sizes and configurations. Apparently a certain arrangement of the design elements against a certain background produces optimal detectability. Specification of these parameters based on current data is not possible.

The determination of optimal stripe widths, color ratios, and height-to-width ratios for barricades, panels, and drums was executed as the driver detected and identified these device simulations in isolation, against a background of visual clutter, designed to simulate informational loadings in the real world. In reality, these devices are not generally perceived alone but as a cluster or array that protects and channels traffic away from hazardous zones. Therefore, the design recommendations and findings are inputs to field tests that examine these individual devices in combination rather than alone.

Our purpose was not to generate the single channelizing device of optimum detectability but rather to generate input for field testing and to eliminate those elements that were rated consistently poor in performance. Our laboratory studies suggest the best and the worst designs that should be tried under real driving conditions so that their ability to display a hazard situation effectively and channel drivers around it with the least perturbance of normal driving can be evaluated.

ACKNOWLEDGMENT

The research reported here was conducted as a part of the NCHRP evaluation of traffic controls for street and highway work zones. The able assistance of those others associated with this project is gratefully appreciated. The opinions and conclusions expressed or implied in this report are those of the research agency. They are not necessarily those of the Transportation Research Board, the National Academy of Sciences, the Federal Highway Administration, the American Association of State Highway and Transportation Officials, or of the individual states participating in NCHRP.

REFERENCES

1. F. Attneave. Some Informational Aspects of Visual Perception. Psychological Review, Vol. 61, 1954, pp. 183-193.
2. I. Rock. An Introduction to Perception. Macmillan, New York, 1975, Chap. 8.
3. Manual on Uniform Traffic Control Devices, Part VI: Traffic Controls for Street and Highway Construction and Maintenance Operations. U.S. Department of Transportation, Sept. 1978.
4. Traffic Controls for Highway Construction and Maintenance Operations. Texas A&M Univ., Texas Office of Traffic Safety, 1977.
5. Traffic Safety Manual. New York State Thruway Authority, April 1975.

Abridgment

Visibility Requirements for Traffic-Control Devices in Work Zones

Hugh W. McGee, Wagner-McGee Associates, Alexandria, Virginia
Beverly G. Knapp, BioTechnology, Inc., Falls Church, Virginia

Highway safety officials are concerned that traffic-control devices used at work zones are not as visible as they should be due to insufficient reflective properties or because dirt has rendered them ineffective. It has therefore been suggested that a performance standard be established for reflective devices used in work zones. Accordingly, the objective of this study was to develop a performance requirement or standard for the detection and recognition of retroreflective traffic devices used in work zones.

The scope of the study was limited to an analytical exercise and drew on existing information and data where possible. The discussion focuses primarily on those channelization devices frequently used in work zones (i.e., drums, barricades, panels, and cones). The performance standard developed in this study was established from the principles of driver information needs and, specifically, the requirement for decision sight distance. The performance standard is presented in terms of visibility requirements, that is, the distance at which motorists should be able to detect and recognize the devices at night.

INFORMATION REQUIREMENTS FOR WORK ZONES

The concept of decision sight distance has been defined by Alexander and Lunenfeld (1) as

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

It is one of the underlying components of the broader concept of positive guidance, which has been given the following operational definition (2):

> Any information carrier, including the highway, that assists or directs the driver in making speed or path decisions provides guidance information. Positive guidance information is provided when that information is presented unequivocally, unambiguously, and conspicuously enough to meet decision sight distance criteria and enhance the probability of appropriate speed and path decisions.

The work zone, in almost all instances, requires the motorist to make some change in speed and path. Therefore, by applying the principles of positive guidance and, more specifically, the concept of decision sight distance, one can develop analytical performance standards for reflective devices in work zones.

Information Handling Zones

A procedure described in the User's Guide (2) includes the determination of information handling zones. The whole process of positive guidance is based on the premise that the motorist has to contend with different hazards during the guidance level of driver performance (i.e., the driver's task of selecting a safe speed and path on the highway). Hence, one of the zones is referred to as the hazard zone.

A construction or work zone typically fits within the category of a highway condition hazard. As stated in the User's Guide (2), a condition hazard is "any location where the condition of the highway needs to be interpreted by the driver as a cause for extra caution". The primary hazard associated with any construction zone is the actual work site where people and machinery congregate; however, the devices that channel the motorist around this hazard become, paradoxically, hazards themselves. These devices (barricades, cones, drums, and panels), when placed across the lane, are obstacles that the motorist must avoid. Therefore, detection and recognition of these devices is critical to the successful negotiation of the work zone.

The next information handling zone defined in the positive guidance process is immediately upstream of the hazard and is referred to as the nonrecovery zone. This zone is defined as the distance required to execute an avoidance maneuver, or the point beyond which the motorist cannot avoid the hazard unless he or she resorts to erratic maneuvers. This distance corresponds to the stopping sight distance as described by the American Association of State Highway and Transportation Officials (AASHTO) (3). The nonrecovery zone starts at the beginning of each hazard zone and extends upstream for a distance. This distance corresponds to the stopping sight distance for the speed at which the vehicle was operating.

The next zone upstream from the nonrecovery zone is called the approach zone. This corresponds to the decision sight distance minus the stopping sight distance. The decision sight distance, which is marked off from the leading edge of the hazard zone, should be sufficient for the motorist to detect and to react safely and efficiently to the hazard. In principle, this distance should be the key element of a specification or performance standard for reflectivity of traffic-control devices applied in the work zone.

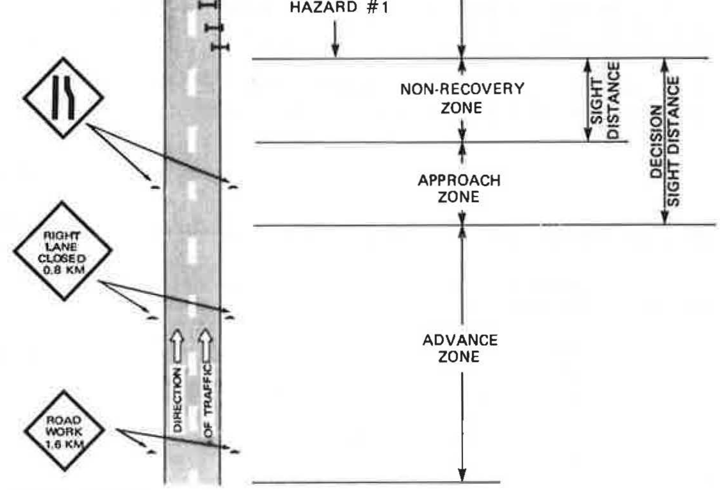
The final upstream zone is called the advance zone. By definition established in the positive guidance procedure, it represents the area where hazards or inefficiencies do not yet affect the driver's task. Hence, although labeled a zone, it is really unbounded on the upstream end. For the purpose of a work-zone situation, the advance zone would start where the first device that warns of a work zone ahead is visible to the motorist. The zone ends at the decision sight distance point (the beginning of the approach zone).

Figure 1 shows how each of the information handling zones fit together at a typical work-zone site. The example is a one-lane closure on a divided highway. Note that the nonrecovery zone and the approach zones are not plotted with respect to any particular longitudinal distance.

Decision Sight Distance Requirements

In a previous study (4), we developed specific criteria to be applied to the concept of decision sight distance.

Figure 1. Designation of information handling zones related to positive guidance procedure.



Notes: 1 km = 0.6 mile.
Non-recovery, approach and advance zone are not plotted to any scale for this example.

In that study, the conceptual definition of decision sight distance was translated into a hazard avoidance model, which was then employed to formulate appropriate values. The model describes a sequence of events that occur in hazard avoidance, starting from detection of the hazard and ending with the completion of the avoidance maneuver. The process is briefly described as follows:

1. Hazard becomes visible (time t_0)—This is the baseline-time point when the hazard is within the driver's sight line.
2. Hazard is detected (time t_1)—Driver's eye fixates on the hazard.
3. Hazard is recognized (time t_2)—The image on the eye is translated by the brain and the hazard is perceived as such.
4. Driver decides on action (time t_3)—Driver analyzes alternative courses of action and selects one.
5. Driver begins response (time t_4)—Driver initiates required action.
6. Maneuver is completed (time t_5)—Driver changes path or speed of vehicle.

The process is a simple additive model. The total time from the moment when the hazard is visible to the completion of hazard avoidance maneuver equals the sum of the incremental times for detection (t_0-t_1), recognition (t_1-t_2), decision (t_2-t_3), response (t_3-t_4), and vehicle maneuver (t_4-t_5).

Information from the literature plus some limited field experiments were used to develop times for the incremental steps and to prepare the specific decision sight distance criteria for highway work zones. The incremental times for the phases of the hazard avoidance process were determined to be as follows:

Process	Time (s)
Detection-recognition	1.5- 3.0
Decision-response	4.2
Maneuver (lane change situation)	4.5
Total	10.2-11.7

These time values can be applied to various operating speeds to arrive at the required visibility distances shown in Table 1. The lower values would be applicable to the rural environment or any situation where there is a lack of high background luminance, and the higher value is applicable to the urban environment or an area of high background luminance.

To present these visibility requirements in perspective, it is necessary to discuss the conditions for which they were developed and to which they apply:

1. The values apply to a work zone where a lane closure necessitates a lane change. This appears to be the most common situation and the one that requires the longest maneuver time.
2. The values are based on the assumption of a single vehicle approaching the work zone, not influenced by vehicles downstream. These distances should apply to a driver with 20/40 acuity (the requirement in most states) and the vehicle headlights at low beam.
3. These values are based on an unalerted driver and represent the upper percentile range of the driving public in terms of reaction and maneuver times. Furthermore, we assumed that the driver has only information from the devices in question (i.e., the barricades or panels) that are being used for channelization. This assumption ignores the fact that the motorist is alerted and informed by advance signs and other long-range detection devices, such as flashing-arrow boards or steady-burn lights. Although this assumption makes these values conservative, it is justified for safety reasons, since many work zones do not have the full complement of warning devices and therefore must rely on the reflectivity capabilities of the devices. Also, some drivers either give low primacy to the advance warning devices or simply fail to detect them.

Table 1. Visibility requirements for reflective devices at work zones.

85th Percentile Speed (km/h)	Detection Through Maneuver Time (s)		Visibility Distance (m)	
	Low	High	Computed	Rounded for Design
40	10.2	11.7	113-156	120-160
60	10.2	11.7	170-233	170-230
80	10.2	11.7	227-311	230-310
100	10.2	11.7	306-397	310-400
120	10.2	11.7	357-467	360-470
140	10.2	11.7	416-544	420-540

Note: 1 km/h = 0.62 mph; 1 m = 3.28 ft.

RECOMMENDED VISIBILITY REQUIREMENTS FOR REFLECTIVE DEVICES

From the visibility distances shown in Table 1, a performance standard for the reflective devices discussed here can be presented in a form appropriate for the Manual of Uniform Traffic Control Devices, such as:

The [barricade, panel, drum, cone] shall be installed and maintained so as to be visible at night under normal atmospheric conditions from a minimum distance of 275 m (900 ft) when illuminated by the low beams of standard automobile headlights.

The selection of 275 m seems reasonable, albeit somewhat arbitrary. It is nearly the midpoint of low-high values for 96.54 km/h (55 mph). This standard essentially ignores the fact that visibility requirements are less than 275 m at lower speeds. This is so because, for reasons of economy, the devices have been, and will continue to be, fabricated for use in all highway situations. Contractors or government agencies are not about to stockpile devices of varying reflectance qualities to be used at work-zone locations that vary by speed, environment, or any other variable.

This performance standard, although developed primarily for reflectance devices, should apply to any device used for channelization purposes in the work zone. This standard is not applicable to advance warning signs. Also, it should be considered a preliminary standard until further research is completed or until such time as this performance standard can be validated by field studies.

ACKNOWLEDGMENT

This paper is based on a study performed by BioTechnology for the Federal Highway Administration. The opinions, findings, and conclusions are ours and not necessarily those of the sponsor.

REFERENCES

1. G. J. Alexander and H. Lunenfeld. Positive Guidance in Traffic Control. Federal Highway Administration, Superintendent of Documents, Stock No. 050-001-00094, April 1975.
2. T. E. Post, H. D. Robertson, H. E. Price, G. J. Alexander, and H. Lunenfeld. A User's Guide to

Positive Guidance. Federal Highway Administration, Jan. 1977.
3. A Policy on Design Standards for Stopping Sight Distance. AASHO, Washington, DC, 1971.
4. H. W. McGee, W. Moore, B. G. Knapp, and J. H. Sanders; BioTechnology. Decision Sight Distance for Highway Design and Traffic Control Requirements. Federal Highway Administration, Jan. 1978.

Effects of Taper Length on Traffic Operations in Construction Zones

Jerry L. Graham, Douglas W. Harwood, and Michael C. Sharp, Midwest Research Institute, Kansas City, Missouri

The study dealt with a proposed taper length formula that yields shorter tapers at design speeds below 96 km/h (60 mph) than does the existing formula (L = WS, when S is in mph). This paper reports on a direct comparison of traffic operations using both the standard and proposed taper lengths in the same construction zones. Speed, erratic maneuvers, traffic conflicts, and lane encroachment data were collected at four sites, day and night, for a variety of design speeds and taper lengths. The analyses of the data collected do not imply that the proposed taper lengths are more hazardous than the standard taper length. Use of the proposed length did not produce a greater number of erratic maneuvers and slow-moving vehicle conflicts than did the standard or existing taper length. There was no indication that the proposed taper lengths resulted in a greater number of passenger vehicle or truck encroachments on adjacent lanes.

The Manual on Uniform Traffic Control Devices (MUTCD) (1) specifies that the length of lane-drop tapers in construction zones should be computed as

$$L = WS \quad (1a)$$

where

L = Minimum length of lane-drop taper (ft),
W = Width of offset (ft), and
S = Speed limit or 85th percentile speed (mph),

or for the metric computation,

$$L = WS/1.62 \quad (1b)$$

In application the speed (S) can be considered as the design speed of the construction zone (not necessarily that of the highway). The design speed is the maximum safe speed through the construction zone. An alternative formula has been proposed to replace the standard formula:

$$L = WS^2/60 \quad (2a)$$

or for the metric computation,

$$L = WS^2/157.5 \quad (2b)$$

A comparison of taper length computed by use of each of these formulas is shown in the table below (1 km/h = 0.62 mph; 1 m = 3.28 ft).

Design Speed (km/h)	Taper Length (m) Using L = WS/1.62 (W = 3.7 m)	Taper Length (m) Using $L = WS^2/157.5$ (W = 3.7 m)
96	220	220
89	201	185
80	183	152
72	165	123
65	146	98
56	128	75
50	110	55
40	91	38
32	73	24
25	55	14

At a design speed of 96 km/h (60 mph) a taper length of 220 m (720 ft) is computed using both formulas, at 72 km/h (45 mph) the taper length is 165 m (540 ft) using the standard formula and,using the proposed formula, 125 m (405 ft), only 75 percent as long as the standard taper length. At 50 km/h (30 mph) the standard taper length is 110 m (360 ft) and the proposed taper length is 55 m (180 ft), only 50 percent as long as standard; at 25 km/h (15 mph) the standard taper length is 55 m and the proposed taper length is 14 m (45 ft), 25 percent as long as the standard.

The proposed formula is theoretically appealing because the ability to stop and change direction is known to be inversely proportional to the square of the velocity. Therefore, if the standard taper length is adequate for 96 km/h (60 mph), then standard taper lengths for speeds less than 96 km/h are excessively long. Proponents of the revised formula point out the advantages of the shorter taper lengths: They require fewer traffic-control devices and, at urban sites, interfere with fewer driveways and intersections.

Opponents of the proposed formula believe that the taper lengths computed by the proposed formula are too short at low speeds [25 to 40 km/h (15 to 25 mph)] and that the short tapers are not sufficient to allow large vehicles such as trucks and buses to change lanes without encroaching on adjacent lanes and to prevent such large vehicles from turning over.

STUDY SITES

The alternative taper formulas were evaluated in four construction zones—one in Missouri and three in Florida. The design speeds of these four construction zones ranged from 25 to 72 km/h (15 to 45 mph). The characteristics of the four construction zones are described in Table 1.

Site 1 was studied in September 1976, in conjunction with earlier field work. These field studies considered the effects of funneling and reduction of lane width as