting height—1 to 1½ ft above pavement surface.

Finally, observations confirmed the utility of cones for application in short-term lane closures.

Field observation of continuous-moving maintenance activity resulted in a number of findings. Three lighting systems produced improved driver responses by comparison with "standard" two-bulb rotating beacons. The light bar produced slightly improved advanced lane change behaviors than either the Ohio light or the rotating beacon plus flashing light combination. (Preference for light bar use was substantiated by its superior performance in the laboratory study.) However, the remaining two lighting systems were rated nearly as good and were recommended for certain maintenance vehicle types (e.g., snowplows) that do not readily lend themselves to light bar application. The shadow vehicle, following 500 ft behind the moving maintenance operation, proved more effective than lighting systems at eliciting advance lane changes. Additionally, orange flags mounted on moving maintenance vehicles (to supplement two-bulb rotating beacon) elicited an improvement, while a static truck-mounted symbol MEN WORKING sign demonstrated no sustained benefit.

Field observation of shoulder closure operations was based on vehicle speed reductions, and occupancy shifts away from adjacent lanes were observed for various traffic control treatments. Application of test treatments was found to favorably affect adjacent lane traffic flow. Resulting recommendations indicated that supplementary flags be placed on warning signs 750 ft in advance of the shoulder closure. It was also recommended that application of lighting devices for shoulder operations be considered discretionary for use in extreme conditions, e.g., high volume combined with poor sight distance, inadequate lateral safety margin, long-term work durations, and nighttime maintenance activity.

Guidelines for work zone traffic control at short-term and moving operations were prepared using the results of the field and closed-field tests. The guide (see Appendix A) is designed for use as follows. Specific information (roadway type, duration and type of work activity, traffic volume) is entered in a decision-aid diagram that guides the user through a series of choices until the appropriate work zone category is found. By turning to the chart with the generic traffic control plan for that category, the user finds traffic control guidelines for the work zone classification being used.

The guidelines specify service vehicle lighting. Typical recommendations for moving operations include the use of light bar or Ohio light or two rotating beacons plus a flashing light. For short-term or stopped operations, the two rotating beacons plus flasher or Ohio light are recommended. Agencies must use their discretion on the type of lighting where vehicles must be used for both stopped and moving operations.

Guidance for ground-mounted signing is also included. For example, the mounting height of temporary signs placed on shoulders affected drivers and should be a minimum of 1 ft above the road surface, and three advance warning signs at 500, 1,000, and 1,500 ft are sufficient. Additionally, flags proved beneficial and are recommended for use on ground-mounted signs and moving service vehicles.

Because it is often difficult to weigh cost and time requirements versus safety benefits for particular traffic control schemes, cost-benefit results were applied in the development of the user's guide. Specifically, a cost-benefit logic addresses use of the shadow vehicle. Its cost is high, but the effect on driver behavior exceeds that of all other devices. The suggested cost-benefit scheme applies state accident data to help the maintenance administrator decide whether expected safety justifies shadow vehicle costs.

Recommendations for further research include developing a warning light that optimizes both information transmission and conspicuity, testing the traffic control recommendations in additional regions of the country to further generalize the findings, and developing innovative traffic control devices that meet driver information requirements but greatly reduce the time needed for set-up and removal.

CHAPTER ONE

INTRODUCTION AND RESEARCH APPROACH

PROBLEM STATEMENT

Construction and maintenance work on or adjacent to the highway present special hazards both to motorists and to workers. Most research to date has been directed at developing traffic control measures for use in relatively long-term work zones that generally involve extensive, ground-based traffic control devices. These traffic control measures may not be directly applicable to short-term (i.e., 15 min or less) or slow moving (i.e., 8 mph) maintenance operations for a number of reasons. First, the implementation of traffic control measures for long-term (longer than 15 min) work zones is too time consuming and costly for short-term or slow-moving operations. Second, the constant changing of ground-based traffic control systems to keep them current for slow-moving operations may create unnecessary driver confusion and increase worker exposure to hazards.

Service vehicles moving slowly or temporarily stopped on or adjacent to the travel lanes present a serious driving hazard, as evidenced by the substantial number of accidents involving such equipment. The frequency of these hazards has increased over the past few years as the requirements to rehabilitate and improve the existing road networks have increased. The problem has been compounded by rising traffic volumes, especially in urban areas.

RESEARCH OBJECTIVE

The overall objective of this two-phase project (17-6 and 17-6A) was to develop empirically based guidelines for the use of service vehicle warning light systems and ground-mounted traffic control devices in short-term and slow-moving maintenance operations. The specific objective of NCHRP Project 17-6A (Phase II) was to carry out the laboratory and field tests to confirm the effectiveness of the devices and systems proposed in Phase I.

RESEARCH APPROACH

To meet the project objectives, the research plan consisted of seven tasks. These tasks and the type of work performed are summarized as follows:

1. *Determine the state of the art in warning and traffic control device systems*—The state of the art was determined using three techniques. First, a literature review was conducted of U.S. and foreign research on the use and effectiveness of warning light and traffic control devices (TCD). Second, a survey was undertaken to obtain a representative sample of the experience of state traffic and maintenance engineers. This survey queried engineers regarding: (1) warning light use and experience, (2) TCD use in short-term and moving operations, and (3) accident experience in those operations. Third, a survey of warning light manufacturers requested catalogs, brochures, or data sheets giving the relevant product characteristics. The information provided was then synthesized for project use.

2. *Identify and classify short-term and moving work zone situations*—A task listing for short-term and moving work was developed based on the literature review, the experience of maintenance engineer consultants, the results of a nationwide traffic/maintenance engineer survey, and the information obtained from state maintenance or traffic control device manuals. The various working and site conditions found in short-term and moving operations were identified, and a scheme for classifying these work zones was developed.

3. *Identify alternative warning light and traffic control systems*—An analysis of the information requirements of the driver was based on the data obtained during tasks 1 and 2. Gaps or inadequacies in the information presented to drivers were identified by comparing this analysis with the usage of the traffic control devices and vehicle marking and warning systems revealed during Tasks 1 and 2. Warning light and traffic control alternatives were devised to provide the required driver information.

4. *Prepare a work plan and interim report*—The effort in tasks 1 through 3, which was primarily analytical in nature, formed the basis for identifying the experiments needed to provide the empirical data which would support the development of the guidelines. In this task, the experimental work plans were developed.

5. *Optimize vehicle markings and warning lights*—Three laboratory experiments were conducted. The first examined drivers' ability to rapidly and accurately identify markings on service vehicles. This was a static experiment, in that slides of actual truck markings were presented tachistoscopically to small groups of subjects. The second and third experiments were dynamic, in that they were conducted in a closed highway field setting. Subjects performed identification and interpretation tasks from a moving vehicle while observing moving vehicles. Warning light characteristics were varied in these experiments. The observed design characteristics were: intensity, light type (rotating, strobe, flasher), flash rate, mounting configuration, and combinations of light types. This final experiment measured information transmitted to the driver in terms of closure rate (how quickly the gap between driver and service vehicle was closing). On the basis of previous research findings, conspicuity was not considered in these laboratory experiments but was reserved for the field study.

6. *Determine effectiveness of warning lights and traffic control devices in operational use*—Field studies were carried out in three states: Maryland, New York, and Louisiana. Four warning light treatments showing greatest promise from task 5 and several traffic control device systems were installed on operating service vehicles and at short-term work zones. Extensive data were collected on driver response to baseline (e.g., existing standard) and test treatments. For the lighting systems, driver responses revealed both the conspicuousness and the effectiveness of information transmission. Different terrain and work-type scenarios

were included so that the results would be generalized to the population of moving and short-term work zones.

7. *Prepare a final report describing the research in detail and an operations guide describing recommended vehicle warning and traffic control systems*—The final report and operations guide have been prepared describing the recommended vehicle warning and traffic control systems developed under this project. The guide is designed to facilitate direct incorporation into state and local manuals used by service personnel in short-term and moving work zones.

The remainder of this report presents the results of the task 7 efforts. The operations guide developed in the research is provided as a self-contained document in Appendix A. The operations guide can be extracted from this report, adopted by the appropriate authorities and incorporated into state, local, and utility manuals for use by service personnel in short-term and slow-moving maintenance and utility operations.

The main body of the report is organized in the following manner. Chapter Two discusses the principal findings in this research effort. Chapter Three contains an interpretation and application of the findings, and Chapter Four outlines the conclusions and recommendations for further research. Appendix A provides the guidelines for use of vehicle warning lights and traffic control devices, both ground-mounted and vehicle-mounted, for each of the 11 categories of short-term and slow-moving maintenance operations. Each of the work tasks discussed previously is supported by an appendix (A through G) which describes the task in detail.

CHAPTER TWO

FINDINGS

The principal research findings presented in the following sections correspond to the project tasks identified in Chapter One. The state of the art identified in the literature review and survey of current practice is presented first, followed by an identification and classification of short-term and moving work zone activities. The results of an analysis of driver information needs, the findings of the indoor and outdoor laboratory experiments, and the results of the operation field studies are discussed next. The final two sections of this chapter deal with the benefits and costs of the field tested devices and the devices recommended for application to maintenance activities.

STATE OF THE ART

The state of the art in the area of service vehicle lighting and traffic control systems for short-term and slow-moving maintenance and utility work operations was determined through a review of the research literature and a survey of current practice. The literature fell into four basic areas: traffic guidance systems using signs and arrowboards, physical restraint systems such as crash cushions, traffic accident analyses, and vehicle visibility/lighting systems. Current practices used by state DOTs were determined by an examination of traffic control manuals and a survey of state traffic and maintenance engineers. Lighting systems were reviewed from a survey of manufacturers.

Literature Review

In the area of traffic guidance systems, data were identified on the mechanisms for providing information to drivers and drivers' requirements for information. In the former category, Owens (*1*) found that a 30-in. by 40-in. variable message sign located on a police vehicle at the scene of an accident had a significant effect on reducing the number of secondary accidents. The variable message was visible up to 1,000 ft and legible from 600 ft, day or night. Bryden (*2*) found that a large arrowboard was more effective than a small or no arrowboard. The large arrowboard was 36 in. high by 72 in. wide and the small arrowboard was 24 in. by 48 in. This finding was supported by the results of a study conducted by Hanscom (*3*) who noted that variable message signs were effective in providing information to drivers in advance of lane closures on high-speed freeways. Dudek (*4*) developed guidelines for using variable message signs at freeway work zones. In addition to providing drivers information through variable message signs and arrowboards, Richards et al. (*5*) found that the use of a STOP/SLOW sign paddle by a flagperson or hand motions was more effective in alerting and slowing drivers than any signals made with flags. The researchers also found that the effectiveness of flaggers can be improved through training in the appropriate procedures and through the wearing of the proper attire, e.g., vests.

Richards and Dudek (*6*) noted that providing drivers with the proper information in advance of the work zone was not sufficient for many drivers to take immediate action. Drivers tended not to change lanes in advance of a lane closure until they could see the work zone. In other words, advance warning signs have insufficient credibility. The researchers recommended a 1,500-ft advanced warning distance on freeways. The driver's need to see the work area is a critical element in the evaluation of signing requirements for short-term and slow-moving maintenance and utility operations that may be hidden over a hill crest or around a sharp curve.

A number of research reports were found on systems designed to physically prohibit vehicles from entering the work area. Most of this literature described energy-absorbing devices that are mounted on the rear of heavy utility vehicles or mounted on a trailer pulled by a heavy utility vehicle. The consensus of the reports is that these vehicle crash cushions are effective at protecting workers and the motoring public and they are cost effective, particularly on high speed, heavy volume roads. Most vehicle crash cushions in use today are cumbersome to maneuver and are expensive. To reduce these shortcomings, Carney (*7*) designed a crash cushion that is effective, light in weight, and low cost. In addition to the vehicle crash cushions, researchers have developed other systems that physically prohibit vehicles from entering the work area. One system designed by Sicking et al. (*8*) used abandoned cars aligned in single file with guardrail attached to both sides. This system is moved with the maintenance operation and is effective at prohibiting vehicles from entering the work area. The principal shortcoming for this system is that it requires that an additional traffic lane be closed. Benson and Ross (1985) designed, built, and crash tested a system designed to prevent vehicle intrusion into the work area. This system, known as a truck-mounted portable maintenance barrier, consists of a three-beam guardrail mounted between two trucks with dollies to provide guardrail support. It is effective and can be deployed in 15 min.

There are a number of studies on the characteristics of vehicle accidents that occur in short-term and slow-moving maintenance and utility work operations. These studies indicate that the most frequent accidents in these work areas involve rear-end collisions. In addition, trucks and truck-trailer combinations are overrepresented in the accident data. An interesting finding is that inclement weather does not appear to be a substantial factor in accidents involving many short-term or slow-moving maintenance operations. This fact, of course, reflects the very limited exposure during foul weather. Snow-plowing operations, however, are an exception where rear-end accidents are prominent.

Service and emergency vehicle lighting and vehicle rear lighting studies were reviewed. A clear finding from the literature is the nonuniformity of lighting regulations or standardization for emergency and service vehicles across cities, counties, and states (*9, 10*). The lack of standardization tends to confuse motorists and pedestrians. For example, a motorist accustomed to red on police vehicles may think the blue and white on police vehicles in another state is a nonpolice emergency or a service function. There is also considerable nonstandardization of light parameters, i.e., type of light, flash rate, mounting positions. This problem was substantiated in discussions with maintenance and traffic engineers, and manufacturers of lighting products.

A research study conducted by Lum (*11*) found that the standard four-way flasher is an effective device for reducing the hazardousness involved when a slow-moving vehicle is being overtaken by a fast-moving vehicle. Reaction distance, speed reduction and vehicle-following characteristics were all improved when this device was used. Tobey and Knoblauch (*12*) and Lyles (*13*) found similar results.

The results of light color and configuration studies were described in several reports. Berkhout (*14*) found that red lights were generally superior to blue, and monocolor lights were superior to combinations of red and blue. Twin lights outperformed single beacons, and light bars fared better than single lights. Most importantly, a trade-off was noted between conspicuity and information transfer. Lights that were most conspicuous against a road environment background did not have the best information transfer characteristics, i.e., closure rate.

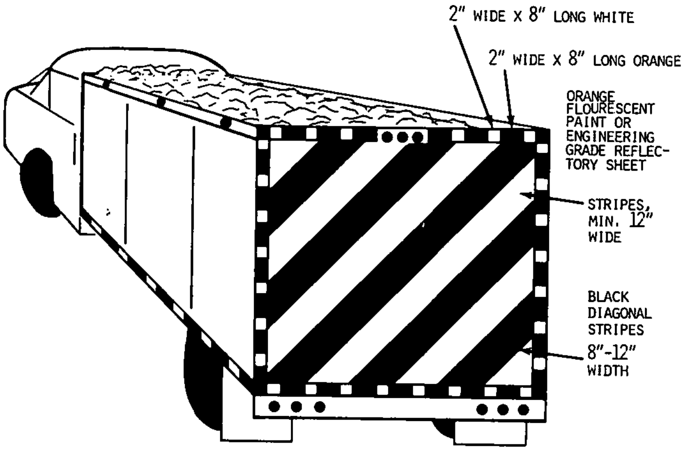


Figure 1. Recommended marking scheme for service vehicles. (Adapted from Burger, et al., 1981)

Analyses of information requirements and laboratory studies in an NHTSA-funded study resulted in recommended rear-end treatments for semi-trailer and flat-trailer trucks (Burger et al. (*15*) and Zeidman et al. (*16*)). Figure 1 (adapted from Burger et al.) shows a marking scheme recommended for service vehicles. Only the dashed pattern outlining the rear and side of the trailer shown in Figure 1 represents the treatment applied to a fleet of 2,000 trucks. The tested dashed pattern, however, used white and red, not white and orange reflectorized sheeting as shown in Figure 1. Another 2,000 trailers were not treated. The test and control fleet accumulated 106 million miles of travel and was involved in 612 crashes, of which 273 were considered related to conspicuity; e.g., a head-on crash had little to do with rear-end truck conspicuity. Statistical analysis showed an 18 percent reduction in crashes for the treated trucks (16.3 percent during the day and 21.1 percent at night). Thus, the reflectorized conspicuity enhancement was effective in reducing accidents.

Another aspect of driver behavior related to truck conspicuity concerns the cues the motorist uses to determine when to decelerate when approaching another vehicle. Burger et al. (*17*) found that certain reflective treatments improved drivers' ability to perceive closure rate under daylight conditions and at night. At night, taillights are the major cue used by a following driver to detect the presence of a vehicle and to determine if and when deceleration is required. Parker, Gilbert, and Dillon (*18*) found that, of the visual cues (change in visual angle, apparent brightness, and apparent size of the taillights) overtaking behavior was a function of the change in visual angle. Reilly et al. (*19*) further studied the rate of change of the visual angle subtended by the taillights of the lead vehicle, i.e., angular velocity. They confirmed that angular velocity is a key variable; however, it is moderated by approach speed. In both the Parker and Reilly studies, the lead vehicle was stopped. Janssen, Michon and Harvey (*20*) confirmed in laboratory and field experiments that angular velocity is the primary cue to detecting relative motion in depth. Because the lead cars in this study were moving, the results generalize the earlier findings. Further studies of car-following at night led Janssen (*21*) to conclude that, while angular velocity is a primary cue, perception is not always correct.

Table 1. Summary of state manual review.

Does the manual have:	Yes	No
• Special section on moving operations?	2	17
• Special section on short-term operations?	2	17
• Specific criteria or guidelines for traffic control set-ups for moving operations?	4	15
• Specific criteria or guidelines for traffic control set-ups for moving operations?	4	15
• Guidelines for use of lights on vehicles performing moving operations?	5	14
• Guidelines for use of lights on vehicles performing short-term operations?	1	16
• Any special devices or protective measures called out for moving operations?	3	16
• Any special devices or protective measures called out for short-term operations?	3	16

In other words, drivers' perception of change in angular velocity is not linear with the physical rate of change. The result of this behavior is that drivers may be led to approach a lead vehicle faster and closer than they intended.

Current Practices

The identification of current practice was determined through a review of traffic control manuals and a survey of state traffic and maintenance engineers.

State maintenance manuals available at FHWA were reviewed to determine if states give specific guidance for traffic control in short-term or moving operations. Table 1 summarizes the findings (a more detailed discussion of the findings is contained in Appendix A.

The review of state maintenance manuals revealed that maintenance operations are generally categorized by duration of the activity, i.e., long-term, short-term, intermittent, and moving. The division between long-term and short-term varies between various states with the extremes being 48 hours or 15 min. The category of intermittent is used by some states to identify operations requiring 5-min to 15-min stops. On the basis of this information, in order to make each category mutually exclusive, the following definitions were used throughout the remainder of this report. Any maintenance or utility operation that remains at one location for more than 12 hours is considered to be a *long-term* operation; and for less than 12 hours, but more than 15 min it is considered to be *short-term.* The intermittent and moving categories were combined into the single category of *moving* that may include brief stops of up to 15 min.

A small number of traffic control handbooks used by utilities were reviewed. The findings indicate that most of the guides conform to the requirements specified in Section 6 of the *Manual on Uniform Traffic Control Devices* (MUTCD). Discussions with local utilities suggest that there are differences between procedures described in the handbooks and actual practice. For long-term activities on major high-speed facilities the utilities tend to follow the guidance in MUTCD without deviation. However, for short-term operations, they tend to depend on the service vehicle's warning light systems. The apparent lack of adherence to the guides in certain instances may be because many utilities have small inventories of traffic control device types. Their mainstays are generally cones, a limited variety of signs, and vehicle warning lights. Utilities are increasingly finding arrowboards useful and effective; therefore, these devices are more in evidence. Another potential cause may be differences in emphasis and training provided by various utility companies.

To obtain information on current practices, questionnaires were sent to the state traffic engineers and maintenance engineers. Sixty-eight percent of the states responded. Engineers were asked to identify the lighting devices most often used on service vehicles, where they are placed on the service vehicles, problems they have encountered, driver behavior associated with particular warning lights, and traffic control problems with moving and short-term maintenance operations. These responses are summarized as follows:

- *Service Vehicle Lighting Devices*

  The following lighting devices are listed in order of preference:

DEVICE	COMMENT
Strobes	Good daytime visibility
Rotating beacons	Slow rotation effectively attracts attention
Arrowboards	Easily interpreted and effective for eliciting desired behavior

  Other cited devices were four-way flashers, high-mounted pairs of alternately flashing amber lights, and quartz halogen "on and off" lights. Amber was cited as the most common color used.

- *Lighting Device Placement (Figure 2)*

NUMBER OF DEVICE	PLACEMENT
One	Placed on top-center of cab or top-front of trailer
Two	(1) One placed each side on top of the cab or on top-front of trailer, or (2) one placed center of cab or top-front of trailer with the other placed back center of trailer (top or bottom)
Three	One same as No. 1, above, plus one placed each side on back of trailer (top or bottom)
Four	One placed on top at each corner of the trailer

- *Problems Identified with Warning Lights*

DEVICE	COMMENTS
Strobe	Maintenance repairs almost impossible, high failure rate, and flashback during snowfall
Rotating beacons	High energy consumption, batteries discharge when beacons are operating and equipment is idling; rotating mechanism tends to fail; requires considerable maintenance; difficult to determine burn-out in daylight; and poor daytime visibility

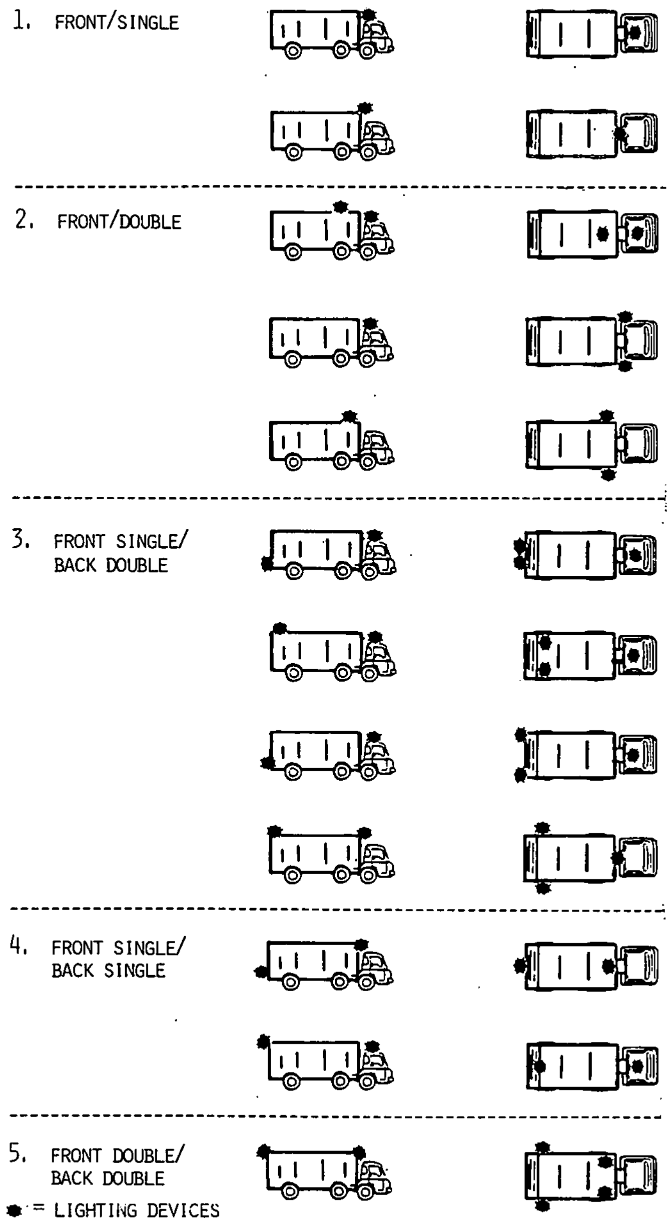


Figure 2. Five light placement configurations with variations, as determined from state survey.

Arrowboards	Unnecessary use and misapplication; must preserve credibility by using only when work is in progress
Flashing amber lights	Some effectiveness lost because of increased use on all manner of vehicles through the years

- *Patterns of Driver Behavior Associated with Warning Lights*

Device	Comments
Strobe	Light flashback during snowplow operations can cause mesmerization or hypnosis of the utility truck driver when used without secondary flash
Rotating beacons	Drivers slow considerably when exposed to blue flashing beacons
Arrowboards	Good driver response when flashing arrowboards in use for lane closure
Flashing amber lights	Motorists sometimes overreact to flashing amber lights by slowing too much

- *Traffic Control Problems with Moving and Short-Term Maintenance Operations*

  Inattentive motorists and truck drivers; problems range from driver's ignoring or not seeing lights and signs to inability to recognize extreme speed differentials.

  Rear-end collisions.

  Problems with traffic control devices; keeping the TCDs in proper position, maintaining adequate distance between shadow and maintenance vehicle(s), traffic backing up beyond the TCDs.

  Centerline marking operations require more equipment and personnel for traffic control than for actual work.

IDENTIFICATION AND CLASSIFICATION OF MAINTENANCE ACTIVITIES

Using traffic engineering handbooks, maintenance manuals, and personal experience, a wide variety of maintenance activity types were identified. The activities were grouped according to the typical length of time required to accomplish the activity. Table 2 presents typical maintenance situations. The classification of a specific activity as being short term, moving, or long term will vary, depending on the level of effort required to accomplish the task.

In addition to activity duration, there are other measurable factors that affect the safety of the workers and the motoring public and, thus, should influence the types of warning/traffic control required. These factors, including duration of the activity, are (1) type of roadway, (2) traffic volume, (3) duration of operation, (4) location of operation, and (5) sight distance.

In organizing these five variables into a usable scheme, one of several approaches (matrix, decision tree) could be taken. The *Louisiana Maintenance Control Handbook* (*22*) used the decision tree approach to cover all maintenance activities. Each of the typical maintenance activities was analyzed using the Louisiana decision guide. Figure 3 is a modification of that decision guide. The branches for long-term operations have been removed, leaving only the short-term and moving operations. There are 11 short-term and moving maintenance operations that may require separate driver information needs. The traffic volume differences do not change the information a driver needs. Instead, the way the information is presented may vary. For example, on a two-lane road, traffic still requires the advance warning and approach information, but it may be closer to the work activity. Under low-volume conditions, a single flagger may suffice, but heavy traffic may require two flaggers.

Sight distance was not specifically addressed in the selected scheme. For all types of maintenance and utility operations independent of the duration, adequate sight distance is very impor-

Table 2. Typical maintenance operations classified by duration.

MOVING

- Roadway Inspection
- Machine Mowing
- Chemical Weed Control
- Blading Shoulders
- Seeding and Mulching
- Pulling Ditches/Motor Grader
- Sign Inspection
- Snow Plowing/Sanding
- Sweeping/Vacuuming
- Pavement Striping - Centerline & Edgeline
- Apply Dust Palliative
- Clean Ditches/Excavator
- Inspect Drainage Structures
- Minor Drainage Maintenance
- Minor Clean Up of Debris
- Signal Repair (Relamping)
- Relamping Street Lights
- Temporary Repairs
- Litter Pickup
- Clean Catch Basins
- Servicing Litter Barrels
- Clean Traffic Signs
- Clean Tunnels
- Treat Bleeding Pavement (With Sand)
- Blade Gravel Roads
- Leaf Pickup
- Premarking for Centerline Location

SHORT TERM (Less Than 12 Hours)

- Concrete Pavement Patching
- Utility Repair
- Culvert Replacement
- Guardrail Replacement
- Impact Attenuator Repair
- Ground Mount Sign Installation
- Sign Replacement/Repair
- Delineator Replacement/Repair
- Clean Bridge Decks
- Cutting/Cleaning PCC Joints
- Erosion Repair
- Brush Cutting/Hand Mowing
- Debris Removal
- Special Striping (Crosswalks, Messages)
- Signal Repair (Major)
- Line Stringing (Utilities)
- Line Inspection (Utilities)
- Emergency Maintenance
- Maintenance of Landscaped Areas
- Fence Repair
- Planing/Cold Milling
- Repair/Replace Cattle Guards
- Erect/Remove Snow Fence
- Place Under Drain
- Utility Repair
- Tree Removal
- Railroad Crossing Maintenance (Minor)
- Mud Jacking (Adjusting Concrete Slabs)
- Pothole Patching
- Cracking Sealing

LONG TERM

- Plant Mix Overlay
- Chip Sealing - Speed Control
- Slurry Sealing - Road Closure
- Bridge Painting
- Emergency Maintenance (Major)
- Betterment Work by In-House Maintenance Forces
- Sidewalk Repair/Replacement
- Railroad Crossing Maintenance (Major)

tant for the safety of the work crew and the motoring public. Whenever a work crew is on the downside of a hill (below the crest) or around a sharp curve, sight distance can be severely limited. Actions must be taken in all maintenance operations to provide adequate sight distance. For moving operations, the shadow vehicle should remain at the crest of the hill or in advance of a sharp curve until the operating crew moves to a position where adequate sight distance is available. For all maintenance and utility activities at restricted sight distance locations, the advanced warning signs should be placed at greater intervals than shown in the guide in order to provide adequate warning to motorists.

INFORMATION NEEDS OF DRIVERS

Figure 3 shows 11 branches or categories, each representing a unique work zone situation (see also Figures 4 through 14. The information requirements of the driver were developed by representing each situation diagrammatically; dividing each situation into four distinct areas—advance, approach, work area (which includes the taper, if necessary), and exit; listing the actions a driver must take to pass the work zone with minimal flow perturbation and optimal safety; and listing information the driver needs to perform the desired actions. The results of this analysis are described in detail in Appendix B.

The information requirements reinforced several problems found in the state-of-the-art analysis. Included were:

1. Providing information with adequate decision sight distance in both short-term and moving situations.
2. Providing sufficient information for short-term operations in high volume situations, i.e., the traffic control far exceeds the time and cost of the actual work program.
3. Providing accurate and credible information. Hostetter et al. (*23*) found 11 information problem types with work zone information presentation, based on an assessment of 133 operating work zones. An average of 42 problems were found at each work zone site. The 11 problem types were grouped into four categories: (a) misleading information, (b) nonspecific information, (c) contradictory information, and (d) improper or nonstandard application of MUTCD guidelines. The information requirements analysis suggested a need for correct distance and content specificity, especially in the short-term setting.
4. Need to conform to MUTCD guidelines. The information requirements analysis suggests the MUTCD guidelines provide for the correct information in short-term settings. As Hostetter et al. (*24*) point out, 34 percent of the problems they found were violations of MUTCD guidelines. Simply doing what is known would improve work zone efficiency and safety. This same conclusion was reached by Pain, McGee, and Knapp (*25*) while working with channelizing devices.

The driver information analysis also identified the need to provide drivers attempting to exit or enter on ramps and at intersections with information about a convoy operation (e.g., striping).

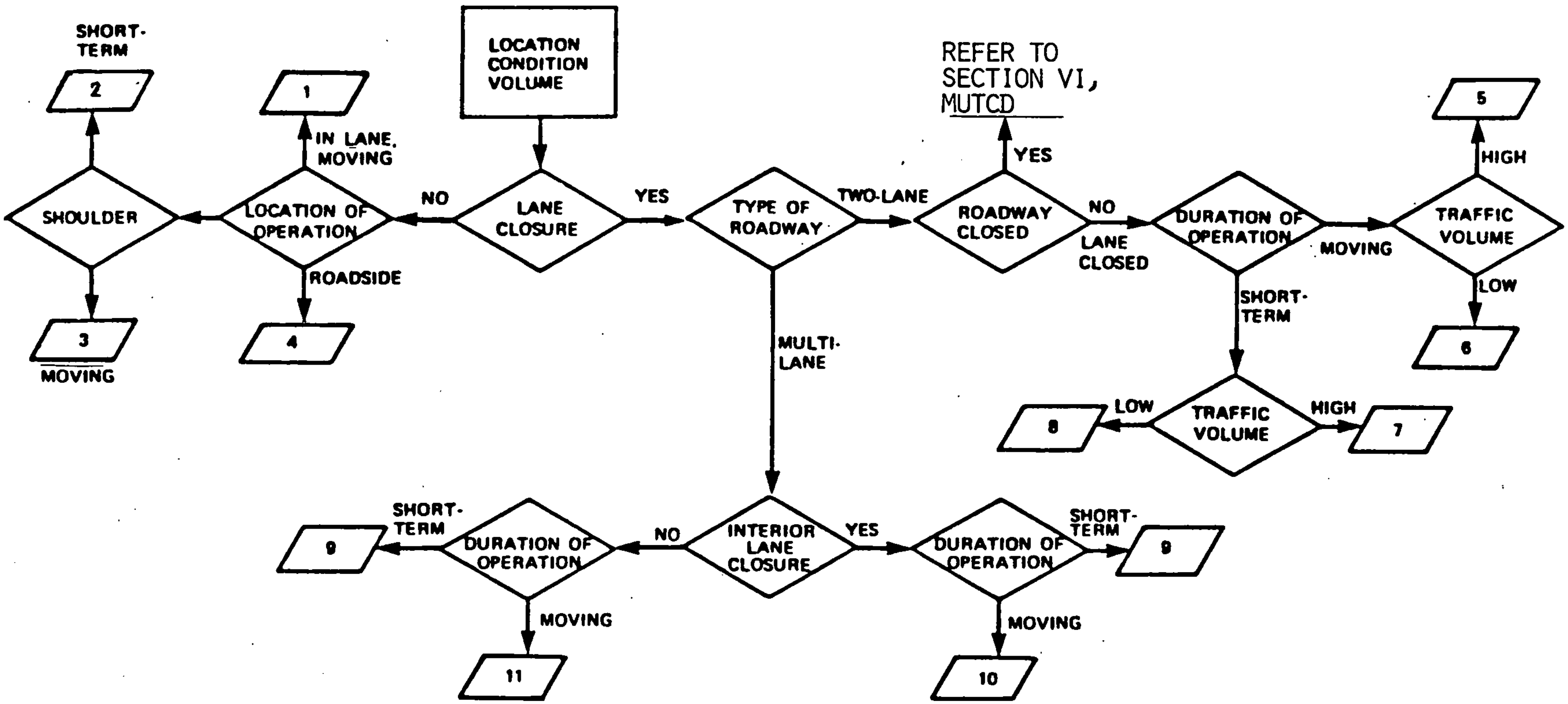
LABORATORY STUDIES

The purpose of the laboratory experiments was twofold: (1) to identify those marking and lighting schemes suitable for use on maintenance service vehicles, and (2) to determine if signs designed to meet certain driver information requirements and solve state-identified problems with moving maintenance operations were understood by motorists and elicited the desired behaviors. The laboratory studies consisted of three experiments, one conducted indoors and two conducted outdoors. The purpose of the indoor experiment was to examine drivers' ability to rapidly and accurately identify signs (text) and markings (no text) on the rear of service vehicles. Slides of actual signs and truck markings were presented to small groups of subjects and their reactions were recorded. In the second and third experiments the subjects were placed in a moving vehicle that was approaching a slower moving vehicle and were asked to perform specific tasks in response to their reactions.

More detailed discussion of these experiments is given in Appendixes C and D.

Indoor Laboratory Experiment

Full-size signs (text) were designed and built to be displayed on the last truck of a convoy (1) to indicate the next exit is temporarily blocked, (2) to dissuade motorists from cutting through a convoy (particularly a striping operation), and (3) to note which lane ahead is blocked. Figure 15 shows the sign messages and layout. The full-size signs were photographed mounted on the back of a State of Maryland dump truck that



Adapted from:
"Maintenance Traffic Control Handbook,"
Louisiana Department of Transportation
and Development, 1979.

Figure 3. Decision aid to categorize short-term and moving operations.

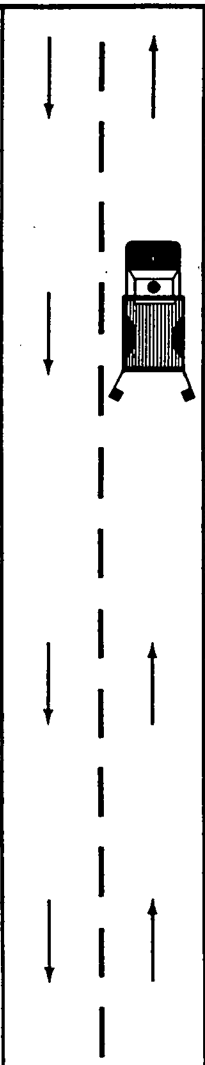
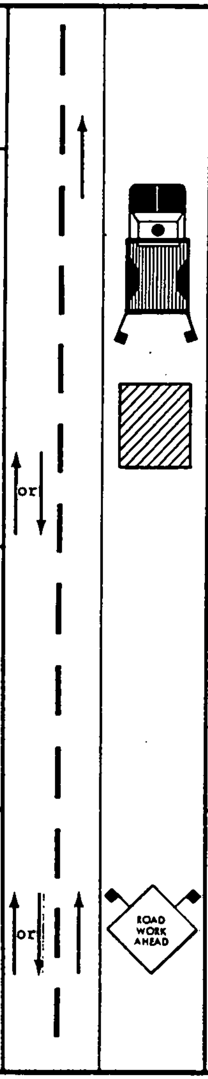
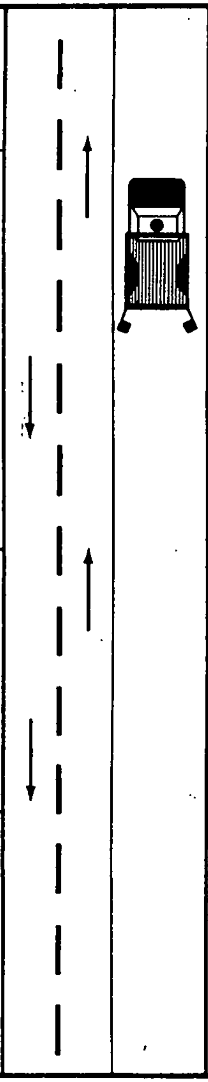
		ACTION TO BE TAKEN	INFORMATION REQUIREMENT	DEVICE/SYSTEM	RELEVANT STUDY FINDINGS		
					LAB/CLOSED FIELD	FIELD STUDY	LITERATURE
EXIT AREA		Two-Lane • Detect vehicle in time to sense rate of closure • Slow to speed of work activity • Execute safe pass if appropriate • Do not pass-wait for operation to pull over or wait flagging instructions/or stop	Two-Lane • See vehicle • Detect speed difference • Passing conditions not clear to driver e.g. flag or pass with caution • Sight distance 1000-1500'	• No requirement			
WORK AREA		Multi-Lane • Detect vehicle • Decide if room & gap to change lanes & go around/if not slow to flow speeds • Execute lane change & go by work activity • Do not cut thru convoy	Multi-Lane • See vehicle • Detect speed difference • If sight distance short need 1000-1500' • Driver needs to know what to do when close to exit • On entering wait for convoy to pass	• Vehicle-mounted lighting: -light bar on pick-up trucks & dump trucks must have 360° visibility -two rotating beacons + flasher on other vehicles, e.g. snowplow -Ohio light + truck-mounted symbol sign • Vehicle-mounted orange flags	• Two small arrows, light bar or arrow-board best • Other light types need to be supplemented by four-way or cab mounted flasher	• Best results from light bar • Good results using two rotating lights and flasher: good results from Ohio light + truck-mounted symbol sign • Flags improve driver performance when supplementing lighting devices	
APPROACH AREA		• Read signing/info • Watch for work activity	• Nature of work activity-moving/stationary • Speed guidance • Path guidance-if change is required	• Shadow vehicle (optional) -use should be based on acccident reduction potential		• Preferred on basis of performance to any lighting system -use with static arrow -base use on criteria: 1. reduces accidents 3-6/year 2. Eliminates 1fatal	
ADVANCE AREA		• Increased alertness & awareness of pending work zone • Look for further information	• Get driver attention • Notify of approaching work zone	• Need met by approach area devices or vehicle-mounted devices		fatal/16 years	

Figure 4. Information requirements and device recommendations, category 1: in-lane, moving.



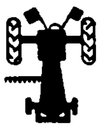
	ACTION TO BE TAKEN	INFORMATION REQUIREMENT	DEVICE/SYSTEM	RELEVANT STUDY FINDINGS		
				LAB/CLOSED FIELD	FIELD STUDY	LITERATURE
EXIT AREA	• Maintain quasi-steady state	• Work zone ends	• No requirement			
WORK AREA	• Maintain quasi-steady state (continue normal driving)	• Through lane signing and marking	• Channelizing device cone or other device, taper and tangent as in MUTCD • Service vehicle light (optional) two ratating beacons plus flasher	• Since closure rate not as important , any rotating/ flashing light to gain attention is adequate	• Current taper/tangent guidelines adequate • Rotating beacons acceptable , need for warning lights determined by con- ditions,e.g., work close to high-speed roadway,short-sight distance, nighttime	• 28" or larger cones effective in taper
APPROACH AREA	• Maintain quasi-steady state • Prepare to react to unexpected intrusion into traffic lane	• Indication of work activity for cell 2 conditions • Path (lane) demarcation • No misleading path, sign or light info guiding driver out of lane • Indication that thru lanes are open	• No requirement if good sight distance (1500+ft.) & lane edge marking,if not, extend device taper & / or tangent			
ADVANCE AREA	• Maintain quasi-steady state- no speed or path change necessary	• Driver made aware of work activity presence- cell 6 conditions	• Ground-mounted sign 750' in advance of work area,36", orange on side,min.mounting height 1.5' above pavement-orange flags on sign		• 750' advance placement adequate • Flags improve driver response	

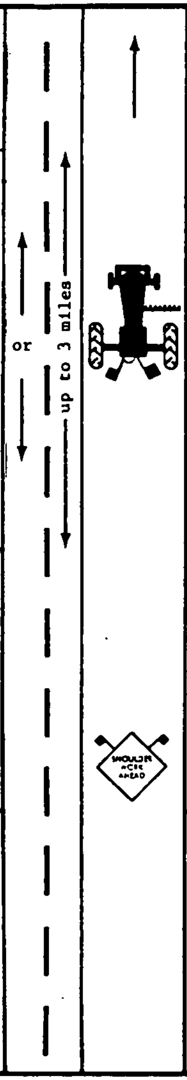
Figure 5. Information requirements and device recommendations, category 2: on-shoulder, short-term.



	ACTION TO BE TAKEN	INFORMATION REQUIREMENT	DEVICE/SYSTEM	RELEVANT STUDY FINDINGS: LAB/CLOSED FIELD	RELEVANT STUDY FINDINGS: FIELD STUDY	RELEVANT STUDY FINDINGS: LITERATURE
EXIT AREA	• Maintain quasi-steady state	• Work zone ends	• No requirement			
WORK AREA	• Maintain quasi-steady state (continue normal driving)	• Through lane signing and marking	• Vehicle mounted flags and use vehicle's four way flashers • Vehicle mounted lighting (optional) -only under extreme conditions, e.g. night, poor visibility, high-speed, high-volume	• Same as Category 2	• Vehicle -mounted flags improved driver response to maintenance activity • Use of supplemental flags proved effective for shoulder closure operations • Warning lights had no sustained benefit over flags in daytime. Therefore lights recommended only for more extreme conditions	
APPROACH AREA	• Maintain quasi-steady state -prepare to react to unexpected intrusion into traffic lane	• Indication of work activity for cell 2 conditions • Path (lane) demarcation -no misleading path, sign or light info guiding driver out of lane • Indication that thru lanes are open	• No requirement			
ADVANCE AREA	• Maintain quasi-steady state -no speed or path change necessary	• Driver made aware of work activity presence- cell 6 conditions	• No requirement			

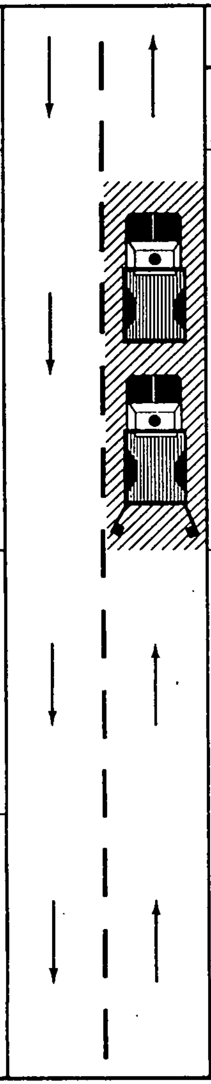
Figure 6. Information requirements and device recommendations, category 3: on-shoulder, moving operations.





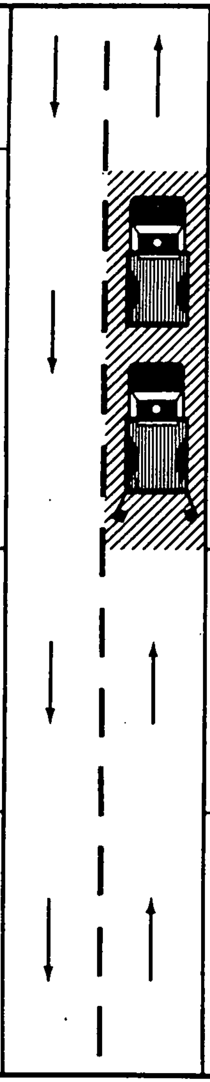
	ACTION TO BE TAKEN	INFORMATION REQUIREMENT	DEVICE/SYSTEM	RELEVANT STUDY FINDINGS		
				LAB/CLOSED FIELD	FIELD STUDY	LITERATURE
EXIT AREA	• Continue normal driving	• Work activity ends	• No requirement			
WORK AREA	• Aware of work next to road - avoid heading for it • No stopping/slowing near work activity	• Lane definition - path guidance - see where work is taking place • Minimal distraction of driver	• Supplement orange <u>flags</u> - vehicle-mounted • <u>Warning Light</u> for vehicles stopped on shoulder during roadside operation at single rotating beacon in addition to standard four-way flasher is adequate		• Orange flags effective as warning at maintenance activity	
APPROACH AREA	• Become aware of start of work area	• Start of work zone • Location of work activity -in relation to path -in relation to distance • Type of work activity	• <u>Ground-mounted sign</u> 750' in advance of work Use supplemental orange flags Mount sign 1.5' above pavement		• Advance ground-mounted sign effectiveness enhanced by orange flags • Sign effective if mounted 1.5' above pavement	
ADVANCE AREA	• Initial awareness & looking for more info	• Work zone ahead, more info will be provided	• Sufficient info provided in approach			

Figure 7. Information requirements and device recommendations, category 4: roadside moving or short-term.



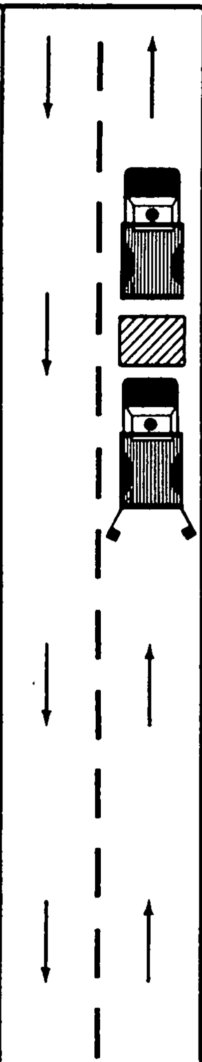
	ACTION TO BE TAKEN	INFORMATION REQUIREMENT	DEVICE/SYSTEM	RELEVANT STUDY FINDINGS		
				LAB/CLOSED FIELD	FIELD STUDY	LITERATURE
EXIT AREA	• Resume normal driving	• End of work zone	• No requirement			
WORK AREA	• Follow direction of flag/signal/pilot car • Proceed around work activity • Return to correct lane • Stay in traveled path, maintaining designated speed	• Location of work zone • Where & when to pass work activity • Path around work activity	• Vehicle-mounted <u>lighting</u> -light bar on pick-up or dump truck, or two rotating beacons + flasher, or Ohio light on other vehicles • Vehicle-mounted <u>orange flags</u>	• Two small arrows or light bar are best • Arrowboard, rotating strobe lights need to be supplemented with four-way flashers or cab mounted flasher light	• Good results with light bar • Good results with two rotating & flasher; also Ohio light • Flags enhance driver behavior	• Must have 360° visibility for lights
APPROACH AREA	• Detect info on location & source of further info • Detect flag/signal • Follow direction of flag/signal • Detect queue if any Slow to enter queue	• Info presented at location to be credible, e.g., work activity visible, flagger/signal visible (1000-1500ft sight distance)	• <u>Shadow vehicle</u> (optional) -base use on accident reduction potential -operators on shoulder -use "Lane Blocked Ahead, Pass with Care" sign, in addition to warning lights		• For use criteria, see Category 1 • Shadow vehicle more affective than any lighting system	
ADVANCE AREA	• Become aware of work zone coming up • Look for additional information	• Work zone area-more guidance forthcoming	• No requirement			

Figure 8. Information requirements and device recommendations, category 5: two-lane, high-volume road; moving operation, lane closure.



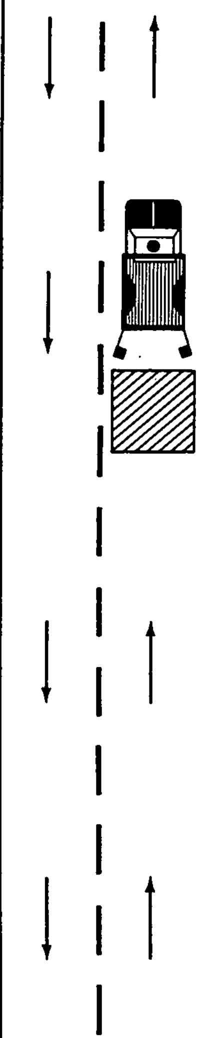
	ACTION TO BE TAKEN	INFORMATION REQUIREMENT	DEVICE/SYSTEM	RELEVANT STUDY FINDINGS		
				LAB/CLOSED FIELD	FIELD STUDY	LITERATURE
EXIT AREA	• Resume normal driving	• End of work zone	• No requirement			
WORK AREA	• Proceed around work activity • Return to correct lane • Stay in traveled path, maintaining designated speed	• Location of work zone • Where & when to pass work activity • Path around work activity	• Vehicle-mounted lighting -light bar on pick-up or dump truck -two rotating beacons + flasher; or Ohio light + symbol sign • Vehicle-mounted orange flags	• For slower (35mph or less), more urban operations four-way flasher as or more effective than cab mounted flasher	• Light bar more effective in moving, but not stationary operation • Truck mounted symbol sign advantageous in limited sight distance situation • Effective supplement to lights	• Lights must be visible 360
APPROACH AREA	• Detect info on location & source of further info • Detect flag/signal • Follow direction of flag/signal • Detect queue if any Slow to enter queue	• Info presented at location to be credible, e.g.,work activity visible (1000-1500 ft. sight distance)	• Provided by lights & & flags, (see above)			• Lights visible at 1000-1500 ft. at 55 mph.
ADVANCE AREA	• Become aware of work zone coming up • Look for additional information	• Work zone area-more guidance forthcoming	• No requirement			

Figure 9. Information requirements and device recommendations, category 6: two-lane, low-volume road; moving operation with lane blocked.



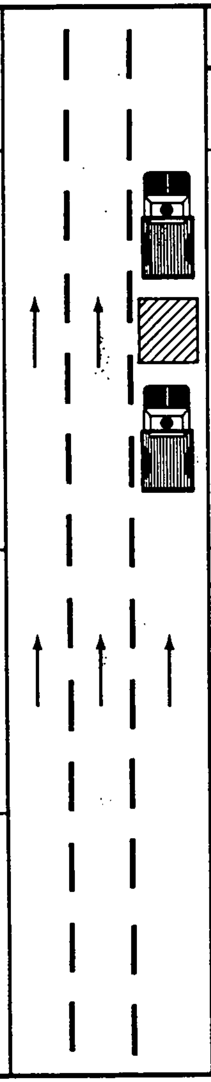
	ACTION TO BE TAKEN	INFORMATION REQUIREMENT	DEVICE/SYSTEM	RELEVANT STUDY FINDINGS		
				LAB/CLOSED FIELD	FIELD STUDY	LITERATURE
EXIT AREA	• Resume normal driving	• Work zone end	• No requirement			
WORK AREA	• Detect work zone • Begin to slow • Identify place to stop • Detect source of proceed guidance • Follow guidance • Follow path-no intrusion into work area • Return to normal driving lane	• Work activity-lane closure (1000-1500') • Speed difference • Need to slow/stop • Proceed guidance-stop, pass • Path guidance	• Vehicle-mounted <u>lighting</u> -two rotating beacons + flasher • Vehicle-mounted <u>orange flags</u>	• The slower the speed the less accurate the driver perception of closure rate. Lighting sight distance of 1000-1500'(for 55+mph roads) imperative	• For stationary operations best result from using rotating beacons plus cab mounted flasher • Effective at warning of maintenance vehicle presence	• Vehicle-mounted flags are standard in Louisiana
APPROACH AREA	• Detect information • Read information • Look for work area • If needed begin to slow stop-especially if queue formed	• Lane is closed • How to proceed (pass/stop) source of guidance • Where passing/stopping takes place • If queue - detect slow traffic	• Flagging/pilot <u>operation</u> -in accordance with current practice			• The flagging procedures and devices
ADVANCE AREA	• Become aware of pending work zone • Look for more information	• Work zone forthcoming	• <u>Advance signing</u> -if closure duration 15 min.(or longer) or sight distance less than 1500' use MUTCD specified sign, 750' in advance, mounted 1.5' off ground, supplement with orange flags		• 1.5' above ground was effective mounting height • Flags effectively supplement signs	

Figure 10. Information requirements and device recommendations, category 7: two-lane, high-volume road; short-term lane closure.



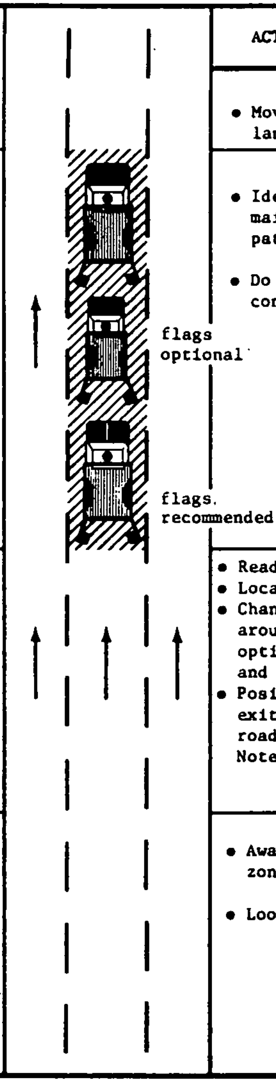
	ACTION TO BE TAKEN	INFORMATION REQUIREMENT	DEVICE/SYSTEM	RELEVANT STUDY FINDINGS: LAB/CLOSED FIELD	RELEVANT STUDY FINDINGS: FIELD STUDY	RELEVANT STUDY FINDINGS: LITERATURE
EXIT AREA	• Return to normal lane and driving	• Work activity ends	• No requirement			
WORK AREA	• Stop or slow before work zone • Prepare to pass-check on-coming traffic • Pass when clear • If flag present, follow direction	• Location of work zone-point at which stop must occur if pass not executed • If used, visible flag giving clear directions • At vertical or horizontal curves sight distance or 1000' at 55mph must be maintained or supplemental advance warning used • If passing restricted by sight distance, provide alternative guidance	• Vehicle-mounted Lighting Two rotating beacons plus flasher • Vehicle-mounted orange flags	• Driver closure rate perception deteriorates at slower speeds Lights need to be visible 1000-1500' on 55mph road.	• Best results with two rotating plus flasher combination • Effectively enhances warning of service vehicle presence	• Vehicle-mounted flags are standard in Louisiana
APPROACH AREA	• Detect work zone • Decide how to proceed, slow, stop, pass, as appropriate • If flag present, detect and understand signal	• Presence of work zone • How to proceed-slow, stop, look for flag, pass • Where to pass-left, right	• Flagging/pilot car (optional) If deemed necessary by maintenance foreman, due to traffic conditions, apply in accordance with current procedure			• TTI flagging procedures & devices
ADVANCE AREA	• Aware of pending work zone • Look for additional information	• Work zone information forthcoming	• Ground-mounted sign 750' in advance if duration 15+minutes of sight distance obstruction (less than 1000' sight distance) supplement with orange flags		• Flags enhance response to sign	

Figure 11. Information requirements and device recommendations, category 8: two-lane, low-volume road; short-term lane closure.



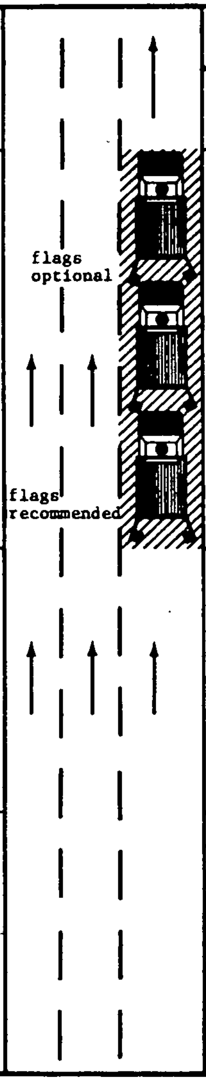
	ACTION TO BE TAKEN	INFORMATION REQUIREMENT	DEVICE/SYSTEM	RELEVANT STUDY FINDINGS		
				LAB/CLOSED FIELD	FIELD STUDY	LITERATURE
EXIT AREA	• If appropriate move back to original lane. Resume speed/increase	• Work zone ends				
WORK AREA	• Follow channelization • Maintain posted speed • Concentrate on car following and path- not work activity (rubber-necking)	• Define path around work activity • Provide with adequate decision sight distance (DSD) • If DSD lacking provide supplemental info sources	• Vehicle LightingSystem 3x5 arrowboard on last truck 2 rotating beacons + flasher or 3'x5' arrowboard • Orange Cone Taper Use current MUTCD placement;sight distance to cone taper 1000' • Lane Blocked Sign (optional) if sight distance short, consider using sign (understood by 73% of subjects)	• Arrowboard with 4-way flashers, two 20"x24" arrows provided best closure rate info- not necessarily the most conspicuous	• Best results for short-term two rotating beacons + flasher light	• Arrowboard most effective device for clearing lanes • Orange 28"+ cones effective in daytime, require 150-200 in of reflective bands at night • TTI field tests show lane blocked sign effective
APPROACH AREA	• Read signing/info • Identify/locate change in path-lane closure • Change lanes at a point that minimizes flow perturbation	• Provide lane/path info with sufficient decision sight distance • Notify which lane closed and where • Define path driver must take • Advance notice of physical start of work zone	• Ground-mounted signs 500' & 1000' prior to cone taper-1000'Right Lane Closed Ahead- 500'lane merges sign two orange flags per sign--minimum mounting height 1.5' above pavement • Cone Taper per MUTCD practice		• Advance signing- 3 sign array with advance warning 1500' from start of taper • Flags on signs induce earlier lane changes • Minimum mounting height 1' above pavement surface	• 28" orange cones minimum- see above
ADVANCE AREA	• Aware of pending work zone • Look for further information	• Draw driver attention • Notify of approaching work zone	• Ground-mounted sign- Road Work Ahead, 1500' in advance of taper, two orange flags per sign, 1.5' above pavement mounting height			

Figure 12. Information requirements and device recommendations, category 9: multi-lane road, short-term lane closure.



	ACTION TO BE TAKEN	INFORMATION REQUIREMENT	DEVICE/SYSTEM	RELEVANT STUDY FINDINGS		
				LAB/CLOSED FIELD	FIELD STUDY	LITERATURE
EXIT AREA	• Move back to interior lane	• Work activity ended	• No requirement			
WORK AREA	• Identify convoy, maintain speed and path • Do not cross through convoy	• Beginning of convoy • Length/duration of work zone/convoy, i.e., positive path identification • Indication not to cross through convoy	• Vehicle-mounted lighting light bar on pick-ups or dump trucks two rotating beacons + flasher on other vehicle types Ohio light + truck-mounted symbol sign • Vehicle-mounted orange flags • If convoy-use signs on last vehicle-"Convoy Ahead, stay (left, right, either side)"	• Best understood of convoy signs tested in lab	• Light bar effective on moving operation • Good results with Ohio light + truck-mounted symbol sign or 2 rotating beacons + flasher • Driver response improved by flags • Signs not yet field tested	• Need 360 light visibility
APPROACH AREA	• Read signs/info • Locate moving work • Change lanes to go around work convoy at optimum point for flow and safety • Position correctly for exit or entrance from roadway Note: Do not cut through convoy	• Lane closure & location • How to get around work zone • How to exit highway • Info given with adequate DSD otherwise supplement • Info maintains reasonable distance to convoy	• Arrowboard mounted on last truck of convoy • Shadow vehicle (optional) base use on state accident reduction potential decision; vehicle-mounted sign Lane Blocked or Arrowboard on shadow vehicle (optional) • Truck-mounted Lane Blocked Sign (optional)	• Understood by 73% of subjects	• Shadow vehicle preferred on performance basis to any lighting device tested. Base use on accident reduction benefit	• Arrowboard effective in clearing lane • TTI found effective in field tests • TTI found sign on shoulder useful for long ques or short sight distance situations
ADVANCE AREA	• Aware of moving work zone ahead • Look for further info	• Draw driver attention • Notify of work zone				

Figure 13. Information requirements and device recommendations, category 10: multi-lane, moving on interior lane.



	ACTION TO BE TAKEN	INFORMATION REQUIREMENT	DEVICE/SYSTEM	RELEVANT STUDY FINDINGS		
				LAB/CLOSED FIELD	FIELD STUDY	LITERATURE
EXIT AREA	• Move back to exterior lane	• Work activity ends	• No requirement		• Good results using light bar; good re-	
WORK AREA	• Identify convoy, maintain speed and path • Maintain position for exit if required • If entering from ramp/street, wait for convoy to pass NOTE: Do not cut through convoy	• Beginning of convoy • Length/duration of convoy, i.e. positive path identification • Warning of convoy at ramps/cross streets • Indication not to cut through convoy	• <u>Vehicle-mntd lighting</u> Light bar on pick-ups, dump trucks;2 rotating beacons +flashing light or Ohio lightw/truck-mnt symbol sign on other vehicles (e.g.snow plows • <u>Vehicle-mntd orange flag</u> • <u>Vehicle-mntd signs</u> -"Convoy Ahead,stay (left/right)"sign on rear of convoy -If blocking exits while moving show sign ¼-½ml. before exit will be blocked on last truck in convoy;Follow me to Exit"	• Correct driving maneuver choosen by 64.5% of subjects • 88% of subjects choose correct driving maneuver in lab	• Good results using light bar;good results with Ohio light or 2 rotating lights + flashing light • Improved driver behavior when present with lights • Not field tested	• Need all warning lights visible for 360°
APPROACH AREA	• Read signs/info • Locate moving work activity-on-line,or from entrance • Change lanes to pass convoy-minimize flow perturbation • Position for exit, if desired	• Location of work & lane closure • How to get around con convoy • How to exit highway(go around or wait behind convoy) • Provide info with adequate DSD, otherwise supplement • Keep info w/in reasonable distance,i.e.+1mile	• <u>Arrowboard</u> on last truck in convoy • Where sight distance or traffic queques are problems use either • <u>Lane Blocked</u> sign(optnl mounted on truck on shoulder • <u>Shadow vehicle</u>(optional base use on state accident reduction potential;use static arrow	• Sign understood by 73% of subjects	• Preferred,based on performance to any light device.Base use on accident reduction benefit potential	• Arrowboard effective in moving traffic out of occupied lane • TTI field test showed sign effective
ADVANCE AREA	• Aware of moving work zone ahead • Look for further info	• Draw driver attention • Notify of work zone	• Meet by approach area devices			

Figure 14. Information requirements and device recommendations, category 11: multi-lane, exterior-lane, moving.

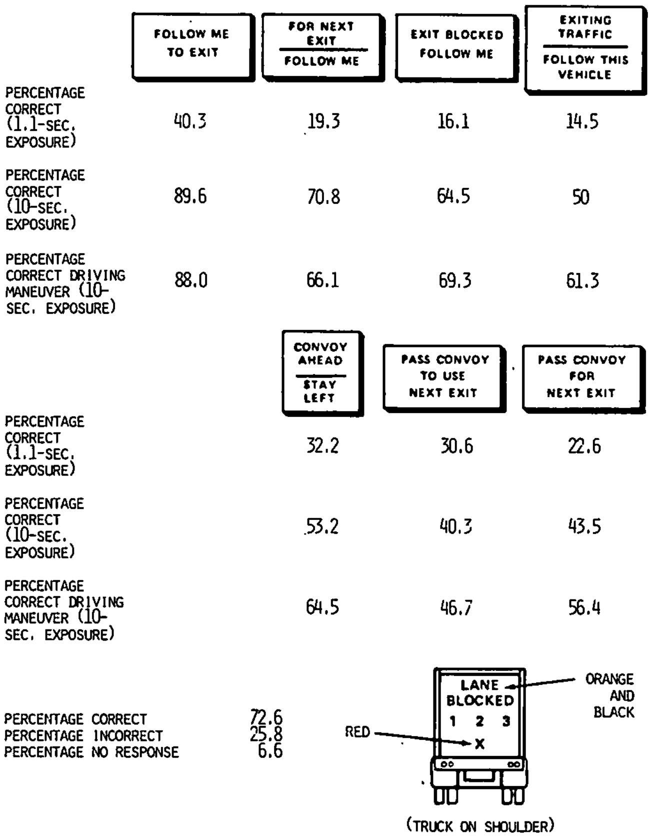


Figure 15. Summary of responses to signs.

was positioned in a lane of a four-lane divided highway that was not open to traffic. Pictures (slides) were taken at 300-ft and 100-ft distances from the signs.

Eleven truck markings (no text) were mocked up full scale. The markings were truck mounted and photographed as previously described. Figure 16 depicts the markings used.

The sign slides and the marking slides were grouped in pairs, the first slide in each pair being from 300 ft and the second of the same item from 100 ft. The pairs were randomly ordered. Slides were then shown to groups of subjects: sign slides for 1.1 sec and the marking slides for 0.11 sec. After seeing a pair of sign slides, they wrote down what the sign said and how they would respond to the sign if they were driving. After seeing a pair of marking slides, subjects answered questions about which marking they had just seen, which lane the truck was in, and what they would do if they saw this marking while driving. Responses were recorded on paper. Testing took 45 min. Sixty-two usable test protocols were collected. A detailed description of the experiment is contained in Appendix D.

Four versions of a sign to indicate a temporarily closed/blocked exit ahead were shown in Figure 15. The first alternative, FOLLOW ME TO EXIT, was clearly the most successful for all three measures of effectiveness.

Among the three signs telling motorists not to cut through a convoy and to pass the convoy for the next exit, the CONVOY AHEAD, STAY LEFT sign was the more successful. The percentage of correct responses for the three measures of effectiveness (MOE) was marginal. The comments and nature of the errors suggest the word "convoy" is not well understood. A different word such as "work train" may result in better understanding. Some improvement in driver understanding would also result if drivers were exposed to the sign and experienced convoy operations. The LANE BLOCKED sign, shown in Figure 15, had 72.6 percent correct responses to it. This is consistent with Texas findings that the sign is relatively effective in laboratory and field settings in telling drivers to move out of a lane that is blocked, before they can see the obstacle/lane closure.

The comprehension test (seeing the sign for 10 sec and then writing the content and intended meaning) followed the glance recognition findings, i.e., the higher the percentage correct on one MOE, the higher on the other MOE.

The number of times each truck marking was correctly selected is shown in Figure 16. The baseline or currently used markings, numbers 6, 9, and 10 were correctly identified 62.9, 58.1, and 48.4 percent. The diagonal stripe combined with the NHTSA-recommended reflective markings (number 1) were correctly identified 76.6 percent, a 22 percent or more improvement.

A one-way analysis of variance showed that there were statistically significant differences between the markings. Post hoc tests found that markings 1, 2, and 3 (all in the 70 to 75 percent correct range) were different from the markings in the 40 to 60 percent correct range.

A striking, but not surprising, result was that between 12.9 and 29.0 percent of the subjects marked they could pass on either side of the truck in response to a chevron, 0 to 3 percent in response to the diagonal stripe, and 0 percent in response to the NHTSA marking scheme. Thus, chevrons pointing left or right clearly are not an appropriate marking for rear end of trucks.

Based on the results of this experiment and the NHTSA research, a truck marking scheme that is recognizable and has rear-end accident reduction potential is the diagonal black stripe on an orange background with alternating white and orange outlining the truck body (marking number 1 in Figure 16). The orange should be reflectorized. Specifications for the reflectorization were given by Burger et al. (*26*): SIA values of 250 to 300 $cd/lx/m^2$ for orange and 500 $cd/lx/m^2$ for white, where SIA is the specific intensity per unit area and $cd/lx/m^2$ stands for candelas/lux/meter squared.

Closed Field Experiments

From the state survey, several problems with moving and short-term service vehicle operations were identified. A common denominator among these problems was that drivers fail to recognize that service vehicles are moving more slowly than their own vehicles. As a result, cars and trucks approaching the work space barely miss or collide with service vehicles.

Over the years, service vehicles have been made more conspicuous by adding lights, increasing intensity, changing the type of light, and varying color and flash rate. In the quest for conspicuousness, the question of information content and its extraction by drivers has seldom been addressed. Two experiments were performed in a closed field setting to determine how effective existing warning lights are in prompting drivers about closure rate and speed of a service vehicle.

The first experiment examined type of light, light intensity, type of light motion, and flash rate in day and night settings

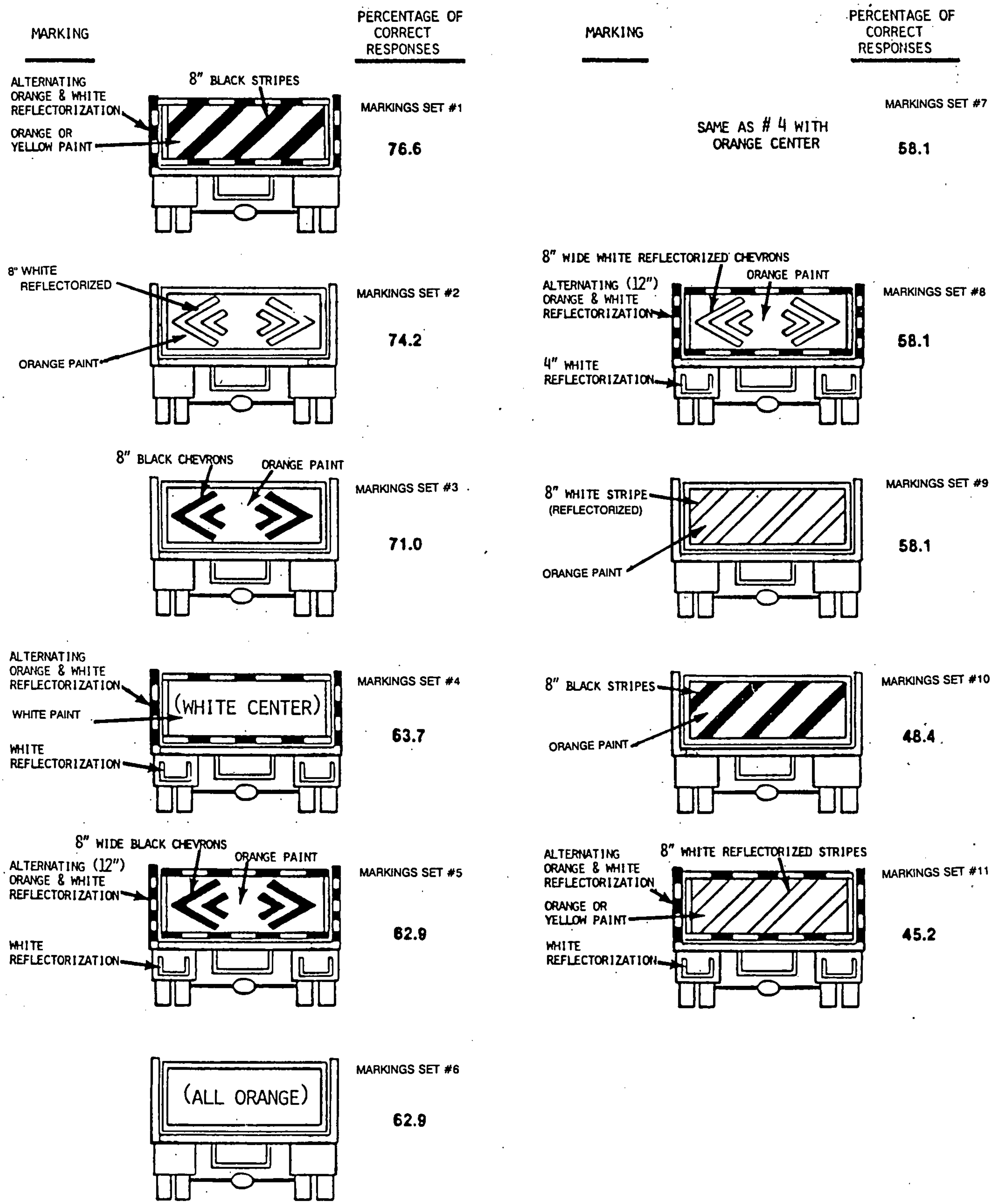


Figure 16. Truck markings and experimental results.

Table 3. Summary of speed and distance conditions for experiments 1 and 2.

Van Speeds, mph	Distance Between Truck & Van	Truck Speeds, mph 4	14	28
35	350	X	X	X
55	750	X	X	X

and at different driver and service vehicle speeds. The second experiment studied current and new light placements on the service vehicles and combinations of lights. A more detailed description of the two experiments and the findings can be found in Appendix D.

The test site was an unopened 3,000-ft section of Maryland Route 100, a four-lane divided portland cement concrete roadway with traffic markings. Ninety-six people were tested—48 per experiment. Within each experiment, 24 people were tested at night and 24 during the day. A division of subjects by gender (50 percent each), and age (25 percent 16 to 24 years old, 50 percent 25 to 54 years, and 25 percent 55-plus years) was generally but not perfectly achieved.

The procedure used in both experiments had five subjects riding in a van at 35 mph or 55 mph. The subjects were behind a large window-type shade. When the van went 35 mph, the shade went down for 4 sec, revealing a dump truck (freshly painted Maryland orange) 350 ft ahead moving at 4, 14, or 28 mph. A different light treatment was on the truck at each viewing. When the van was going 55 mph the screen went down when the vehicles were 750 ft apart. Table 3 summarizes these conditions.

Reliability measures were taken at the beginning and end of each experiment to assure that the truck and van spacing and speeds were correct. Errors were consistently less than 0.9 sec, well below subject threshold to detect any difference in van-truck gap or speed.

Subjects responded to the warning lights by choosing one of ten speed categories the truck could be traveling (0, 1 to 4, 5 to 9, . . . to 44 mph) and rating how fast they were closing on the service vehicle (1 very fast to 4 not at all). Additionally, biographical data (*27*), including the Roberts, Hutchinson and Hanscom expressive self-testing profile, were collected.

Light types, flash rates, intensities, light placements, and combinations of lights were selected for testing based on the state practices. The light types tested in experiment 1 and the light configurations evaluated in experiment 2 are given in Tables 4 and 5, respectively.

The estimate of service vehicle speed was the measure collected from the subjects; however, it is not a direct measure of the correctness of information transmitted to the driver. A correctness score was obtained by comparing the subject's speed estimate with the actual speed of the service vehicle.

There were no statistically significant differences between day and night responses. Analysis of variance (ANOVA) found no differences between the order of treatment presentation. Thus, day versus night, order of presentation, and length of test sessions did not have a noticeable effect on subject responding.

Five general findings emerge. First, if only one type of warning light device is used (experiment 1) on a vehicle, two or four four-way flashers provide the most accurate information to drivers about service vehicle speed and closure rate. These are followed by the two 20-in. by 24-in. arrows operating together, and the light bar. The remaining devices (strobe, rotating beacon, flashing incandescent, and 3-ft by 5-ft arrowboard) are not as effective in presenting information about service vehicles speed and closure rate.

Second, simply adding more of the same type of lights on the service vehicle does not increase the amount of information provided to the driver or enhance the driver's ability to extract information from the lights. Third, changing the location of the light(s) on the service vehicle does not increase information or ability to extract the information.

Fourth, the range of the lighting parameters studied in the experiments had no impact on information extracted by drivers, e.g., flash rates between 60 and 100 cpm and medium- and high-intensity lights had little effect on drivers responding. And fifth, adding four-way flashers to strobe, rotating, flashing, or arrowboard warning lights increases the amount of information

Table 4. Light types tested in experiment 1.

Test Number	Light Type	
	Strobes (360-degree visibility)	
1.	Single-flash	
2.	Double-flash	
	Rotating Beacons (Incandescent)	
	Medium intensity	
3.	60-80 cpm	
4.	100-120 cpm	
	High intensity (halogen)	
5.	60-80 cpm	
6.	100-120 cpm	
	Flashing Incandescent	
	Medium intensity	
7.	60-80 cpm	
8.	100-120 cpm	
	High intensity (halogen)	
9.	100-120 cpm	
	Arrowboards	
10.	1 - 3 x 5 ft	
11.	2 - 24 x 20 in	Mounted on dump bed door, both pointing in same direction and flashing together
	Four-way Flashers	
12.	2 units Mounted at the bottom of dump bed	
13.	4 units Two at bottom and two above dump bed	

Notes: 1. Lighting treatment mounted on top and center of the dump bed tailgate unless otherwise noted
2. Only one treatment was visible to the subject at a time.

Table 5. Light types and configurations tested in experiment 2.

Test Number	Light Combinations
	Strobe*, double-flash
1.	2 - Rotating Beacons**, medium intensity, 60-80 cpm
2.	2 - Four-way flashers
3.	2 - Four-way flashers
	Rotating Beacons** (2), medium intensity, 60-80 cpm
4.	1 - Flashing Incandescent*, high intensity, 100-120 cpm
5.	2 - Four-way flashers
6.	4 - Four-way flashers
	Flashing Incandescent*, high intensity, 100-120 cpm
7.	4 - Four-way flasher
	Arrowboard, 3 x 3 feet
8.	2 - Four-way flasher
9.	Light Bar, sequenced flashing, six lights

* Front center-mount
** Rear (both sides) mount

provided to the driver. A flashing incandescent in combination with rotating beacons has a similar effect. It appears that the closure rate information from a flashing light (e.g., flashing beacon, four-way flasher) is effectively extracted by the human sensing and perceiving system. However, strobe lights with a very short flash duration of a strobe, even in a double flash mode, are not as effectively interpreted as the longer duration incandescent flash. The discrete incandescent flash (e.g., flashing incandescent, four-way flasher) also appears to be more effectively interpreted, at least in terms of closure rate information, than the rotating beacon, which perceptually does not have as discrete an on/off cycle. Another aspect of four-way flashers is that they have come to be associated with slow-moving or stopped vehicles, particularly trucks. Thus, a coded meaning alerts drivers to attend to speed differences in the presence of a flashing light. Drivers are more likely to look for the speed difference from the vehicle with a four-way flasher operating.

The foregoing discussion does not take into account service vehicle conspicuity. The need to use medium- to high-intensity lights (strobe, rotating beacons, flashing incandescent, or arrowboard) to gain motorist attention is very important. However, to provide motorists with more complete hazard warning about speed differentials, a flashing light component appears warranted.

Another result from the closed field experiments is that the speed of the service vehicle has more impact than any of the warning lights on driver perception of service vehicle speed and closure rate. This effect (with the associated estimation error that the service vehicle is perceived as going faster than its actual speed) is most severe at the very low (0 to 8 mph) service vehicle speeds. As testified by the literature and accident and survey data, these short-term and slow-moving work operations are at greatest risk. Drawing the motorist's attention to the operation as early as possible (through use of arrowboards, high-intensity lights, shadow vehicles, advance signing), then optimizing the information provided to the motorist (e.g., using flashers to improve driver speed estimation), and supplementing lights with markings (e.g., those described in the laboratory experiment and literature review) on the service vehicle appear to be the major countermeasures for this phenomenon.

OPERATIONAL FIELD STUDIES

The objective of the operational field studies was to evaluate the effectiveness of vehicle lighting and traffic control systems identified in the previous portions of this study. These systems were evaluated under actual highway conditions using simulated slow-moving, short-term lane-closure, and shoulder-closure operations. Slow-moving operations are defined as moving at approximately 8 mph, and short-term operations refer to maintenance activity ranging from 15 min to 12 hours.

A state-of-the-art review and a nationwide survey of maintenance engineers revealed that the following device requirements were deemed critical: (1) vehicle-mounted warning devices—low cost, low maintenance required, highly visible, need to convey message, not to interfere with maintenance work; and (2) ground-mounted signs—conspicuity, convey message, minimal effort to deploy and remove. It is of interest to note, also, that specific applicable devices (i.e., traffic cones and arrowboards) had been studied in recent previous research and, thus, limited the scope of the current project; however, the results of that prior research were applied to the recommendations made in this report.

Slow-Moving Operations

Tests

Using the survey of state traffic and maintenance engineers, results of the laboratory experiments, and applicable state standards at the test sites, the following devices were selected for testing in the slow-moving (i.e., 8 mph) maintenance operations:

1. *Service vehicle lighting systems:* (a) strobe, high intensity, double-flash; (b) two rotating beacons plus incandescent flasher; (c) four-way flasher plus a single incandescent flasher; (d) light bar, sequence flashing six lights; (e) Ohio light, a double-faced, high-intensity, amber light, mounted on either side of the maintenance vehicle.
2. Truck-mounted MEN WORKING sign.
3. Flags mounted on maintenance vehicle.
4. Shadow vehicle.

The foregoing treatments were observed in simulated slow-moving maintenance operations in Louisiana, Maryland, and New York. For comparative purposes, the state traffic control standard for slow-moving operations was used as the "baseline" condition. The standard in Louisiana and Maryland is a two-bulb rotating beacon (incandescent) mounted in the center of the dump truck cab. In New York the standard is a pick-up truck used as a shadow vehicle with a static arrow sign placed below a LANE CLOSED sign mounted on the tail gate. A moving dump truck was the maintenance vehicle in each state. The various test lighting configurations for slow-moving operations are shown in Figure 17. Figure 18 shows photographs of other tested, truck-mounted devices.

Based on the results of the literature review, the appropriate measure of effectiveness of the various treatments was "lane change time." This measure is the time from initiation of a following vehicle's lane change (i.e., exiting the lane that is obstructed by the maintenance activity) until the vehicle arrives at the maintenance operation. Two specific variables identified using this approach are: (1) *mean lane change time*—average value for specific test condition; and (2) *critical lane change time*—tenth percentile value to indicate lane change occurrence dangerously close to maintenance operation.

A summary of results for all configurations tested is given in Table 6. Results of the tests conducted in Louisiana indicated that the addition of an Ohio light, a truck-mounted sign, or flags mounted on the maintenance vehicles produced an improvement over the state standard. Maryland findings based on mean change time indicated that the light bar provided the best performance by comparison with all other lighting systems tested. New York's use of a shadow vehicle produced superior results by comparison to the rotating beacon used as the standard in the other two states. A significant improvement was noted in New York when the light bar was mounted on the cab of the maintenance vehicle.

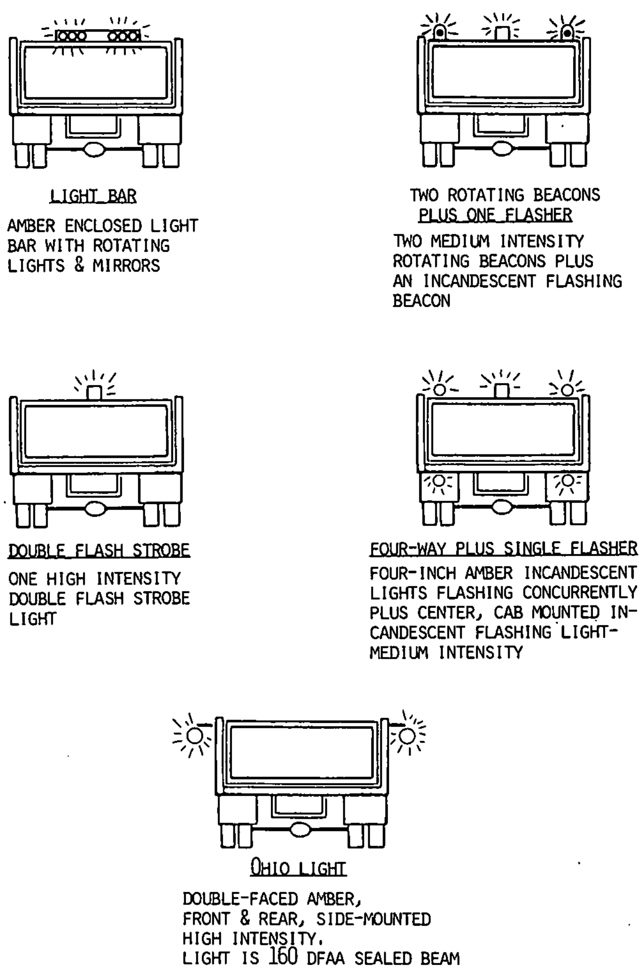


Figure 17. Field-tested service-vehicle warning lighting systems.

Results of Specific Device Applications for Slow-Moving Situation

Vehicle Lighting Systems. Three lighting systems (light bar, Ohio light, and rotating beacon and incandescent flasher combination) performed better than static signing and the other lighting devices tested. The light bar's superior results in the slow-moving situation are likely due, in part, to motorists' associations with its use on moving vehicles (e.g., towing vehicles).

Shadow Vehicle. The shadow vehicle produced the longest lane change times across all test conditions. Therefore, this device is considered to provide the safest traffic flow conditions approaching a slow-moving maintenance operation. A major issue is the cost-effectiveness of shadow vehicle use. The shadow vehicle may be economically justified based on accident reduction experience discussed later in this report.

Truck-Mounted "Road Work" Symbol Sign. The sign, shown in Figure 18, was tested at two locations in Louisiana. It was found to be less effective than the rotating beacon and flashing incandescent combination or the flags mounted on the sides of the dump truck. However, based on critical lane change behaviors, the symbol sign demonstrated an improvement over the two-bulb rotating beacon (current state standard).

Flags Mounted on Maintenance Vehicle. The addition of flags to a moving maintenance truck (also shown in Figure 18) in Louisiana and to the shadow vehicle in New York proved beneficial. The advantage of vehicle-mounted flags is improved vehicle conspicuity at a very low cost.

Table 7 summarizes the findings related to specific device applications for the slow-moving situation.

Short-Term Lane Closures

Tests

State "standard" set-ups (see Figure 19) were applied as a baseline condition for determining the relative effectiveness of specific alternative treatments. The following devices were selected for testing in the short-term lane closure:

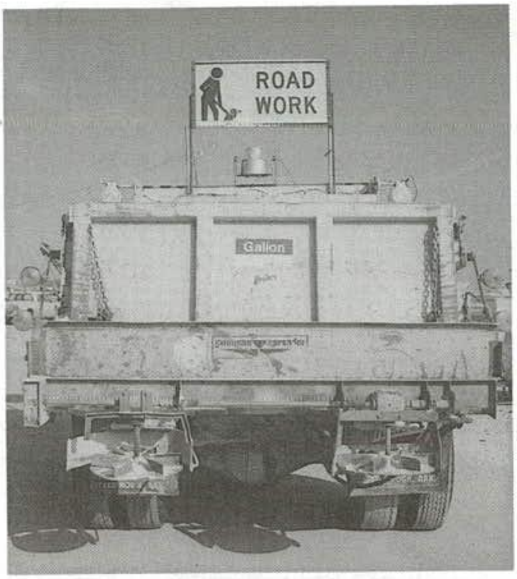
1. *Service vehicle lighting systems:* (a) strobe, high intensity, double-flash; (b) two rotating beacons plus incandescent flasher; (c) four-way flasher plus incandescent flasher; (d) light bar, sequence flashing, six lights.
2. *Ground-mounted traffic control systems:* (a) with and without supplementary flags on the signs; (b) placement of specific signs (first advance warning—1 mile, ½ mile, 1,500 ft; taper symbol sign—1,000 ft and 1,500 ft).

Schematics of the service vehicle lighting systems tested were previously shown in Figure 17; Figure 20 shows photographs of three, tested ground-mounted signing variations. Experimental lighting systems and ground-mounted device treatments were tested as follows:

Louisiana
- Lighting systems
  - Two rotating beacons plus incandescent flasher
  - Double-flash strobe
  - Four-way flasher plus incandescent flasher
- Ground-mounted devices
  - Supplementary flags on signs
  - First advance warning, 1,500 ft advance placement

Maryland
- Lighting systems
  - Arrowboard
  - Light bar
  - Two rotating beacons plus incandescent flasher
  - Double-flash strobes
  - Four-way flasher plus incandescent flasher
- Ground-mounted devices
  - Supplementary flags on signs
  - Taper symbol sign, 1,000 feet advance placement

New York
- Lighting systems
  - Two rotating beacons plus incandescent flasher
  - Light bar
  - Double-flash strobes
  - Four-way flasher plus incandescent flasher
- Ground-mounted devices
  - Supplementary flags on signs
  - First advance warning, ½ mile



TRUCK-MOUNTED SYMBOL SIGN IN COMBINATION WITH OHIO LIGHT

OHIO LIGHT

SHADOW VEHICLE

FLAGS MOUNTED ON MAINTENANCE VEHICLE

Figure 18. Truck-mounted devices tested for continuous moving operation.

Results of the data analysis for short-term lane closures using lane change time as a measure of effectiveness are summarized in Table 8. The left-hand portion of the table contains results based on mean lane change time, and the right-hand side notes critical lane change effects. For each site, the table ranks devices (best to worst) and indicates significant differences between devices. An overview of the findings is first noted by region of the country. Following this, findings are summarized for specific device types.

The Louisiana data indicate that flags attached to the standard ground-mounted sign and the use of a rotating beacon and an incandescent flasher combination mounted on the dump truck

Table 6. Results of device effectiveness comparisons—slow moving operation.

SITE	MEAN LANE CHANGE EFFECT	CRITICAL LANE CHANGE EFFECT
I-10, Louisiana	Ranked Devices - Best to Worst 1. Two-bulb rotating beacon plus truck-mounted flags 2. Ohio Light 3. Two-bulb rotating beacon (Louisiana standard) 4. Truck-mounted symbol sign Significant Differences Two-bulb rotating beacon plus truck-mounted flags Better than Two-bulb rotating beacon (Louisiana standard) truck-mounted symbol sign Ohio Light Better than Two-bulb rotating beacon (Louisiana standard) truck-mounted symbol sign	Ranked Devices - Best to Worst 1. Two-bulb rotating beacon plus truck-mounted flags 2. Ohio Light 3. Truck-mounted symbol sign 4. Two-bulb rotating beacon (Louisiana standard) Significant Differences Significant reduction (67%) in critical lane change occurrences elicited by Ohio light and flags mounted on truck. Slight reduction (30%) observed with truck-mounted sign.
US61, Louisiana	Ranked Devices - Best to Worst 1. Ohio Light 2. Two-bulb rotating beacon plus truck-mounted flags 3. Truck mounted symbol sign 4. Two-bulb rotating beacon (Louisiana standard) Significant Differences Ohio Light Better than Two-bulb rotating beacon (Louisiana standard) Two-bulb rotating beacon plus truck-mounted flags Better than Two-bulb rotating beacon without flags Truck-mounted symbol sign Better than Two-bulb rotating beacon (Louisiana standard)	Ranked Devices - Best to Worst 1. Truck-mounted symbol sign 2. Ohio Light 3. Two-bulb rotating beacon plus truck-mounted flags 4. Two-bulb rotating beacon (Louisiana standard) Significant Differences Improved performances associated with use of both Ohio Light and truck-mounted sign (65% and 46% critical lane change behavior reductions, respectively).
US301, Maryland	Ranked Devices - Best to Worst 1. Light bar 2. Four-way flasher plus SOS flasher 3. Two Federal 312 rotating beacons plus SOS flasher 4. Double flash strobe 5. Two-bulb rotating beacon (Maryland standard) Significant Differences Light bar Better than All Others Four-way flasher plus SOS flasher Better than Two Federal 312 rotating beacons plus SOS flasher Double flash strobe Standard two-bulb rotating beacon Two Federal 312 rotating beacons plus SOS flasher Better than Double flash strobe Standard two-bulb rotating beacon	Ranked Devices - Best to Worst 1. Four-way flasher plus SOS flasher 2. Two Federal 312 rotating beacons plus SOS flasher 3. Light bar 4. Double flash strobe 5. Two-bulb rotating beacon (Maryland standard) Significant Differences Improved with Light bar, Federal 312/SOS combination and Four-way/SOS flasher combination (63%, 65% and 73% critical lane change reductions, respectively).
I-90, New York	Ranked Devices - Best to Worst 1. Shadow vehicle with static arrow (New York standard) 2. Light bar on maintenance vehicle 3. Flags mounted on shadow vehicle 4. Two Federal 312 rotating beacons plus SOS flasher 5. Four-way flasher plus SOS flasher 6. Double flash strobe Significant Differences Shadow vehicle with arrow (New York standard) Better than Four-way flasher plus SOS flasher Double flash strobe	Ranked Devices - Best to Worst 1. Light bar on maintenance vehicle 2. Flags mounted on shadow vehicle 3. Shadow vehicle with static arrow (New York standard) 4. Two Federal 312 rotating beacons plus SOS flasher 5. Four-way flasher plus SOS flasher 6. Double flash strobe Significant Differences Best performance (38% reduction in critical lane changes) associated with Light bar usage; second best (19% reduction) with shadow vehicle, both with and without flags.

did improve driver responses; however, critical lane change behaviors failed to confirm the benefit of flag use. Confirmation of the effectiveness of the rotating beacon and incandescent flasher combination was noted in Maryland.

Results of the New York field tests generally corroborated the foregoing findings. The addition of the rotating beacons and incandescent flasher combination to the service vehicle produced superior results compared with static signing treatments. This finding was also noted for the left-lane closure.

Table 7. Summary of continuous-moving maintenance operation findings.

Vehicle Lighting Systems

- Best results obtained using light bar
- Good results obtained using Ohio Light or combination of two rotating beacons with single flasher
- Acceptable results obtained with combination of four-way flasher with single flasher
- No benefit associated with double flash strobes

Shadow Vehicle

- Preferred on basis of performance to any tested lighting system; recommended use with static arrow or flags

Truck-mounted Symbol Sign

- Slight benefit over existing standard

Flags Mounted on Maintenance Vehicle

- Improvement when used as supplement to lighting device

Results Related to Specific Traffic Control Schemes and Vehicle Lighting Devices for Short-Term Lane Closures

Vehicle Lighting Systems. Uniform results across all three test states indicated that the rotating beacon and incandescent flasher system produced favorable advance lane change responses. Field application of this system consistently demonstrated improvement by comparison with static signing set-ups and other tested lighting systems. While the light bar was often associated with improved mean lane change responses, this effect was not manifested in the reduction of late lane changes (a measure of system ability to alert inattentive motorists). This result was likely due to motorists' association of the light bar with a *moving* hazard.

Another significant finding regarding vehicle light system effectiveness is that two systems (i.e., double-flash strobes and the four-way flasher and incandescent flasher combination) produced no sustained improvement in traffic flow conditions. Therefore, the light bar, double flash strobe, and four-way flasher should not be applied for short-term closures.

Ground-Mounted Sign Placement. In terms of improved mean lane change responses, there was no associated benefit with a 1-mile or ½-mile as opposed to a 1,500 ft advance warning sign. However, if it is likely that traffic will backup beyond the 1,500 ft advance warning sign, consideration should be given to installing additional signs.

Ground-Mounted Sign Characteristics. All tested ground-mounted signs approaching short-term lane closure maintenance operations were standard construction zone orange in color and dimensioned 36 in. on a side. Improved driver responses were obtained in two states where approach signs were mounted approximately 1.0 to 1.5 ft above the pavement on standard tripods, as opposed to a lesser height. Apparently, increased sign conspicuity resulting from this practice improved driver response, thus supporting a recommendation for a 1.5 ft mounting height above the pavement.

Flags on Ground-Mounted Signs. Supplemental use of flags on ground-mounted signs was observed in all three test states. While supplemental flags added to a three-sign array produced an improvement, no benefit was realized from their use on four-sign arrays. Furthermore, no benefit was determined from use of three, as opposed to two, flags.

Table 9 summarizes the findings related to the specific traffic control schemes and vehicle lighting devices for the short-term lane closures.

Shoulder Closure Operations

Tests

Average speeds and proportion of traffic using lanes adjacent to the shoulder closure operation were selected as the appropriate measures of effectiveness in this portion of the study. Tests of various traffic control measures and devices were conducted in Louisiana and New York. For comparative purposes, the state traffic control standard for shoulder closure operations was used as the "baseline" condition. The standards for shoulder closure in Louisiana and New York are shown in Figure 21. Note that the use of a warning sign and a flashing amber light on the first maintenance vehicle is standard traffic control layout for Louisiana. Tested traffic control treatments were as follows: two rotating beacons with incandescent flasher, arrowboard in "flashing bar" mode, and supplemental flags on ground-mounted signs. Figure 22 shows photographs of tested shoulder-closure treatments. All test conditions employed cones to delineate the shoulder enclosed work area.

Data were collected simultaneously at the shoulder closure site and at a geometrically matched "control" (no shoulder closure treatment) selected site in advance of the shoulder closure. This experimental procedure permitted observation of the same vehicle sample under both treated and untreated conditions. The standard shoulder closure treatment in each state was observed initially and, then, specific treatments (e.g., flags, lighting systems) were applied. The treatment effects and concurrent control data are summarized in Table 10. Adequate samples were obtained to support statistical reliability of results.

Results

As can be seen from a comparison of the traffic behavior data in Table 10, the results from the Louisiana site support a recommendation that flags be mounted on an advance sign placed 750 ft in advance of the shoulder work area. This relatively short distance is sufficient to allow for advance motorist preparation and increases the likelihood of warning-sign retention in driver short-term memory.

In order to determine the relative effects of the tested devices, an assessment was based on the incremental improvement shown for each device treatment. The first step in the New York experiment involved the application of flags to the advance sign which produced both a speed reduction and traffic shift away from the lane closure. The strength of this result, supported by concurrent control site data, attests to the ability of flags to effectively

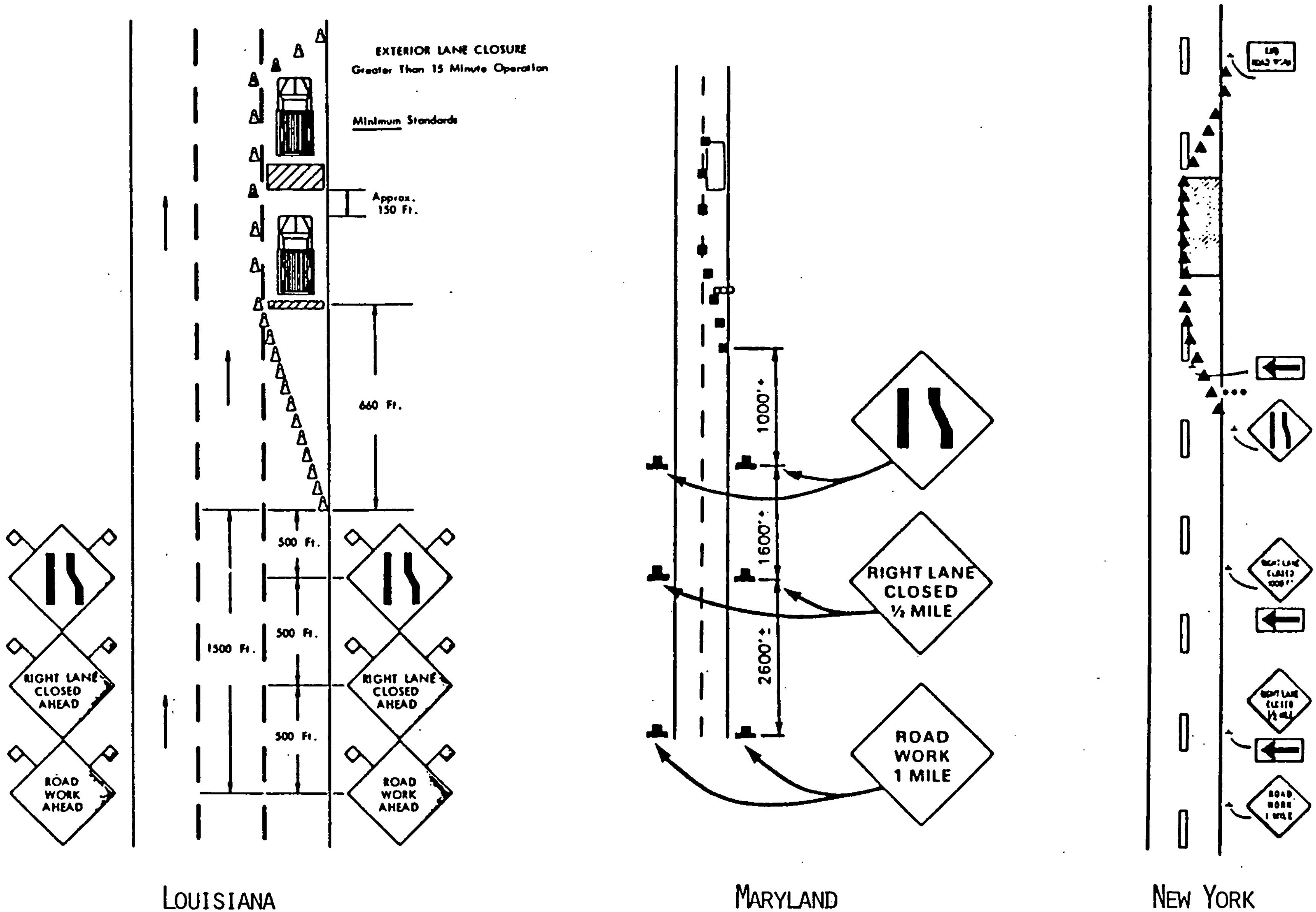


Figure 19. State "baseline" traffic control device set-ups for short-term lane closures.

SUPPLEMENTAL DIRECTIONAL ARROW (ONE-FOOT MOUNTING HEIGHT)

SUPPLEMENTAL FLAGS (MOUNTING HEIGHT FLUSH WITH PAVEMENT)

SUPPLEMENTAL FLAGS (ONE-FOOT MOUNTING HEIGHT)

Figure 20. Observed variations in ground-mounted signing in advance of short-term lane closures.

Table 8. Results of device effectiveness comparisons—short-term lane closure.

SITE	MEAN LANE CHANGE EFFECT	CRITICAL LANE CHANGE EFFECT
US61, Louisiana	Ranked Devices - Best to Worst 1. Standard Louisiana signing with flags 2. Standard Louisiana signing Significant Differences Standard signing with flags Better than Signing without flags	Ranked Devices - Best to Worst 1. Standard Louisiana signing with flags 2. Standard Louisiana signing Significant Differences No significant reduction in critical lane change behavior was elicited with use of flags.
I-10, Louisiana	Ranked Devices - Best to Worst 1. Two Federal 312 rotating beacons plus SOS flasher 2. Standard Louisiana signing 3. Double flash strobe 4. Four-way flasher plus SOs flasher Significant Differences Two Federal 312 rotating beacons plus SOS flasher Better than Four-way flasher plus SOS flasher	Ranked Devices - Best to Worst 1. Two Federal 312 rotating beacons plus SOS flasher 2. Double flash strobe 3. Four-way flasher plus SOS flasher 4. Standard Louisiana signing Significant Differences 67% reduction in critical lane change behavior with Federal 312 beacon plus SOS flasher combination
US301, Maryland	Ranked Devices - Best to Worst 1. Arrowboard * 2. Light bar 3. Two Federal 312 rotating beacons plus SOS flasher and Flags on ground-mounted signs 4. Two Federal 312 rotating beacons with SOS flasher 5. Double flash strobes 6. Signing - with flags (Maryland standard) 7. Modified sign placement - 1000' closure advisory (standard is 1500') 8. Four-way flasher plus SOS flasher Significant Differences Arrowboard* Better than All others Light bar Better than Modified signing - 1000' advisory of closure Four-way flasher and SOS flasher Two Federal 312 rotating beacons with SOS flasher Better than Modified signing - 1000' advisory of closure Four-way flasher and SOS flasher	Ranked Devices - Best to Worst 1. Arrowboard * 2. Two Federal 312 rotating beacons plus SOS flasher 3. Two Federal 312 rotating beacons plus SOS flasher with flags 4. Double flash strobes 5. Light bar 6. Signing - with flags (Maryland standard) 7. Modified sign placement - 1000' closure advisory (standard is 1500') 8. Four-way flasher plus SOS flasher Significant Differences Significant improvement (70% reduction in critical lane changes) with arrowboard and Federal 312/SOS flasher combination. Little improvement (15% reduction) with Light bar.
I-90, New York	Ranked Devices - Best to Worst 1. Two Federal 312 rotating beacons with SOS flasher 2. Standard New York State signing with flags 3. Standard New York State signing - 1 mile advance 4. Modified sign placement - 1/2 mile advance 5. Double flash strobes 6. Light bar Significant Differences Two Federal 312 rotating beacons with SOS flasher Better than Modified sign placement condition - 1/2 mile advance Double flash strobe Standard New York State signing Better than Double flash strobe Standard New York State signing with flags Better than Double flash strobe Light bar Better than Double flash strobe	Ranked Devices - Best to Worst 1. Two Federal 312 rotating beacons with SOS flasher 2. Standard New York State signing - 1 mile advance 3. Light bar 4. Standard New York State signing with flags 5. Modified sign placement - 1/2 mile advance 6. Double flash strobes Significant Differences Reduction in critical lane change occurrences only with use of federal 312 and SOS flasher
I-890, New York Right Lane	Ranked Devices - Best to Worst 1. Four-way flasher plus SOS flasher 2. Double flash strobes 3. Standard New York signing 4. Standard New York signing with flags Significant Differences Four-way flasher plus SOS flasher Better than New York State standard signing with flags	Ranked Devices - Best to Worst 1. Double flash strobes 2. Standard New York signing 3. Four-way flasher plus SOS flasher 4. Standard New York signing with flags Significant Differences Very slight benefit (11% critical lane change reduction) associated with double flash strobe usage. No improvement with flags on signs as four-way flasher usage.
I-890, New York Left Lane	Ranked Devices - Best to Worst 1. Two Federal 312 rotating beacon plus SOS flasher 2. Standard New York State signing Significant Differences Two Federal 312 rotating beacons plus SOS flasher Better than Standard New York State signing	Ranked Devices - Best to Worst 1. Two Federal 312 rotating beacons plus SOS flasher 2. Standard New York State signing Significant Differences 70% reduction in critical lane change occurrences with Federal 312/SOS flasher combination.

warn of the shoulder closure work activity. (The lack of driver response to the flags in Louisiana, apparently, was because they were overridden by the lighting system already in place.)

Subsequent applications of an arrowboard (in flashing bar mode) in the New York experiment and a rotating beacon with incandescent flasher each produced the same effect, i.e., a further shift of traffic away from the shoulder work; yet, no further speed reduction. The fact that neither of these lighting systems produced a further speed change raises some question regarding their incremental cost benefit.

Consequently, these findings support the recommendation that flags be mounted on an advance sign placed 750 ft in advance of the shoulder work area. Further, the findings indicate only small incremental safety benefits associated with the use of lighting devices for shoulder operations, making it difficult to justify the costs to add them to the vehicles except for discretionary application in extreme conditions; e.g., high volume combined with poor sight distance, inadequate lateral safety margin, long-term work durations, and nighttime maintenance activity. If the vehicles are already equipped with lights, a benefit is realized from their use.

Table 11 summarizes the traffic control devices recommended for shoulder closure operations.

Ambient Brightness Effects on Vehicle Lighting System

Ambient conditions (i.e., sunny, cloudy weather) were studied, to the extent possible, in view of the importance of visual impact to the driver of tested devices. Data were gathered as weather conditions permitted. This strategy enabled two lighting systems to be observed in controlled experiments under both bright sunlight and cloudy conditions. Mean lane change times (seconds) for both samples are as follows.

	SUNLIGHT	CLOUDY
Beacon/flasher (Maryland, Slow-Moving)	5.0	5.3
Double flash strobe (New York, Lane Closure)	16.4	16.9

Sufficient samples were obtained to detect a statistical difference at the 0.05 confidence level. These differences are not significant, indicating no degradation of light performance under sunny conditions.

Recapitulation of Field Study Findings

A field study of the effectiveness of traffic control devices applied in maintenance work was conducted in three states: Louisiana, Maryland, and New York. A sample was obtained of 27,784 vehicle behavioral observations for three maintenance operations: short-term lane closures, slow-moving activity, and right shoulder closures. Experimental devices were applied in simulated maintenance work in actual highway settings in order to determine their effectiveness.

Each studied traffic control scheme was observed at two sites—most frequently in different states. Repeated measurements of driver responses to state standard set-ups (i.e., as data collection commenced and again as the final setup) indicated no detrimental learning effect. The device effectiveness measure applied to lane closures (both short-term and slow-moving) was "lane change time." This behavior refers to the time between lane change initiation for a vehicle approaching a closure and when the vehicle actually reaches the maintenance operation. Lane change time increased when improved warning of maintenance activity was provided by the tested traffic control scheme. For shoulder closure operations, the traffic behavior measures applied were vehicle slowing and lane occupancy reductions in adjacent traffic lanes.

Table 9. Summary of short-term lane-closure findings.

Vehicle Lighting Systems

- Best results obtained using combination of two rotating beacons with single flasher
- Little benefit obtained with light bar use
- No benefit associated with either double flash strobe, or four-way flasher with single flasher combination

Temporary Advance Ground-mounted Sign Placement

- Three signs as effective as four
- No benefit of 1 mile or 1/2 mile advance warning
- Recommended array: 3 signs, 1500-foot first advance warning

Flags on Ground-mounted Signs

- Earlier mean lane changes in case of three-sign arrays
- No benefit for four-sign arrays

Ground-mounted Sign Vertical Height

- Recommended mounting height: minimum one foot above pavement surface

Extensive field observation of *slow-moving* maintenance activity resulted in a number of findings. Three experimental lighting systems produced improved driver responses by comparison with standard two-bulb rotating beacons. While conflicting results were obtained between states on the basis of critical lane changes, the light bar was viewed as slightly better than the beacon with flasher combination and the Ohio light. (Preference for light bar use was also based on its superior performance in the laboratory study.) However, the remaining two lighting systems were nearly as good and were recommended for certain maintenance vehicle types (e.g., snowplows) that do not readily lend themselves to light bar application.

The improved performance of the light bar in the slow-moving operation (by comparison to the short-term closure) was likely due to drivers' association of this device with moving applications. The failure of the light bar to reduce critically close lane changes in the short-term closure was inclined to result from drivers confusing the set-up with a moving vehicle such as a tow truck. Consequently, drivers changed lanes only after getting sufficiently close to observe the maintenance operation. Recommendation of the light bar, therefore, is limited to moving maintenance activity.

The shadow vehicle, following 500 ft behind the moving maintenance operation, proved more effective than lighting systems at eliciting advance lane changes. Additionally, orange flags mounted on moving maintenance vehicles (to supplement two-bulb rotating beacon) elicited an improvement, while a static

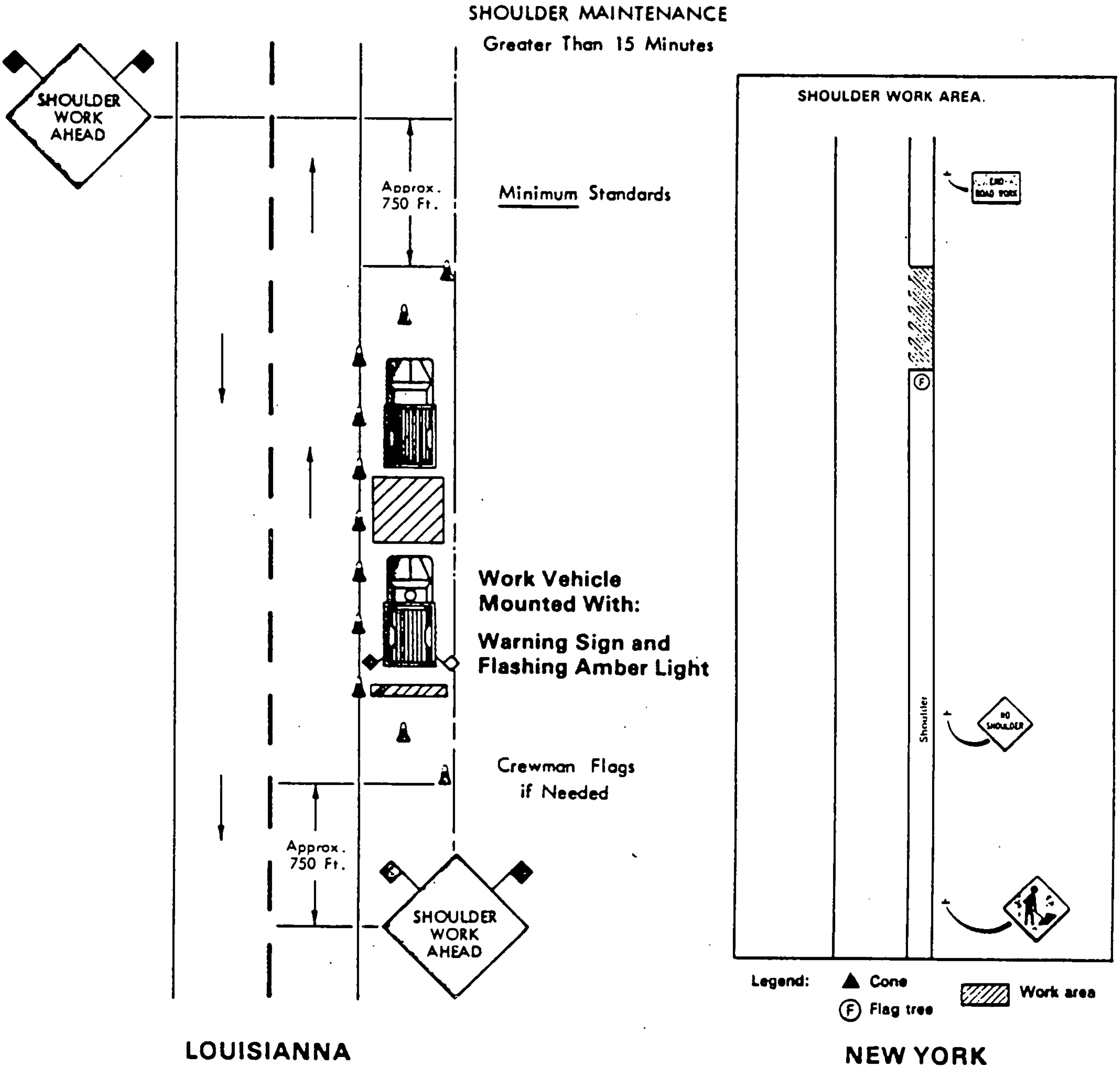
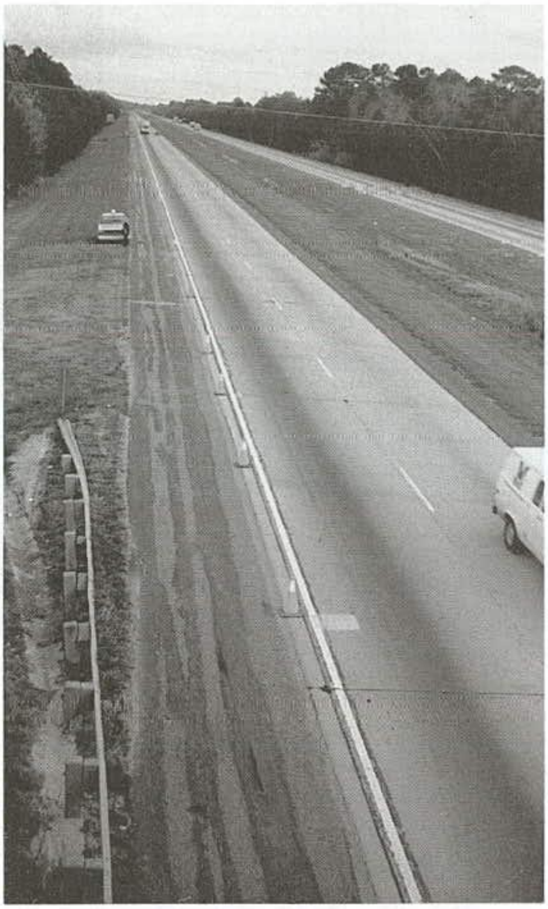


Figure 21. Louisiana and New York standards for shoulder closure operations.

SUPPLEMENTAL FLAGS
ON ADVANCE SIGN



ROTATING BEACON
ON MAINTENANCE
TRUCK

CONE TAPER, ARROWBOARD IN
"FLASHING BAR" MODE

Figure 22. Tested shoulder closure treatments.

Table 10. Comparison of various closure treatments based on right lane speeds and percent lane occupancy.

New York		Louisiana	
Treatment	Control	Treatment	Control
State Standard Cones		State Standard Cones Truck Sign Cab Light	
57.6 mph 41%	55.4 mph 47%	57.1 mph** 64%**	58.7 mph 72%
Flags on Signs		Flags on Signs	
56.4 mph* 32%*(**)	55.1 mph 47%	57.0 mph** 62%**	59.2 mph 68%
Arrowboard Bar display			
56.4 mph* 16%*(**)	56.0 mph 42%		
Vehicle Service Lights Federal 312 beacons plus SOS flasher			
55.1 mph* 19%*(**)	55.2 mph 45%		

Legend
*Significant reduction (.05 confidence) from standard condition
**Significant reduction (.05 confidence) from control condition

Table 11. Summary of shoulder closure recommendations.

Temporary ground-mounted sign application

- Use supplemental flags
- Placement 750 feet in advance of cone taper

Cone Taper

- Use in conformance with current practice

Vehicle service light

- Discretionary usage under extreme conditions (e.g., short approach sight distance; poor lateral clearance, work close to high speed travel lane; high speed and traffic volume under nighttime conditions
- Rotating beacon is acceptable

truck-mounted symbol MEN WORKING sign demonstrated no sustained benefit when applied to the slow-moving operation.

Specific study findings applicable to *short-term closures* are as follows. One lighting system (two rotating beacons with incandescent flasher) was notably superior to other tested alternatives. The promise demonstrated by the light bar at affecting mean lane change behavior was not sustained in terms of critical lane change reductions. Two other tested lighting systems (double flash strobe and four-way flasher with single flasher combination) did not consistently produce an improvement over static signing, traffic control setups; hence, their use is not recommended.

A number of ground-mounted sign applications proved beneficial. These are:

- *Placement*—1,500, 1,000, and 500-ft in advance of taper. No advantage was found for additional sign at either 1-mile or ½-mile placement.
- *Flags*—Two supplemental orange flags placed on sign array are recommended.
- *Mounting height*—1 to 1½ ft above pavement surface.

Table 12. Operational benefits (critical lane change time improvement) and costs of selected devices tested in short-term closure and continuous moving maintenance operations.

Device	Annualized Device Cost ($)	Operational Benefit (seconds)		Cost per Unit Benefit ($)	
		Continuous Moving	Lane Closure	Continuous Moving	Lane Closure
Arrowboard	1,500		2.82		532
Shadow Vehicle	30,982	1.60		19,364	
Federal Signal 312 beacons with SOS flasher	198	.72	.79	275	251
Light Bar	222	.74		300	
Ohio Light	79	.46		172	
Flags on maintenance vehicles	7	.37	.22	19	32
Flags on ground-mounted signs	20	.10		200	

Previous research (e.g., Pain et al.) recommended orange cone tapers for lane closures. Observations in the current study confirmed the utility of cones.

A different field experimental procedure was applied in the case of *shoulder closures,* because lane changing was not the appropriate traffic control device effectiveness measure. Speed reductions and vehicle occupancy shifts away from adjacent lanes were observed. Use of vehicle service lights and supplemental flags on ground-mounted signs were seen to favorably affect adjacent lane traffic flow. In view of their high cost-effectiveness, supplemental flags were the control devices recommended to improve worker safety in shoulder closure activity. A vehicle service light (a single two-bulb rotating cab light) was recommended for discretionary application during extreme conditions (e.g., short approach sight distance, atypically high volume and speed).

BENEFITS AND COSTS OF FIELD TESTED DEVICES

The approach to assessing the relative benefits and costs associated with tested devices considers that a safer traffic operational condition exists with increased lane change times. Cost and benefit data contained in Table 12 depict the annual capital investment required to increase lane change time, on the average, by the number of seconds shown. Device data are given for both short-term closures and slow-moving operations. Values given in the table represent incremental benefits and costs beyond those associated with state standard maintenance traffic control schemes. Right-hand columns contain the calculated cost per second of increased motorist's lane change time response associated with each recommended treatment. The resulting gross numerical differences seen in these unit cost figures clearly illustrate differential economies associated with each of three device types. Very high cost-benefit was seen for use of flags; good benefit was realized from lighting system application; and use of the shadow vehicle was seen as quite costly.

Inclusion of the arrowboard in the benefit-cost analysis was applied to provide a reference base for evaluating effects of tested lighting systems. The observed critical lane change benefit (2.82 sec) was superior to other lighting alternatives; yet, its "unit cost" was less than one-fourth that of the shadow vehicle and twice that of the beacon and flasher combination or light bar.

Obviously, different benefit-cost implications exist for the shadow vehicle use by comparison with other tested treatments. As also seen in Table 12, the critical lane change time benefit associated with the shadow vehicle was 1.6 sec compared to 0.10 to 0.79 sec for other field-tested devices; however, its higher cost warrants further benefit-cost evaluation. While the shadow vehicle demonstrated obvious capability for increasing safety, the accident-reducing potential associated with the critical 1.6-sec driver response improvement remains unknown.

In order to examine the feasibility of shadow vehicle use on the basis of accident statistics within the constrains of this project, a limited survey of accident statistics was undertaken and is documented in Appendix G. From these findings, the following decision-making algorithm was developed to address shadow vehicle utility for use by state maintenance personnel. For the shadow vehicle to be cost effective, it must meet one of the following requirements: (1) prevent one fatal accident (reduce severity of one fatal to an injury-only accident) in 16 years of operation, or (2) eliminate 3 to 6 property damage or injury accidents per year.

In summary, two types of cost-effectiveness evaluation were conducted for maintenance traffic control devices found to improve driver responses. First, comparisons for specific devices were based on incremental (difference between "standard" device application and tested improvement) costs and benefits. The traffic operational benefit, in this case, was increased lane change time compared with dollar cost of upgrading the standard traffic control set-up. Results were that very high benefit-cost trade-offs were associated with supplemental flags and service vehicle lighting systems. Although a substantial operational benefit was seen for the shadow vehicle, its higher cost warranted a second approach to examine its cost-effectiveness. An overview of work zone accident statistics indicates that, for a device as expensive as the shadow vehicle to be cost effective, it must meet one of the specific accident-reduction requirements noted above.

DEVICE RECOMMENDATIONS

Recommended devices applicable to slow-moving maintenance activity are three lighting systems (light bar, preferred; two rotating beacons plus incandescent flasher and Ohio light, acceptable) because each elicited improvements over a single two-bulb rotating incandescent beacon; orange flags are also recommended to supplement the applied lighting system.

Although the shadow vehicle proved highly effective, it is currently considered an "optional" device because of its relatively high cost of operation (e.g., necessitated by additional vehicle with driver). To be cost effective, it is estimated that use of the shadow vehicle must reduce 3 to 6 property damage or injury accidents per year, or it must eliminate one fatality in 16 years. A final decision regarding its use thus remains with appropriate highway authorities, based on this accident-reduction criterion.

For short-term lane closures, the two-rotating beacon plus incandescent flasher system consistently produced a benefit over existing state standard use of a single rotating beacon; therefore, this system is recommended. Orange cone tapers in advance of the closure are recommended for high traffic volume roadways. Ground-mounted advance sign placement is recommended at 1,500, 1,000, and 500 ft approaching the taper, because no advantage was found for 1- or 1½-mile advance placement. Mounting height of 1 to 1½ ft above the roadway surface is recommended in order to ensure adequate sign visibility.

In the case of shoulder closures, vehicle service lights and supplemental flags on ground-mounted signs were seen to favorably affect adjacent lane traffic flow. Because of their high cost-effectiveness, supplemental flags were recommended. A vehicle service light (a single two-bulb rotating cab light was effective) is recommended for discretionary application during extreme conditions (e.g., short approach sight distance, atypically high volume and speed). The recommended device system for shoulder closure activity is comprised of cone protection for the maintenance work in combination with an advance ground-mounted sign (750-ft advance placement) and supplemental orange flags.

Table 13. Summary of recommended traffic control devices applicable to maintenance situations.

SHORT-TERM LANE CLOSURE

- Effective service vehicle lighting systems
  - Two rotating beacons with single flasher, acceptable
- Temporary ground-mounted signs
  - Advance Placement
    - Use 500, 1000, and 1500 feet
    - Do not use 1-mile or 1/2-mile advance warning
  - Characteristics
    - 36"x36", construction zone orange
    - Mounted 1 - 1 1/2 feet above pavement surface
  - Use two orange supplemental flags per sign
- Orange cone taper
  - Use in accordance with currently accepted spacing and taper practice

CONTINUOUS MOVING OPERATION

- Effective service vehicle lighting systems
  1. Light bar, preferred
  2. Two rotating beacons with single flasher, acceptable
  3. Ohio Light, acceptable
- Shadow vehicle
  - Highly effective but costly
  - Base use decision on following accident reduction criterion
    1. Reduces accidents by 3-6 per year, or
    2. Eliminated one fatality in 16 years
- Supplemental flags on maintenance vehicle
  - Side-mounted auxiliary to lighting system

SHOULDER CLOSURE

- Ground-mounted sign
  - 750 feet advance placement
  - Use supplemental flags
- Cone taper
  - Use in accordance with currently accepted spacing and taper practice
- Service vehicle with rotating beacon
  - Use as discretionary under extreme conditions (e.g., limited approach sight distance, poor lateral clearance, high speed and volume)

Table 13 summarizes the traffic control devices recommended for continuous-moving operation, short-term closure, and shoulder closure.

CHAPTER THREE

INTERPRETATION AND APPLICATION

This chapter synthesizes and interprets the findings of the various tasks reported in Chapter Two. Driver response to warning lights and other devices are discussed first. The characteristics of warning lights and light types are discussed next. Finally noted is the ultimate application of the research findings into the 11 work zone types which characterize moving and short-term operations. This categorization provides the basis for development of the User's Guide.

DRIVER RESPONSE TO WARNING LIGHTS

The empirical study undertaken in this research found that the speed of the service vehicle contributed more heavily to driver perceptions of the vehicle's speed and closing rate (i.e., between service vehicle and approaching vehicles) than did any of the tested warning light systems. Generally, the slower the service vehicle was moving the less accurate was the driver's perception. This suggests that early or advance warning with light devices visible for long sight distances (over 1,000 ft at 55 mph), which allow drivers sufficient time to perceive and understand the situation, is crucial to safe operations at work zones. Where sight distance is restricted, provision of an approach traffic control device lighting system is necessary to warn and prepare drivers for the work zone.

Another finding of interest was that not all warning lights improved driver closure rate or speed of perception of service vehicle. Some of the lights apparently had a negative effect, i.e., drivers judged the service vehicle to be going faster than its actual speed. This meant the driver would close on the service vehicle sooner than the driver expected. The recommended lighting systems resulted in no such error, or in only small degrees of this misperception or in a positive misperception (i.e., overly conservative closure perception with negative safety consequences).

The observed tendency for some degree of driver misperception mandates careful application of the recommended warning light traffic control devices.

DRIVER RESPONSE TO OTHER DEVICES

The results obtained for certain truck-mounted non-light devices (i.e., signing symbols, arrows, flags) and ground-mounted devices (i.e., signs, supplementary flags) impacted the development of the device guidelines. Specifically improved driver responses to low-cost device alternatives, e.g., most noticeably supplementary flags, advocated their use on certain signing alternatives and on maintenance trucks used in slow-moving operations. Although a specific warning sign and arrow combination placed on a following pick-up truck (i.e., the shadow vehicle) produced significant benefits, substantial costs (e.g., driver time, vehicle maintenance, fuel) are involved in its application. Therefore, separate cost-effectiveness criteria are included as a basis for agency-specific decisions regarding its use.

Certain ground-mounted signing applications, and the use of supplemental flags in particular, also proved effective in achieving low-cost improvement. Additionally, improved driver responses were associated with specific mounting-height applications. Therefore, these characteristics are integrated into guideline recommendations based on the field study results.

WARNING LIGHT CHARACTERISTICS

Flashing has been known to increase conspicuity of lights for many years. Flash rate has also been studied. In addition, the results of this research have indicated that the flash rates (between 60 to 110 cpm) equally affect driver performance. A true flash as distinct from an apparent flash (as seen with a rotating light) improves drivers' ability to estimate the speed of the preceding vehicle and the gap closure rate. Duty cycle (light on-off cycle) is related to driver perception also. The strobe gives a distinct flash, but drivers' do no better extracting information than with a rotating light. The flashing light, four-way flashers, and flashing arrow treatments all were more successful in conveying gap/speed information. The duty cycles of these lights appeared adequate.

Intensity of lights (only medium to high intensity lights were tested) did not have an effect on driver ability to estimate preceding vehicle speed or gap closure rate. This finding was clear in the closed field experiments where conspicuity was not a factor. In the full field tests the less intense four-way lights were not as effective. When a flashing light and rotating light were used together, driver performance improved as shown in the field testing. Thus, distinct flashing combined with the intensity of the rotating lights (and possibly the attention-gaining characteristics of the light rotation) provide two somewhat distinct types of information—attention gaining and speed estimation/closure rate. A contributing factor to flashing light effectiveness is the learned meaning or symbol nature of flashing lights, particularly four-way flashers that are associated with slow-moving or stopped vehicles.

Placement of warning lights, e.g., front, rear, sides, center, had no significant impact on driver response. The key placement feature is to have the lights visible from all angles that drivers might approach the service vehicle.

Number of lights (1 to 4) had no significant effect on drivers responding in the closed field testing. In the full field tests multiple light treatments outperformed single light treatments. Drivers continually scan and search, so it would not be surprising that a treatment with lights on both sides of the service vehicle would be seen and responded to earlier in the highway setting.

Type of light did make a difference in driver response. In considering both the closed field and the field results, it was found that incandescent flashing lights (e.g., four-way flasher, cab-mounted flasher, Ohio Light) conveyed more speed and gap information—but only the larger, brighter Ohio Light performed as well in operational settings. Rotating lights did not perform as well as flashing lights in closed field settings but, when paired with flashing lights, were excellent on the highway. The double flash strobe light provided more information to drivers than single flash strobe lights in the closed setting. However, the double flash strobe did not perform as well as flashing and rotating lights on the highway. The arrow treatments (3-ft by 5-ft arrowboard; two small arrows) performed well in both the closed field and operational environments. The light bar performed adequately in the closed field and well under some circumstances in the field (for moving operations) but, based on the results, would not be considered an all-around replacement or substitute for other light types.

In summary, the type of light and method of flashing are the two light characteristics that had the greatest impact on light effectiveness within the intensities and flash rates studied. Number and placement of lights had little impact on driver response to warning lights.

INTEGRATED RESULTS FOR EACH CATEGORY OF SHORT-TERM AND MOVING WORK ZONE

Eleven categories of short-term and moving work zones were shown in Figures 4 through 14. The driver actions and corresponding information requirements are listed in these figures, and they are followed by the recommended traffic control device and vehicle warning light systems. Each figure concludes with the relevant study findings supporting the TCD and warning light recommendations.

The last step in the research application was to synthesize the project results into a format that is usable by the practitioner community. Thus, the User's Guide (contained in Appendix A) is the product of this effort.

CHAPTER FOUR

CONCLUSIONS AND SUGGESTED RESEARCH

CONCLUSIONS

Various traffic control devices amenable to highway maintenance practice were shown to be effective in the field study. The applied procedure demonstrated an operational benefit of certain devices to affect motorists' behavioral responses. Subsequent cost-effectiveness evaluation prioritized lower cost devices (flags, lighting systems) and developed specific criteria for the use of the higher cost shadow vehicle, so as to facilitate implementation decisions. The product of this overall process comprises readily implementable guidelines for new traffic control applications based on empirical study. As such, the devices included in the guide are known to be effective.

However, traffic control implementation decisions must consider the long-term goal of accident reduction. While traffic operational studies strongly support initial decisions regarding TCD applications and guideline development, sustained performance to increase safety through accident reduction is the ultimate measure of device effectiveness.

Like most research and development involving human behavior and performance, the findings of this project are not as simple or as clear as desired. However, many useful results did emerge which made it possible to develop the guidelines for traffic control in short-term and moving maintenance operations.

This research demonstrated that moving and short-term activities, although many in number, have common information requirements that must be met through traffic control and application. From the many maintenance activities, 11 sets of information requirements were extracted which encompass all the activities. These information requirements were the base for developing the traffic control guidelines.

Prior research suggested that there were some behavioral differences in response to the various warning lights; however, it was not known whether these differences would be evident in work zone settings. This research demonstrated that human response to warning lights varied by the type of light both in closed field and operational tests.

Two of the findings regarding driver response to lights were useful for a broader scope of highway/vehicle design than work zones. First, for short distances, e.g., under 1,000 ft, a driver's ability to estimate the speed of the vehicle in front of him/her and to judge the rate of closure of the gap between the vehicles was not consistent. The slower the lead vehicle speed (between 0 to 28 mph), the more inaccurate the driver's perception of that speed (at least between 35 and 55 mph). Unfortunately, the misperception was in the direction of seeing the lead vehicle going faster than it actually was.

The second finding was that, generally, rotating and strobe lights were not as effective in providing speed and closure rate information to drivers as flashing lights, especially when the service vehicle was stopped. However, flashing lights were not as effective in providing attention value from longer distances. Therefore, several of the lighting recommendations combine the two types of light in order to ensure optimum information transmission and conspicuity. The lighting systems recommended in this project somewhat ameliorated the noted perceptual errors.

Many of the characteristics of lights currently on the market are quite adequate, at least from the perspective of human response; for example, flash rate, duty cycle or dwell time, color, and the higher intensities of rotating lights (traditional or halogen). The development of higher intensities of flashing lights might improve the attention-getting function of this type of light. The strobe lights were easily seen, but the fast duty cycle does not provide adequate time for the human visual system to sense speed (vehicle movement). This was true for single and double flash systems, particularly in the operational tests.

There is no simple answer to the trade-off between cost of device and safety. Therefore, a cost-benefit algorithm was developed to aid in making some of the decisions. This approach, if it proves useful, may have further relevance to construction zone and other traffic control planning decisions.

SUGGESTED RESEARCH

Extensive indoor laboratory, closed field, and actual highway observation undertaken during the course of NCHRP Project 17-6A gave rise to a number of suggestions for future research. This research falls into two distinct areas: (1) human factors development of traffic control devices, and (2) traffic engineering application of these devices.

Device Development

No one light is maximally effective in both transmitting information and gaining attention. A much brighter flashing light than any of those tested, which combines these two qualities, would simplify the warning light situation.

Several of the information requirements for convoy operations are currently not met. Signs were developed and laboratory tested in this research; however, resource limitations prevented their field testing. Operational tests with such signs would be useful to demonstrate their effectiveness.

This research did not completely resolve the conflict between the need for time-consuming deployment and removal of traffic control versus the very short time spent at any one work site. During task 2 of the effort, several novel ideas for devices were advanced which could both reduce set-up and removal time and meet driver information requirements. Because these devices were outside the project scope, they were not pursued. The need to develop these and other ideas still exists. The potential cost benefit to maintenance authorities for such devices is great.

In the field study, regional differences were observed in response to the same device. This fact suggests that it would be possible to further generalize the recommendations emanating from this research if they were tested in a wider variety of geographic locations.

Furthermore, the findings of this study raise serious doubts that additional costs associated with lighting devices applied in shoulder closure operations would produce an incremental safety benefit. (Although additional vehicular lane occupancy shifts occurred with lighting devices at the New York site, the reader is cautioned against an attempt to elicit such behavior in a high-density traffic situation.) The resulting recommendation was that lighting devices for shoulder operations be considered discretionary for use in extreme conditions, e.g., high volume combined with poor distance, inadequate lateral safety margin, long-term work durations, and nighttime maintenance activity. However, this situation warrants further study.

Driver perception and vehicle behavior (slowing and lane changing) were the applied measures of effectiveness. Further application of the recommended devices should be evaluated using the ultimate criterion: accident frequency and severity.

The high cost in dollars and lives at high speed work zones necessitated that operational testing be undertaken in that setting. Lower speed and more congested urban areas frequently, as in this project, were not represented. The results of this research and innumerable related work zone findings would benefit from replication in such settings. The general thinking is that if it works in the high speed setting, surely it will work at lower speeds. This assumption needs to be tested, particularly in highly congested, blocked, or limited visibility urban settings.

Device Application

The need to consider long-term accident prevention (and severity reduction) became evident during the course of assessing the benefit-cost trade-off associated with the highly (operationally) effective shadow vehicle. The relatively large investment required for shadow vehicle operation emphasizes the need for close examination of accident-cost savings realized by highway agencies in order to support its operation.

The magnitude of the work zone safety problem is staggering. For example, 1986 data suggest that 5-year cost consequences of this problem in New York alone exceed 36 million dollars. More significantly, the problem is expected to increase as major highway reconstruction projects are continually undertaken.

While work conducted under NCHRP Project 17-6A demonstrated that certain traffic control measures were effective for short-term maintenance application, the need again became evident for detailed study of accidents to better define specific aspects of highway work area safety. Large expenses for accident countermeasure devices cannot be justified unless specific benefits can be reliably estimated prior to their implementation. The shadow vehicle example is but one small case in point. The overall problem is considerably more global.

Detailed investigation, based on analysis of massive accident data (e.g., collision diagrams), is needed to specifically define the work zone safety problem. One obvious aspect of the problem noted from the current project is the need to quantify certain moving maintenance hazards, assign a dollar value to consequences of the specific hazard, and develop the feasibility associated with a specific countermeasure. Previous work (e.g., Graham et al., *28*) to address work zone accident implications failed to categorize accident topologies (e.g., precrash maneuvers) as to support the development of effective countermeasures.

To conduct a detailed accident study during the early 1990s would be considerably facilitated by the current technology employed by numerous highway agencies to computerize detailed accident data. For example, automated accident records in many states include very specifically coded precrash movements, characterizing the level of detail found in collision diagram information. To define the magnitude of the accident problem potentially ameliorated by shadow vehicle use, the following procedure is feasible. Select specific accident codes describing rear-end collisions associated with moving hazards in (or approaching) construction areas. Selection of these codes must be undertaken in such a manner as to describe vehicle interactions resulting from traffic perturbations due to the maintenance and utility work activity. Based on comparisons between conditions with and without shadow vehicle application, determine the number of accidents with associated severity (i.e., property damage, injury, severity). The finding, in concert with observations of the current study (e.g., vastly improved lane change times associated with shadow vehicle usage), could substantiate the benefit of shadow vehicle use. A wide-scale effort, based on many state databases, is required to support development of cost-saving countermeasures.

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APPENDIX A*

USER'S GUIDE FOR SHORT-TERM AND MOVING WORK ZONE TRAFFIC CONTROL

This guide designates vehicle lighting systems and ground-mounted traffic control devices for use at maintenance work sites. It is intended as a stand-alone document, which may be reproduced and used separately from the research report.

The guide is organized into two sections. The first is a decision-aid for use in selecting the type of moving or short-term work zone of interest. The second section contains 11 charts, which show and describe traffic control devices and vehicle lighting to use in the traffic control plan.

SECTION ONE

Figure A-1 is a decision-aid for matching the traffic situation and the type of maintenance activity with a traffic control strategy. Enter this exhibit with four types of information:

1. Location—the type of road (e.g., two-lane or multilane).
2. Duration—short-term or moving operation.
3. Volume—amount of traffic to be encountered (20,000 ADT and above is high; levels below 9,000 on two-lane and below 16,000 on four-lane roadways are considered low volume).
4. Type of operation—lane closure, shoulder, roadside.

With this type of information, questions indicated in Figure A-1 can be answered. The numbers in the boxes refer to the 11 categories of work zone traffic control maintenance operations. These guidelines, given in Section Two, include suggested devices, application prerequisites, and use criteria.

*Appendix A, as prepared by the research agency, is divided into two major parts. The first part contains the "User's Guide," as published herein, and the second part details the findings of the "State-of-the-Art Review." The latter part of Appendix A has not been included in this report. The reader should refer to the "Foreword" for its availability.

SECTION TWO

The following charts (Categories 1 through 11) and Figure A-2 are designed for use by highway and utility agency personnel responsible for planning and installing maintenance traffic controls.

No guideline can cover all situations perfectly. Therefore, it is expected that these charts will provide generic guidance in developing a site-specific traffic control plan. The suggested devices contained in this guide represent the minimum requirements, for moving and short-term work zone traffic controls, based on the research results. The user is expected to expand or improve the guidelines when the need is deemed to be warranted.

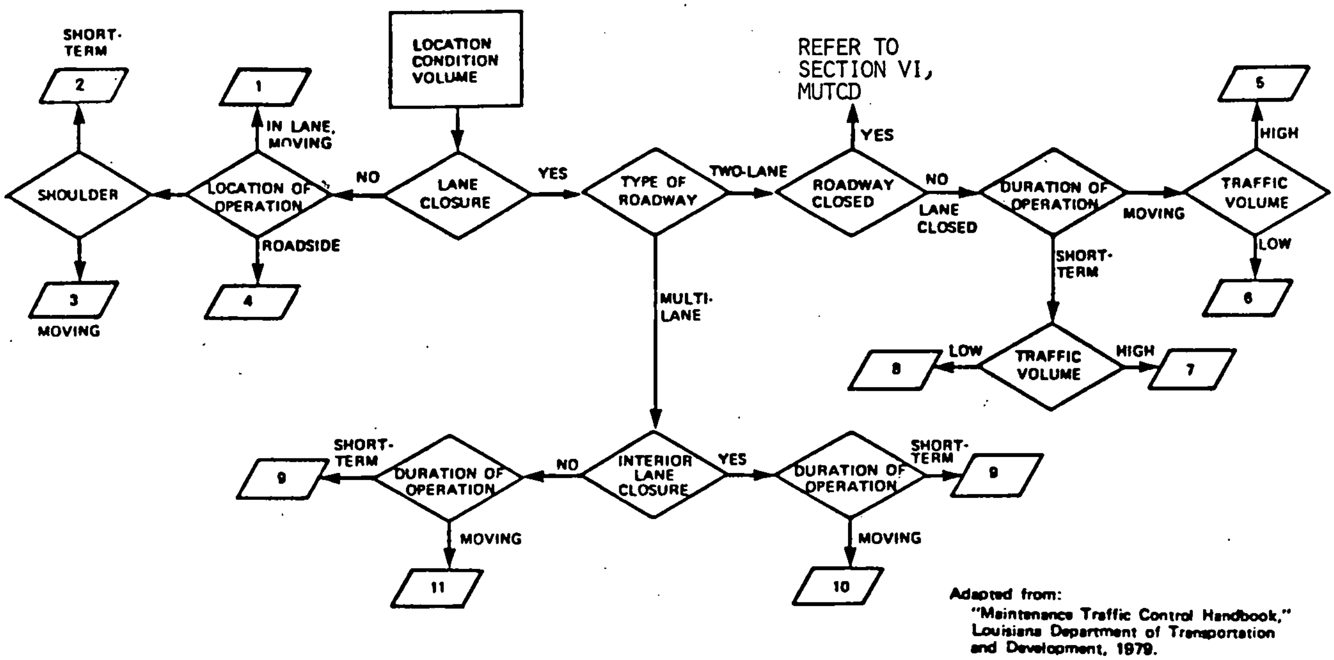


Figure A-1. Decision-aid to categorize short-term and moving operations.

Category 1 - In-lane, Moving

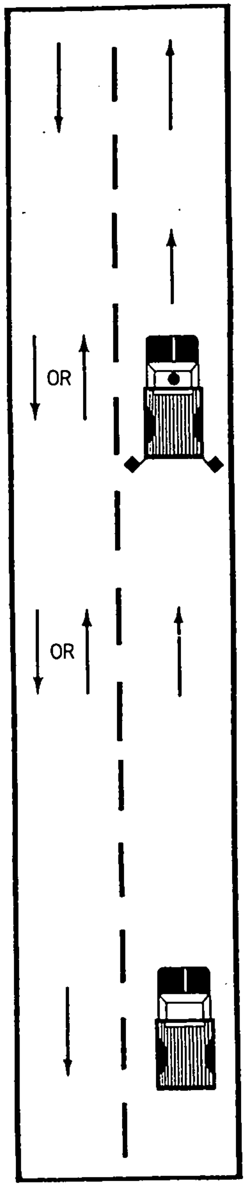
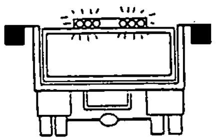


Chart 1

SUGGESTED PRACTICE

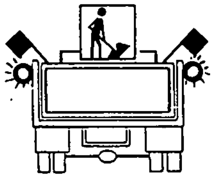
Vehicle Lighting

Best

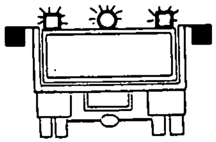


Light Bar

Alternates



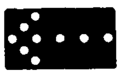
Ohio Light Plus
Truck-mounted Symbol



Two Rotating Beacons
Plus One Flasher

Vehicle-mounted Orange Flags
Minimum 18" x 18", Florescent Orange
Laterally-mounted, Clear of Truck Body

Optional Shadow Vehicle
Sign on Rear Depends on Road Type
Single Lane, "Pass With Care"
Multiple-Lane, Static or Dynamic Arrow

 or 

Minimum Sign Size, 24" x 36

DEVICE DESCRIPTION

1. *Vehicle Lighting*

Light Bar Amber enclosed series of lights or single light with twin-sided reflectors on either end. Acceptable lamp types are: (1) incandescent, 42-watts, 35K beam candlepower; or (2) halogen, 50- to 60-watts, 60K to 65K beam candlepower. Combination of various lamp types are acceptable. Recommended flash rates of 60 to 120 cycles per minute. Mounted on cab with sufficient clearance to provide unobstructed view from surrounding vehicles.

Ohio Light Double-faced (front and rear), flasher-activated, sealed amber beacons, e.g., Cats Eye, 160DF, or Signal Stat CE160DFAA. Dual-mounted on orange-painted brackets so as to provide approximately 10-inch clearance from truck body. Recommended flash rate is 60 to 120 cycles per minute. See Figure A-2 for a schematic diagram of typical assembly dimensions.

Rotating Beacons Two medium-to-high intensity (e.g., minimum 50K candlepower) amber beams at 60-100 cycles per minute. Poor visibility conditions, e.g., fog, require higher intensity (minimum 90K candlepower). Lamp type can be tungsten sealed beam or filament, incandescent, halogen, or quartz halogen. Mounted over the cab on both sides, providing 360-degree visibility with unobstructed view to surrounding vehicles.

Flasher One medium intensity (e.g., 50K to 60K candlepower incandescent (tungsten or halogen) light at 60-100 flashes per minute. Mounted over center of cab so as to provide 360-degree visibility.

2. *Truck-Mounted Symbol Sign*

Black W21-1a "Men Working" symbol on orange background. Rectangular panel (24" to 36" on each side), center-mounted over cab with sufficient clearance to provide unobstructed view to following vehicles.

3. *Shadow Vehicle Use Criteria*

The cost effectiveness of a shadow vehicle can be determined on a state-specific basis, utilizing accident-reduction experience. However, cost information obtained from one user state suggests that use of a shadow vehicle can be economically justified based on any one of the following criteria:

1. Elimination of one fatality in 16 years of use.
2. Severity reduction from injury to Property Damage Only for six accidents per year.
3. Elimination of three accidents per year.

The vehicle should be placed so drivers see the sign at least 1500 feet in advance of the work zone. When the work zone is moving, the vehicle should follow at a distance of 1/4 to 1/2 mile.

Category 2 - On-shoulder, Short-term

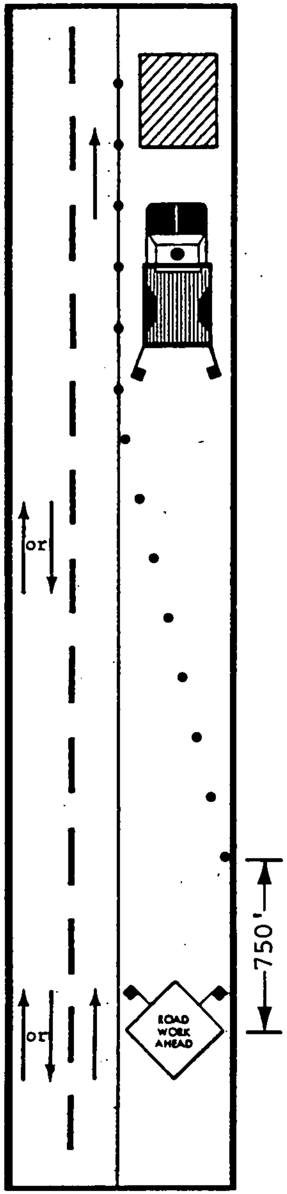
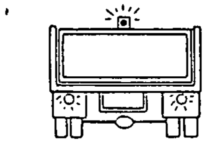


Chart 2

SUGGESTED PRACTICE

Vehicle Lighting

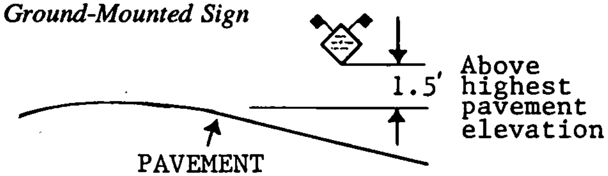


One Rotating Beacon
Plus Four-way
Emergency Flasher

Channelizing Devices

Florescent Orange Cones, 28" Minimum Height
Florescent Orange Tubes, 36" Minimum Height
Reflectorized for Nighttime Application
Spacing and Taper Length as Noted

Ground-Mounted Sign



W21-5 36" x 36" Sign
Supplemented with Florescent Orange Flags
Minimum 12" x 12"
Mounted at 45-degree Angle with Sign Face

DEVICE DESCRIPTION

1. *Vehicle Lighting*

<u>One Rotating Beacon</u> One medium-to-high intensity (e.g., minimum 50K candlepower) amber beams at 60-100 cycles per minute. Poor visibility conditions, e.g., fog, require higher intensity (minimum 90,000 candlepower). Lamp type can be tungsten sealed beam or filament, incandescent, halogen, or quartz halogen. Mounted over cab providing 360-degree visibility with unobstructed view from surrounding vehicles.

<u>Four-way Emergency Flasher</u> (Vehicle emergency flasher system) refers to vehicle's own emergency flasher.

2. *Channelizing Devices*

<u>Taper and Spacing Guidelines</u>. MUTCD taper guidelines are recommended. They are:

Roads with speed limits of 45 mph or greater -
Taper length (ft.) = speed (mph) x lane width (ft.)
Roads with speed limits under 45 mph -
Taper length = $\frac{\text{speed (ft.) x lane width (mph)}}{40}$

MUTCD spacing guideline is: spacing (ft.) equal to speed limit.

<u>Alternative spacing suggestion.</u> Spacing between devices is: (1) 40 feet when the speed limit is 45 mph or less, or (2) 80 feet when the limit is greater than 45 mph.

Category 3 - On-shoulder, Moving

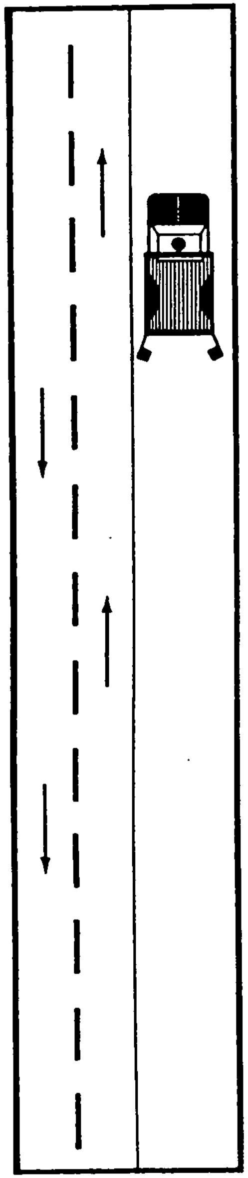
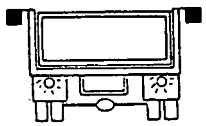


Chart 3

SUGGESTED PRACTICE

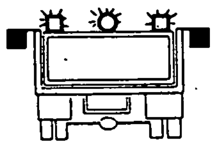
Vehicle Lighting

Acceptable



Four-way Emergency Flasher

Alternate



Two Rotating Beacons Plus One Flasher

Vehicle-mounted Orange Flags

Minimum 18" x 18", Florescent Orange
Laterally-mounted, Clear of Truck Body

DEVICE DESCRIPTION

1. *Vehicle Lighting*

Four-way Emergency Flasher Refers to vehicle's own emergency flasher.

Two Rotating Beacons Two medium-to-high intensity (e.g., minimum 50K candlepower) amber beams at 60-100 cycles per minute. Poor visibility conditions, e.g., fog, require higher intensity (minimum 90,000 candlepower). Lamp type can be tungsten sealed beam or filament, incandescent, halogen, or quartz halogen. Mounted over the cab on both sides, providing 360-degree visibility with unobstructed view from surrounding vehicles.

Flasher One medium intensity (e.g., 50K to 60K candlepower incandescent (tungsten or halogen) light at 60-120 flashes per minute. Mounted over center of cab so as to provide 360-degree visibility.

Category 4 - Roadside, Moving or Short-term

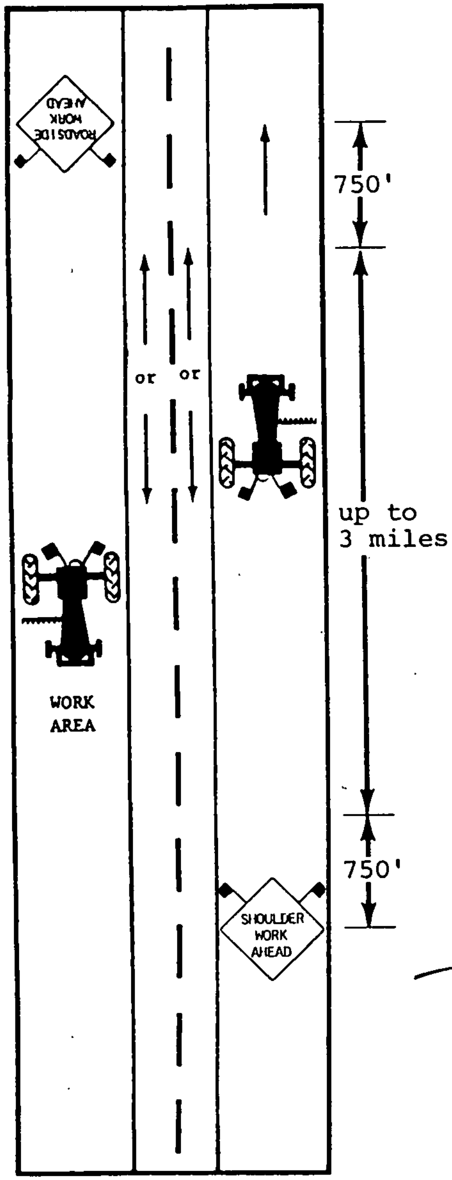


Chart 4

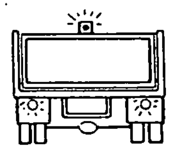
SUGGESTED PRACTICE

Vehicle-mounted Orange Flags

Minimum 18" x 18", Florescent Orange
Flags mounted laterally on vehicle/machinery

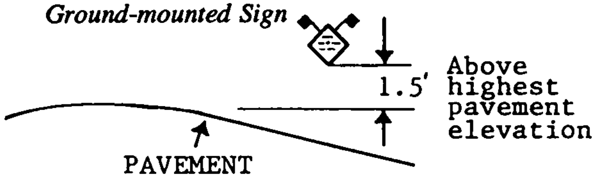
Vehicle Lighting

Stopped Vehicles Only
(Includes mowers, etc.)



One Rotating Beacon
Plus Four-way
Emergency Flasher

Ground-mounted Sign



W21-5 36" x 36" Sign
Supplemented with Florescent Orange Flags
Minimum 12" x 12"
Mounted at 45-degree Angle with Sign Face

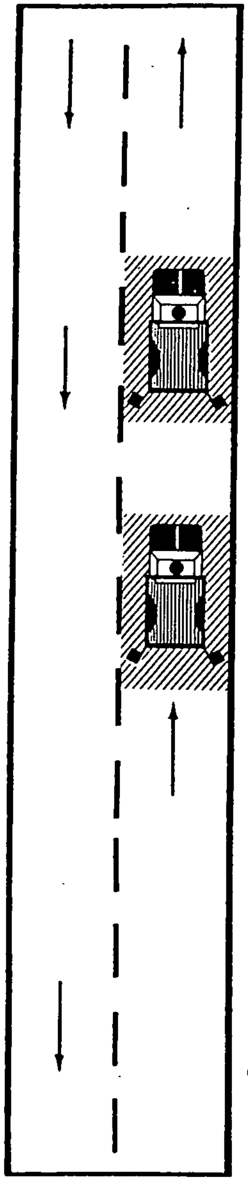
DEVICE DESCRIPTION

1. *Vehicle Lighting*

One Rotating Beacon One medium-to-high intensity (e.g., minimum 50K candlepower) amber beams at 60-100 cycles per minute. Poor visibility conditions, e.g., fog, require higher intensity (minimum 90K candlepower). Lamp type can be tungsten sealed beam or filament, incandescent, halogen, or quartz halogen. Mounted so as to provide a 360-degree visibility with unobstructed view from surrounding vehicles.

Four-way Emergency Flasher (Truck emergency flasher system) refers to vehicle's own emergency flasher.

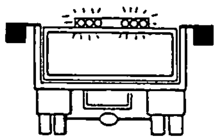
Category 5 - Two-lane, High Volume, Moving, Lane Blocked



SUGGESTED PRACTICE

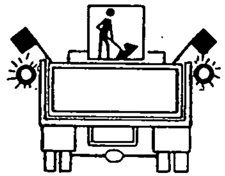
Vehicle Lighting

Best

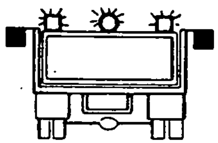


Light Bar

Alternates



Ohio Light Plus
Truck-mounted Symbol

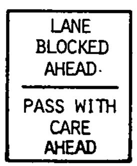


Two Rotating Beacons
Plus One Flasher

Vehicle-mounted Orange Flags
Flags Optional on Lead Vehicle
Flags Recommended on Following Vehicle
Minimum 18" x 18", Florescent Orange
Laterally-mounted, Clear of Truck Body

Optional Shadow Vehicle
Operate on Shoulder of Roadway

Sign on Rear:



Black Letters
8" Minimum
Orange Background

DEVICE DESCRIPTION

1. *Vehicle Lighting*

Light Bar Amber enclosed series of lights or single light with twin-sided reflectors on either end. Acceptable lamp types are: (1) incandescent, 42-watts, 35K beam candlepower; or (2) halogen, 50- to 60-watts, 60K to 65K beam candlepower. Combination of various lamp types are acceptable. Recommended flash rates are 60-120 cycles per minute. Mounted on cab with sufficient clearance to provide unobstructed view from surrounding vehicles.

Ohio Light Double-faced (front and rear), flasher-activated, sealed amber beacons, e.g., Cats Eye, 160DF, or Signal Stat CE160DFAA. Dual-mounted on orange-painted brackets so as to provide approximately 10-inch clearance from truck body. Recommended flash rate is 60 to 120 cycles per minute. See Figure A-2 for a schematic diagram of typical assembly dimensions.

Rotating Beacons Two medium-to-high intensity (e.g., minimum 50K candlepower) amber beams at 60-100 cycles per minute. Poor visibility conditions, e.g., fog, require higher intensity (minimum 90K candlepower). Lamp type can be tungsten sealed beam or filament, incandescent, halogen, or quartz halogen. Mounted over the cab on both sides, providing 360-degree visibility with unobstructed view to surrounding vehicles.

Flasher One medium intensity (e.g., 50K to 60K candlepower incandescent (tungsten or halogen) light at 60-100 flashes per minute. Mounted over center of cab so as to provide 360-degree visibility.

2. *Truck-Mounted Symbol Sign*

Black W21-1a "Men Working" symbol on orange background. Rectangular panel (24" to 36" on each side), center-mounted over cab with sufficient clearance to provide unobstructed view to following vehicles.

3. *Shadow Vehicle Use Criteria*

The cost effectiveness of a shadow vehicle can be determined on a state-specific basis, utilizing accident-reduction experience. However, cost information obtained from one user state suggests that use of a shadow vehicle can be economically justified based on any one of the following criteria:

1. Elimination of one fatality in 16 years of use.
2. Severity reduction from injury to Property Damage Only for six accidents per year.
3. Elimination of three accidents per year.

The vehicle should be placed so drivers see the sign at least 1500 feet in advance of the work zone. The vehicle should be on the roadway shoulder in order to avoid a double-pass situation for the motorist. When the work zone is moving, the vehicle should follow at a distance of 1/4 to 1/2 mile. If traffic queues develop, the sign should be moved to stay with the leading edge of the queue.

Chart 5

Category 6 - Two-lane, Low Volume, Moving, Lane Blocked

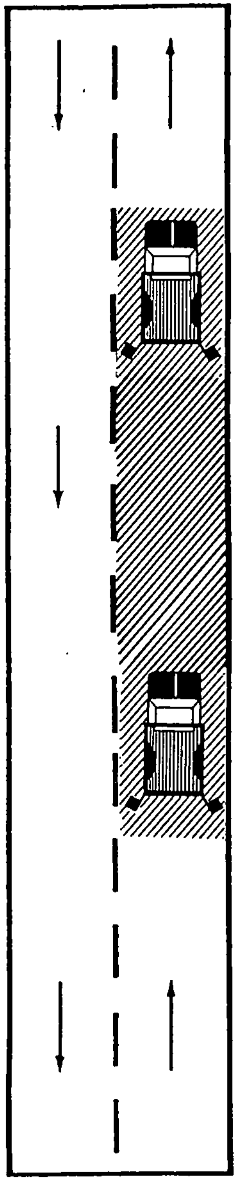
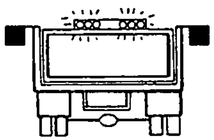


Chart 6

SUGGESTED PRACTICE

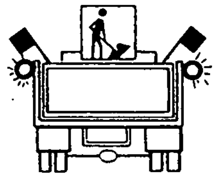
Vehicle Lighting

Best

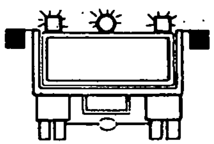


Light Bar

Alternates



Ohio Light Plus
Truck-mounted Symbol



Two Rotating Beacons
Plus One Flasher

Vehicle-mounted Orange Flags

Flags Optional on Lead Vehicle
Flags Recommended on Following Vehicle
Minimum 18" x 18", Florescent Orange
Laterally-mounted, Clear of Truck Body

DEVICE DESCRIPTION

1. *Vehicle Lighting*

Light Bar Amber enclosed series of lights or single light with twin-sided reflectors on either end. Acceptable lamp types are: (1) incandescent, 42-watts, 35K beam candlepower; or (2) halogen, 50- to 60-watts, 60K to 65K beam candlepower. Combination of various lamp types are acceptable. Recommended flash rates of 60 to 120 cycles per minute. Mounted on cab with sufficient clearance to provide unobstructed view from surrounding vehicles.

Ohio Light Double-faced (front and rear), flasher-activated, sealed amber beacons, e.g., Cats Eye, 160DF, or Signal Stat CE160DFAA. Dual-mounted on orange-painted brackets so as to provide approximately 10-inch clearance from truck body. Recommended flash rate is 60 to 120 cycles per minute. See Figure A-2. for a schematic diagram of typical assembly dimensions.

Rotating Beacons Two medium-to-high intensity (e.g., minimum 50K candlepower) amber beams at 60-100 cycles per minute. Poor visibility conditions, e.g., fog, require higher intensity (minimum 90K candlepower). Lamp type can be tungsten sealed beam or filament, incandescent, halogen, or quartz halogen. Mounted over the cab on both sides, providing 360-degree visibility with unobstructed view to surrounding vehicles.

Flasher One medium intensity (e.g., 50K to 60K candlepower incandescent (tungsten or halogen) light at 60-100 flashes per minute. Mounted over center of cab so as to provide 360-degree visibility.

2. *Truck-Mounted Symbol Sign*

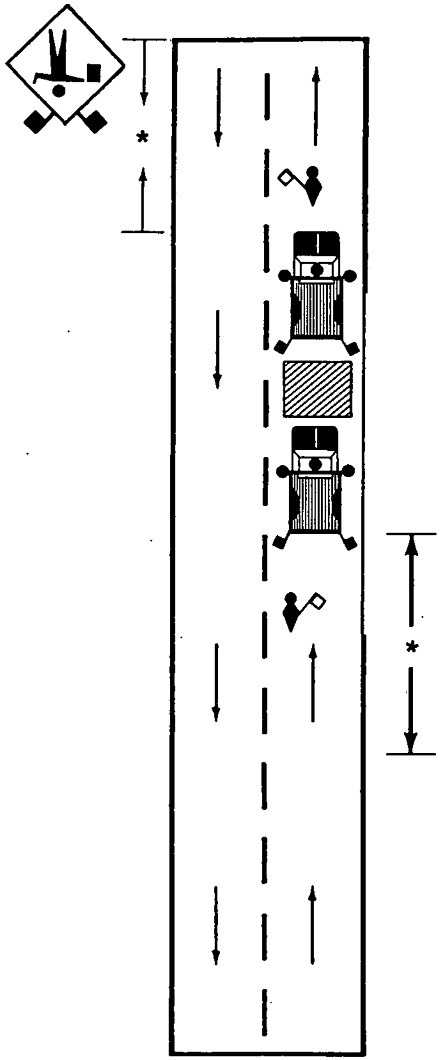
Black W21-1a "Men Working" symbol on orange background. Rectangular panel (24" to 36" on each side), center-mounted over cab with sufficient clearance to provide unobstructed view to following vehicles.

3. *Placement of Following Vehicle*

Positioning of the following vehicle must provide adequate sight-distance to permit driver detection and response. The vehicle should be placed so as to provide advance detection in accordance with decision sight-distances as follows:

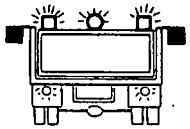
Approach Speed (mph)	Distance (mi.)
30	.10
40	.20
50	.20
60	.25

Category 7 - Two-Lane, High Volume, Short-term, Lane Blocked



SUGGESTED PRACTICE

Vehicle Lighting



Two Rotating Beacons
Plus One Flasher

Vehicle-mounted Orange Flags

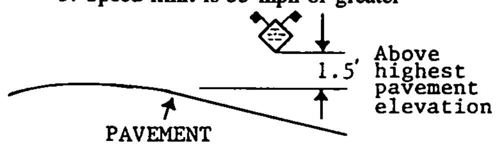
Flags Optional on Lead Vehicle
Flags Recommended on Following Vehicle

Minimum 18" x 18", Florescent Orange
Laterally-mounted, Clear of Truck Body

Ground-Mounted Sign

Use if any of the following conditions apply:

1. Closure is longer than 15 minutes
2. Sight distance is less than 1000 feet
3. Speed limit is 55 mph or greater



W21-5 36" x 36" Sign
Supplemented with Florescent Orange Flags
Minimum 12" x 12"
Mounted at 45-degree Angle with Sign Face

* See Device Description # 3

DEVICE DESCRIPTION

1. Vehicle Lighting

Two Rotating Beacons Two medium-to-high intensity (e.g., minimum 50K candlepower) amber beams at 60-100 cycles per minute. Poor visibility conditions, e.g., fog, require higher intensity (minimum 90K candlepower). Lamp type can be tungsten sealed beam or filament, incandescent, halogen, or quartz halogen. Mounted over the cab on both sides, providing 360-degree visibility with unobstructed view from surrounding vehicles.

Flasher One medium intensity (e.g., 50K to 60K candlepower incandescent (tungsten or halogen) light at 60-100 flashes per minute. Mounted over center of cab so as to provide 360-degree visibility.

2. One-way Traffic Control

Where traffic in both directions must use a single lane, provision should be made for alternate one-way movement to pass traffic through the constricted section by one of the following means:

Flagger Control Where the one-lane section is short enough so that each end is visible from the other end, traffic may be controlled by means of a flagger at each end of the section. Where the end of the section is not visible from the other end, the flaggers may maintain contact via radio.

Pilot Car Where the one-lane section is long and may require hazardous or difficult route negotiation, a pilot car can be used to guide cars past the work site. This activity is coordinated with flagging operations.

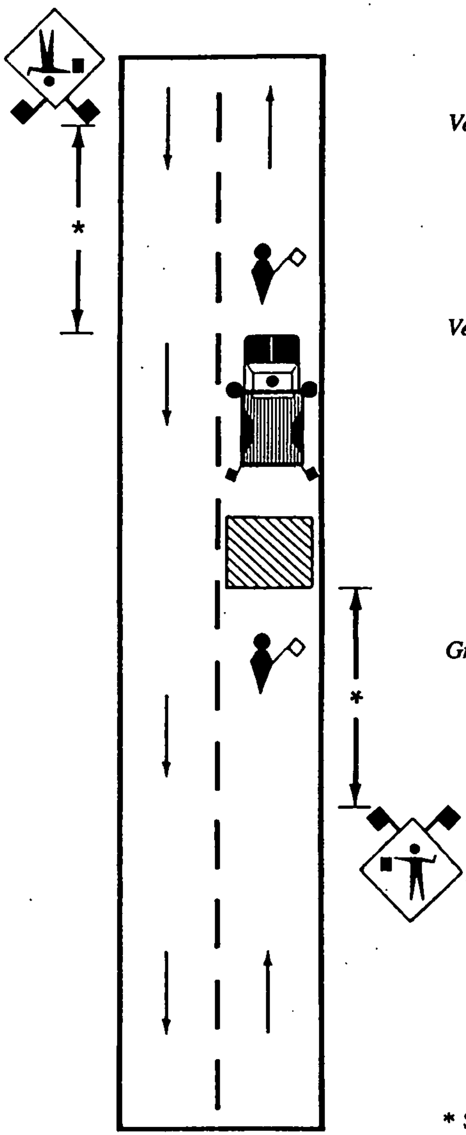
One-way traffic control procedures must comply with established *Manual of Uniform Traffic Control Device* or adopted State procedures.

3. Ground-mounted Sign Placement

Placement of the ground-mounted sign must provide adequate sight-distance to permit driver detection and response. Signs should be placed so as to provide advance detection in accordance with decision sight-distances as follows:

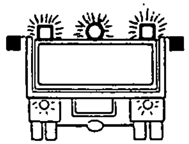
Approach Speed (mph)	Distance (mi)
30	.10
40	.20
50	.20
60	.25

Category 8 - Two-lane, Short-term, Low Volume, Lane Closure



SUGGESTED PRACTICE

Vehicle Lighting



Two Rotating Beacons
Plus One Flasher

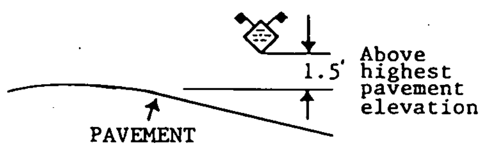
Vehicle-mounted Orange Flags

Minimum 18" x 18", Florescent Orange
Laterally-mounted, Clear of Truck Body

Ground-Mounted Sign

Use if any of the following conditions apply:

1. Closure is longer than 15 minutes
2. Sight distance is less than 1000 feet
3. Speed limit is 55 mph or greater



W21-5 36" x 36" Sign
Supplemented with Florescent Orange Flags
Minimum 12" x 12"
Mounted at 45-degree Angle with Sign Face

* See Device Description # 3

DEVICE DESCRIPTION

1. Vehicle Lighting

Two Rotating Beacons Two medium-to-high intensity (e.g., minimum 50K candlepower) amber beams at 60-100 cycles per minute. Poor visibility conditions, e.g., fog, require higher intensity (minimum 90K candlepower). Lamp type can be tungsten sealed beam or filament, incandescent, halogen, or quartz halogen. Mounted over the cab on both sides, providing 360-degree visibility with unobstructed view from surrounding vehicles.

Flasher One medium intensity (e.g., 50K to 60K candlepower incandescent (tungsten or halogen) light at 60-100 flashes per minute. Mounted over center of cab so as to provide 360-degree visibility.

2. One-way Traffic Control

Where traffic in both directions must use a single lane, provision should be made for alternate one-way movement to pass traffic through the constricted section using flagging operations: Where the one-lane section is short enough so that each end is visible from the other end, traffic may be controlled by means of a flagger at each end of the section. Where the end of the section is not visible from the other end, the flaggers may maintain contact via radio.

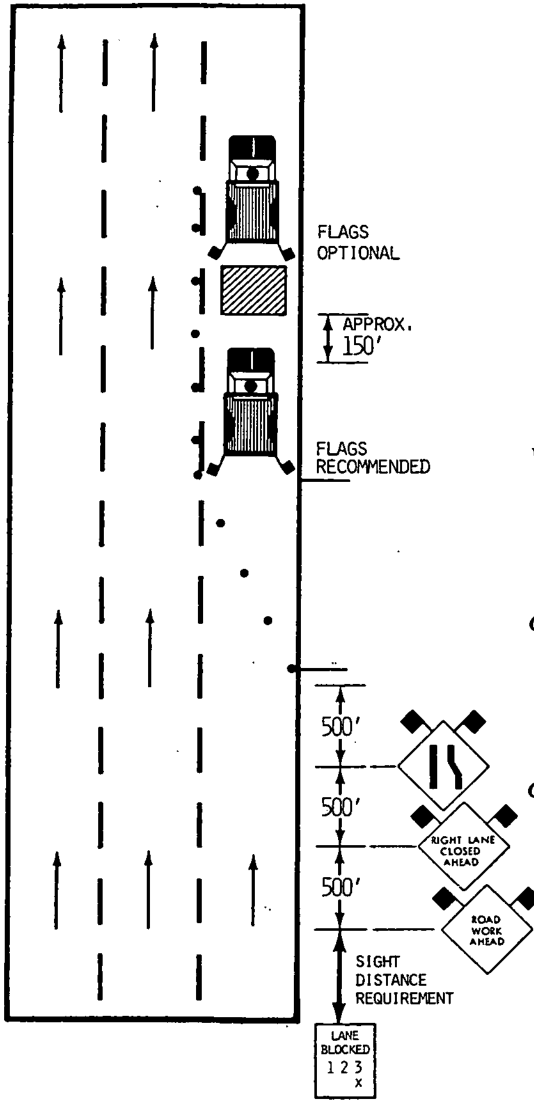
One-way traffic control procedures must comply with established *Manual of Uniform Traffic Control Device* or adopted State procedures.

3. Ground-mounted Sign Placement

Placement of the ground-mounted sign must provide adequate sight-distance to permit driver detection and response. Signs should be placed so as to provide advance detection in accordance with decision sight-distances as follows:

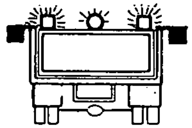
Approach Speed (mph)	Distance (mi)
30	.10
40	.20
50	.20
60	.25

Category 9 - Multi-lane road, Short-term Lane Closure



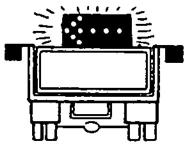
SUGGESTED PRACTICE

Vehicle Lighting



Two Rotating Beacons
Plus One Flasher

or



Truck-mounted
Arrowboard

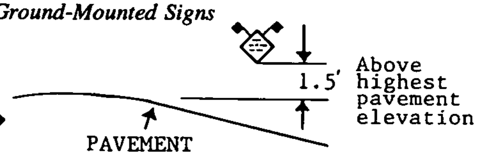
Vehicle-mounted Orange Flags

Flags Optional on Lead Vehicle
Flags Recommended on Following Vehicle
Minimum 18" x 18", Florescent Orange
Laterally-mounted, Clear of Truck Body

Channelizing Devices

Florescent Orange Cones, 28" Minimum Height
Florescent Orange Tubes, 36" Minimum Height
Reflectorized for Nighttime Application
Spacing and Taper Length as Noted in # 2

Ground-Mounted Signs



W4-2, W9-1, W20-1 36" x 36" Signs
Supplemented with Florescent Orange Flags
Minimum 12" x 12"
Mounted at 45-degree Angle with Sign Face

Use "Lane Blocked" Sign if Sight Distance
Conditions Warrant; See Description # 3

DEVICE DESCRIPTION

1. *Vehicle Lighting*

<u>Two Rotating Beacons</u> Two medium-to-high intensity (e.g., minimum 50K candlepower) amber beams at 60-100 cycles per minute. Poor visibility conditions, e.g., fog, require higher intensity (minimum 90K candlepower). Lamp type can be tungsten sealed beam or filament, incandescent, halogen, or quartz halogen. Mounted over the cab on both sides, providing 360-degree visibility with unobstructed view from surrounding vehicles.

<u>Flasher</u> One medium intensity (e.g., 50K to 60K candlepower incandescent (tungsten or halogen) light at 60-100 flashes per minute. Mounted over center of cab so as to provide 360-degree visibility.

<u>Truck-mounted Arrowboard</u> Use single board with sequential arrow or two arrowboards with alternating displays. Minimum size board, 20" x 36".

2. *Channelizing Devices*

<u>Taper and Spacing Guidelines</u>. MUTCD taper guidelines are recommended. They are:

Roads with speed limits of 45 mph or greater -
Taper length (ft.) = speed (mph) x lane width (ft.)
Roads with speed limits under 45 mph -
Taper length = $\frac{\text{speed (ft.) x lane width (mph)}}{40}$

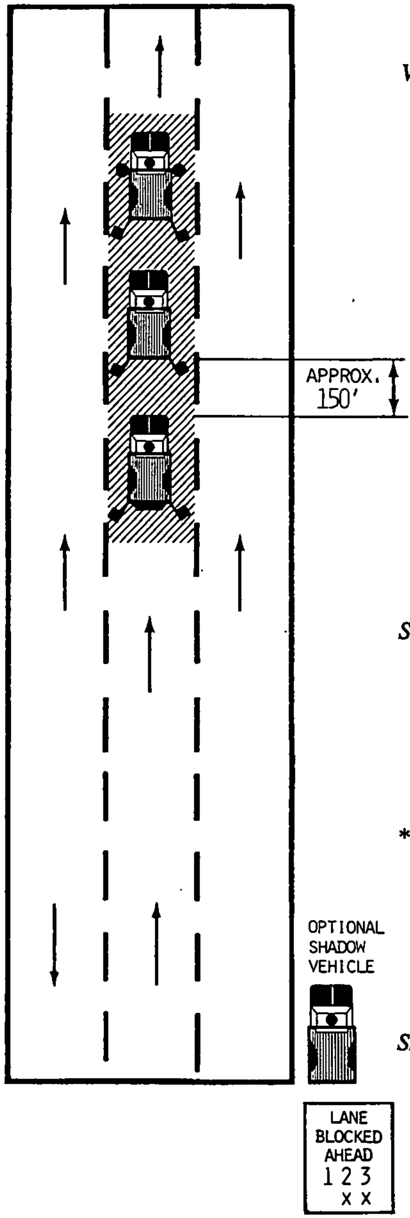
Recommended spacing between devices is: (1) 40 feet when the speed limit is 45 mph or less, or (2) 80 feet when the limit is greater than 45 mph. Skip-line spacing may be used as an aid to placing the channelizing devices.

3. *"Lane Blocked" Sign*

Use is warranted where sight-distance to cone taper is 1000' or less. The lane blocked sign should be used as a pick-up or other truck-mounted sign. The truck is parked on the right or both shoulders. As the purpose of the sign is to warn drivers of maintenance operations they cannot see directly, the sign should be placed so drivers see the sign at least 1500 feet in advance of the taper. If traffic queues develop, the sign should be moved to stay with the following edge of the queue.

Black letters 8" minimum	LANE BLOCKED	Orange reflectorized background
	1 2 3 X	Red reflectorized 10" minimum

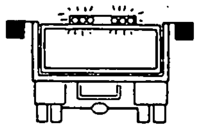
Category 10 - Multi-lane, Moving on Interior Lane



SUGGESTED PRACTICE

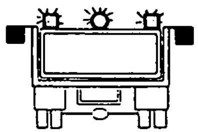
Vehicle Lighting

For Use on Dump and Pick-up Trucks*



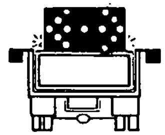
Light Bar

For Use on All Vehicle Types*



Two Rotating Beacons Plus One Flasher

Last Vehicle in Convoy*



Arrowboard

Sign on Following Vehicles

See Device Requirement # 2

CONVOY AHEAD
STAY OUT
OF THIS LANE

**Vehicle-mounted Orange Flags*

Flags Optional on Lead Vehicle

Flags Recommended on Following Vehicles

Minimum 18" x 18", Florescent Orange

Laterally-mounted, Clear of Truck Body

Shadow Vehicle with "Lane Blocked Ahead" Sign

Use Where Sight-distance Conditions Warrant

See Device Description # 3

DEVICE DESCRIPTION

1. *Vehicle Lighting*

Light Bar Amber enclosed series of lights or single light with twin-sided reflectors on either end. Acceptable lamp types are: (1) incandescent, 42-watts, 35K beam candlepower; or (2) halogen, 50- to 60-watts, 60K to 65K beam candlepower. Combination of various lamp types are acceptable. Recommended flash rates of 60 to 120 cycles per minute. Mounted on cab with sufficient clearance to provide unobstructed view from surrounding vehicles.

Two Rotating Beacons Two medium-to-high intensity (e.g., minimum 50K candlepower) amber beams at 60-100 cycles per minute. Poor visibility conditions, e.g., fog, require higher intensity (minimum 90K candlepower). Lamp type can be tungsten sealed beam or filament, incandescent, halogen, or quartz halogen. Mounted over the cab on both sides, providing 360-degree visibility with unobstructed view to surrounding vehicles.

Flasher One medium intensity (e.g., 50K to 60K candlepower incandescent (tungsten or halogen) light at 60-100 flashes per minute. Mounted over center of cab so as to provide 360-degree visibility.

Truck-mounted Arrowboard Use single board (3' x 5' minimum) with flashing arrow.

2. *Sign on Following Vehicles*

Convoy Ahead. 24" x 36" minimum, black on white (reflectorized if used at night) mounted on both sides of vehicles behind the lead vehicle and on the rear of the last vehicle.

3. *Shadow Vehicle with "Lane Blocked Ahead" Sign*

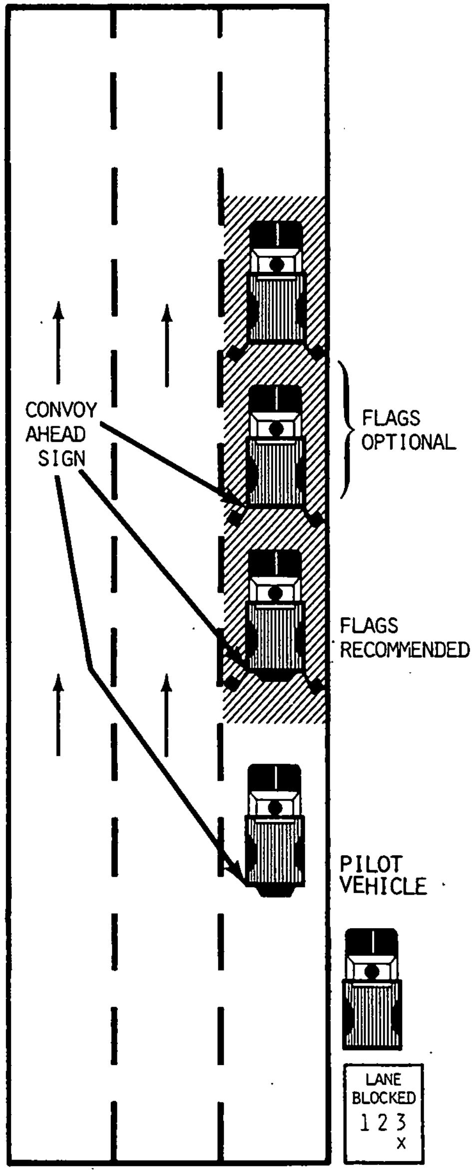
Use is warranted where sight-distance to cone taper is 1000' or less. The vehicle should be placed so drivers see its sign at least 1500 feet in advance of the work zone. When the work zone is moving, the vehicle should follow at a distance of 1/4 to 1/2 mile. If traffic queues develop, the vehicle should be moved to stay with the leading edge of the queue.

"Lane Blocked Ahead" and "1 2 3" legend is black letters (8" minimum height) on orange reflectorized background. Moveable "X" is reflectorized red, 10" minimum height.

The cost effectiveness of a shadow vehicle can be determined on a state-specific basis, utilizing accident-reduction experience. However, cost information obtained from one user state suggests that use of a shadow vehicle can be economically justified based on any one of the following criteria:

1. Elimination of one fatality in 16 years of use.
2. Severity reduction from injury to Property Damage Only for six accidents per year.
3. Elimination of three accidents per year.

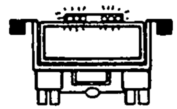
Category 11 - Multi-lane, Exterior Lane, Moving



SUGGESTED PRACTICE

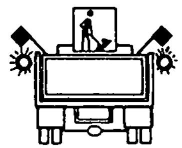
Vehicle Lighting

Best*

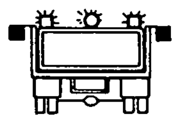


Light Bar

Alternates*



Ohio Light Plus
Truck-mounted Symbol



Two Rotating Beacons
Plus One Flasher

Sign on Following Vehicles

See Device Requirement # 2
for Specifications

Arrowboard on Last Convoy and Pilot Vehicles
See Device Requirement # 1 for Specifications

**Vehicle-mounted Orange Flags*
Flags Optional on Lead Vehicle
Flags Recommended on Following Vehicles
Minimum 18" x 18", Florescent Orange
Laterally-mounted, Clear of Truck Body

Sign on Pilot Vehicle
Use Where Exits Are Blocked

See Device Requirement # 3
for Operation and Use Conditions

Shadow Vehicle with "Lane Blocked" Sign
Use Where Traffic and Sight-distance
Conditions Warrant.
See Device Requirement # 4

DEVICE DESCRIPTION

1. Vehicle Lighting

Light Bar Amber enclosed series of lights or single light with twin-sided reflectors on either end. Acceptable lamp types are: (1) incandescent, 42-watts, 35K beam candlepower; or (2) halogen, 50- to 60-watts, 60K to 65K beam candlepower. Combination of various lamp types are acceptable. Recommended flash rates of 60 to 120 cycles per minute. Mounted on cab with sufficient clearance to provide unobstructed view from surrounding vehicles.

Ohio Light Double-faced (front and rear), flasher-activated, sealed amber beacons, e.g., Cats Eye, 160DF, or Signal Stat CE160DFAA. Dual-mounted on orange-painted brackets so as to provide approximately 10-inch clearance from truck body. Recommended flash rate is 60 to 120 cycles per minute. See Figure A-2 for diagram of typical assembly dimensions.

Rotating Beacons Two medium-to-high intensity (e.g., minimum 50K candlepower) amber beams at 60-100 cycles per minute. Poor visibility conditions, e.g., fog, require higher intensity (minimum 90K candlepower). Lamp type can be tungsten sealed beam or filament, incandescent, halogen, or quartz halogen. Mounted over the cab on both sides, providing 360-degree visibility with unobstructed view to surrounding vehicles.

Flasher One medium intensity (e.g., 50K to 60K candlepower incandescent (tungsten or halogen) light at 60-100 flashes per minute. Mounted over center of cab so as to provide 360-degree visibility.

Truck-mounted Arrowboard Use single board (3' x 5' minimum) with sequential or flashing arrow. Displayed on last vehicle in convoy and pilot vehicle.

2. Sign on Following Vehicles

Convoy Ahead. 39" x 24" minimum, black on white (reflectorized if used at night) can be used on convoy vehicles to reduce vehicles cutting through convoy.

3. Sign on Pilot Vehicle

Follow to Exit Sign. Applicable where exits are blocked due to maintenance activity. Sign is 24" x 36" with black 8" letters on white reflectorized background which can be used to keep traffic from using exit behind the convoy. Maximum reccomended detour is 1/4 to 1/2 mile.

4. Shadow Vehicle with "Lane Blocked Ahead" Sign

Use is warranted where sight-distance is affected by traffic queues or adverse geometric conditions. The vehicle should be placed so drivers see its sign at least 1500 feet in advance of the work zone. When the work zone is moving, the vehicle should follow at a distance of 1/4 to 1/2 mile. If traffic queues develop, the vehicle should be moved to stay with the leading edge of the queue.

"Lane Blocked Ahead" and "1 2 3" legend is black letters (8" minimum height) on orange reflectorized background. Moveable "X" is reflectorized red, 10" minimum height.

The cost effectiveness of a shadow vehicle can be determined on a state-specific basis, utilizing accident-reduction experience. However, cost information obtained from one user state suggests that use of a shadow vehicle can be economically justified based on any one of the following criteria:

1. Elimination of one fatality in 16 years of use.
2. Severity reduction from injury to Property Damage Only for six accidents per year.
3. Elimination of three accidents per year.

DESCRIPTION OF MATERIALS REQUIRED			
QUANTITY	DESCRIPTION	QUANTITY	DESCRIPTION
1	7" x 3" x 1/4" H.R.S.	1	STANDARD 3/8" GREASE ZURK
1	3/4" x 1 3/16" NIPPLE	1	3/16" x 1/2" BOLT
1	2 7/8" x 1" x 3 3/8" x 5/8" ALUMINUM STOCK	1	3/16" NUT
2	11/16" x 7/8" PLASTIC BUSHINGS	1	1/4" RUBBER COVERED WIRE CLAMP
1	3 1/4" x 1 3/16" o.d. & 11/16 id STEEL BUSHING		
1	3/8" THIN WASHER		

STATE OF OHIO
DEPARTMENT OF TRANSPORTATION

LIGHT MOUNTING BRACKET ASSEMBLY

PART Nº D.O.T-105

ED CHRISTOPHER | SCALE - FULL | DATE 3-7-73

D.. #7

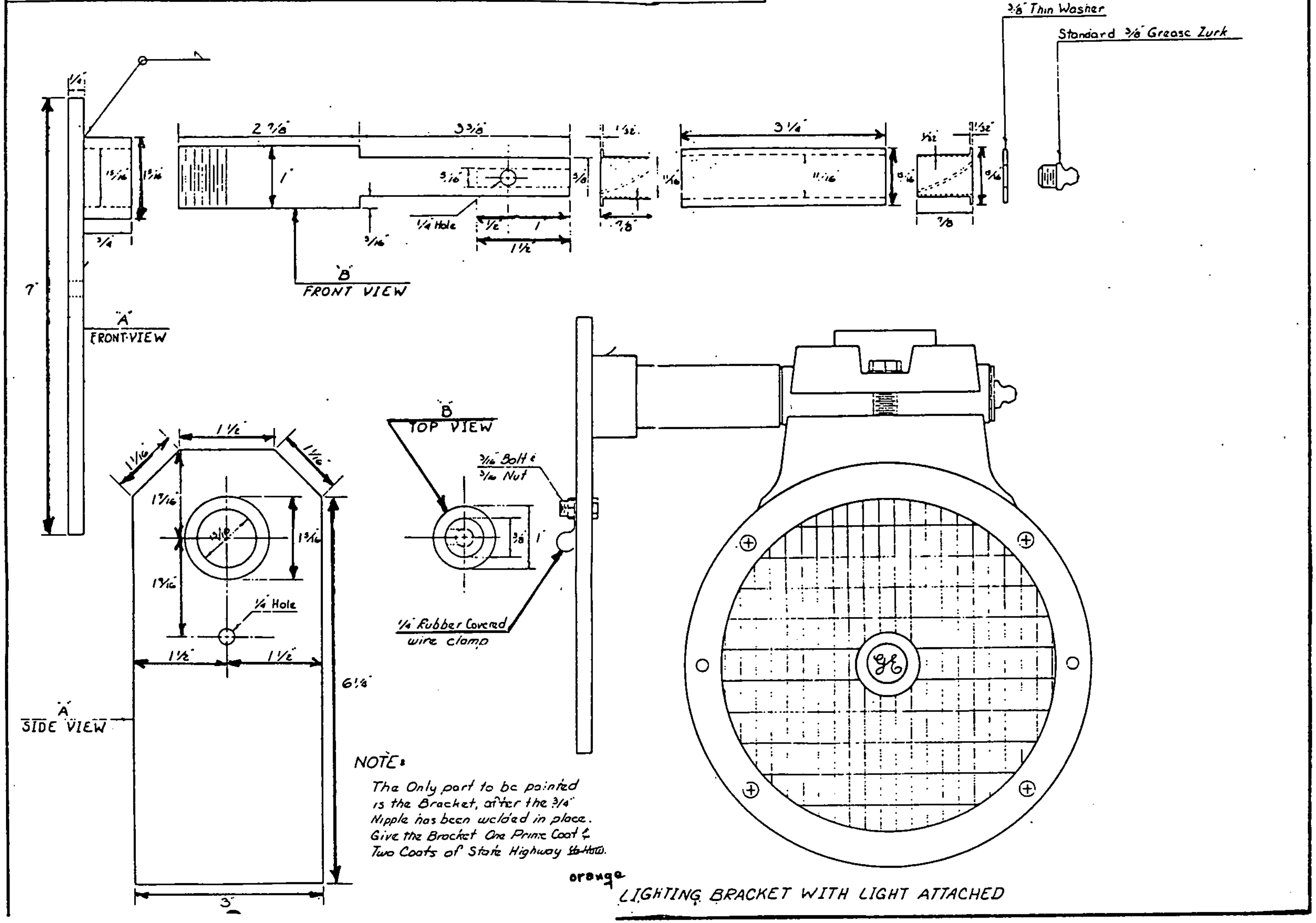


Figure A-2. Schematic of Ohio Light assembly.

APPENDIXES

B, C, D, E, F. G

Appendixes B through G (and the complete Appendix A) contained in the final report as submitted by the research agency are not published herein. Their titles are listed here for the convenience of those interested in the subject area. A limited number of copies of the agency-prepared report, entitled "Service Vehicle Lighting and Traffic Control Systems for Short-Term and Moving Work Zones," January 1990, are available on loan, from the NCHRP, Transportation Research Board, 2101 Constitution Avenue, N.W., Washington, D.C. 20418.

The titles of the appendixes are as follows (see "Foreword" for further details regarding their contents).

Appendix A—User's Guide for Short-Term and Moving Work Zone Traffic Control (Part 1); State-of-the-Art Review (Part 2, including sections on Technical Literature Review, Summary of Warning Light Devices, Summary of State Requirements for Moving and Short-Term Operations, State Survey, Summary of State Maintenance Engineer Questionnaire Responses, Summary of State Traffic Engineer Questionnaire Responses)

Appendix B—Information Requirements, Analysis, and Problem Identification

Appendix C—Signs and Markings for Moving Maintenance Operations: Laboratory Experiment

Appendix D—Closed Field Experiment

Appendix E—Task 6: Field Study

Appendix F—Lane Change Time Data

Appendix G—Cost-Effectiveness of Recommended Devices

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