NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP Report 358

Recommended Practices for Use of Traffic Barrier and Control Treatments for Restricted Work Zones

Transportation Research Board
National Research Council

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Recommended Practices for Use of Traffic Barrier and Control Treatments for Restricted Work Zones

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

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FOREWORD

By Staff
Transportation Research Board

This report is recommended to persons involved with the design and construction of highways, particularly those persons responsible for the development, implementation, and maintenance of traffic control plans for work zones. The report provides guidelines—developed from empirical and analytical studies—intended to enhance the safety of the motoring public and construction workers.

NCHRP Project 17-8 was initiated in response to the need to improve practices related to work zone traffic control in this era of highway rehabilitation and reconstruction. The researchers investigated the nature of restricted work zones through site visits and interviews with highway design and construction personnel, and developed a general classification of restricted situations. The study attempted to develop concepts for safe and cost-effective treatments of these situations by using combinations of conventional and innovative traffic control treatments and barrier applications. Full-scale crash tests were conducted of commonly available barriers to validate their crashworthiness in typical restricted work zone situations. The crash tests were used to calibrate modified versions of the Highway Vehicle Object Simulation Model (HVOSM), which were then used to analyze the likely behavior of vehicles over a wider range of speeds and impact angles than would be possible with crash tests.

The findings of these tests and analyses provided the basis for the development of guidelines for the treatment of restricted work zone situations considering different traffic, geometric, and terrain conditions. The researchers' report describes the development of the guidelines including the application of benefit/cost analysis procedures to analyze alternative treatments and to establish criteria for the recommended treatments. These guidelines were packaged in a separate user's guide to facilitate use by agencies wishing to adopt them. This user's manual represents the bulk of this report. The researchers' full final report for this project, which describes more specifically the research efforts undertaken, is available on a loan basis from the NCHRP.

The full-scale crash testing that was undertaken during this project was conducted according to the testing procedures outlined in *NCHRP Report 230*, "Recommended Procedures for the Safety Performance Evaluation of Highway Appurtenances." Crash test details and severity index computations for this study have been documented in Appendixes A and B of the final report. Appendixes C and D of the final report describe HVOSM modifications for simulations of fixed and movable barriers and the subsequent calibrations of the model and analyses undertaken with it. Volumes II and III of the final report (which contain the Appendixes) and the crash test films are available on a loan basis from the NCHRP.

An informational video was also prepared as part of the project. This 14-minute video describes the problems of restricted work zones, shows the consequences of crashes into barriers used in restricted work zones, introduces the recommended procedures for traffic controls in restricted work zone situations, and demonstrates how the procedures would be applied for a typical situation. Loan copies of the video are available from the NCHRP; individual copies of the video can be obtained for the cost of generating a reproduction from the master copy. The text of the contractor's report and the AutoCAD files for the graphics incorporated in the report are available on disk for interested agencies.

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RECOMMENDED PRACTICES FOR USE OF TRAFFIC BARRIER AND CONTROL TREATMENTS FOR RESTRICTED WORK ZONES

SUMMARY

Many construction projects require the use of traffic barriers to adequately protect the motoring public and construction workers. Geometric and operational restrictions in these work zones frequently preclude the use of the same design standards for these barriers and terminals that normally apply to permanently installed systems. A restricted work zone is defined as one in which standard barrier treatments, such as those given in the 1989 AASHTO *Roadside Design Guide*, cannot be accommodated with available space.

In these restricted situations, once it has been determined a work zone barrier is to be used, it is necessary to identify length-of-need requirements and select appropriate end treatments. One common example of a restricted work zone involves two-lane, two-way bridges where one-half of the bridge is repaired while maintaining alternating one-way traffic in the remaining lane (usually with temporary traffic control signals). The most common method of traffic control is to install a concrete barrier on the bridge approaches and across the bridge to protect the motorists and workers. Although this practice normally provides an acceptable measure of safety for motorists and workers, problems occur when an intersecting highway or driveway that cannot be closed exists near the end of the bridge. In this example, and in other restricted situations, there is often inadequate room to install a barrier runout at the specified flare rate, an impact attenuator, or other terminal treatments meeting the performance standards for permanent barrier systems.

The objectives of this research were to 1) develop improved end treatments for temporary traffic barriers, 2) formulate effective traffic control plans, and 3) prepare user guidelines for restricted work zone situations.

A literature search was conducted in the initial part of the project, which indicated that while standards for handling traffic at work zones have been developed, the standards are not exhaustive and do not always provide adequate guidance for developing safe and efficient traffic control plans (TCPs) for every work zone situation. In particular, they provide little specific guidance on what to do in restricted work zones. There is, however, an extensive body of knowledge on (1) the safety problems in work zones, (2) motorist information needs, (3) traffic control principles, (4) alternative traffic control and delineation devices and treatments, and (5) evaluation procedures for comparing alternatives. The literature review also analyzed documents related to the design, analysis, and crash test evaluations of various precast concrete safety-shaped barriers (CSSB). Of these references,

only three were found to have direct relevance to the problems of restricted work zones. Two publications describe the development of guidelines (warrants) for barrier use in construction zones. In these reports, benefit/cost (B/C) procedures were used to examine alternatives, including alternative end treatments for the concrete barrier. The effectiveness of the B/C techniques used indicated that they would be a viable analysis tool for the restricted work zone problems. Another publication describes the development and testing for an end treatment for shielding the end of the concrete barrier in work zones.

Field investigations of 31 restricted work zone sites in five states were made. The sites were selected to cover the various types of restricted work zone situations of concern. These efforts led to a classification scheme for restricted work zone problems. The objectives of the classification process were to (1) identify those roadway, geometric, and traffic conditions that commonly cause restricted work zones and (2) group together those conditions that may be amenable to the same type of treatment.

Restricted work zone situations may arise on two-lane or multilane highways or streets in rural or urban areas. The restriction on the space available for the barrier end treatment typically results from intersecting roadways that must be kept open near or within the work activity area. The intersecting roadways may be public highways, private driveways, or roadways for contractor access to the work area. The most common restricted work zone situations are on roadways with at-grade intersections (two-lane or multilane highways and streets). The situations are divided into three cases: A, B, and C. Cases A and B restricted work zones have intersecting roadways near the work activity area that restrict the space available for the barrier end treatments on the approaches to the work area, whereas Case C restricted work zones have intersecting roadways within the work activity area that require openings within the length of run of the barrier. The principal distinction between Cases A and B is that Case A involves work zones on open roadways with no stop sign or signal control (generally in rural areas), whereas Case B involves work zones within reduced speed zones or on stop- or signal-controlled legs of an at-grade intersection (generally in a rural town or small urban area).

In another part of the study, a preliminary evaluation was made of the impact performance of barrier terminal treatments applicable for use in restricted work zones. This evaluation involved the use of standard engineering analysis procedures (principles of mechanics), vehicle/barrier computer programs, and benefit/cost analyses. Key factors considered in the evaluation included design impact conditions (mass, speed, and approach angle of impacting vehicle) and the cost effectiveness of each respective terminal treatment. After a review of survey data, it was clear impact performance requirements for many work zone barriers, including the terminal treatments, do not need to satisfy permanent barrier requirements as currently recommended. In many restricted work zones, the operating speeds are considerably lower than the recommended design speed of 60 mph. Hence, a considerable effort was made to conceptualize barrier terminal treatments for lower design speeds on the order of 45 mph.

Conceptual traffic control treatments were developed to address the different restricted work zone clarifications. These treatments incorporated current practices and new ideas for controlling traffic through restricted work zones. General guidelines and recommendations regarding the advance warning, delineation, and channelization of each category were formed. The *Manual on Uniform Traffic Control Devices* (MUCTD), observations of restricted work zones during the site visits, standard traffic control plans from several states, and previous research were used as the basis for these guidelines. The basic philosophy is to modify standard traffic control schemes in accordance with standard traffic control principles to better treat restricted work zones.

After carefully reviewing the findings of these efforts, the project panel and the researchers concluded that the research should concentrate on a more in-depth analysis of commonly used barrier treatments rather than continued development and testing of new terminal treatment designs. This decision was reached after consideration of the probability of success associated with the development of new concepts and the preliminary results, which indicated variations of existing treatments would be viable and cost effective.

A key finding was that run-outs for the concrete safety-shaped barrier (CSSB) could be cost-effectively flared at an angle considerably larger than recommended standards for permanent barriers. Many states use concrete, sloped-end sections to terminate the end of a CSSB because it is relatively inexpensive, durable, portable, reusable, and requires minimal space. Although it is known to have poor impact performance for high-speed impacts, its performance at speeds common to most restricted work zones was largely unknown. To verify its impact performance, 14 full-scale crash tests were conducted to evaluate vehicular and barrier performance to determine occupant risks during impact. Eight of the tests were used to study the effects of flare rate of the CSSB in the run-out section, and six were used to study the performance of two sloped-end treatment designs used at the barrier terminal. A widely used precast CSSB was used in the flare-rate study. A conventional sloped-end treatment and a special shaped, sloped-end treatment were evaluated. Tests were conducted with small and large cars at impact speeds and angles commensurate with those in restricted work zones. A modified version of the Highway-Vehicle-Object-Simulation-Model (HVOSM) computer program was used to augment crash test results for the CSSB and the sloped-end treatments. Results of the crash tests and the computer study were used in the development of end treatment selection guidelines.

A key objective of the project was to develop guidelines for the selection and placement of barrier elements in the run-out section of the CSSB and treatments for the end of the CSSB in a restricted work zone, once a decision had been made to use a barrier (the project did not address warrants or barrier need). A benefit/cost analysis procedure was used to analyze the cost-effectiveness of alternative (1) flare rate of the run-out section and (2) safety treatment at the end of the barrier. Safety end treatments evaluated included the concrete sloped-end section, the inertial crash cushion, and the $GREAT_{cz}$ and ADIEM barrier systems. Factors considered in the analysis included roadway type, traffic volume, period of time barrier in use, offset of end of barrier from traffic, impact performance characteristics of barrier treatments, accident or societal costs, and barrier costs. The guidelines were developed for and are applicable to two- or four-lane rural arterials with speed limits of 55 mph or less and two- or four-lane urban arterials with speed limits of approximately 45 mph or less. However, in the absence of more definitive data, the guidelines may also be used for rural and urban local and collector roadways.

This user's manual of recommended practices was prepared as a separate document. The purpose of the manual was to present a synthesis of findings in a format that would enable highways engineers to readily implement the recommendations. Thus, it contains guidelines for selecting a traffic control plan and a barrier end treatment for a restricted work zone. Emphasis was placed on two-lane roadways because the majority of restricted work zone problems occur on these roadway types. The suggested treatments are applicable to high-speed roadways (posted speed limit of 45 mph or less on approaches to construction zone). Examples are provided in this document to illustrate the use of the guidelines. These include the run-out or flared portion of the CSSB and the safety treatment at the end of the CSSB.

The researchers recommended studying the more promising barrier terminal treatments conceptualized in the project, and monitoring the proposed barrier end treatments and traffic control treatments described herein, to evaluate their efficacy in mitigating restricted work zone problems in a safe and cost effective manner. Additional research is needed to determine the nature of run-off-the-road accidents in restricted work zones, in particular, and in all work zones, in general, and to evaluate the capacity of pin-and-loop joint connection for the precast CSSB.

CHAPTER 1

INTRODUCTION

1.1 PURPOSE AND SCOPE

Many construction projects require the use of traffic barriers to protect the motoring public and construction workers. Most states try to follow permanent barrier guidelines at these project sites. In some cases, however, geometric and operational conditions (particularly intersecting roadways that must be kept open within or near the work activity area[1]) restrict the space available in the work zone to the same design standards that normally apply to areas with permanent systems. At present, however, there are no guidelines that identify recommended end treatments for work zone installations.

NCHRP Project 17-8, "Traffic Barrier and Control Treatments for Restricted Work Zones," was undertaken in response to this problem. The objective of this project was to develop improved end treatments for temporary traffic barriers, traffic control plans, and user guidelines for restricted work zone situations.

The scope was limited to work zone situations at which a traffic barrier was required and design guidelines for permanent barriers could not be implemented. The project addressed the development and use of end treatments for work zone barriers and traffic control treatments for restricted work zones. It did not address the need for the barrier itself and did not develop work zone barrier warrants.

1.2 RESTRICTED WORK ZONES

Most work zones are restricted in some way (with respect to design speed, cross section, operating conditions, etc.). For the purposes of this manual, however, a restricted work zone is defined more specifically as a work zone in which conditions restrict the use of standard barrier end treatments. The term "standard barrier end treatment" refers to standards for *permanent* barriers as recommended in the 1989 AASHTO *Roadside Design Guide* (*2*).

A typical example of a restricted work zone is a bridge on a two-lane highway where one-half of the bridge is repaired while maintaining alternating one-way traffic in the remaining lane (usually with temporary traffic control signals). The most common method of traffic control is to install a portable concrete barrier on the bridge approaches and across the bridge. This method normally provides an acceptable measure of safety; however, problems occur when an intersecting highway or driveway that cannot be closed exists near the end of the bridge. In this case, and in other restricted situations, there is often inadequate room to install a standard barrier end treatment (such as the barrier runout at the specified flare rate, an impact attenuator, or other terminal treatments meeting the performance standards for permanent barrier systems).

[1]The term *work zone* denotes "the general location of a work activity or the subject of work area traffic control" and the more specific term *work activity* area denotes "that portion of the roadway where any closure is in effect and where the work activity is taking place" (*1*). The work activity area includes both the work space and buffer space and corresponds to the tangent section of the traffic barrier.

1.3 OBJECTIVE OF THE USER'S MANUAL

The objective of this user's manual is to synthesize research results in a manner that enables design engineers to quickly implement findings of NCHRP Project 17-8. It is anticipated that the manual will be used primarily by design engineers or those responsible for agency policies and standards relative to traffic control plans and safety in work zones. Guidelines are presented on the appropriate application of the traffic

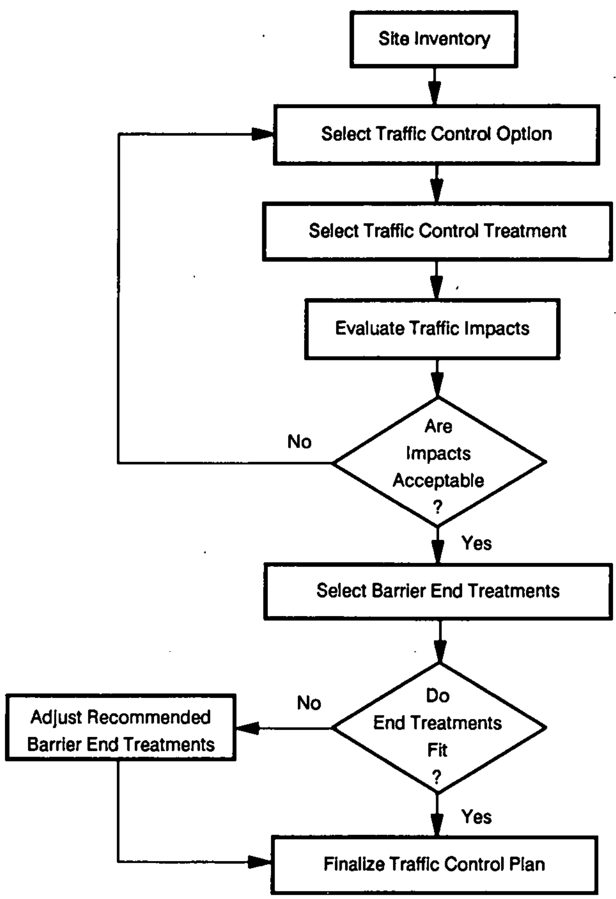


Figure 1.1. Traffic control and barrier end treatment selection process.

barrier and control treatments developed for use in restricted work zones.

1.4 ORGANIZATION OF THE USER'S MANUAL

The main body of the user's manual is divided into three parts. Chapter 2 outlines a classification scheme for restricted work zone problems. Chapter 3 presents typical traffic control treatments for restricted work zones, and guidelines on barrier end treatment use are provided in Chapter 4. Figure 1.1 is a flowchart that illustrates the use of the manual for selecting traffic control and barrier end treatments. The flowchart is divided into two parts corresponding to Chapters 3 and 4. The first step is to perform a site inventory to determine the construction type and location; the roadway type, geometry, and cross section; the intersecting roadway location(s); and traffic volumes and speeds.

Chapter 3 also presents traffic-control-related guidelines and design considerations. A traffic control option (e.g., maintain two-lane, two-way traffic or maintain alternating one-way traffic) should be selected based on the site inventory. The corresponding traffic control treatment may be selected from the typical applications presented in Chapter 3. The traffic impacts (reduction in traffic-handling capacity, delays, and additional road user costs) of the selected option should be estimated. Then, it should be determined whether or not those traffic impacts are acceptable. If the traffic impacts of the option are not acceptable, then another option should be selected and evaluated.

Chapter 4 presents guidelines on the selection of barrier end treatments. These guidelines may be followed for determining the recommended flare rate, barrier end offset, and safety treatment of the end of the barrier. Then, it should be determined whether or not the recommended barrier end treatments fit within the available space. If they do, then the traffic control plan may be finalized. If there is not sufficient space for the recommended barrier end treatments, then the barrier end treatments should be adjusted to fit within the available space, and the traffic control plan may be finalized using the adjusted barrier end treatments.

Chapter 5 presents several examples that demonstrate the use of the manual for determining traffic control and barrier end treatments at restricted work zones.

Chapters Three and Four of the main report, which provide background on the crash tests, are published herein as Appendixes A and B, respectively. References corresponding to Appendixes A and B are provided in Appendix C.

CHAPTER 2

CLASSIFICATION OF RESTRICTED WORK ZONE PROBLEMS

2.1 INTRODUCTION

This chapter presents a classification scheme for restricted work zone problems. The classification scheme was developed on the basis of site visits to more than 30 restricted work zones in 5 states and telephone interviews with highway agency officials in 11 states. The objectives of the classification process were to (1) identify those roadway, geometric, and traffic conditions that commonly cause restricted work zones and (2) group together those conditions that may be amenable to the same type of treatment.

2.2 CLASSIFICATION

Restricted work zone situations may arise on two-lane or multilane highways or streets in rural or urban areas. The restriction on the space available for the barrier end treatment typically results from intersecting roadways that must be kept open near or within the work activity area. The intersecting roadways may be public highways, private driveways, or roadways for contractor access to the work area. The intersections may or may not be signalized.

Figure 2.1 illustrates the most common restricted work zone situations on roadways with at-grade intersections (two-lane or multilane highways and streets). The situations are divided into three cases: A, B, and C. Case A and Case B restricted work zones have intersecting roadways *near* the work activity area that restrict the space available for the barrier end treatments on the approaches to the work area, whereas Case C restricted work zones have intersecting roadways *within* the work activity area that require openings within the length of run of the barrier. The principal distinction between Cases A and B is that Case A involves work zones on open roadways with no stop sign or signal control (generally in rural areas), whereas Case B involves work zones within reduced speed zones or on stop- or signal-controlled legs of an at-grade intersection (generally in a rural town or small urban area).

2.2.1 Case A

Case A involves two-lane or multilane highways in rural areas that would generally be classified functionally as arterials or collectors. That is, they serve primarily long-distance travelers at relatively high speeds (typically 45–55 mph speed limits). Traffic on these roadways is not impeded by stop signs or traffic signals. Therefore, motorists have little or no expectation of the need to slow down or to stop.

Figure 2.1 illustrates the most commonly observed restrictions at the ends of work zones on this type of roadway: intersecting roadways that must be kept open near one or both ends of the work activity area. Compounding the problem may be the need to maintain openings at the ends of the work zone that are wide enough for the contractor's work vehicles to gain access to the work activity area. The need for such openings may restrict the lateral distance available to install standard end treatments.

There are two potential hazards to motorists at Case A restricted work zones:

1. The exposure of approaching through traffic to the barrier end treatments, and
2. The opportunity for through or turning traffic to enter the work activity area from the ends of the work zone.

Exposure problems may exist at both the upstream and downstream ends of the work zone, but the more severe exposure problem is for through traffic approaching the upstream end of the closed lane. There may be opportunities for vehicles to enter the work activity area from both the upstream or downstream ends, depending on the barrier end and traffic control treatments used.

Case A restricted work zones are common at bridge redecking and rehabilitation projects on rural two-lane highways. Intersecting roadways or driveways located near the ends of the bridge restrict the longitudinal distance available to install standard barrier terminal treatments.

Figures 2.2 through 2.4 illustrate three such locations in Pennsylvania. Figure 2.2 is the site of a future bridge rehabilitation project on a two-lane rural collector road. T-intersections a short distance downstream from both ends of the bridge (in the near left and far right of the picture) will restrict the barrier end treatments that can be used and the horizontal curvature will restrict sight distance approaching the work zone. Figure 2.3 illustrates another future bridge rehabilitation site with an intersecting street that must be kept open immediately downstream of the bridge. A railroad grade crossing on the far side of the bridge further complicates the development of the traffic control plan for this site. Figure 2.4 shows another bridge scheduled for rehabilitation on a two-lane rural arterial with a two-way left-turn lane. Route 34 forms a T-intersection only 20–30 ft from the downstream end of the bridge.

2.2.2 Case B

Case B restricted work zones involved roadways with stop signs, traffic signals, and reduced speed zones and are typically found in small urban areas or on rural highways through small towns. The roadways may be either two-lane or multilane highways or streets.

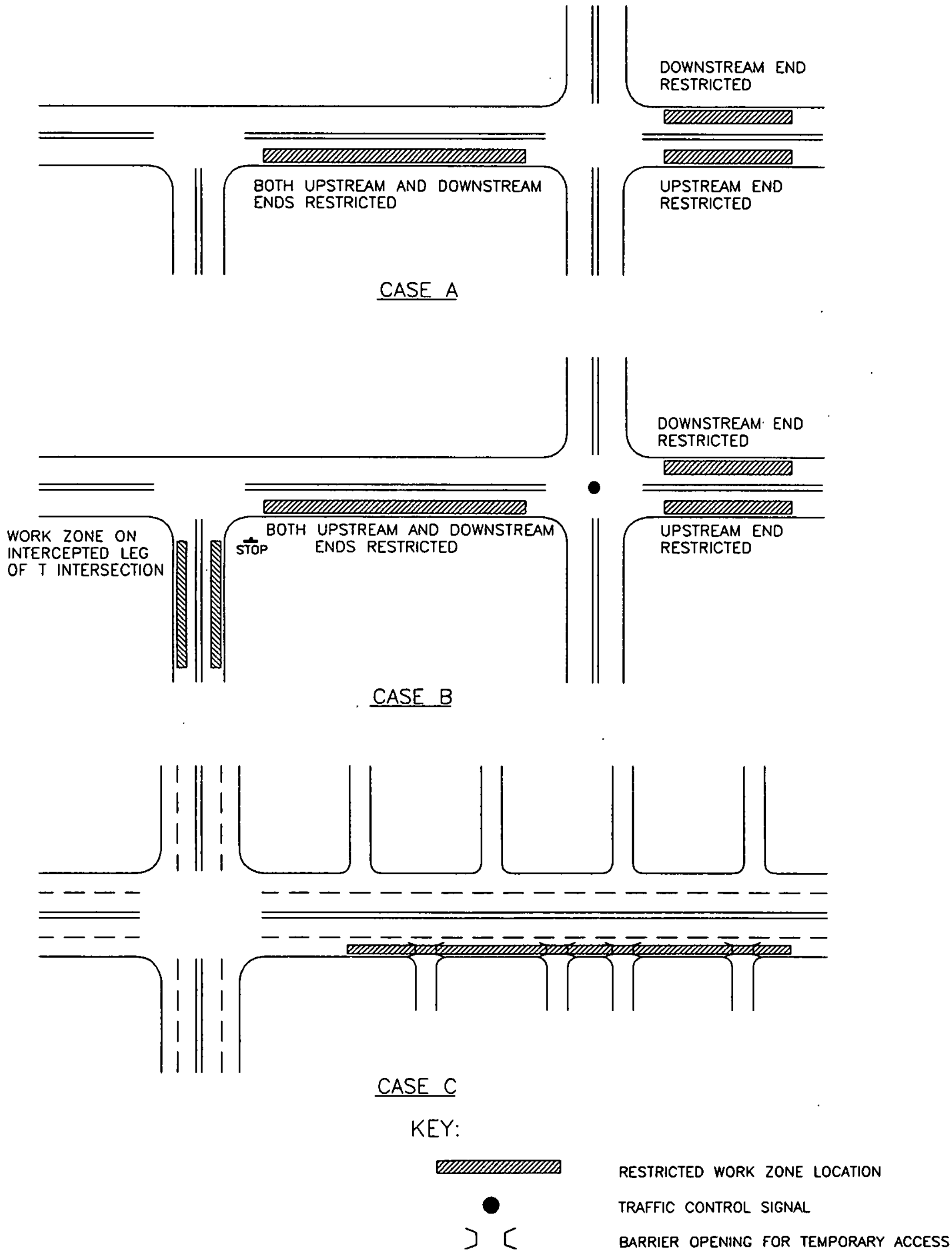


Figure 2.1. Typical restricted work zone situations.

Case A and Case B restricted work zones involve similar barrier end treatment problems and solutions. They differ primarily in terms of the following traffic conditions:

- The expectations of motorists approaching the work zone,
- The speed of approaching traffic, and
- The volume of vehicular and pedestrian traffic that must be accommodated through the work zone.

Generally, motorists approaching a Case B restricted work zone are more likely to be prepared to reduce speed or stop than those approaching a Case A work zone because of the type of roadway on which the work zone is located. The roadways in Case B generally have lower speed limits (35–45 mph) than those in Case A (45–55 mph). Case B work zones in small urban areas or rural towns generally must accommodate more vehicular traffic than Case A work zones in purely rural areas. Pedestrian traffic is much more likely to be a factor in Case B than in Case A.

As illustrated in Figure 2.1, typical situations that would be classified as Case B restricted work zones include the following:

Figure 2.2. Site of a future Case A restricted work zone.

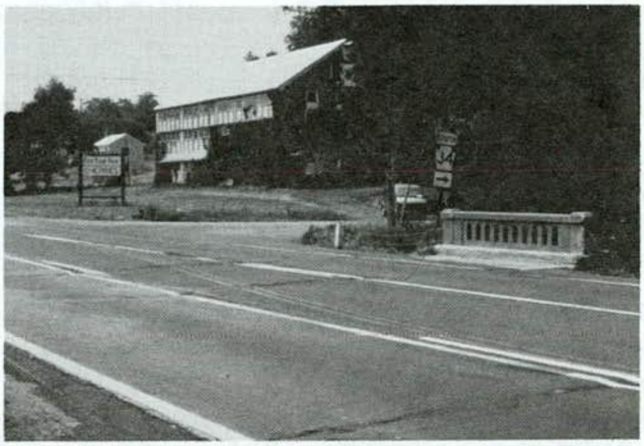


Figure 2.4. Site of a future Case A restricted work zone.

- Work activity areas on stop- or signal-controlled legs of at-grade intersections,
- Work activity areas on the intercepted roadway of a T-intersection near the juncture with the through roadway, and
- Work activity areas on uncontrolled legs of at-grade intersections within a reduced speed zone.

In any of these situations, the intersecting roadway restricts the longitudinal distance available to install standard barrier end treatments. In addition, the need to maintain access for work vehicles at the ends of the work zone may restrict the lateral distance available for terminal treatments.

The potential hazards to motorists approaching a Case B restricted work zone include (1) the exposure of approaching traffic to nonstandard barrier terminal treatments, and (2) the opportunity for turning traffic to enter the work activity area.

Case B work zones are likely to represent less hazard to motorists than Case A for two reasons: (1) motorists' expectations of the need to reduce speeds or to stop are greater in Case B than in Case A, and (2) the approach speeds to the work zone are lower in Case B than in Case A.

Figures 2.5 through 2.7 illustrate three examples of Case B restricted work zones. Figure 2.5 illustrates a work zone on a four-lane undivided arterial in a small urban area at the approach to a signalized at-grade intersection. The bridge being rehabilitated is very close to the intersection and, therefore, there was insufficient room for a standard barrier end treatment.

Figure 2.6 illustrates a bridge rehabilitation project in a rural area on the intercepted roadway of a T-intersection. The proximity of the bridge to the juncture with the through roadway restricts the longitudinal distance available for the barrier end treatment and the need to provide the contractor access to the bridge restricts the lateral distance.

Figure 2.7 shows a bridge that was recently rehabilitated on a two-lane arterial in a small town. The intersecting roadways and access drives in close proximity to both ends of the bridge restricted the barrier end treatments that could be used during the rehabilitation project.

2.2.3 Case C

In Case C, illustrated in Figure 2.1, the ends of the barriers on the approaches to the work zone may or may not be restricted, as in Cases A and B. The problem unique to Case C is the treatment of the barrier ends at openings that provide access within the work activity area. The openings may be for access by the contractor to the work area or by motorists to

Figure 2.3. Site of a future Case A restricted work zone.

Figure 2.5. Case B restricted work zone in a small urban area.

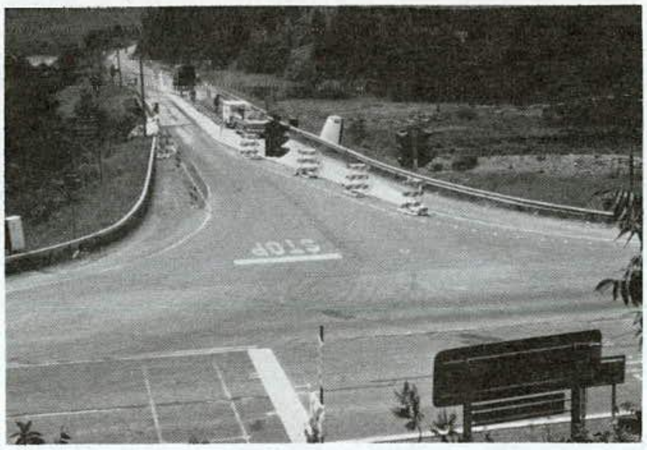


Figure 2.6. Case B restricted work zone at a T-intersection.

Figure 2.7. Site of a past Case B restricted work zone.

Figure 2.8. Barrier openings for access at a Case C restricted work zone. (Note: Treatments shown in Figures 2.8 and 2.9 are not necessarily recommended.)

Figure 2.9. Temporary barrier opening for contractor access at a Case C restricted work zone.

adjoining properties. There may be one or many barrier openings within the work activity area. The principal restriction to the use of standard end treatments at the barrier openings is limited lateral distance, although longitudinal distance may also be limited where access points are closely spaced.

The potential hazards to motorists in Case C restricted work zones include the following:

- Exposure to nonstandard end treatments at the barrier openings within the work zone,
- The opportunity to enter the work activity area at the barrier openings, and
- Sight distance restrictions for vehicles entering the arterial from the barrier openings.

Case C restricted work zones are common on urban multilane arterials, which have frequent roadway or driveway intersections that must be kept open. They may occur on rural highways, but access points are not so frequent in rural areas that Case C work zones are common.

Figure 2.8 illustrates a Case C restricted work zone for a widening project on a multilane, undivided urban arterial. A barrier was used to separate the work area from the travel lanes, but the need to maintain access to adjoining commercial properties required numerous barrier openings whose ends were difficult to treat.

Figure 2.9 illustrates a temporary barrier opening for contractor access to a work zone on a multilane rural highway. Barrier sections were removed during the day to allow access to the work area and were returned to place after the work day was completed.

2.3 SUMMARY

This chapter describes three typical cases of restricted work zone problems that are caused by intersecting roadways that must be kept open near or within the work activity area. The proximity of these intersecting roadways to the work activity area restricts the space available for barrier end treatments. The remaining chapters describe barrier end and traffic control treatments for these problems.

CHAPTER 3

TRAFFIC CONTROL TREATMENTS FOR RESTRICTED WORK ZONES

3.1 INTRODUCTION

This chapter provides typical traffic control treatments for various restricted work zone situations. The chapter summarizes current state practices with respect to barrier end and traffic control treatments and discusses design considerations in developing traffic control plans for Case A, Case B, and Case C restricted work zones. First, typical traffic control applications are given for Case A and Case B restricted work zones. Then, a potential treatment for Case C restricted work zones is also presented.

3.2 INTERSECTING ROADWAYS NEAR THE WORK ACTIVITY AREA (CASES A AND B)

3.2.1 Current State Practices

Most states have no existing guidelines for handling traffic at restricted work zones. In general, states follow the guidelines presented in the *Manual on Uniform Traffic Control Devices* (MUTCD) (*3*) or their corresponding state manual, which are designed for the most common situations and do not specifically address restricted work zones. Section 6A-3, Application of Standards, in the MUTCD states in part:

> . . . Since it is not practical to prescribe detailed standards of application for all the situations that may conceivably arise, minimum standards are presented here for the most common situations. It is emphasized that these are minimum desirable standards for normal situations and that additional protection must be provided when special complexities and hazards prevail. The protection prescribed for each situation shall be based on the speed and volume of traffic, duration of operation, and exposure to hazards.

Because no typical treatments for restricted work zones have been available, most states have considered traffic control treatments at restricted work zones on a case-by-case basis. Furthermore, there are no nationally recognized guidelines that objectively identify the conditions for which a temporary work zone barrier is needed or the appropriate barrier end treatment to be used at a given work zone. In the absence of national guidelines for temporary barrier design, most states have made an effort to follow the guidelines for permanent barriers, given in the 1989 AASHTO *Roadside Design Guide* (*2*) or corresponding state guides.

This section highlights the state of the practice in barrier end and traffic control treatments at restricted work zones for 12 states: California, Illinois, Kansas, Louisiana, Massachusetts, New Mexico, New York, Ohio, Pennsylvania, Texas, Washington, and Wyoming. The practices presented are based on site visits to various states and interviews with state officials. The examples given should not necessarily be considered standards or typical applications but are presented only to show the methods that are currently being used by some states.

3.2.1.1 Barrier End Treatments

With respect to barrier end treatments, common practices include the use of

- Steeper flare rates than standard in order to fit the barrier runout in a shorter than standard longitudinal distance.
- Sloped ends on the concrete barrier.
- Single row of sand-filled barrels to shield barrier ends where adequate lateral distance is not available for a full-size crash cushion.

Figure 3.1 illustrates the use of a steeper barrier flare rate than standard at a restricted work zone. Several states currently use a sloped treatment at the end of the barrier where restricted conditions exist. Figures 3.2 and 3.3 show this treatment being used at restricted work zones on two-lane highways. As shown in Figure 3.4, some states use a single row of sand-filled barrels to shield barrier ends where space for a full-size crash cushion is not available.

3.2.1.2 Traffic Control Treatments

With respect to traffic control treatments, common practices include the use of

- Alternating one-way traffic on one open traffic lane with temporary traffic signals or stop control at isolated work zones.
- Detours to a temporary roadway or an alternative route.
- Work zone speed zoning.
- Barricades, drums, tubular markers, cones, and temporary pavement markings for channelization.

Figure 3.5 presents an example of how most states typically control traffic at restricted work zones on two-lane highways. Both directions of traffic alternate on one open lane through the work zone. Most states use temporary traffic signals (e.g., span-wire installations, post-mounted signals) or portable signals to control alternating one-way traffic, especially under high-volume traffic conditions. Fixed-time control is most common, but actuated control with temporary vehicle detectors is used where traffic conditions warrant. Some states use stop or yield control at alternating one-way work zones. However, stop or yield control are normally used only where traffic volumes are low and visibility through the work zone is inadequate.

A practice used by some states is to detour traffic to a temporary roadway in order to avoid placing barrier end treatments in restricted space. An example of a temporary roadway is shown in Figure 3.6. Where roadway networks permit, traffic may be detoured to an existing alternative route.

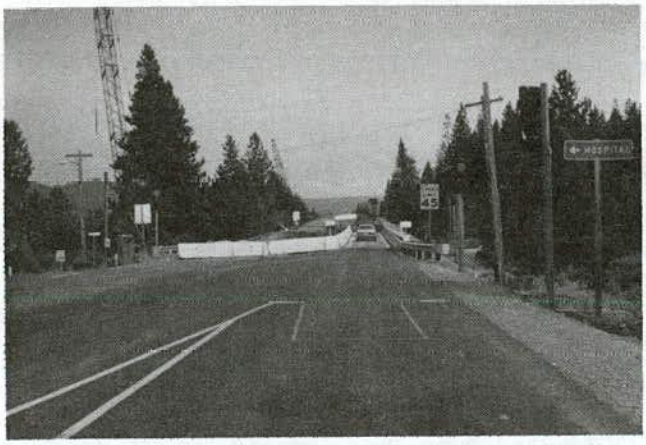


Figure 3.1. Barrier flared at a steeper rate than standard. (Note: Treatments shown in Figures 3.1 to 3.7 are not necessarily recommended.)

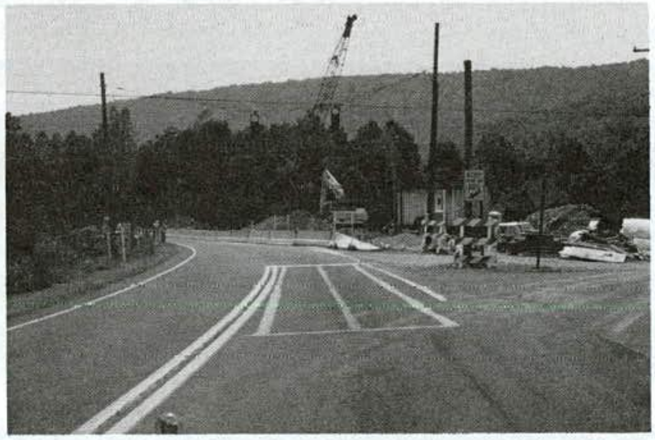


Figure 3.2. Sloped-end treatment at a Case A restricted work zone.

Figure 3.3. Sloped-end treatment at a Case B restricted work zone.

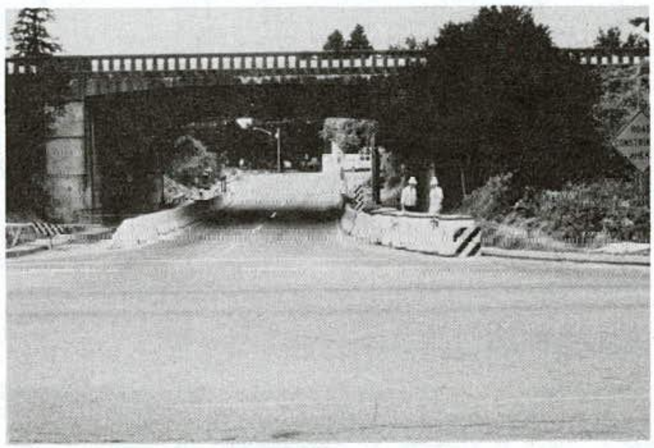


Figure 3.4. Single row of sand-filled barrels placed at the end of the barrier.

In the past, states have been quite liberal in installing reduced regulatory speed limits at work zones. Many states implement reduced speed zoning at restricted work zones in an attempt to lower approach speeds. However, among the states surveyed there is a general trend away from reliance on reduced speed zones because of noncompliance by motorists.

In terms of barrier delineation at restricted work zones, common practice is to place barricades, drums, tubular markers, cones, or temporary pavement markings next to the barrier taper to direct motorist into the open lane. The use of barricades at a restricted work zone is shown in Figure 3.7. The MUTCD requires portable concrete barriers in night use to be delineated with "standard delineation or channelization markings or devices." The selection of devices is usually determined on a case-by-case basis depending on the work zone geometry, barrier visibility, and approach speed. A variety of methods is used for delineating a portable concrete barrier. Some states place reflectors on the top or side of the barrier (or both), while others use steady burn lights. A common practice is to place a temporary white edgeline (temporary pavement marking or temporary raised pavement markers) next to the barrier throughout the entire lane closure.

3.2.2 Traffic Control Options

This section identifies the basic options available for handling traffic at Case A and B restricted work zones. Design considerations and the process for selecting the appropriate traffic control strategy to be used at a particular work site are presented in section 3.2.3, and typical traffic control applications are shown in section 3.2.4. This manual concentrates on two-lane rural highways, which are the most common location of Cases A and B restricted work zones. On multilane highways, it is generally possible to use standard lane closures or crossovers and to maintain at least two-lane, two-way traffic. However, special consideration should be given to the design of the access for the intersecting roadway within the work zone.

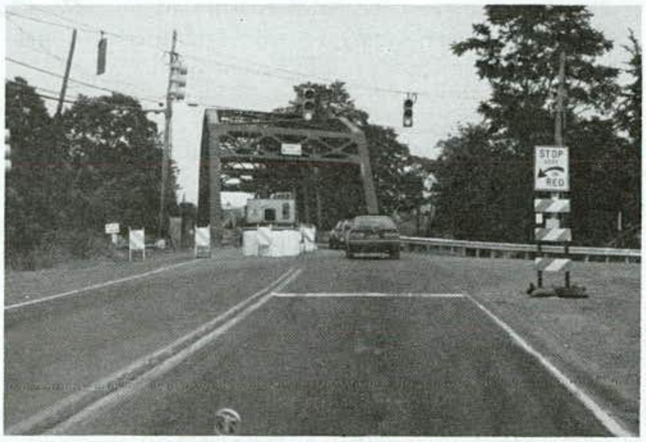


Figure 3.5. Alternating one-way traffic at a Case A restricted work zone.

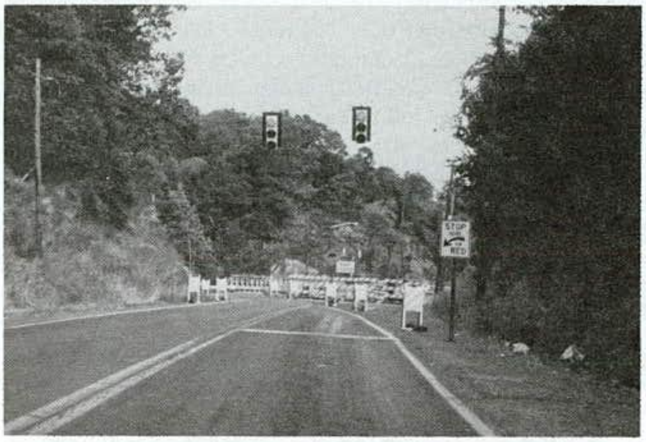


Figure 3.6. Traffic detour to a temporary roadway.

Figure 3.7. Barricades placed at the end of the barrier.

Several options are available for handling traffic at restricted Case A and Case B work zones on two-lane highways. Options include the following:

- Temporarily closing or relocating the restricting intersecting roadway,
- Detouring traffic to a temporary roadway or alternative route,
- Maintaining two-lane, two-way traffic, and
- Alternating one-way traffic on one open lane.

When the work activity allows at least two lanes for traffic, there is generally more space available to treat the restriction. Therefore, most of the discussion in this manual is devoted to the worst case scenario: those restricted work zones at which it is necessary to maintain alternating one-way traffic on one open lane. However, a brief discussion of the other options is also presented.

3.2.2.1 Temporary Closure or Relocation of the Restricting Intersecting Roadway

The first option that should be considered at any restricted work zone is to eliminate the cause of the restriction, which would require temporarily closing or relocating the intersecting roadway that restricts the use of standard barrier end treatments. Whether closing the intersecting roadway is appropriate depends on the number of motorists affected by the closure and the severity of the inconvenience to them. If good alternative routes are available, the inconvenience may be tolerable. Closure may not be feasible in the absence of alternative routes. At some locations with favorable terrain, it may be feasible to temporarily relocate the intersecting roadway far enough away from the work activity area to permit the use of standard traffic control and barrier end treatments.

3.2.2.2 Detour

The second option for handling traffic at restricted work zones is to detour traffic around the work activity. A detour is initiated when traffic is directed to leave the normal roadway. There are two steps of detours: on-site and off-site (*1*). An on-site detour involves total closure of the roadway and rerouting the traffic to a temporary roadway constructed within or adjacent to the highway right of way. The cost of a temporary roadway depends on site conditions and may or may not be justifiable. Constructing a temporary roadway may be justified if (1) the type of work activity requires closure of the roadway and construction of a temporary roadway or (2) the traffic volumes necessitate two travel lanes. An off-site detour involves diverting traffic to an existing alternative route in order to bypass the work site. If a good alternative route is available, then an off-site detour may be a desirable strategy. In many rural areas, however, routes are widely spaced, and the inconvenience to motorists could be considerable.

The advantage of the detour option is that traffic is removed from the work site, thereby minimizing the conflicts between traffic and the work activity and possibly reducing the duration of the project. In most cases when a detour is used, a barrier will not be needed, thereby eliminating the problem of placing a barrier end treatment in restricted space. Several potential negative impacts of the detour strategy are longer driving time, more delays and higher operating costs, congestion or deterioration of the alternative route, higher accident rates on the alternative route, and driver confusion.

Substantial traffic control is required to implement a traffic detour. Adequate driver information must be provided in advance of and throughout the detour to guide motorists around the work activity. The MUTCD provides typical applications of traffic control devices for on-site and off-site detours, which may be adapted for restricted work zone situations.

3.2.2.3 Maintain Two-Way, Two-Lane Traffic

The third option that may be available for handling traffic at restricted work zones is to maintain two-lane, two-way traffic through the work site by using the shoulder as a temporary travel lane on a two-lane highway. This option is implemented by shifting traffic laterally one travel lane from their normal travel path in order to accommodate a work activity in the roadway. However, a basic requirement for using this option is that the two-lane roadway have shoulders.

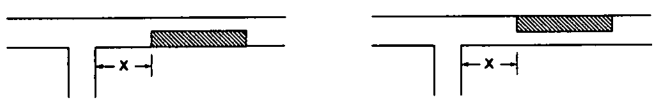
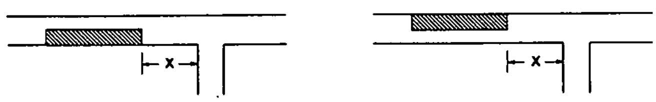
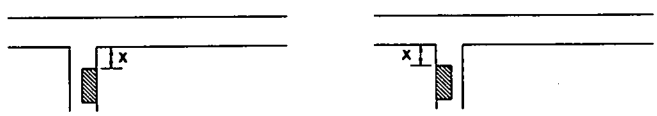
This traffic control strategy allows the same number of traffic lanes to pass through the work zone as before construction. Thus, a primary advantage for using this strategy is that the capacity of the roadway will only be minimally affected by the work activity. (A typical traffic control application is shown in Figure 3.12 in Section 3.2.4.)

3.2.2.4 Alternating One-Way Traffic

The fourth option for handling traffic at restricted work zones is to maintain alternating one-way traffic on one open lane through the work zone. Alternating one-way traffic control involves closing one traffic lane to accommodate a work activity while using the remaining open lane for both directions of traffic. This type of control generally requires approaching vehicles to slow down or stop on a roadway where such actions are typically not required. Therefore, special attention should be given to using appropriate signing in advance of the work zone to warn motorists of the need to slow down or stop. The use of supplemental signs and flashing warning lights on the signs may be justified at Case A restricted work zones because motorists are not expecting the need to slow down or stop.

The long-term duration of work activities that require the use of a barrier generally necessitates a self-operating type of control (i.e., one that does not require manpower continuously at the site). Control methods that may be used to maintain alternating one-way traffic on one open lane at restricted work zones are the following: (1) traffic signal control, (2) stop control, and (3) yield control. Table 3.1 shows the fea-

TABLE 3.1. Feasible traffic control methods for alternating one-way traffic operations

Restricted Work Zone Configuration	x[a] (ft)	Number of Approaches	Traffic Control Methods		
			Signal	Stop	Yield
	≥ 0	3	●[b]		
	≥ 115[c]	2	●	●	●
	≥ 0	3	●		
	≥ 165[d]	2	●	●	●
	≥ 0	3	●		

[a]Distance from intersecting roadway to work activity area.
[b]Feasible traffic control method.
[c]Taper length + distance between stop line and beginning of taper + storage length for 1 vehicle = 50 ft + 40 ft + (1 veh)(25 ft/veh) = 115 ft. (The 40 ft distance assumes the signal is located at the beginning of the taper.)
[d]Taper length + distance between stop line and beginning of taper + storage length for 3 vehicles = 50 ft + 40 ft + (3 veh)(25 ft/veh) = 165 ft. (The 40 ft distance assumes the signal is located at the beginning of the taper.)

sible traffic control methods for various restricted work zone configurations. The methods considered feasible for a particular work site depend on the location of the work activity area relative to the intersecting roadway. If the work activity area is far enough away from the intersecting roadway, the number of approaches to the one-lane segment may be reduced from three to two. In this case, the distance should be such that traffic on the intersecting roadway can adequately merge with traffic traveling through the open lane without causing considerable disruptions in traffic operations.

As shown in Table 3.1, signal control is feasible for all restricted work zone configurations, but stop and yield control are only considered to be viable options in cases where there are two approaches to the one-lane segment. For example, if the work activity area is located 70 ft from the intersecting roadway and on the same side of the roadway as the intersecting roadway, the only option available to handle three traffic approaches to the one-lane segment is signal control. On the other hand, if the work activity area is located 130 ft from the intersecting roadway and on the same side of the roadway, the number of approaches to the one-lane segment may be reduced to two approaches. In this case signal, stop, and yield control are all possible options.

Each of the control methods is discussed in the following sections. The appropriate type of control to be used at a particular restricted work zone should be determined based on site conditions, sight distance, and user and construction costs, as discussed in Section 3.2.3. Typical traffic control applications for handling one-way alternating traffic are shown in Figures 3.13 to 3.36 in Section 3.2.4.

Signal Control. Traffic signals are commonly used to control alternating one-way traffic at restricted work zones, primarily because they provide a positive control over approaching motorists. The MUTCD briefly addresses the use of temporary traffic signals for controlling alternating one-way traffic in construction work areas. The signal and control equipment must meet the applicable standards and specifications established in Part IV (Signals) of the MUTCD. Temporary traffic signals are normally operated in either fixed-time or actuated modes. The MUTCD specifies that an all-red interval of sufficient duration for traffic to clear the one-way zone at the posted speed limit must be provided. Signal timing is affected by the length of the closure, the number and location of signals, and the speed and volume of traffic passing through the work zone. The location of intersecting roadways with respect to the work activity area and the need for contractor access will determine the placement of traffic signals, barriers, and other traffic control devices.

A common advance warning sign sequence for temporary traffic signals is as follows: ROAD CONSTRUCTION 1/2 MILE, ONE LANE ROAD 1000 FT, SIGNAL AHEAD, STOP HERE ON RED, and END CONSTRUCTION. A supplementary sign, BE PREPARED TO STOP, may be placed before the SIGNAL AHEAD sign to warn motorists of the need to stop and increase their expectation for stopping. The STOP HERE ON RED sign, placed adjacent to the stop bar, reinforces the need for stopping and adds credibility to the presence of the signals. The same sign sequence may be used on all approaches to the work zone.

Supplemental signs may be required where sight distance is limited by the horizontal or vertical alignment of the roadway. In this case, supplemental signs such as ONE LANE ROAD AHEAD 1500 FT, ONE LANE ROAD 1000 FT, and ONE LANE ROAD 500 FT could provide the additional warning necessary to ensure safe passage through the work zone. Advisory speed signs may be placed below some or all of the advance warning signs. In some cases, regulatory reduced speed limits may be posted in the work zone.

A temporary stop bar is recommended on all approaches. Stop bars help motorists identify the point where they should stop on approaches to alternating one-way operations (*4*).

Stop Control. The use of stop signs is one method for controlling alternating one-way traffic on low-volume roadways for short-distance lane closures when the line of sight through the one-lane segment is unobstructed. One state, for example, allows the use of stop control when the length of the one-lane section is no longer than 150 ft and the average daily traffic (ADT) is not greater than 1500 vehicles per day (*5*). Stop control requires drivers on both approaches to stop in advance of the one-lane segment and determine if conflicting traffic is present. If it is, then the driver must wait for the traffic to clear the one-lane segment before proceeding. If conflicting traffic is not present, the driver continues through the one-lane segment.

The typical warning sign sequence for stop control is as follows: ROAD CONSTRUCTION 1/2 MILE, ONE LANE ROAD 1000 FT, STOP AHEAD, STOP, and END CONSTRUCTION. The same signing sequence may be used on both approaches. Supplementary signs adjacent to the STOP sign are used by a number of states to provide additional information relative to movements of other vehicles within the work zone. These legends include: YIELD TO ONCOMING TRAFFIC, PROCEED WHEN BRIDGE IS CLEAR, PROCEED WHEN CLEAR, or WAIT FOR SAFE CLEARANCE BEFORE CROSSING BRIDGE. The legend AFTER STOP PROCEED WHEN CLEAR is placed below the STOP sign by one state.

Intersecting roadways near the work activity area make traffic control more complex but do not eliminate stop control as a feasible alternative. Stop control, however, should be considered as an option only in cases where the work activity area is far enough away from the intersecting roadway that two separate areas of control exist. Stop control is feasible if the length of the closure is relatively short. As the lane closure becomes longer, the applicability of stop control for restricted work zones diminishes.

Yield Control. The use of yield signs is another effective method for controlling alternating one-way traffic on low-volume roadways. Yield control should be used only at sites with adequate sight distance on the approaches to the one-lane segment and only for relatively short work activity areas on low-volume roadways. For example, one state permits yield control in rural areas for work areas shorter than 400 ft and with an ADT less than 4000 vehicles per day (*6*). Under normal conditions, a driver approaching the work zone must determine whether oncoming, conflicting traffic is present. If it is not, then the driver passes through the work area. If conflicting traffic is present, the driver must stop and wait until it is safe to proceed.

A typical signing sequence for yield control is as follows: ROAD CONSTRUCTION 1500 FT, ONE LANE ROAD 1000 FT, YIELD

AHEAD 500 FT, YIELD TO ONCOMING TRAFFIC, and END CONSTRUCTION. The sequence is similar for both approaches to the one-lane segment. If a roadway intersects nearby, a typical ROAD CONSTRUCTION AHEAD, STOP AHEAD, and STOP sign sequence should be placed on the intersecting roadway.

Intersecting roadways near the ends of the work activity area may complicate the use of yield control. A major concern is that the assignment of right of way on the approaches may not be fully understood by motorists. Because of possible confusion by motorists that could result in accidents and delay, yield control is not recommended for situations where major roadways intersect near the work activity area. Yield control should be used in situations where there are only two traffic approaches to the one-lane segment. This requires that any intersecting roadways be located far enough away from the work activity area so that they do not adversely affect the alternating one-way traffic operations. Yield control may be used for contractor access or a local driveway within the work zone. In this case, motorists using the access point should be familiar with the right-of-way assignment, and confusion should be minimal.

3.2.3 Design Considerations

Traffic control at restricted work zones should be planned and conducted with the safety of motorists and workers in mind. Because the traffic-handling strategy affects the project design and construction phasing, the design and preparation of the traffic control plan should be an integral part of the project-planning process. It is desirable to implement the most cost-effective traffic-handling option that will provide safe and efficient operations throughout the work zone. In most cases, possible traffic control strategies for a particular project can be identified quickly based on site location and geometrics, traffic conditions, and type of construction. The selection of the most appropriate traffic control strategy is then a matter of determining the impacts of the alternative strategies and choosing the best overall strategy. Particular design elements that should be considered in selecting and developing traffic control for restricted work zones include sight distance, user costs, speed control, channelization and barrier delineation, and temporary traffic signals. These design considerations are discussed in this section for Case A and B restricted work zones.

3.2.3.1 Sight-Distance Issues

Sight distance is an important consideration during the planning, design, and implementation of traffic control plans for restricted work zones. To provide safe and efficient traffic operations, it is critical that drivers approaching or traveling through the work zone be able to see traffic control devices and other vehicles in the area. Adequate sight distance is even more important at locations where intersecting roadways and additional conflicting traffic movements are present. The potential for vehicle conflicts may be minimized by providing adequate sight distances.

Sight distances at restricted work zones should meet standard design criteria for permanent facilities given in AASHTO's *A Policy on Geometric Design of Highways and Streets* (*7*) or a state's design manual. With respect to sight-distance considerations for at-grade intersections, AASHTO states that "the operator of a vehicle approaching an intersection at-grade should have an unobstructed view of the entire intersection and sufficient lengths of the intersecting highway to permit control of the vehicle to avoid collisions. When traffic at the intersection is controlled by signals or signs, the unobstructed views may be limited to the area of control." Special attention should be given to the selection and placement of work zone traffic control devices due to the potential interference with drivers' sight distance. To the extent possible, work vehicles and equipment should be kept at locations that do not block the driver's view. At night, when a driver's visibility is sharply reduced and low-light conditions exist, it may be necessary to illuminate the work activity area. Care should be taken to adequately illuminate the desired area without creating glare in the eyes of drivers traveling through the work zone.

Sufficient sight distances in accordance with AASHTO criteria (*8*) should be provided on the approaches to the work activity area so that drivers may confirm advance warnings and respond appropriately to the traffic control devices. Because of the unexpected and complex nature of many restricted work zones, longer sight distances (i.e., decision sight distance) may be desirable to provide drivers an additional margin of safety. If appropriate sight distance is not available because of horizontal or vertical curvature, the work zone channelization devices should be extended to a point where they are visible to approaching drivers.

The most important factor in selecting the type of control for alternating one-way traffic operations is sight distance. Stop or yield control should be used only if sight distance through the work zone is available for traffic on each approach. If the line of sight through the one-lane segment is obstructed, then the only option available would be signal control. In cases where an intersecting roadway is controlled by signals, sight distance based on AASHTO Case III intersection sight-distance procedures (i.e., criteria for stop control of at-grade intersections) should be provided (7). The hazard related to unanticipated vehicle conflicts at these intersections, such as violations of the signal, signal malfunction, or use of flashing red/yellow mode, justifies Case III sight distance at signal-controlled restricted work zones.

3.2.3.2 User Cost Considerations

The total cost of a project should be carefully evaluated during the planning and design stage so that the most cost-effective construction methods and traffic-handling strategies may be implemented. Although many individual costs contribute to the total project cost, most costs usually fall under two basic categories: the cost of construction and the cost to the highway user. The impacts of various construction methods and traffic-handling strategies must be quantified in order to estimate the total project costs. The impacts worth noting include the following:

- Traffic Impacts
  - –Delay
  - –Stops
  - –Fuel consumption
  - –Operating costs
  - –Accidents

- Construction Impacts
  - –Traffic Control Costs
  - –Construction Costs

Traffic impacts directly affect the highway user, whereas construction impacts affect the costs for traffic control devices, temporary facilities, and construction. The construction costs should be estimated for alternative strategies and combined with user costs to determine the total project cost. The focus of this section, however, is to discuss issues related to user costs and particularly to the cost of vehicle delay. The costs associated with construction impacts are not addressed herein but should be considered in the overall cost analysis.

Delay Estimation. Delay is the traffic impact most apparent and important to motorists. Thus, the vehicle delay should be estimated during the analysis of each potential strategy. Procedures that can be used to estimate vehicle delay at work zones are summarized herein (*8*).

The delay attributed to a work zone is the difference between the normal travel time on the roadway and the estimated travel time through the work zone. The basic steps for estimating vehicle delay at work zones are as follows (*8*):

1. Identify highway sections of uniform characteristics;
2. Identify which delay element(s) are significant in each section;
3. Compute the estimated delay time for each delay element; and
4. Summarize the delays for the total work zone.

The first step is to identify the highway sections that will be affected by the work activity. These sections should be easily recognized during the development of the construction plan. The analysis should include all sections on which queuing or reduced speeds are expected during the work activity.

The second step is to identify the element(s) of delay that can be expected on each section. The vehicle delay or road-user delay may consist of one or more of the following elements (*8*):

- Delays due to increased travel distance and/or reduced speed;
- Delays due to insufficient capacity; and
- Delays due to temporary stoppage of traffic flow.

Table 3.2 provides a general guide to assist in identifying potential delay elements for given traffic-handling options.

Following the identification of the affected delay elements, the next step is to compute the delay time for each delay element. Procedures for estimating each delay element are presented in the following sections. Finally, the delays for the total work zone are summarized.

Delay Due to Increased Travel or Speed Changes. A change in path and travel distance may occur at restricted work zones. Furthermore, the average speed at which motorists travel through or around a work zone may be different from the normal speed on the route. The increased travel distance or change in speed could result in additional delay. Average vehicular delay due to increased travel distance or reduced speed can be estimated from one of the following equations (*8*) depending on the available data.

$$AD = TT_w - TT_n$$

$$AD = \frac{D_w}{S_w} - TT_n$$

$$AD = \frac{D_w}{S_w} - \frac{D_n}{S_n}$$

Where:

AD = Average delay
TT_w = Travel time on work zone route
TT_n = Travel time on normal route
D_w = Work zone route distance
D_n = Normal route distance
S_w = Work zone route travel speed
S_n = Normal route travel speed

Average speeds for the highway may be estimated from volume/speed curves in the 1985 *Highway Capacity Manual*

TABLE 3.2. Guide for identifying uniform sections and delay elements

Work Zone Strategy	Section	Potential Delay Elements
On-site Detour	Bypass Section	1
Off-site Detour	Detour Route	1,2,3
Alternating One-Way	Upstream of one lane/intersection	3
Maintain Two-Way Traffic	Section of Shoulder Usage	1,2

Delay Elements:
1. Delay due to increased travel distance and/or reduced speed;
2. Delay due to insufficient capacity;
3. Delay due to temporary stoppage of traffic flow.

(*9*) or from local collected data, if available. Travel time on the work zone route in which there is no capacity restraint should be estimated on the basis of engineering judgment and experience from other areas. Speeds through work zones are generally restricted to speeds below the normal speed limit (*8*). A reasonable assumption for the speed through the work zone may be 80 to 90 percent of the normal speed limit. The delay can then be computed using the equations presented previously as the difference between the travel time through or around the work zone and the travel time under normal conditions.

Delay Due to Insufficient Capacity. Restricted work zones usually affect the capacity of the roadway, especially in cases where the number of lanes is reduced or where an alternative route is used. For example, when one or more lanes of a multilane highway are closed for a work activity and traffic is directed to use the remaining open lanes, the capacity of the roadway is reduced. Also, when traffic is detoured to an alternative route, the additional demand placed on the alternative route could exceed the available capacity. If the capacity of the work zone route or the detour route is insufficient, vehicle delays are likely to occur.

In this case vehicle delay may be calculated using an estimate of the work zone capacity, traffic demand, and the length of the vehicle queue. Figure 3.8 is a graphical representation of the traffic volume-capacity relationships. The straight line shown in Figure 3.8 represents the capacity (C) at the bottleneck over a period of time. At time t_1, the traffic volume (V) entering the bottleneck exceeds the capacity and a queue begins to form upstream of the bottleneck. The queue reaches a maximum (Q_m) at time t_2 when the entering volume (V) begins to drop below the capacity (C) of the bottleneck. At this point, a vehicle entering the queue will experience the maximum delay (D_m). The queue dissipates as the volume (V) decreases relative to the capacity (C). Finally, at time t_3, the queue disappears. The total vehicular delay due to the queuing process is represented by the shaded area in Figure 3.8.

The delay may be computed using the following equations:

$$Q_t = Q_{t-1} + (V_t - C)$$

$$D_t = \frac{Q_t}{C}$$

Average delay per vehicle except last congested hour:

$$AD_t = \frac{(D_{t-1} + D_t)}{2}$$

Average delay per vehicle entering for the last congested hour:

$$AD_t = D_{t-1} \times \left(\frac{Q_{t-1}}{(C - V_t)}\right)$$

Total Delay:

$$TD = \sum (V_t \times AD_t)$$

Where:

C = Capacity
Q_t = Queue at time t
V_t = Hourly volume at time t
D_t = Delay at time t
AD_t = Average delay at time t
TD = Total delay

Delay Due to Temporary Stoppage. Vehicle delays also result from temporary stoppage of traffic flow such as at alternating one-way controlled work zones. Several options including traffic signals, and stop or yield signs, as discussed in Section 3.2.2, are available for controlling alternating one-way traffic. The delay associated with each control option should be estimated to determine the most appropriate traffic control for a given work zone. Methods for selecting among the traffic control options and determining vehicle delays are presented in this section.

Several factors should be considered in selecting the optimal type of control for a particular restricted work zone. These include site configuration, sight distance, traffic-handling capacity of the one-lane segment, and vehicle delays. The configuration of the work zone and available sight distance should determine the feasible traffic control options as discussed elsewhere in this manual. After site configuration and sight distance constraints, the most desirable type of control could be selected based on capacity and delay considerations. With respect to capacity estimates, the maximum two-way flow rates that can be maintained are approximately 1200–1300 vehicles per hour (vph) for signal control and 700–800 vph for stop or yield control (*4,10*).

The total vehicle delay at alternating one-way traffic operations is a function of the length of the one-lane segment, the maximum speed through the work zone, and the approach volumes. The length of the one-lane segment and the speed through the work zone can be taken into account collectively by estimating the traverse or clearance time, namely, the mean clearance interval (MCI). The MCI is the average of (1) "the time it takes for a vehicle leaving from a stopped condition to travel from stop line to stop line" and (2) "the time it takes a vehicle which does not stop to travel from stop line to stop line" at the speed limit (*11*). In the absence of actual field data, Figure 3.9 may be used to estimate the MCI for various combinations of speed limit and length of one-lane segment. To use Figure 3.9, enter the horizontal axis with the length of the one-lane operation and proceed vertically until the proper speed limit is intersected. From that point proceed horizontally to the left and read the MCI from the vertical axis.

With the estimated MCI and traffic demands, the optimal control could be selected and vehicle delay could be estimated for one-lane operations. Where both signal and stop control are feasible alternatives, Figure 3.10 may be used to select the optimal control based upon minimum total delay. To use this figure, find the intersection of the demands for the two approaches. If this point of intersection lies to the right and above the appropriate MCI curve, lower delays will be realized with signal control than with stop control. On the other hand, if the point lies to the left and below the MCI curve,

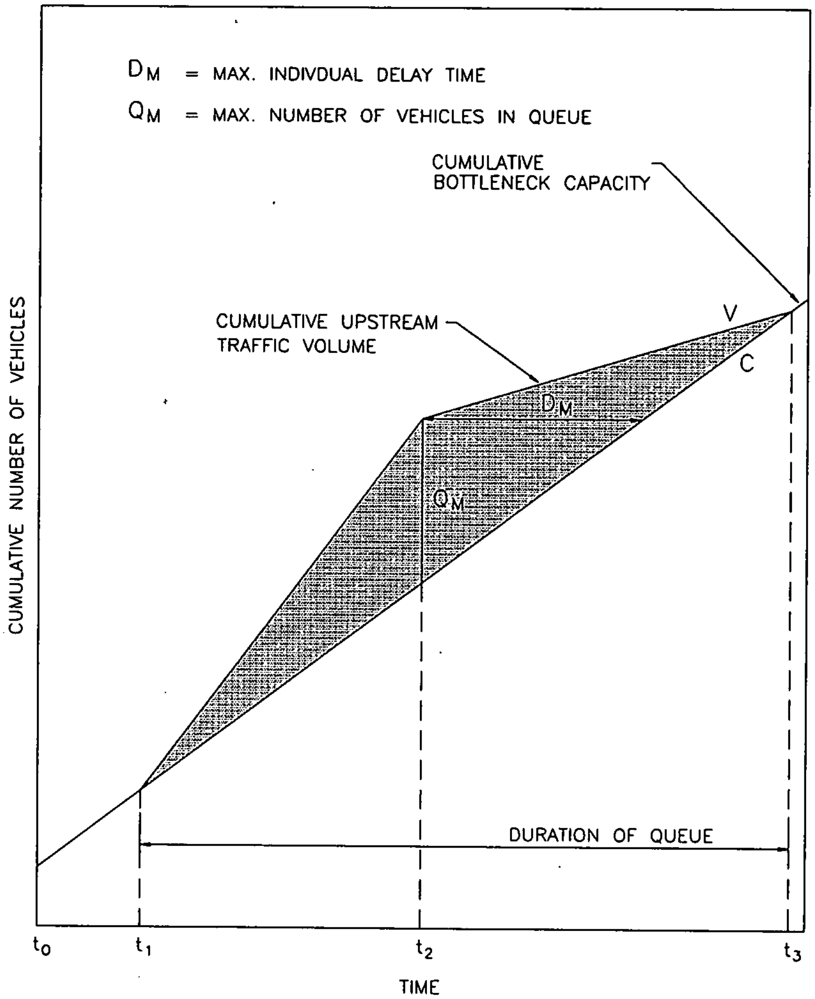


Figure 3.8. Traffic volume-capacity relationships (9).

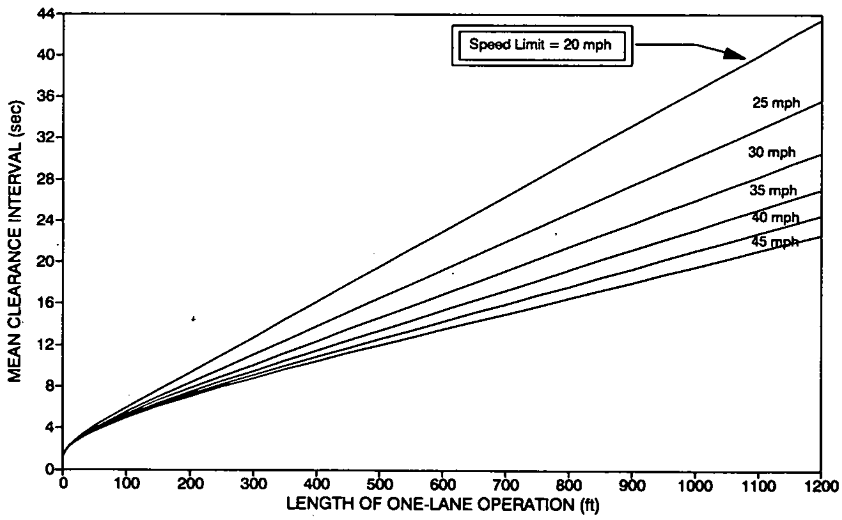


Figure 3.9. Mean clearance intervals for various speed limits and lengths of one-lane segment.

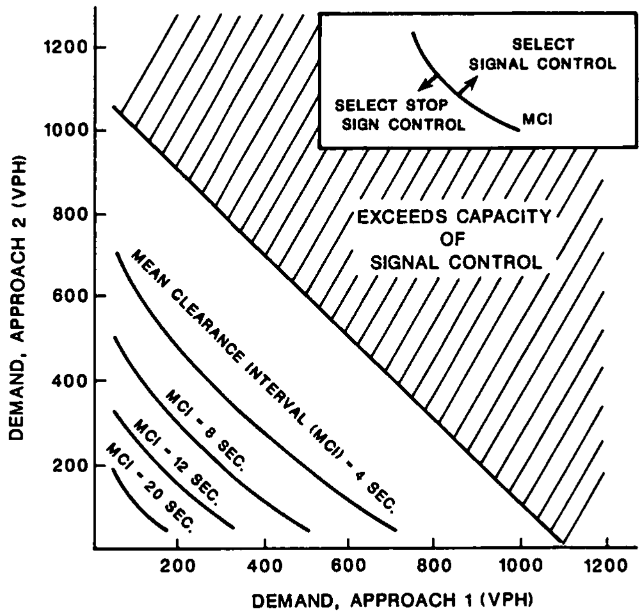


Figure 3.10. Optimal control to minimize total delays for alternating one-way operation (6,11).

lower delays will be realized with stop control than with signal control.

The total vehicle delays for pretimed signal control of alternating one-way traffic for undersaturated conditions are summarized in Table 3.3 for various combinations of MCI's and traffic demands. The delay estimates shown in the table were calculated using analytical methods presented elsewhere (*11,12,13*).

Table 3.4 shows total delays that could be expected where stop signs are used to control alternating one-way traffic. These delays were generated by computer simulations (*10,11*).

The estimated delays for stop control may be used to approximate delays for yield control. In most cases where stop and yield signs are options, the determination of the appropriate type of control will be based upon factors other than vehicle delay.

Cost Estimation. Each of the delay elements can be summarized and converted into monetary values for use in a cost effectiveness or benefit-cost analysis. To convert the estimated delay into costs, the delay is simply multiplied by a dollar value of time. A reasonable estimate of the value of time is $13 per vehicle-hour in 1991 dollars (*14*, updated to January 1991). After the user costs have been estimated for an alternative traffic control strategy, the total project costs should be computed. The total project costs, as discussed earlier, include the cost to the user and the cost for traffic control devices, temporary facilities, and construction. Finally, the most cost-effective strategy that provides safe and efficient traffic operations throughout the work zone should be selected.

3.2.3.3 Speed Control

The selection of a design speed is another important consideration in developing the traffic control plan for a work zone. The MUTCD states the fundamental principle that "Traffic movement should be inhibited as little as practicable." The MUTCD goes on to say that "Traffic control in work sites should be designed on the assumption motorists will only reduce their speeds if they clearly perceive a need to do so. Reduced speed zoning should be avoided as much as practicable."

Although it may be desirable from a safety standpoint to reduce vehicle speeds through work zones, the difficulty in controlling speeds generally makes it more practical to maintain safety by designing the work zone for the speed that motorists will actually drive (*15*). Motorists generally prefer and, therefore, attempt to maintain their normal approach speed through the work zone. As a result, the design speed through the work zone should be as close as practicable to the normal design speed of the highway.

The design speed of a work zone is defined by the most limiting design element in the work zone. The sight distance approaching the work zone, the roadway alignment through the work zone, and the traffic control devices (particularly the traffic barrier and end treatments) should be safe for speeds equaling or exceeding the design speed.

In some cases, including many restricted work zone situations, conditions may necessitate a reduction in the work zone design speed. Where a speed reduction is necessary, the magnitude of the reduction should be kept to a minimum. Recommended maximum speed reductions in work zones are summarized in Table 3.5 by type of highway.

The two most common methods of speed control in work zones are regulatory and advisory speed limit reductions. Reduced speed zoning may not be needed when the work zone design speed equals or exceeds the posted approach speed. If, however, the work zone design speed is less than the posted approach speed, then, for safety and liability reasons, the posted speed limit should be reduced. The posted speed limit should not exceed the design capabilities of the work zone.

In most cases, regulatory and advisory speed limit reductions alone will not produce the desired reduction in actual speeds; thus, it is necessary to supplement these signing methods with additional speed control methods. Other methods that have been employed and evaluated include the following:

- Enforcement,
- Flagging,
- Unmanned radar transmitters,
- Pace car,
- Changeable message signing,
- Transverse striping,
- Rumble strips,
- Lane width reductions, and
- Utilization of a traffic queue (congestion).

Most states' policies indicate the speed control methods that may be used, the appropriate applications, and the procedures for implementing them. Agencies considering the use of new methods in their state should refer to any of several syn-

TABLE 3.3. Total delay for pretimed signal control

Demand (pcph)			Total Delay (hr)									
Approach			Mean Clearance Interval (sec)									
1	2	3	4	8	12	16	20	24	28	32	36	40
100	100	0	0.32	0.55	0.77	0.98	1.18	1.39	1.59	1.79	2.00	2.20
100	100	50	0.60	0.97	1.31	1.64	1.96	2.28	2.59	2.90	3.21	3.52
100	100	100	0.81	1.29	1.73	2.14	2.55	2.95	3.34	3.74	4.13	4.52
200	100	0	0.53	0.87	1.18	1.48	1.77	2.06	2.34	2.63	2.91	3.19
200	100	50	0.95	1.48	1.95	2.40	2.83	3.25	3.67	4.08	4.49	4.90
200	100	100	1.25	1.92	2.52	3.08	3.63	4.16	4.68	5.20	5.72	6.23
200	200	0	0.87	1.38	1.83	2.26	2.68	3.09	3.50	3.90	4.30	4.70
200	200	50	1.48	2.24	2.90	3.52	4.11	4.69	5.26	5.82	6.38	6.93
200	200	100	1.90	2.85	3.67	4.43	5.17	5.88	6.59	7.29	7.98	8.67
200	200	200	2.85	4.17	5.29	6.34	7.34	8.32	9.28	10.23	11.17	12.10
300	100	0	0.78	1.22	1.61	1.97	2.33	2.67	3.01	3.35	3.68	4.02
300	100	50	1.39	2.08	2.66	3.21	3.73	4.24	4.73	5.23	5.71	6.20
300	100	100	1.80	2.66	3.41	4.10	4.76	5.40	6.03	6.65	7.27	7.88
300	200	0	1.26	1.92	2.50	3.04	3.56	4.06	4.56	5.06	5.55	6.04
300	200	50	2.15	3.14	3.98	4.75	5.48	6.19	6.89	7.57	8.26	8.93
300	200	100	2.72	3.95	4.99	5.95	6.87	7.75	8.63	9.49	10.34	11.19
300	200	200	4.09	5.84	7.30	8.64	9.92	11.16	12.38	13.58	14.77	15.95
300	300	0	1.84	2.71	3.46	4.15	4.82	5.46	6.10	6.72	7.35	7.96
300	300	50	3.13	4.44	5.53	6.52	7.45	8.36	9.24	10.11	10.97	11.82
300	300	100	3.94	5.58	6.94	8.18	9.36	10.49	11.61	12.70	13.79	14.87
300	300	200	6.04	8.43	10.40	12.20	13.90	15.55	17.16	18.75	20.32	21.88
300	300	300	9.36	12.83	15.66	18.22	20.64	22.97	25.25	27.50	29.72	31.91
400	100	0	1.11	1.65	2.11	2.54	2.94	3.33	3.71	4.09	4.47	4.84
400	100	50	1.98	2.84	3.55	4.19	4.80	5.38	5.95	6.52	7.07	7.62
400	100	100	2.53	3.62	4.53	5.35	6.12	6.87	7.61	8.33	9.04	9.75
400	200	0	1.78	2.60	3.30	3.94	4.55	5.14	5.73	6.30	6.88	7.44
400	200	50	3.05	4.31	5.35	6.28	7.15	8.00	8.83	9.64	10.44	11.24
400	200	100	3.86	5.43	6.73	7.91	9.02	10.09	11.14	12.18	13.20	14.21
400	200	200	5.92	8.23	10.13	11.84	13.46	15.03	16.56	18.07	19.56	21.04
400	300	0	2.62	3.74	4.67	5.52	6.33	7.11	7.88	8.63	9.38	10.13
400	300	50	4.52	6.24	7.63	8.87	10.03	11.15	12.24	13.31	14.36	15.41
400	300	100	5.74	7.92	9.68	11.27	12.76	14.20	15.60	16.98	18.34	19.69
400	300	200	9.21	12.57	15.29	17.74	20.05	22.27	24.44	26.57	28.68	30.77
400	300	300	15.89	21.35	25.74	29.67	33.35	36.90	40.35	43.75	47.10	50.42
400	400	0	3.83	5.31	6.52	7.62	8.65	9.64	10.611	11.56	12.50	13.44
400	400	50	6.77	9.14	11.00	12.64	14.17	15.63	7.04	18.43	19.79	21.14
400	400	100	8.81	11.89	14.33	16.50	18.53	20.47	22.36	24.21	26.04	27.84
400	400	200	15.65	20.95	25.17	28.93	32.45	35.83	39.12	42.34	45.53	48.68
400	400	300	35.64	47.08	56.14	64.17	71.67	78.86	85.85	92.71	99.47	106.16
500	100	0	1.57	2.23	2.77	3.25	3.70	4.14	4.56	4.98	5.39	5.80
500	100	50	2.82	3.90	4.76	5.51	6.21	6.88	7.53	8.17	8.79	9.41
500	100	100	3.59	4.97	6.07	7.05	7.96	8.84	9.69	10.53	11.35	12.17
500	200	0	2.50	3.52	4.36	5.12	5.84	6.53	7.20	7.86	8.52	9.17
500	200	50	4.38	6.00	7.28	8.41	9.47	10.48	11.46	12.42	13.37	14.31
500	200	100	5.58	7.63	9.28	10.74	12.11	13.42	14.70	15.96	17.20	18.42
500	200	200	8.98	12.17	14.72	17.00	19.14	21.19	23.19	25.15	27.09	29.01
500	300	0	3.78	5.22	6.39	7.44	8.43	9.38	10.31	11.22	12.12	13.01
500	300	50	6.71	9.03	10.84	12.43	13.91	15.31	16.68	18.02	19.33	20.64
500	300	100	8.73	11.75	14.13	16.24	18.21	20.09	21.92	23.71	25.48	27.23
500	300	200	15.53	20.73	24.86	28.52	31.95	35.23	38.42	41.56	44.65	47.71
500	300	300	35.37	46.61	55.47	63.31	70.61	77.61	84.40	91.06	97.63	104.12
500	400	0	5.82	7.86	9.48	10.92	12.26	13.54	14.79	16.02	17.23	18.43
500	400	50	10.82	14.27	16.91	19.20	21.31	23.31	25.25	27.14	28.99	30.83

theses of research on work zone speed control techniques (*16,17,18,19*).

For the types of work zones addressed in this manual, the speed control methods that may be most appropriate and effective at supplementing regulatory or advisory speed limit reductions include enforcement, flagging, and rumble strips. Both the law enforcement and flagging methods have proven effective, but they are labor intensive and are generally not practical for round-the-clock use. Rumble strips may serve both speed control and alerting functions, but because they have not been extensively evaluated, there is no consensus on the appropriateness of their work zone applications. Other

TABLE 3.3. Total delay for pretimed signal control *(continued)*

Demand (pcph)			Total Delay (hr)									
Approach			Mean Clearance Interval (sec)									
1	2	3	4	8	12	16	20	24	28	32	36	40
500	400	100	14.93	19.71	23.42	26.66	29.66	32.52	35.30	38.01	40.68	43.32
500	400	200	34.90	45.80	54.32	61.82	68.79	75.44	81.90	88.22	94.45	100.61
500	500	0	9.85	12.99	15.42	17.55	19.51	21.37	23.18	24.95	26.69	28.40
500	500	50	20.36	26.32	30.78	34.58	38.05	41.31	44.46	47.51	50.51	53.46
500	500	100	33.43	43.29	50.78	57.24	63.17	68.78	74.20	79.49	84.68	89.80
600	100	0	2.24	3.06	3.70	4.25	4.77	5.26	5.73	6.19	6.64	7.09
600	100	50	4.08	5.47	6.52	7.42	8.25	9.03	9.78	10.52	11.24	11.94
600	100	100	5.23	7.02	8.40	9.60	10.71	11.76	12.77	13.77	14.74	15.71
600	200	0	3.61	4.92	5.96	6.87	7.73	8.54	9.34	10.12	10.88	11.64
600	200	50	6.50	8.67	10.32	11.75	13.07	14.32	15.53	16.71	17.87	19.01
600	200	100	8.48	11.31	13.51	15.43	17.20	18.90	20.53	22.14	23.72	25.28
600	200	200	15.12	20.03	23.86	27.22	30.35	33.34	36.24	39.07	41.86	44.63
600	300	0	5.72	7.68	9.22	10.58	11.84	13.05	14.22	15.37	16.50	17.62
600	300	50	10.69	14.04	16.58	18.77	20.78	22.69	24.52	26.31	28.07	29.80
600	300	100	14.76	19.41	22.98	26.10	28.97	31.70	34.35	36.93	39.47	41.98
600	300	200	34.51	45.14	53.39	60.61	67.30	73.68	79.86	85.90	91.85	97.73
600	400	0	9.81	12.92	15.31	17.40	19.32	21.15	22.93	24.66	26.36	28.04
600	400	50	20.29	26.21	30.61	34.36	37.78	40.99	44.09	47.09	50.04	52.94
600	400	100	33.32	43.11	50.51	56.89	62.73	68.27	73.61	78.81	83.92	88.96
600	500	0	21.93	28.29	33.06	37.15	40.88	44.40	47.80	51.10	54.34	57.53
600	500	50	67.12	86.43	99.75	110.94	121.00	130.42	139.42	148.14	156.67	165.04
700	100	0	3.28	4.34	5.13	5.79	6.40	6.96	7.51	8.03	8.55	9.06
700	100	50	6.12	7.98	9.34	10.48	11.51	12.46	13.38	14.26	15.13	15.98
700	100	100	8.01	10.49	12.34	13.91	15.33	16.67	17.96	19.22	20.45	21.65
700	200	0	5.49	7.28	8.64	9.82	10.90	11.93	12.92	13.89	14.84	15.78
700	200	50	10.40	13.53	15.85	17.81	19.60	21.28	22.89	24.46	25.99	27.50
700	200	100	14.37	18.74	22.02	24.85	27.43	29.88	32.23	34.53	36.78	39.00
700	200	200	33.67	43.69	51.33	57.94	64.03	69.80	75.37	80.81	86.15	91.42
700	300	0	9.66	12.65	14.92	16.88	18.69	20.40	22.05	23.66	25.24	26.80
700	300	50	20.07	25.81	30.04	33.63	36.87	39.92	42.84	45.67	48.45	51.18
700	300	100	32.96	42.47	49.60	55.71	61.29	66.55	71.62	76.55	81.39	86.16
700	400	0	21.84	28.13	32.82	36.83	40.49	43.94	47.26	50.49	53.65	56.77
700	400	50	67.90	86.04	99.20	110.21	120.11	129.36	138.20	146.75	155.11	163.32
800	100	0	5.07	6.54	7.58	8.44	9.20	9.91	10.58	11.23	11.86	12.48
800	100	50	9.87	12.61	14.53	16.10	17.50	18.78	20.00	21.17	22.31	23.43
800	100	100	13.69	17.55	20.33	22.65	24.74	26.68	28.53	30.32	32.06	33.78
800	200	0	9.33	12.07	14.10	15.81	17.37	18.83	20.23	21.59	22.92	24.24
800	200	50	19.61	25.01	28.89	32.12	35.02	37.72	40.29	42.78	45.21	47.59
800	200	100	32.22	41.20	47.79	53.36	58.39	63.12	67.65	72.04	76.34	80.57
800	300	0	21.58	27.66	32.16	35.97	39.42	42.67	45.79	48.82	51.78	54.70
800	300	50	67.30	85.01	97.73	108.31	117.77	126.59	134.98	143.10	151.02	158.79

Note: Saturation Flow Rate = 1200 pcphpl, Yellow Interval = 3 sec, Acceleration = 4.84 fpss, and Reaction Time = 2 sec

methods consistent with individual state policies and site conditions may also be considered.

Law enforcement at work zones is one of the most effective speed control techniques (*19*). Three basic enforcement methods are circulating patrols, stationary patrols, and police traffic controllers. The more common and effective method is stationary patrols, in which the officer is parked in a marked vehicle in a conspicuous position immediately upstream of the work zone (*19*). The police traffic controller, a uniformed officer who stands at the side of the road immediately upstream of the work zone (as a flagger would), has also been found to be effective (*16*). Moving patrols, in which the law enforcement officer drives back and forth through the work zone, appears to be the least effective enforcement method (*16*). The use of law enforcement at work zones is often limited by the cost and availability of personnel, and round-the-clock enforcement for extended time periods generally is not feasible.

Flaggers may be nearly as effective as enforcement at reducing speeds through work zones (*19*). In many jurisdictions, the use of flaggers may be more practical than law enforcement since flaggers are generally more available than law enforcement personnel. The flagging method must be carefully implemented: flaggers must be trained adequately, relieved at regular intervals, dressed to be conspicuous, and positioned safely.

Some states permit the use of rumble strips in work zones, whereas other states do not. Rumble strips might be consid-

TABLE 3.4. Total delay for stop control

Mean Clearance Interval (sec)	Demand (pcph)		Total Delay (hr)
	Approach 1	Approach 2	
4	100	100	0.13
	200	100	0.21
	200	200	0.32
	300	100	0.31
	300	200	0.49
	300	300	0.84
	400	100	0.41
	400	200	0.75
	400	300	2.30
	400[a]	400	32.11
	500	100	0.60
	500	200	1.91
	500[a]	300	35.80
	600	100	1.04
	600[a]	200	28.75
	700	100	11.51
	800[a]	100	59.53
8	100	100	0.19
	200	100	0.37
	200	200	0.61
	300	100	0.64
	300	200	3.61
	300[a]	300	29.42
	400	100	1.48
	400[a]	200	46.04
	500[a]	100	26.46
12	100	100	0.29
	200	100	0.77
	200	200	8.04
	300	100	2.08
	300[a]	200	54.04
	400[a]	100	14.68
16	100	100	0.50
	200	100	1.93
	200[a]	200	40.28
	300[a]	100	17.97
20	100	100	0.88
	200	100	8.40
	200[a]	200	67.78
	300[a]	100	52.28
24	100	100	1.71
	200[a]	100	30.23
28	100	100	3.73
	200[a]	100	48.73
32	100[a]	100	12.75

[a]Indicates that demands exceed capacity.

ered to serve speed control and/or alerting functions. Several states have specifications for the use of rumble strips in advance of work zone lane closure tapers. For example, the *Illinois Manual on Uniform Traffic Control Devices* (*20*) includes a schematic for alternating one-way traffic on a rural, two-lane highway in which rumble strips are placed 200 ft upstream of each of the standard advance warning signs in both directions approaching the one-lane section. Pennsylvania guidelines state that "Rumble strips may be used in work zones to capture the attention of drivers or to alert them that unusual maneuvers may be necessary" (*21*). The alerting function of rumble strips may be applicable in Case A and B restricted work zone

TABLE 3.5. Recommended maximum speed reductions in work zones

Type of Highway	Recommended Maximum Speed Reduction (mph)
Rural Two-Lane Highway	10-15
Rural Freeway	5-15
Urban Arterial	10-20
Urban Freeway	5-10

situations. Unfortunately, few studies have evaluated the effectiveness of rumble strips in work zone applications and, therefore, there is no consensus on their effectiveness. Agencies interested in rumble strips should review the recent *Work Zone Traffic Management Synthesis: Use of Rumble Strips in Work Zones* (*22*).

In summary, traffic control plans should be designed for the speeds motorists will actually travel through the work zone. Because those speeds are generally close to the normal approach speeds, reductions in the work zone design speed should be avoided. Where required, work zone design speed reductions should be kept to a minimum. The posted speed limit should not exceed the design capabilities of the work zone. When design speed reductions are necessary, speed limit reductions should be implemented, and supplemental speed control methods should be considered.

3.2.3.4 Channelization and Delineation Considerations

The MUTCD requires that motorists "be guided in a clear and positive manner while approaching and traversing construction and maintenance work areas." Because restricted work zones may present motorists with unexpected and unusual conditions, positive guidance in advance of and through the work area becomes even more critical at these work zones. The intended vehicle path through the work zone should be clearly defined using channelizing devices and delineation treatments that are effective under varying light and weather conditions. The use of channelizing devices in the transition area and delineation treatments through the work area should be consistent with standard practices.

Although a temporary concrete barrier at most Case A and Case B restricted work zones is primarily used for protecting motorists and workers, the barrier performs a secondary function as a channelization device. In this case, the MUTCD specifies that the barrier "should be of a light color for increased visibility" and that "For nighttime use, barriers shall be supplemented by the use of standard delineation or channelization markings or devices." The need for delineation devices is even greater during conditions of adverse visibility—dust, fog, rain, snow, low contrast, and glare—when motorists are deprived of many visual cues that are normally used for guidance through work zones (*23*). Proper barrier delineation treatments will provide drivers a defined path during darkness and adverse weather conditions.

Standard barrier delineation treatments include Type C steady-burn warning lights on top of the barrier, retroreflective devices on the top or side of the barrier, and reflective pavement markings on the side of the barrier. In addition, edgelines or retroreflective raised pavement markers should be applied on the pavement at the base of the barrier to define the edge of the travel lane. Inappropriate existing pavement markings should be obliterated or removed to prevent motorist confusion.

The most critical portion of the work zone in terms of the need for positive guidance is the transition area. Thus, special attention should be given to the placement of devices in this region of the work zone. At restricted work zones, the restricted distance between the work activity area and the intersecting roadway may complicate channelization through the transition area. Even though restricted conditions exist, a taper of channelizing devices should be placed upstream of the barrier end. In addition, a tangent section of channelizing devices may be desirable between the end of the taper and the barrier tangent. The potential benefits of the taper are that it would (1) provide better delineation of the barrier end than treatments placed directly on the barrier itself, (2) move traffic out of the closed lane upstream of the barrier end, (3) serve as a forgiving first alert to a driver deviating from the intended path, (4) create a buffer space between the taper and the barrier end, and, thereby, (5) reduce the probability of vehicles striking the barrier end.

For the alternating one-way traffic situation, the *Traffic Control Devices Handbook* (*24*) indicates that the taper should be 50 to 100 ft long. The short taper is intended to give the appearance of restricted alignment and, thereby, encourage motorists to slow down. An inadequate taper of channelizing devices will most likely produce undesirable traffic operations resulting in potential accidents through the area. The length of the tangent section of channelizing devices varies depending on the site conditions. If space is available, a 30- to 40-ft tangent section is suggested.

The taper may be located upstream or downstream of the restricting intersecting roadway. At many restricted work zones, the distance between the intersecting roadway and barrier is so short that a taper of channelizing devices downstream of the intersecting roadway must be placed immediately in front of the flared portion of the barrier and may not be of standard length. Although improving the delineation of the barrier end, the taper would provide little, if any, buffer space between the taper and the barrier. In order to provide a taper of standard length, it may be necessary to place the taper upstream of the intersecting roadway. Introducing the taper upstream of the intersecting roadway would provide a more desirable buffer space between the taper and the barrier end. However, there are two disadvantages of a taper upstream of the intersecting roadway: (1) it will increase the length of the one-lane operation, thereby increasing motorist delays, and (2) it may restrict the line of sight for motorists on the intersecting roadway. The impacts of the increased length of one-lane operation on traffic-handling capacity and motorist delays, and the effect of the taper on sight distance should be considered in selecting the location and devices of the taper.

Several channelization devices may be used to form the taper. The devices should have a high target value and be capable of remaining in place for the entire length of the project without frequent maintenance. Type I or II barricades, drums, and vertical panels demonstrate these capabilities. Cones and tubular markers are not recommended because of their low target value and their inability to remain in position for long periods of time. The devices should be supplemented with a solid white edgeline placed along the edge of the taper and parallel to the barrier in the tangent section to further enhance path delineation.

Space availability and sight-distance requirements may influence the selection of channelizing devices. For tapers located between the barrier end and the intersecting roadway, the devices with the highest target value that can fit within the available space should be used. As mentioned previously, tapers located upstream of the intersecting roadway may cause sight-distance problems at the intersecting roadway; therefore, sight-distance requirements may dictate the need to use lower profile channelizing devices. Because tapers located upstream of the intersecting roadway provide greater buffer space, the use of lower profile channelizing devices is reasonable.

Perhaps the most important consideration in selecting and placing channelizing devices and delineation treatments is that they should contribute to the total system of traffic control devices at the restricted work zone and should not be considered in isolation. To ensure that delineation devices do not conflict with other traffic control devices, routine inspections of the restricted work zone should be performed during varying conditions of volume, light, and weather. Because restricted work zones are usually long-term projects, devices often remain in the same place for long periods of time. For this reason, there is more opportunity for devices to become dirty or out of their original placement. Monitoring the work zone on regular intervals should ensure that all channelizing and delineation devices are clearly visible, clean, and in good condition.

3.2.3.5 Temporary Traffic Signals

Several design considerations for installing temporary traffic signals at restricted work zones are presented in this section. As mentioned previously, the MUTCD only briefly discusses the use of signals to control traffic in work zones. The MUTCD indicates that the signal and control equipment must meet the applicable standards and specifications established for permanent installations. The design elements that should be considered for temporary traffic signal installations at alternating one-way traffic controlled work zones include: number, size, mounting alternatives, physical arrangement, and placement of the individual signal heads, and signal timing. These elements are briefly discussed herein; however, the reader is referred to Part IV (Signals) of the MUTCD for specific details.

With respect to the signal display, the physical details that affect the driver's ability to see and respond to the intended message are as follows: minimum visibility requirements, number and location of signal faces, size and arrangement of signal indications, and illumination. Traffic signals should be visible to traffic approaching the signals from a "minimum visibility distance," as specified in the MUTCD. This requirement is particularly important where temporary traffic signals are used and motorists are not expecting the need to stop or slow down. In addition, the MUTCD requires that there be a minimum of two signal faces for each through approach. Several criteria that should be considered in locating these signal faces are given in the MUTCD (e.g., vertical, longitudinal, and lateral position of signal faces in terms of the driver's cone of vision).

The two standard sizes of signal indications allowed by the MUTCD are 8- or 12-in.-diameter lenses. The larger size should be used in cases where increased conspicuity is needed to provide the proper visibility. It is recommended that the 12-in. lens be used for approaches where signalization might be unexpected. An acceptable practice is to use a 12-in. circular red indication combined with an 8-in. circular yellow and green. An 8-in. red indication, however, should not be used with a 12-in. yellow or green (*25*).

Several methods may be used to mount signal indications at restricted work zones: span-wire mounted, post-mounted, and portable signals. There are several characteristics and advantages and disadvantages of each type of signal mounting that should be considered during the design and installation of temporary traffic signals. One advantage of the span-wire mounted signals is that the overall conspicuity is greatly improved because the faces are directly in line with the motorist's approach to the intersection. Whereas span-wire mounted signals are more commonly used at restricted work zones, post-mounted signals are also used. A potential problem associated with post-mounted signals located beside the roadway is that the visibility of the signal may be blocked by large trucks. The presence of signals on both sides of the roadway will insure that approaching drivers see the red indication and do not attempt to pass. Furthermore, post-mounted signals located beyond vertical curves may not be high enough to be seen over the crest of the hill. In this case, special consideration must be given to the visibility of the signal. Portable signals may also be used to control alternating one-way traffic on one open lane. The MUTCD specifies that portable traffic signals must meet the physical display and operational requirements of conventional traffic signals.

Temporary traffic signals may operate in either fixed-time or actuated models. Fixed-time operation may be suitable during higher volume daytime periods. During low-volume periods, motorist delays, and consequently the likelihood for violations, might be reduced by operating in actuated mode. If signals are operated in full actuated mode, consideration should be given to having the signal indication for all approaches reside on red until an oncoming vehicle is detected. The reside-on-red strategy, by requiring all vehicles to stop before entering the one-lane segment, may be an effective way of controlling the speeds of vehicles passing through the work zone during low volume periods. Signals may also be operated in semiactuated mode in cases where there are three traffic approaches. Using this type of operation, the signal indication for the intersecting roadway approach resides on red while the other signals operate independently. When a vehicle is detected on the intersecting roadway, the signals on the main roadway turn red allowing the intersecting roadway traffic to traverse the one-lane segment. Semiactuated signals may be an effective operation where traffic volumes on the intersecting roadway are quite low compared to the main roadway traffic.

As has been discussed in earlier sections of this manual, the signal timing is dependent on the length of the closure, the number and location of signals, and the speed and volume of traffic. The signal-timing plan to be used at a particular restricted work zone should provide safe traffic operations while minimizing motorist delays. The cycle length should include an all-red interval of sufficient duration for traffic to clear the one-lane segment at the posted speed limit. The all-red interval has been defined in Section 3.3.3.2 as the mean clearance interval (MCI). To simplify the determination of an optimal cycle length for fixed-time signals, calculations for a range of traffic demands and MCIs are shown in Figure 3.11. To use the figure, enter the horizontal axis with the total demand on all approaches in passenger cars per hour (pcph) and proceed vertically until the proper MCI is intersected. From that point, continue horizontally to the left and read the optimal cycle length from the vertical axis. For MCIs not shown in Figure 3.11, interpolation between the curves is appropriate.

3.2.4 Typical Traffic Control Applications

Examples of typical traffic control applications are presented in this section. The typical applications include traffic control strategies for a variety of situations but do not include a layout for every conceivable situation that may occur. Therefore, typical applications may be altered to fit the conditions of a particular work site. Other traffic control devices may be added to supplement the devices shown in the typical applications where site conditions dictate. Modifications to

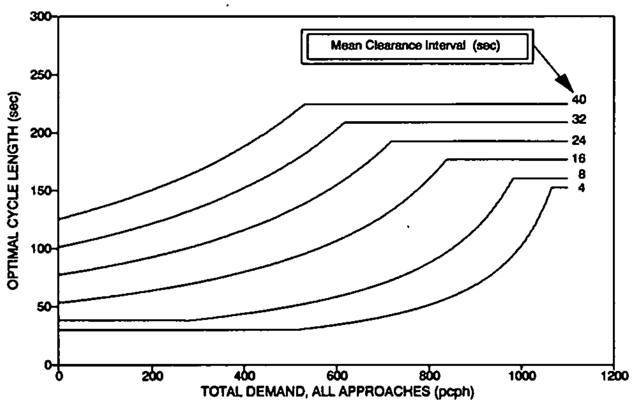


Figure 3.11. Optimal cycle lengths for various mean clearance intervals and traffic demands.

the typical applications should be based on proper engineering judgment.

Typical applications for detours (both on-site and off-site) are presented in the MUTCD and may be used at restricted work zones. Discussions of detours are given in sections 3.2.2 and 3.2.3 of this manual.

Figure 3.12 illustrates the traffic control required to maintain two-lane, two-way traffic on a two-lane highway with shoulders. Refer to sections 3.2.2 and 3.2.3 for discussions of maintaining two-lane, two-way traffic at restricted work zones.

Because most Case A and Case B restricted work zones involve alternating one-way traffic control, the focus of the applications is on this control option. Table 3.6 references by figure number the typical applications for alternating one-way traffic control. The table shows the work zone configuration, the available distance between the work activity area and the intersecting roadway, and the corresponding typical application. To use the table, select the typical application number that corresponds to the restricted work zone configuration and the distance from the work activity area to the intersecting roadway. For sites where the distance from the work activity area to the intersecting roadway is less than 50 ft, a supplemental taper should be placed upstream of the intersecting roadway. If that same distance is greater than or equal to 50 ft, there is available space for the taper to be placed between the work activity area and the intersecting roadway. In both cases, however, traffic signals are required to control the three traffic approaches. If there is adequate space between the work activity area and the intersecting roadway, the number of approaches to the one-lane segment may be reduced from three to two so that stop or yield control may be used. The distance criteria in Table 3.6 were selected based on the distance needed for the intersecting roadway traffic to enter the through traffic lane without causing considerable disruptions in traffic operations. Typical traffic control applications for handling one-way alternating traffic are shown in Figures 3.13 to 3.36.

3.3 INTERSECTING ROADWAYS WITHIN THE WORK ACTIVITY AREA (CASE C)

3.3.1 Current State Practices

Case C restricted work zones have openings within the run of barrier for access by the contractor to the work activity area or by property owners and customers to adjoining properties. The need to maintain as many lanes as possible for traffic on urban arterials with high traffic volumes seriously constrains the lateral offset from the edge of the travel lanes to the barrier and the lateral distance available to incorporate suitable barrier end treatments. Several Case C work zones that involved numerous access openings on urban arterials were observed during visits to various states.

Barrier and traffic control treatments currently used to shield the work activity area from traffic at these work zones include:

- Temporary concrete barrier,
- W-beam-on-barrels,
- Reflective fencing, and
- Barrels.

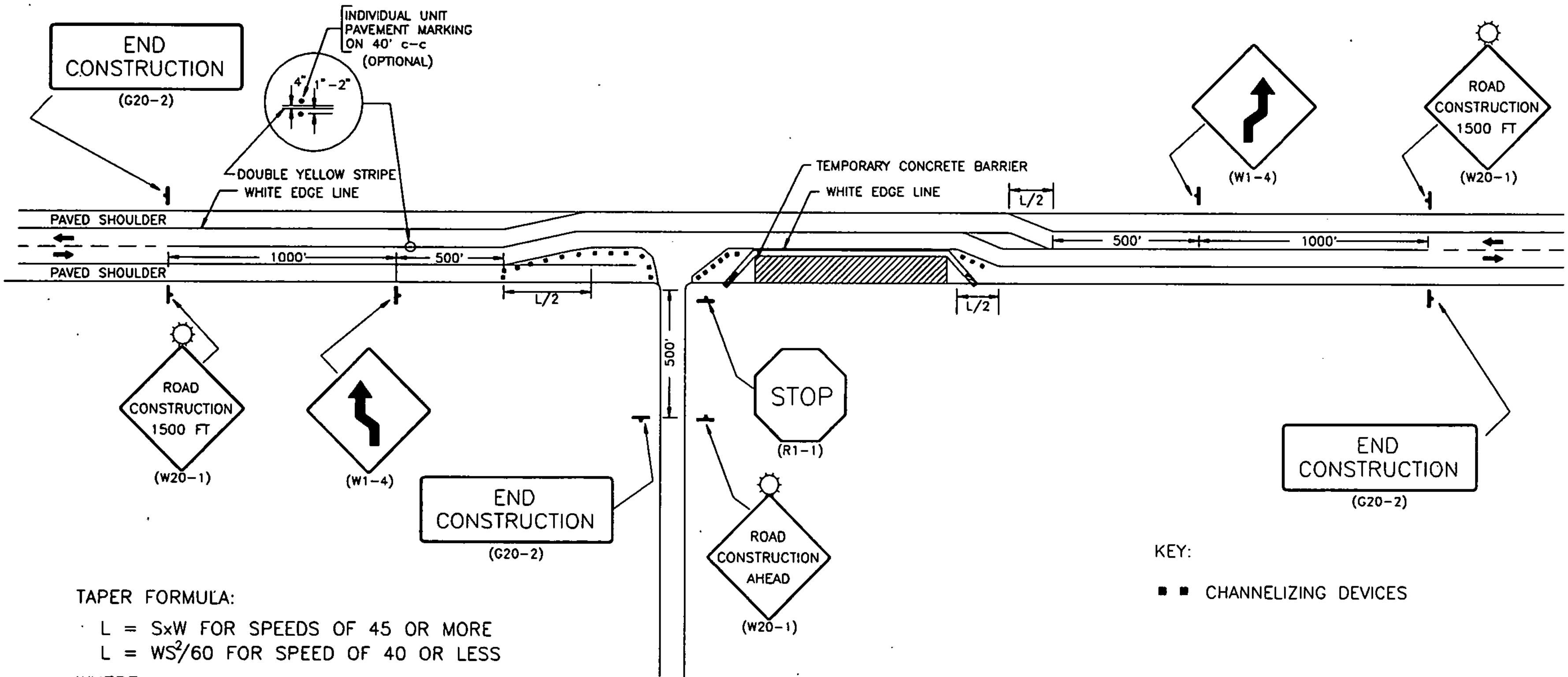
NOTE:

1. Barrier end treatments should be selected based upon guidelines given in Chapter 4 of the User's Manual.

2. No passing lines shall be added where they are not already in place. Existing conflicting pavement markings and retroreflective raised pavement markers in the work area shall be removed.

3. The Type A flashing warning lights should be used to call attention to the advance warning signs.

4. The horizontal or vertical alignment of the roadway may require adjustments in the location of the advance warning signs (the distance shown for advance warning sign spacings are minimums).



TAPER FORMULA:

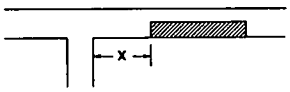
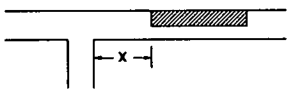
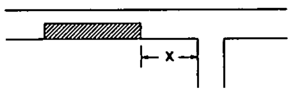
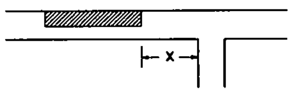
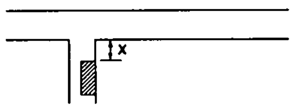
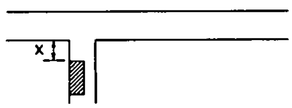
$L = S \times W$ FOR SPEEDS OF 45 OR MORE
$L = WS^2/60$ FOR SPEED OF 40 OR LESS

WHERE

L = MINIMUM LENGTH OF TAPER
S = POSTED SPEED LIMIT PRIOR TO WORK
W = WIDTH OF TAPER OFFSET

Figure 3.12. Typical application for maintaining two-lane, two-way traffic.

TABLE 3.6. Reference guide to typical applications for alternating one-way traffic control

Restricted Work Zone Configuration	x[a] (ft)	Number of Approaches	Figure Number of Typical Applications		
			Signal	Stop	Yield
	< 50	3	III-13	--[b]	--
	≥ 50	3	III-15	--	--
	≥ 115[c]	2	III-17	III-19	III-21
	< 50	3	III-14	--	--
	≥ 50	3	III-16	--	--
	≥ 115[c]	2	III-18	III-20	III-22
	< 50	3	III-23	--	--
	≥ 50	3	III-25	--	--
	≥ 165[d]	2	III-27	III-29	III-31
	< 50	3	III-24	--	--
	≥ 50	3	III-26	--	--
	≥ 165[d]	2	III-28	III-30	III-32
	< 50	3	III-33	--	--
	≥ 50	3	III-35	--	--
	< 50	3	III-34	--	--
	≥ 50	3	III-36	--	--

[a]Distance from work activity area to intersecting roadway.
[b]No Typical Application given for this condition.
[c]Taper length + distance between stop line and beginning of taper + storage length for 1 vehicle = 50 ft + 40 ft + (1 veh)(25 ft/veh) = 115 ft. (The 40 ft distance assumes the signal is located at the beginning of the taper.)
[d]Taper length + distance between stop line and beginning of taper + storage length for 3 vehicles = 50 ft + 40 ft + (3 veh)(25 ft/veh) = 165 ft. (The 40 ft distance assumes the signal is located at the beginning of the taper.)

Figure 3.37 illustrates the use of a temporary concrete barrier at a restricted work zone on an urban arterial. In this case, access to adjoining properties required that openings in the barrier be provided for traffic. The barrier was flared back as much as possible in the restricted space.

Another treatment that was observed is the use of W-beam-on-barrels placed at the edge of the travelway. Figure 3.38 shows the treatment "wrapped around" into the access drive or roadway.

In some states, dropoffs have been delineated using reflective fencing placed along the edge of the dropoff. The fencing is mounted on barrels or stakes. This treatment does not provide a positive barrier between traffic and workers. However, it effectively delineates the edge of the travel lane and alleviates the problems associated with placing a barrier in a restricted space. Pennsylvania's experience with the use of this treatment has been encouraging.

Yet another treatment that has been used at work zones on urban arterials is to place barrels at the edge of the dropoff. Figure 3.39 illustrates the use of barrels in a work zone located on a multilane urban arterial. Ample access to abutting properties is provided with this treatment and the need for end treatments is eliminated. However, the use of barrels alone may leave the work activity area exposed to passing traffic.

NOTE:

1. Barrier end treatments should be selected based upon guidelines given in Chapter 4 of the User's Manual.
2. All traffic signal and control equipment shall meet the applicable standards and specfications prescribed in Part IV of the Manual on Uniform Traffic Control Devices.
3. The Type A flashing warning lights should be used to call attention to the advance warning signs.
4. Adequate area illumination to clearly identify both ends of the work area at night shall be provided.
5. Twenty-four (24) inch stop lines shall be installed at each intersection approach. No passing lines shall be added where they are not already in place. Existing conflicting pavement markings and retroreflective raised pavement markers between the work area and the stop line shall be removed.
6. When the signal is changed to a flash condition, red shall be flashed to all approaches.
7. The horizontal or vertical alignment of the roadway may require adjustments in the location of the advance warning signs (the distance shown for advance warning sign spacings are minimums). The vertical alignment of the roadway may require adjustments in the height of the signal heads (Clearances must be 15 – 19 feet).

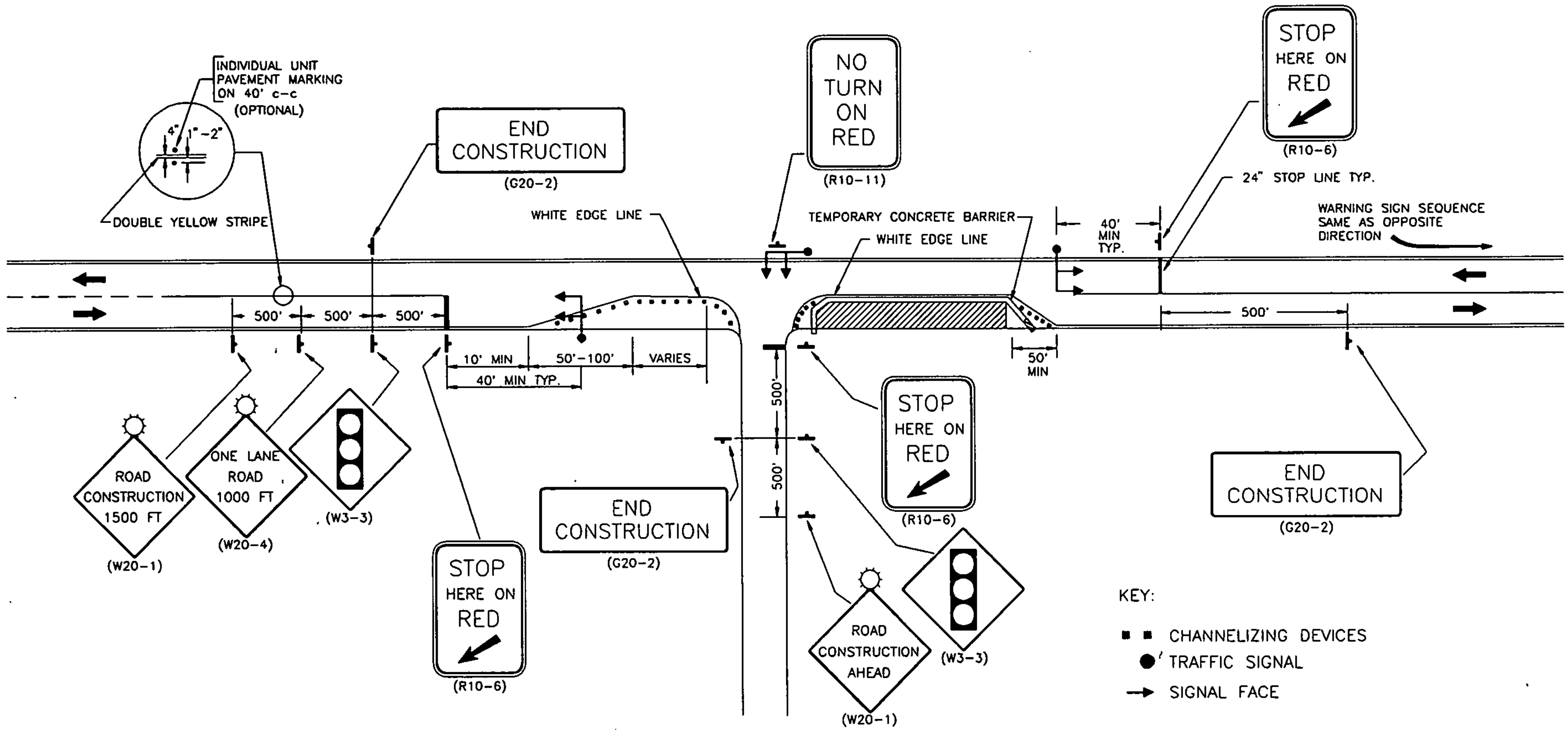


Figure 3.13. Typical application for signal control where work activity area is on same side of and less than 50 ft downstream from intersecting roadway.

NOTE:

1. Barrier end treatments should be selected based upon guidelines given in Chapter 4 of the User's Manual.
2. All traffic signal and control equipment shall meet the applicable standards and specfications prescribed in Part IV of the Manual on Uniform Traffic Control Devices.
3. The Type A flashing warning lights should be used to call attention to the advance warning signs.
4. Adequate area illumination to clearly identify both ends of the work area at night shall be provided.
5. Twenty-four (24) inch stop lines shall be installed at each intersection approach. No passing lines shall be added where they are not already in place. Existing conflicting pavement markings and retroreflective raised pavement markers between the work area and the stop line shall be removed.
6. When the signal is changed to a flash condition, red shall be flashed to all approaches.
7. The horizontal or vertical alignment of the roadway may require adjustments in the location of the advance warning signs (the distance shown for advance warning sign spacings are minimums). The vertical alignment of the roadway may require adjustments in the height of the signal heads (Clearances must be 15 - 19 feet).

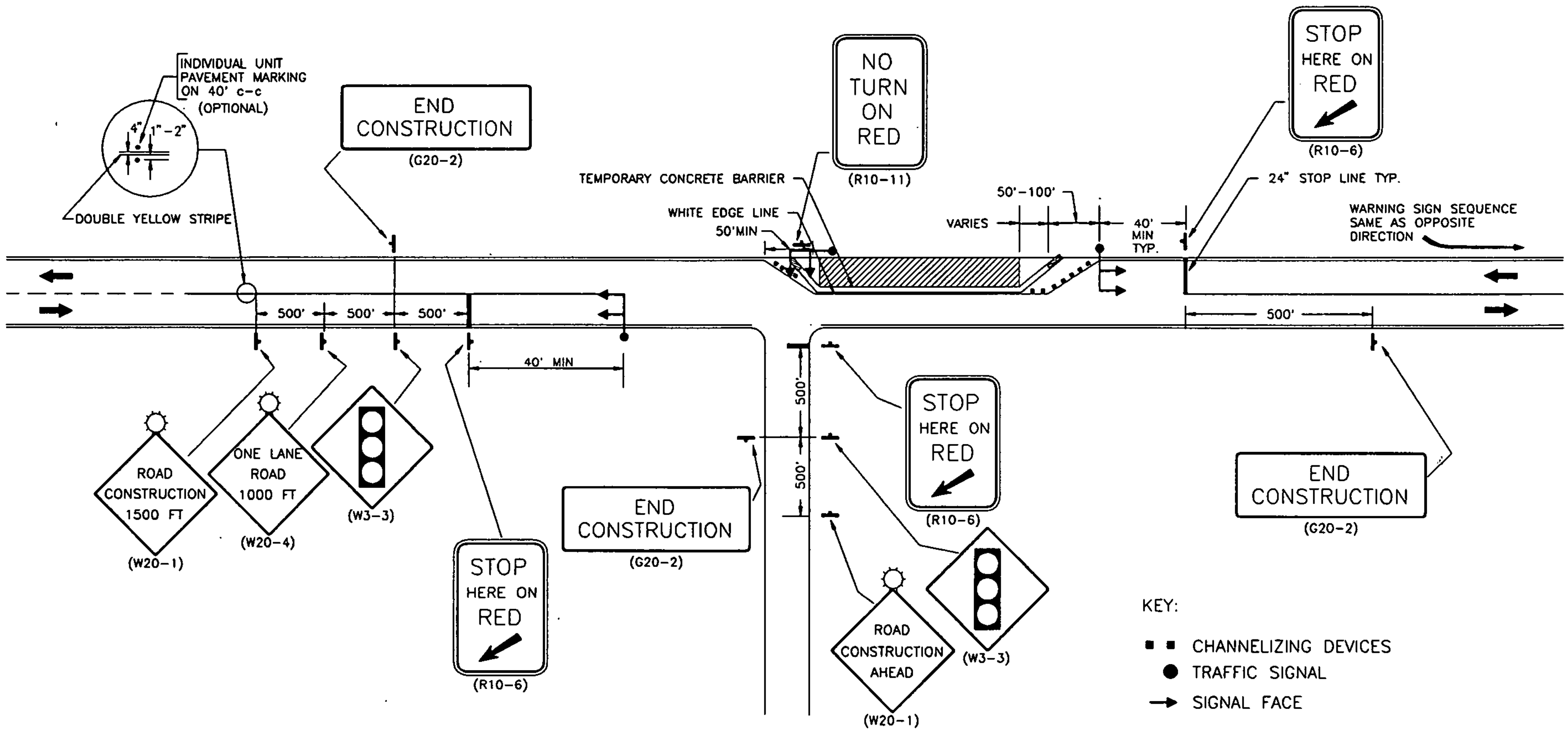


Figure 3.14. Typical application for signal control where work activity area is on opposite side of and less than 50 ft downstream from intersecting roadway.

NOTE:

1. Barrier end treatments should be selected based upon guidelines given in Chapter 4 of the User's Manual.

2. All traffic signal and control equipment shall meet the applicable standards and specfications prescribed in Part IV of the Manual on Uniform Traffic Control Devices.

3. The Type A flashing warning lights should be used to call attention to the advance warning signs.

4. Adequate area illumination to clearly identify both ends of the work area at night shall be provided.

5. Twenty-four (24) inch stop lines shall be installed at each intersection approach. No passing lines shall be added where they are not already in place. Existing conflicting pavement markings and retroreflective raised pavement markers between the work area and the stop line shall be removed.

6. When the signal is changed to a flash condition, red shall be flashed to all approaches.

7. The horizontal or vertical alignment of the roadway may require adjustments in the location of the advance warning signs (the distance shown for advance warning sign spacings are minimums). The vertical alignment of the roadway may require adjustments in the height of the signal heads (Clearances must be 15 – 19 feet).

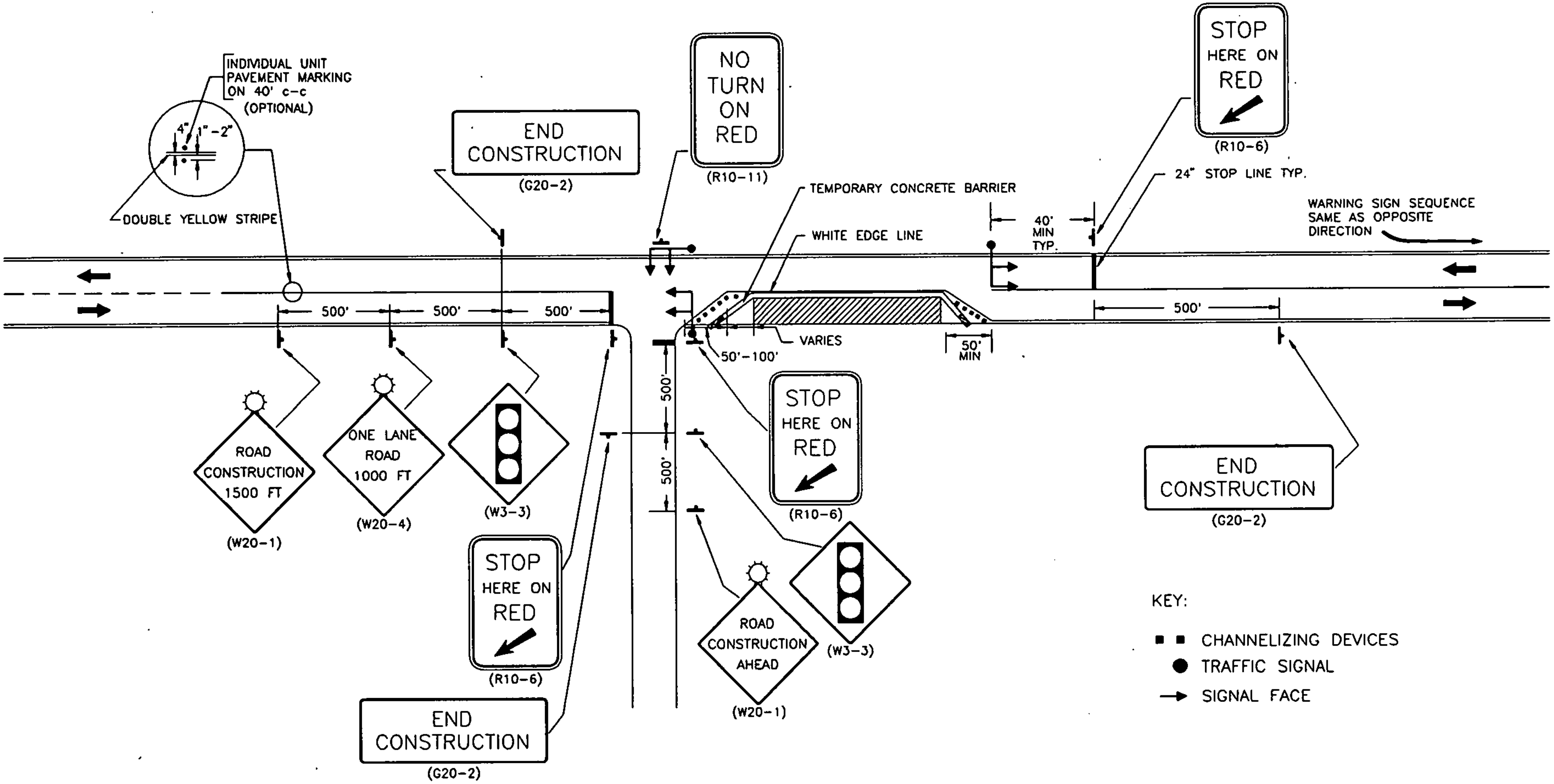


Figure 3.15. Typical application for signal control where work activity area is on same side of and 50 ft or more downstream from intersecting roadway.

NOTE:

1. Barrier end treatments should be selected based upon guidelines given in Chapter 4 of the User's Manual.

2. All traffic signal and control equipment shall meet the applicable standards and specfications prescribed in Part IV of the Manual on Uniform Traffic Control Devices.

3. The Type A flashing warning lights should be used to call attention to the advance warning signs.

4. Adequate area illumination to clearly identify both ends of the work area at night shall be provided.

5. Twenty-four (24) inch stop lines shall be installed at each intersection approach. No passing lines shall be added where they are not already in place. Existing conflicting pavement markings and retroreflective raised pavement markers between the work area and the stop line shall be removed.

6. When the signal is changed to a flash condition, red shall be flashed to all approaches.

7. The horizontal or vertical alignment of the roadway may require adjustments in the location of the advance warning signs (the distance shown for advance warning sign spacings are minimums). The vertical alignment of the roadway may require adjustments in the height of the signal heads (Clearances must be 15 – 19 feet).

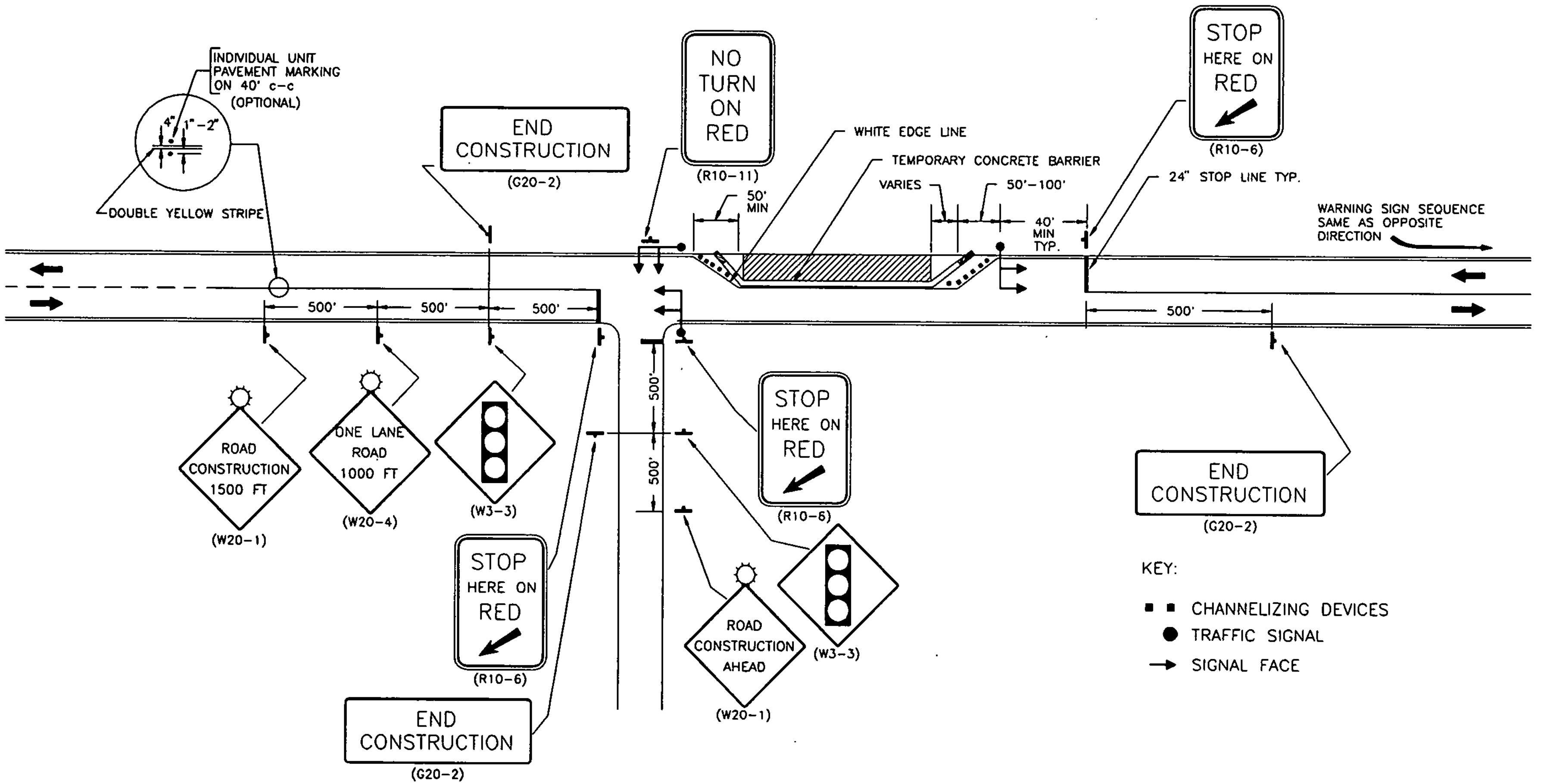


Figure 3.16. Typical application for signal control where work activity area is on opposite side of and 50 ft or more downstream from intersecting roadway.

NOTE:

1. Barrier end treatments should be selected based upon guidelines given in Chapter 4 of the User's Manual.
2. All traffic signal and control equipment shall meet the applicable standards and specfications prescribed in Part IV of the Manual on Uniform Traffic Control Devices.
3. The Type A flashing warning lights should be used to call attention to the advance warning signs.
4. Adequate area illumination to clearly identify both ends of the work area at night shall be provided.
5. Twenty-four (24) inch stop lines shall be installed at each intersection approach. No passing lines shall be added where they are not already in place. Existing conflicting pavement markings and retroreflective raised pavement markers between the work area and the stop line shall be removed.
6. When the signal is changed to a flash condition, red shall be flashed to all approaches.
7. The horizontal or vertical alignment of the roadway may require adjustments in the location of the advance warning signs (the distance shown for advance warning sign spacings are minimums). The vertical alignment of the roadway may require adjustments in the height of the signal heads (Clearances must be 15 – 19 feet).

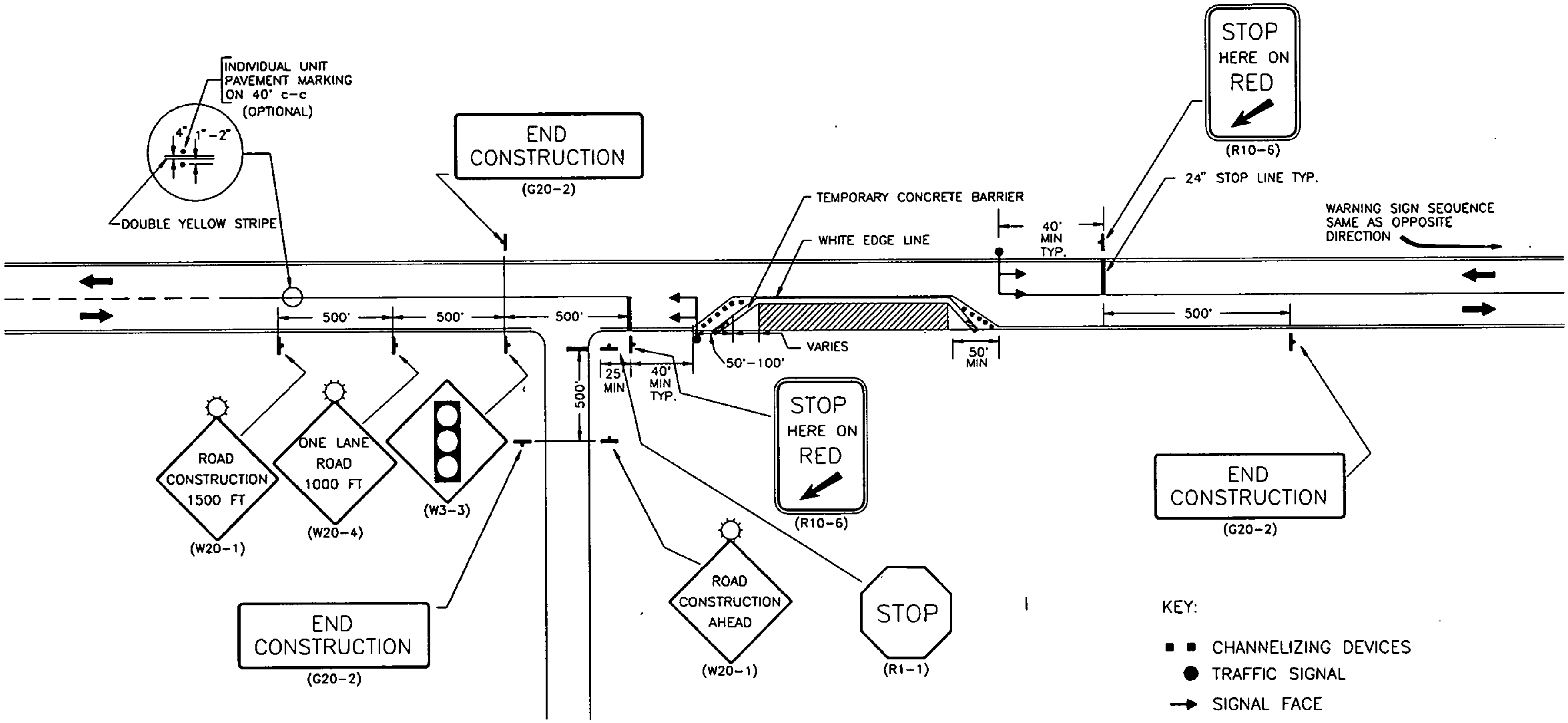


Figure 3.17. Typical application for signal control where work activity area is on same side of and 115 ft or more downstream from intersecting roadway.

NOTE:

1. Barrier end treatments should be selected based upon guidelines given in Chapter 4 of the User's Manual.
2. All traffic signal and control equipment shall meet the applicable standards and specfications prescribed in Part IV of the Manual on Uniform Traffic Control Devices.
3. The Type A flashing warning lights should be used to call attention to the advance warning signs.
4. Adequate area illumination to clearly identify both ends of the work area at night shall be provided.
5. Twenty-four (24) inch stop lines shall be installed at each intersection approach. No passing lines shall be added where they are not already in place. Existing conflicting pavement markings and retroreflective raised pavement markers between the work area and the stop line shall be removed.
6. When the signal is changed to a flash condition, red shall be flashed to all approaches.
7. The horizontal or vertical alignment of the roadway may require adjustments in the location of the advance warning signs (the distance shown for advance warning sign spacings are minimums). The vertical alignment of the roadway may require adjustments in the height of the signal heads (Clearances must be 15 – 19 feet).

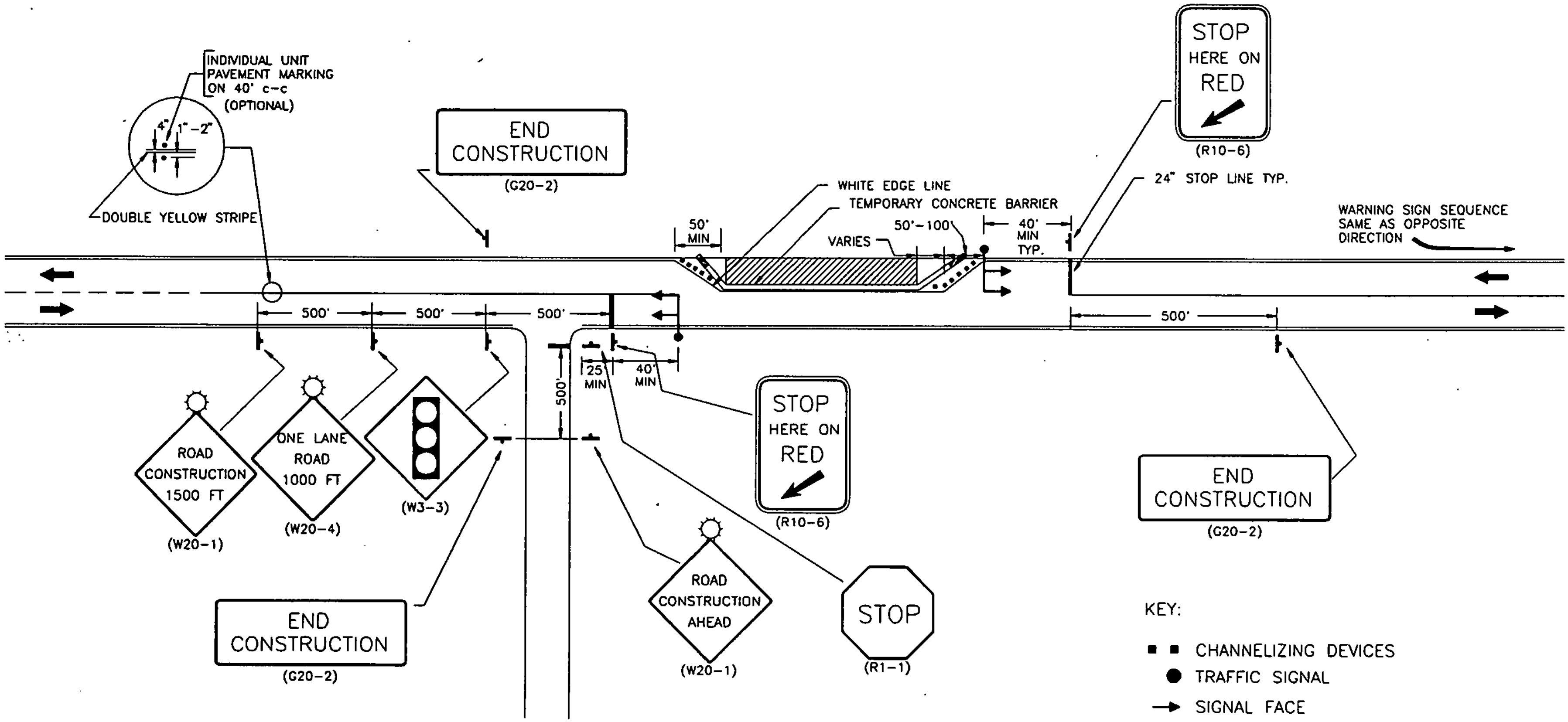


Figure 3.18. Typical application for signal control where work activity area is on opposite side of and is 115 ft or more downstream from intersecting roadway.

NOTE:

1. Barrier end treatments should be selected based upon guidelines given in Chapter 4 of the User's Manual.
2. The Type A flashing warning lights should be used to call attention to the advance warning signs.
3. Adequate area illumination to clearly identify both ends of the work area at night shall be provided.
4. Twenty-four (24) inch stop lines shall be installed at each intersection approach. No passing lines shall be added where they are not already in place. Existing conflicting pavement markings and retroreflective raised pavement markers between the work area and the stop line shall be removed.
5. The horizontal or vertical alignment of the roadway may require adjustments in the location of the advance warning signs (the distance shown for advance warning sign spacings are minimums).

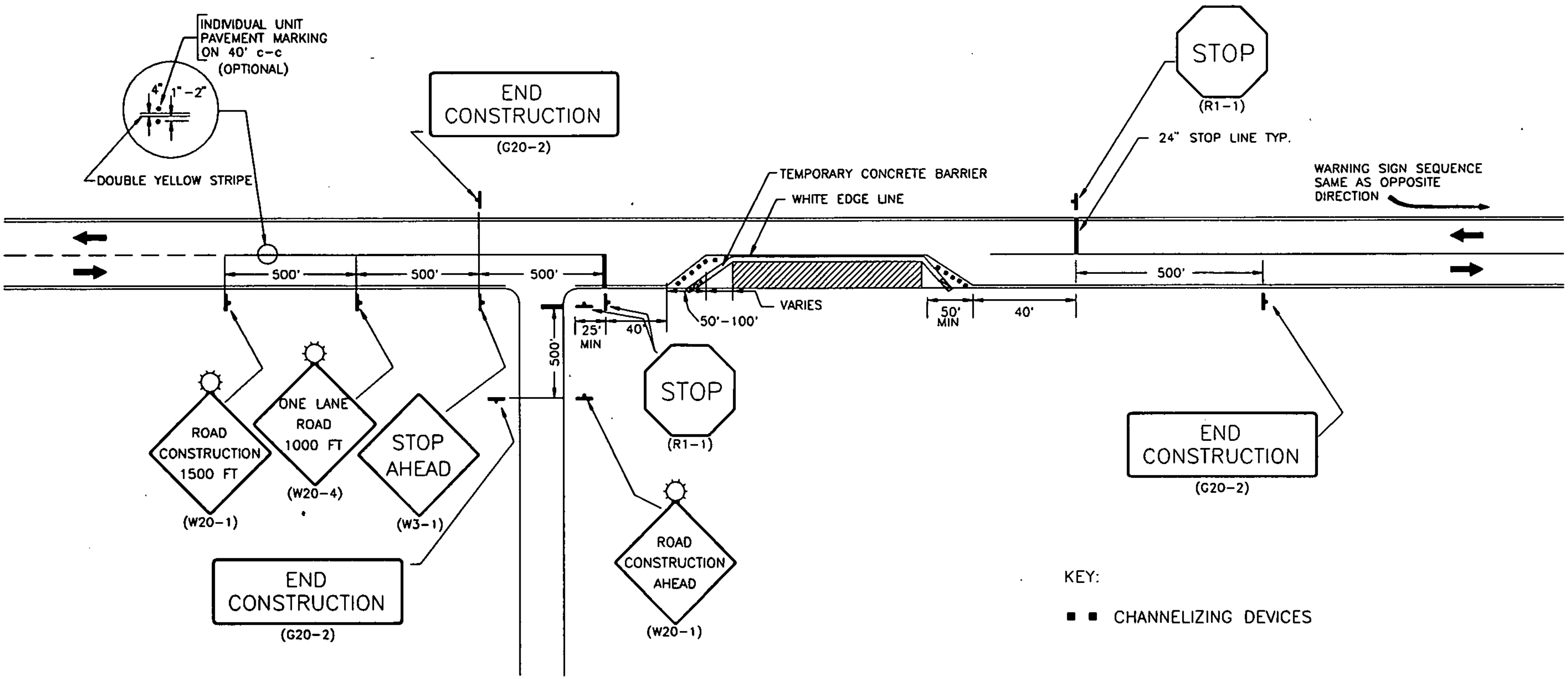


Figure 3.19. Typical application for stop control where work activity area is on same side of and 115 ft or more downstream from intersecting roadway.

NOTE:

1. Barrier end treatments should be selected based upon guidelines given in Chapter 4 of the User's Manual.
2. The Type A flashing warning lights should be used to call attention to the advance warning signs.
3. Adequate area illumination to clearly identify both ends of the work area at night shall be provided.
4. Twenty-four (24) inch stop lines shall be installed at each intersection approach. No passing lines shall be added where they are not already in place. Existing conflicting pavement markings and retroreflective raised pavement markers between the work area and the stop line shall be removed.
5. The horizontal or vertical alignment of the roadway may require adjustments in the location of the advance warning signs (the distance shown for advance warning sign spacings are minimums).

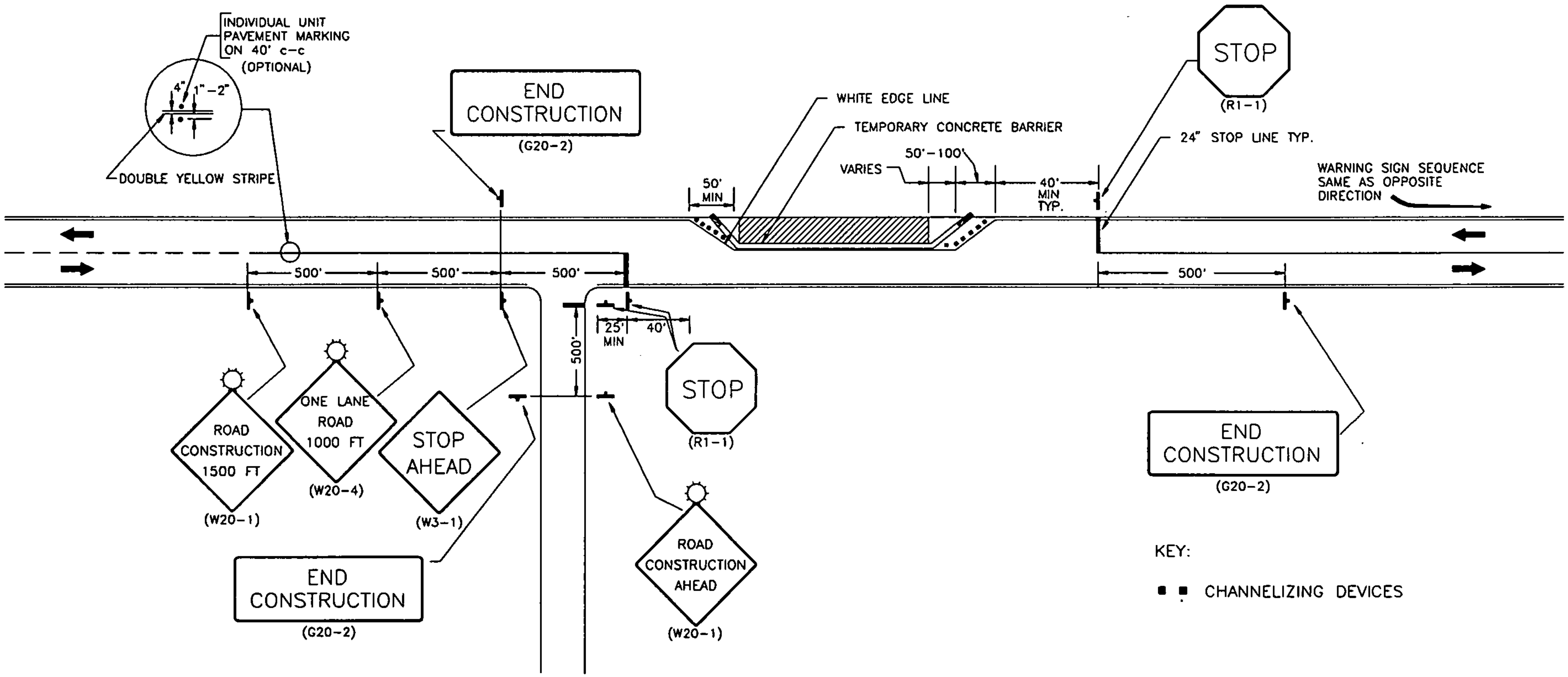


Figure 3.20. Typical application for stop control where work activity area is on opposite side of and 115 ft or more downstream from intersecting roadway.

NOTE:

1. Barrier end treatments should be selected based upon guidelines given in Chapter 4 of the User's Manual.
2. The Type A flashing warning lights should be used to call attention to the advance warning signs.
3. Adequate area illumination to clearly identify both ends of the work area at night shall be provided.
4. No passing lines shall be added where they are not already in place. Existing conflicting pavement markings and retroreflective raised pavement markers between the work area and the stop line shall be removed.
5. The horizontal or vertical alignment of the roadway may require adjustments in the location of the advance warning signs (the distance shown for advance warning sign spacings are minimums).

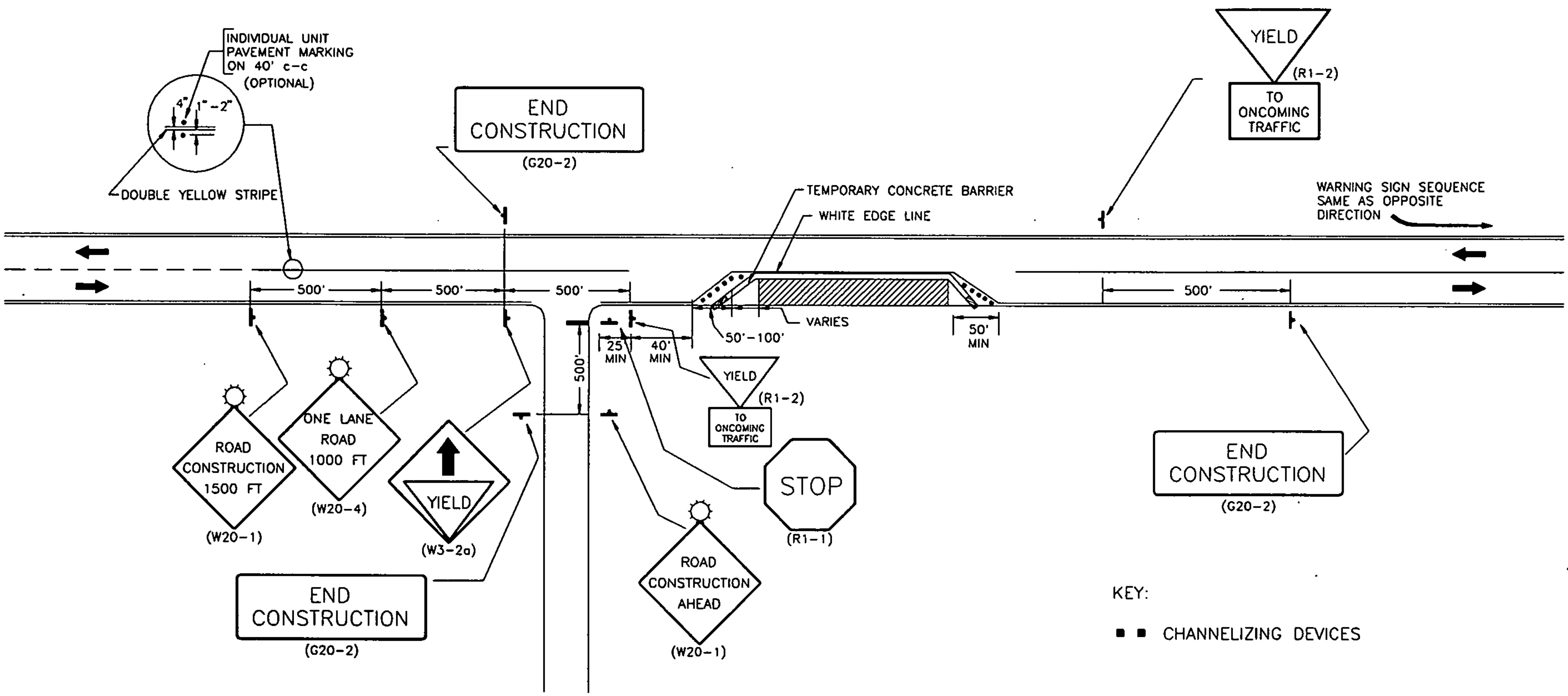


Figure 3.21. Typical application for yield control where work activity area is on same side of and is 115 ft or more downstream from intersecting roadway.

NOTE:

1. Barrier end treatments should be selected based upon guidelines given in Chapter 4 of the User's Manual.
2. The Type A flashing warning lights should be used to call attention to the advance warning signs.
3. Adequate area illumination to clearly identify both ends of the work area at night shall be provided.
4. No passing lines shall be added where they are not already in place. Existing conflicting pavement markings and retroreflective raised pavement markers between the work area and the stop line shall be removed.
5. The horizontal or vertical alignment of the roadway may require adjustments in the location of the advance warning signs (the distance shown for advance warning sign spacings are minimums).

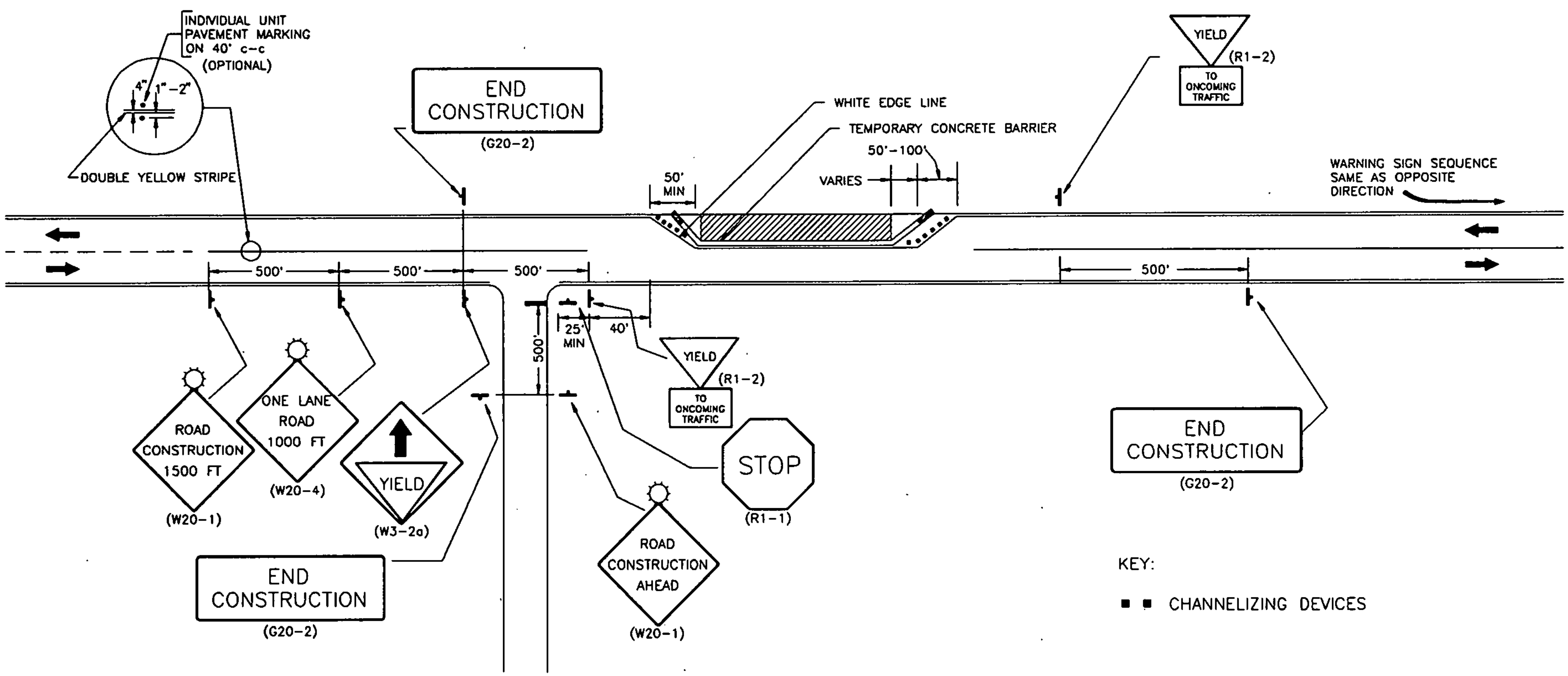


Figure 3.22. Typical application for yield control where work activity area is on opposite side of and 115 ft or more downstream from intersecting roadway.

NOTE:

1. Barrier end treatments should be selected based upon guidelines given in Chapter 4 of the User's Manual.
2. All traffic signal and control equipment shall meet the applicable standards and specfications prescribed in Part IV of the Manual on Uniform Traffic Control Devices.
3. The Type A flashing warning lights should be used to call attention to the advance warning signs.
4. Adequate area illumination to clearly identify both ends of the work area at night shall be provided.
5. Twenty-four (24) inch stop lines shall be installed at each intersection approach. No passing lines shall be added where they are not already in place. Existing conflicting pavement markings and retroreflective raised pavement markers between the work area and the stop line shall be removed.
6. When the signal is changed to a flash condition, red shall be flashed to all approaches.
7. The horizontal or vertical alignment of the roadway may require adjustments in the location of the advance warning signs (the distance shown for advance warning sign spacings are minimums). The vertical alignment of the roadway may require adjustments in the height of the signal heads (Clearances must be 15 – 19 feet).

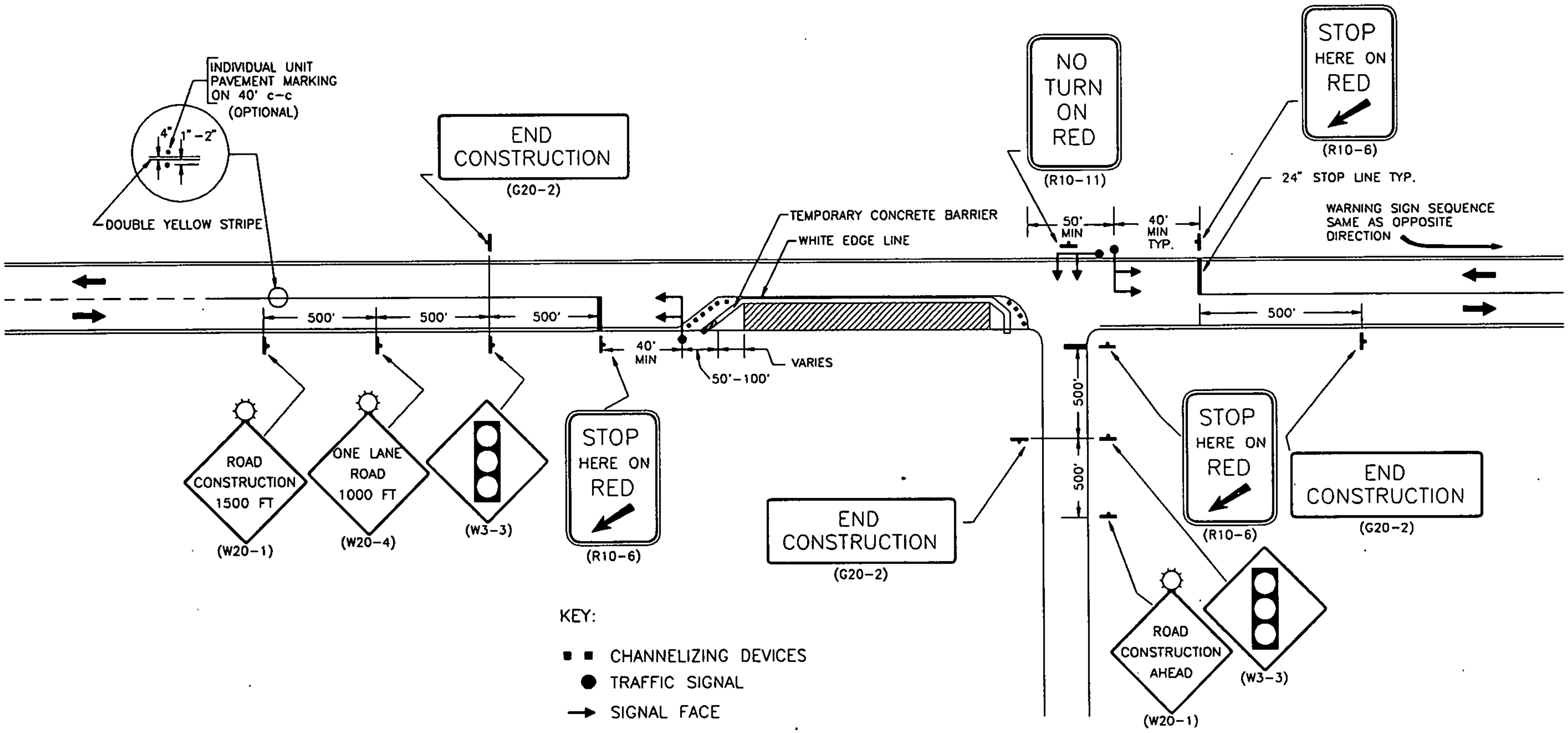


Figure 3.23. Typical application for signal control where work activity area is on same side of and less than 50 ft upstream from intersecting roadway.

NOTE:

1. Barrier end treatments should be selected based upon guidelines given in Chapter 4 of the User's Manual.
2. All traffic signal and control equipment shall meet the applicable standards and specfications prescribed in Part IV of the Manual on Uniform Traffic Control Devices.
3. The Type A flashing warning lights should be used to call attention to the advance warning signs.
4. Adequate area illumination to clearly identify both ends of the work area at night shall be provided.
5. Twenty-four (24) inch stop lines shall be installed at each intersection approach. No passing lines shall be added where they are not already in place. Existing conflicting pavement markings and retroreflective raised pavement markers between the work area and the stop line shall be removed.
6. When the signal is changed to a flash condition, red shall be flashed to all approaches.
7. The horizontal or vertical alignment of the roadway may require adjustments in the location of the advance warning signs (the distance shown for advance warning sign spacings are minimums). The vertical alignment of the roadway may require adjustments in the height of the signal heads (Clearances must be 15 – 19 feet).

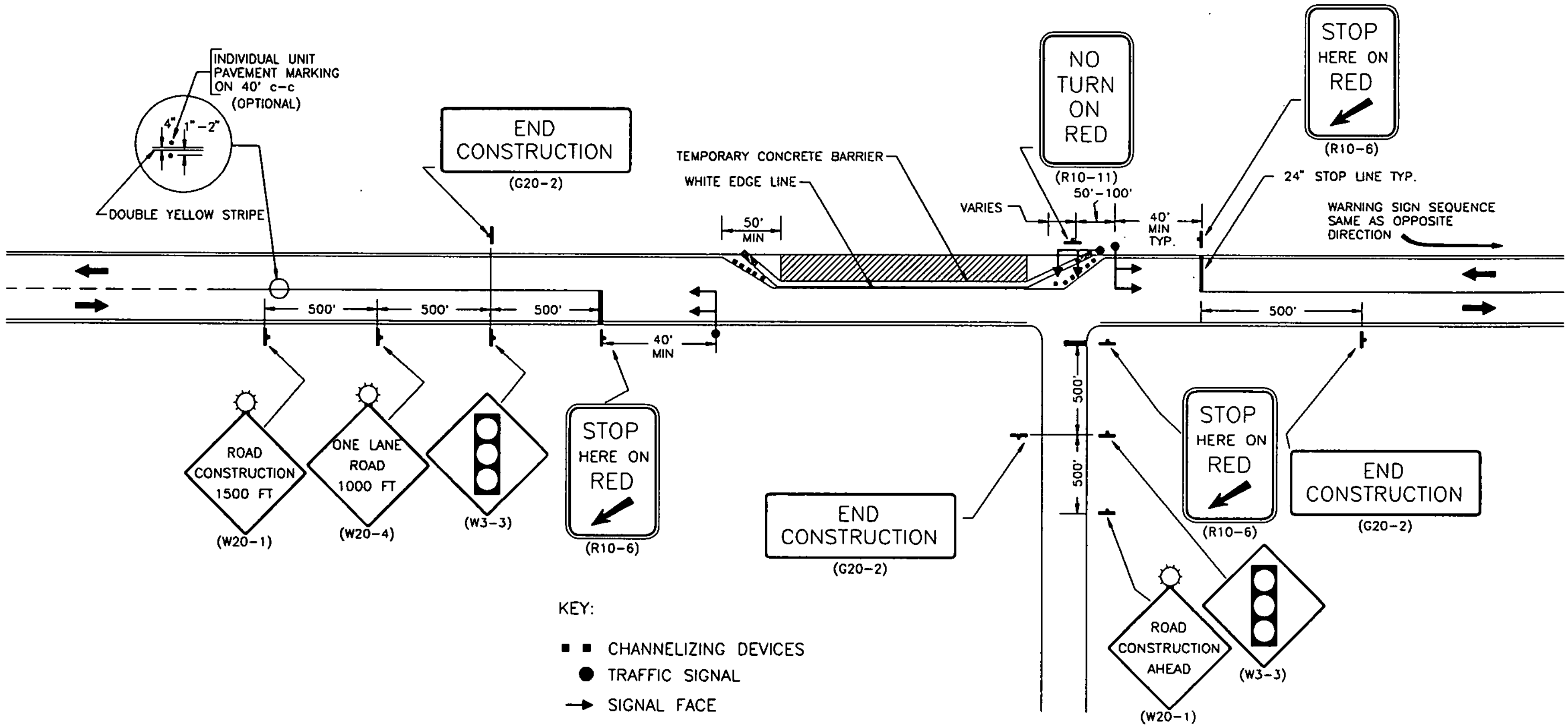


Figure 3.24. Typical application for signal control where work activity area is on opposite side of and less than 50 ft upstream from intersecting roadway.

NOTE:

1. Barrier end treatments should be selected based upon guidelines given in Chapter 4 of the User's Manual.
2. All traffic signal and control equipment shall meet the applicable standards and specfications prescribed in Part IV of the Manual on Uniform Traffic Control Devices.
3. The Type A flashing warning lights should be used to call attention to the advance warning signs.
4. Adequate area illumination to clearly identify both ends of the work area at night shall be provided.
5. Twenty-four (24) inch stop lines shall be installed at each intersection approach. No passing lines shall be added where they are not already in place. Existing conflicting pavement markings and retroreflective raised pavement markers between the work area and the stop line shall be removed.
6. When the signal is changed to a flash condition, red shall be flashed to all approaches.
7. The horizontal or vertical alignment of the roadway may require adjustments in the location of the advance warning signs (the distance shown for advance warning sign spacings are minimums). The vertical alignment of the roadway may require adjustments in the height of the signal heads (Clearances must be 15 – 19 feet).

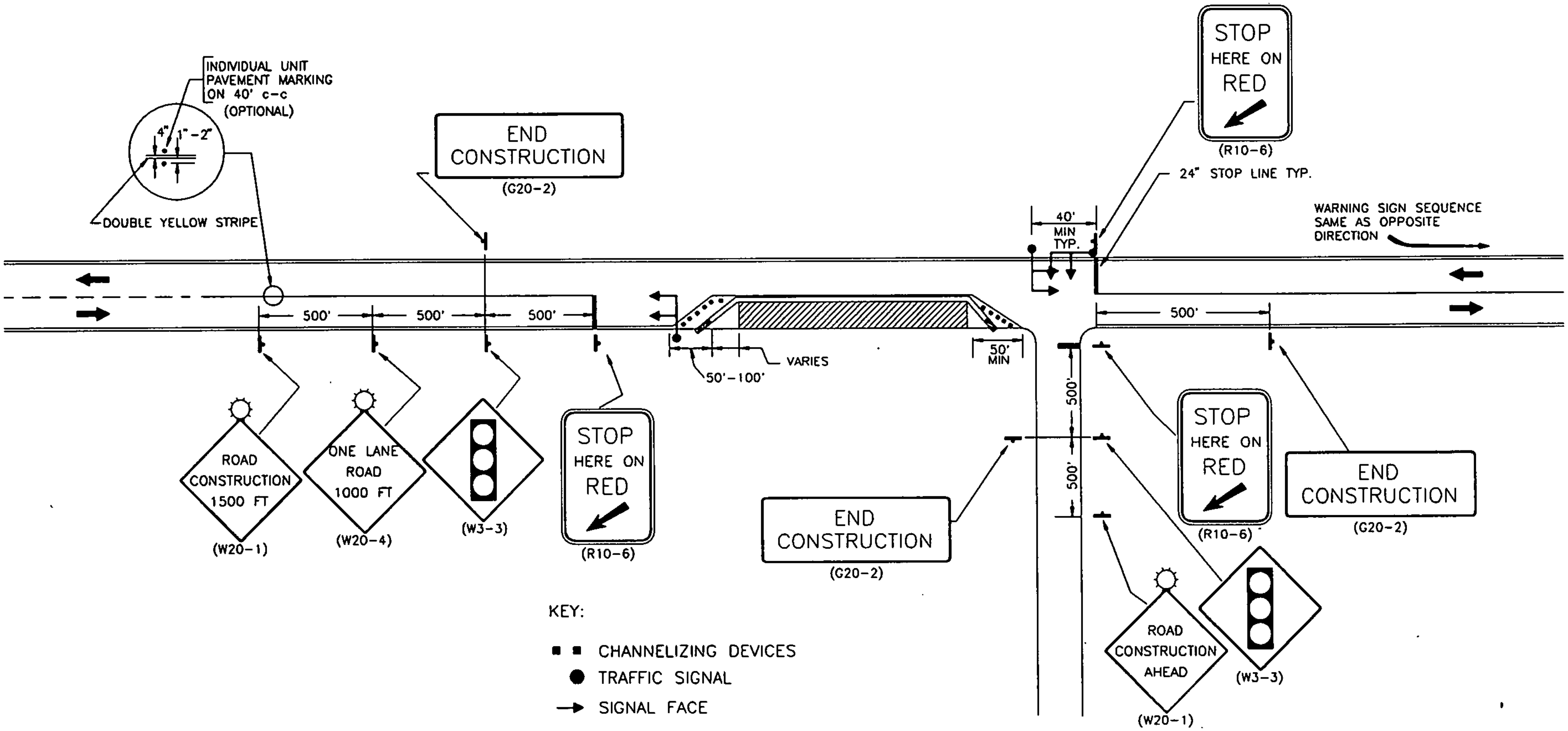


Figure 3.25. Typical application for signal control where work activity area is on same side of and 50 ft or more upstream from intersecting roadway.

NOTE:

1. Barrier end treatments should be selected based upon guidelines given in Chapter 4 of the User's Manual.
2. All traffic signal and control equipment shall meet the applicable standards and specfications prescribed in Part IV of the Manual on Uniform Traffic Control Devices.
3. The Type A flashing warning lights should be used to call attention to the advance warning signs.
4. Adequate area illumination to clearly identify both ends of the work area at night shall be provided.
5. Twenty-four (24) inch stop lines shall be installed at each intersection approach. No passing lines shall be added where they are not already in place. Existing conflicting pavement markings and retroreflective raised pavement markers between the work area and the stop line shall be removed.
6. When the signal is changed to a flash condition, red shall be flashed to all approaches.
7. The horizontal or vertical alignment of the roadway may require adjustments in the location of the advance warning signs (the distance shown for advance warning sign spacings are minimums). The vertical alignment of the roadway may require adjustments in the height of the signal heads (Clearances must be 15 – 19 feet).

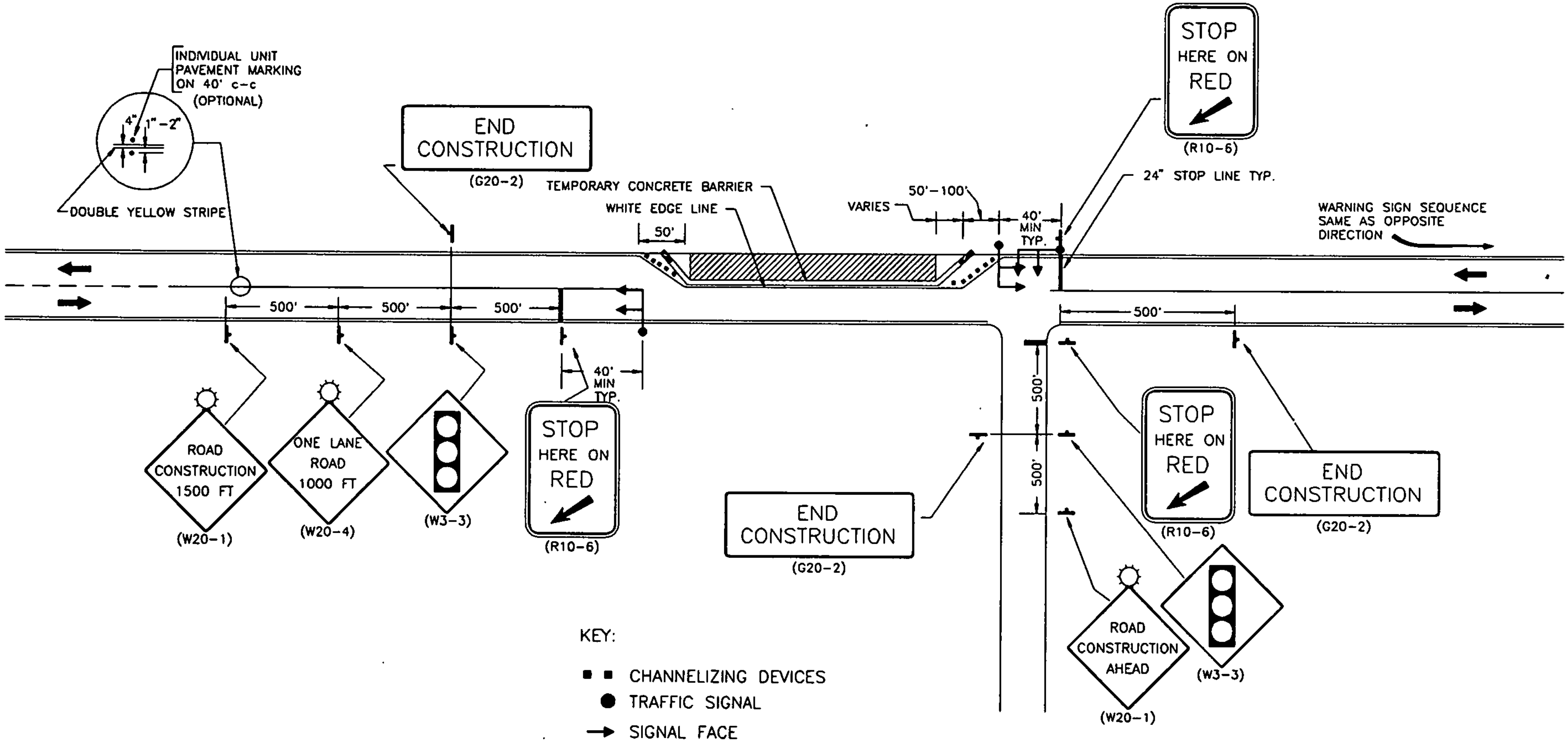


Figure 3.26. Typical application for signal control where work activity area is on opposite side of and 50 ft or more upstream from intersecting roadway.

NOTE:

1. Barrier end treatments should be selected based upon guidelines given in Chapter 4 of the User's Manual.
2. All traffic signal and control equipment shall meet the applicable standards and specfications prescribed in Part IV of the Manual on Uniform Traffic Control Devices.
3. The Type A flashing warning lights should be used to call attention to the advance warning signs.
4. Adequate area illumination to clearly identify both ends of the work area at night shall be provided.
5. Twenty-four (24) inch stop lines shall be installed at each intersection approach. No passing lines shall be added where they are not already in place. Existing conflicting pavement markings and retroreflective raised pavement markers between the work area and the stop line shall be removed.
6. When the signal is changed to a flash condition, red shall be flashed to all approaches.
7. The horizontal or vertical alignment of the roadway may require adjustments in the location of the advance warning signs (the distance shown for advance warning sign spacings are minimums). The vertical alignment of the roadway may require adjustments in the height of the signal heads (Clearances must be 15 – 19 feet).

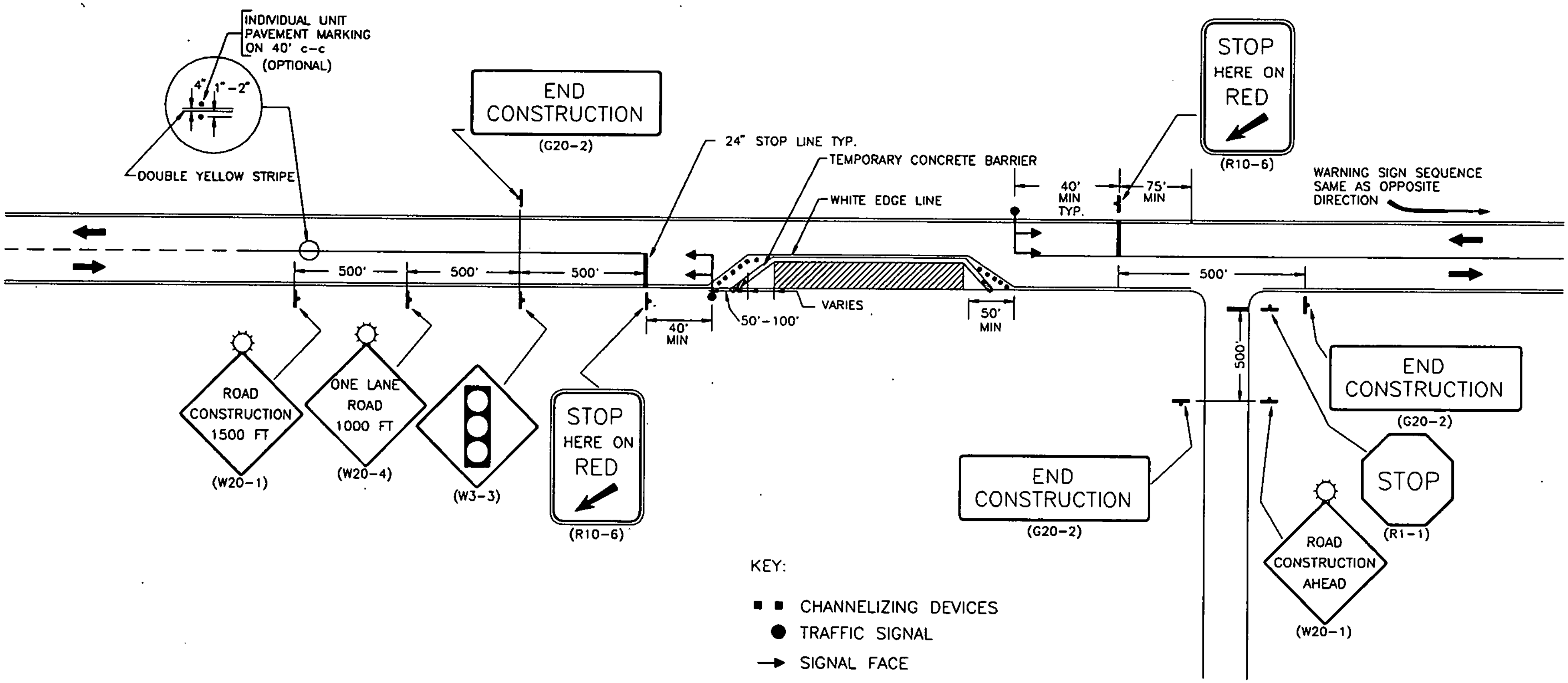


Figure 3.27. Typical application for signal control where work activity area is on same side of and 115 ft or more upstream from intersecting roadway.

NOTE:

1. Barrier end treatments should be selected based upon guidelines given in Chapter 4 of the User's Manual.
2. All traffic signal and control equipment shall meet the applicable standards and specfications prescribed in Part IV of the Manual on Uniform Traffic Control Devices.
3. The Type A flashing warning lights should be used to call attention to the advance warning signs.
4. Adequate area illumination to clearly identify both ends of the work area at night shall be provided.
5. Twenty-four (24) inch stop lines shall be installed at each intersection approach. No passing lines shall be added where they are not already in place. Existing conflicting pavement markings and retroreflective raised pavement markers between the work area and the stop line shall be removed.
6. When the signal is changed to a flash condition, red shall be flashed to all approaches.
7. The horizontal or vertical alignment of the roadway may require adjustments in the location of the advance warning signs (the distance shown for advance warning sign spacings are minimums). The vertical alignment of the roadway may require adjustments in the height of the signal heads (Clearances must be 15 – 19 feet).

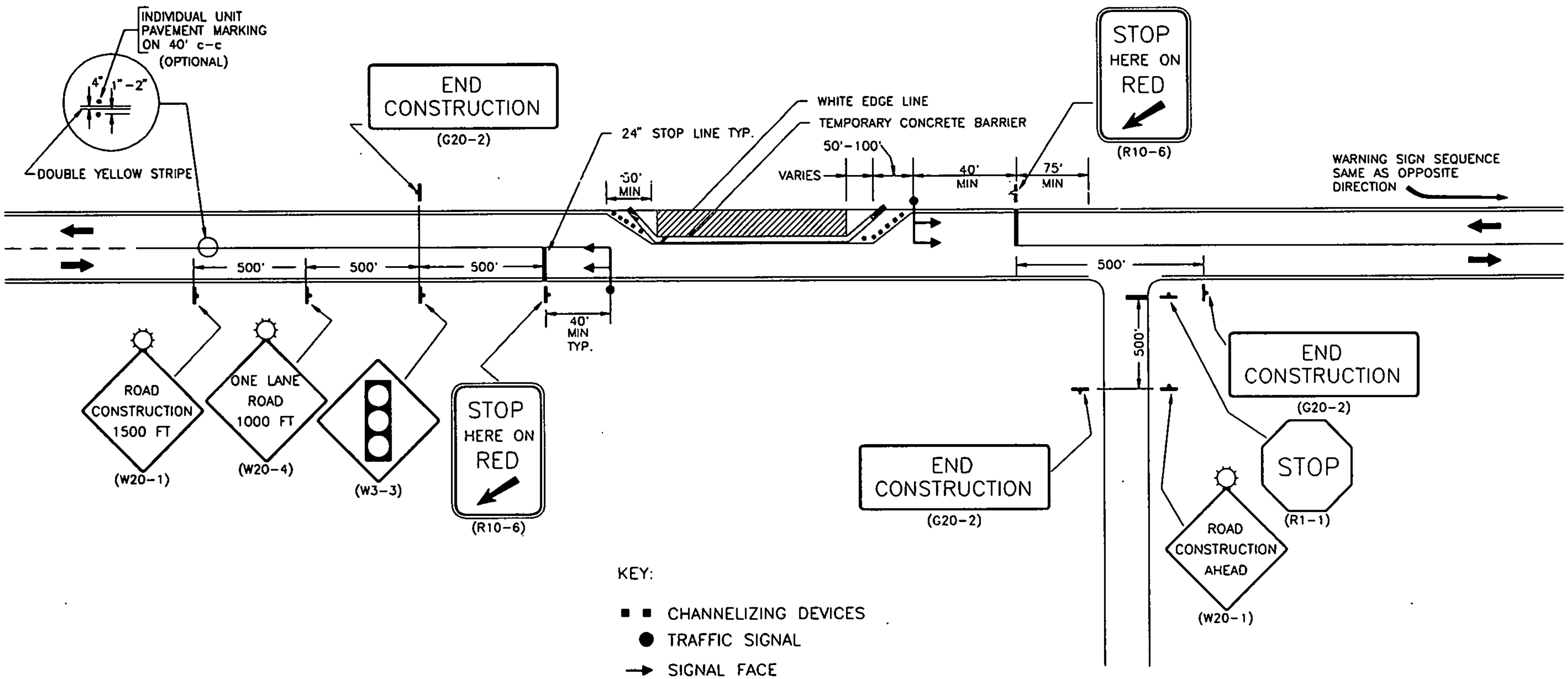


Figure 3.28. Typical application for signal control where work activity area is on opposite side of and is 115 ft or more upstream from intersecting roadway.

NOTE:

1. Barrier end treatments should be selected based upon guidelines given in Chapter 4 of the User's Manual.
2. The Type A flashing warning lights should be used to call attention to the advance warning signs.
3. Adequate area illumination to clearly identify both ends of the work area at night shall be provided.
4. Twenty-four (24) inch stop lines shall be installed at each intersection approach. No passing lines shall be added where they are not already in place. Existing conflicting pavement markings and retroreflective raised pavement markers between the work area and the stop line shall be removed.
5. The horizontal or vertical alignment of the roadway may require adjustments in the location of the advance warning signs (the distance shown for advance warning sign spacings are minimums).

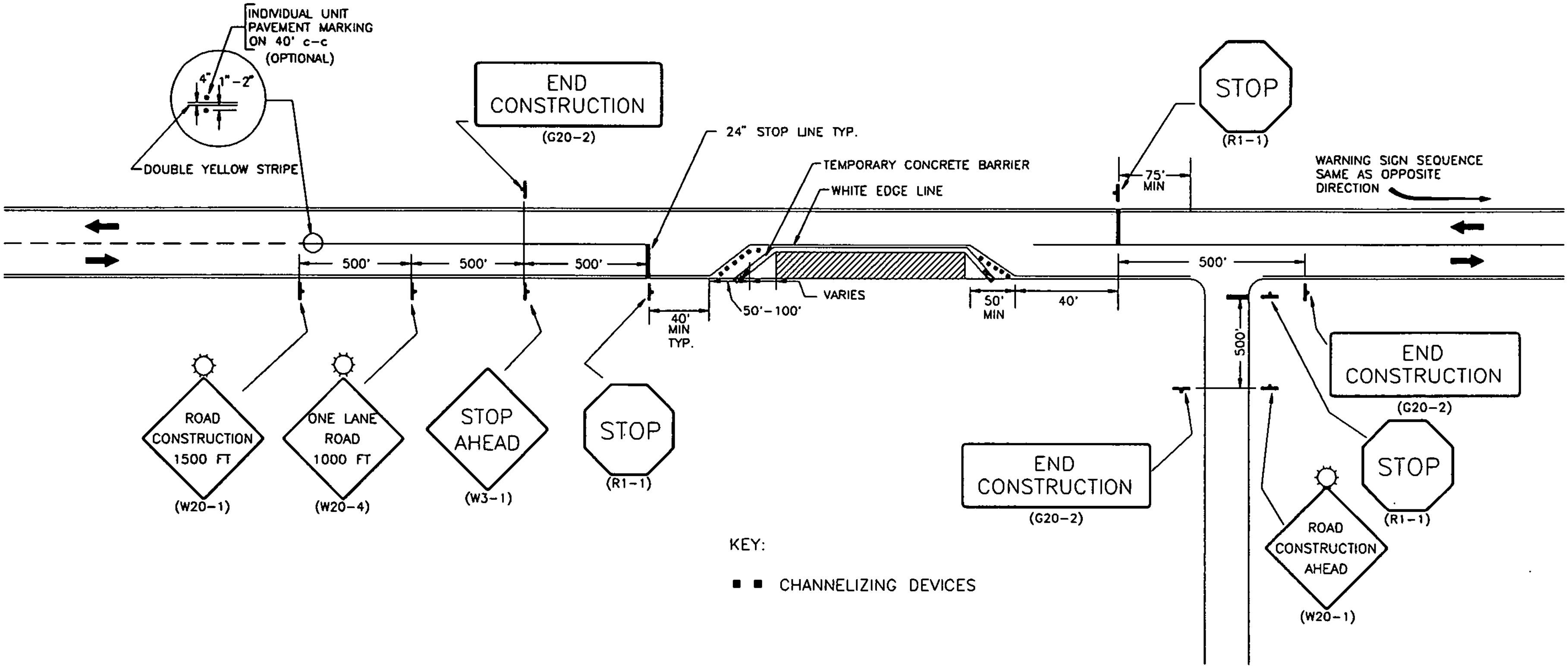


Figure 3.29. Typical application for stop control where work activity area is on same side of and 115 ft or more upstream from intersecting roadway.

NOTE:

1. Barrier end treatments should be selected based upon guidelines given in Chapter 4 of the User's Manual.
2. The Type A flashing warning lights should be used to call attention to the advance warning signs.
3. Adequate area illumination to clearly identify both ends of the work area at night shall be provided.
4. Twenty-four (24) inch stop lines shall be installed at each intersection approach. No passing lines shall be added where they are not already in place. Existing conflicting pavement markings and retroreflective raised pavement markers between the work area and the stop line shall be removed.
5. The horizontal or vertical alignment of the roadway may require adjustments in the location of the advance warning signs (the distance shown for advance warning sign spacings are minimums).

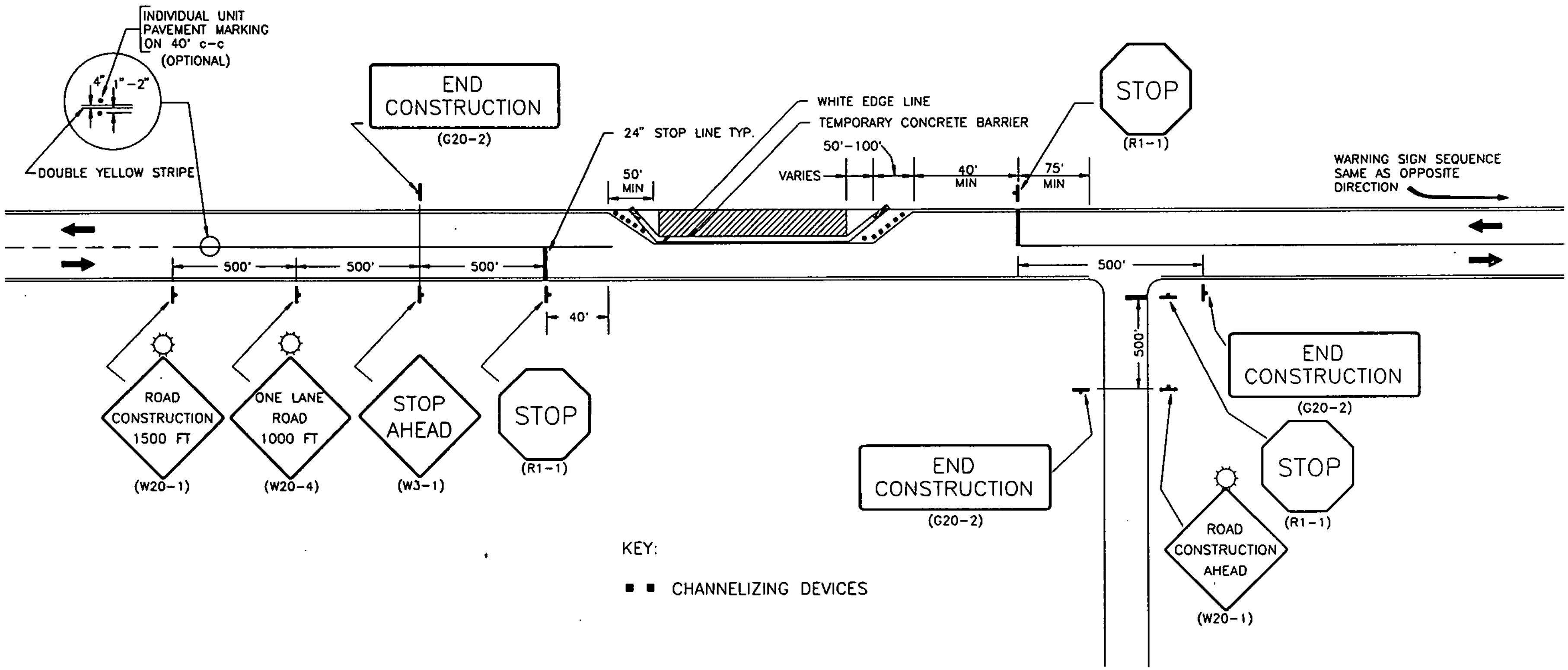


Figure 3.30. Typical application for stop control where work activity area is on opposite side of and 115 ft or more upstream from intersecting roadway.

NOTE:

1. Barrier end treatments should be selected based upon guidelines given in Chapter 4 of the User's Manual.
2. The type A flashing warning lights should be used to call attention to the advance warning signs.
3. Adequate area illumination to clearly identify both ends of the work area at night shall be provided.
4. No passing lines shall be added where they are not already in place. Existing conflicting pavement markings and retroreflective raised pavement markers between the work area and the stop line shall be removed.
5. The horizontal or vertical alignment of the roadway may require adjustments in the location of the advance warning signs (the distance shown for advance warning sign spacings are minimums).

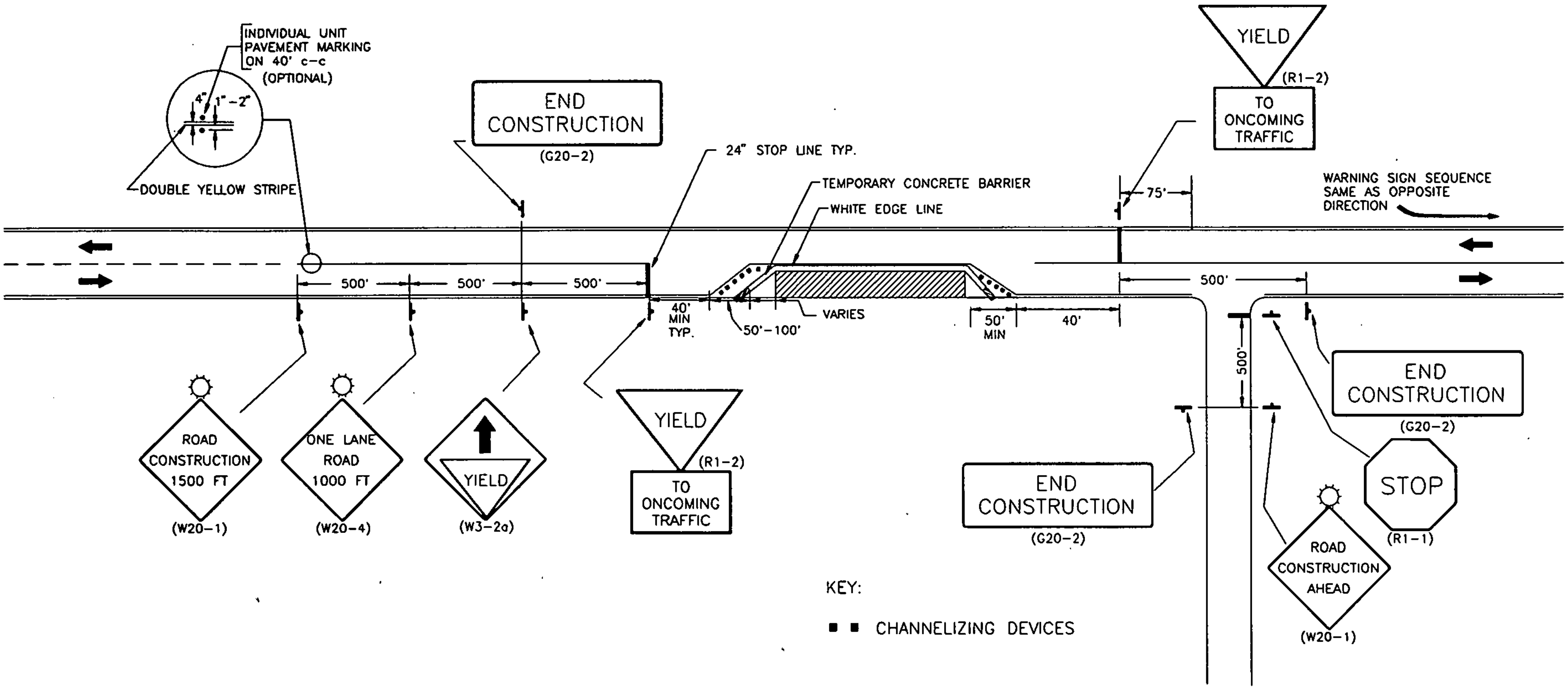


Figure 3.31. Typical application for yield control where work activity area is on same side of and is 115 ft or more upstream from intersecting roadway.

NOTE:

1. Barrier end treatments should be selected based upon guidelines given in Chapter 4 of the User's Manual.
2. The type A flashing warning lights should be used to call attention to the advance warning signs.
3. Adequate area illumination to clearly identify both ends of the work area at night shall be provided.
4. No passing lines shall be added where they are not already in place. Existing conflicting pavement markings and retroreflective raised pavement markers between the work area and the stop line shall be removed.
5. The horizontal or vertical alignment of the roadway may require adjustments in the location of the advance warning signs (the distance shown for advance warning sign spacings are minimums).

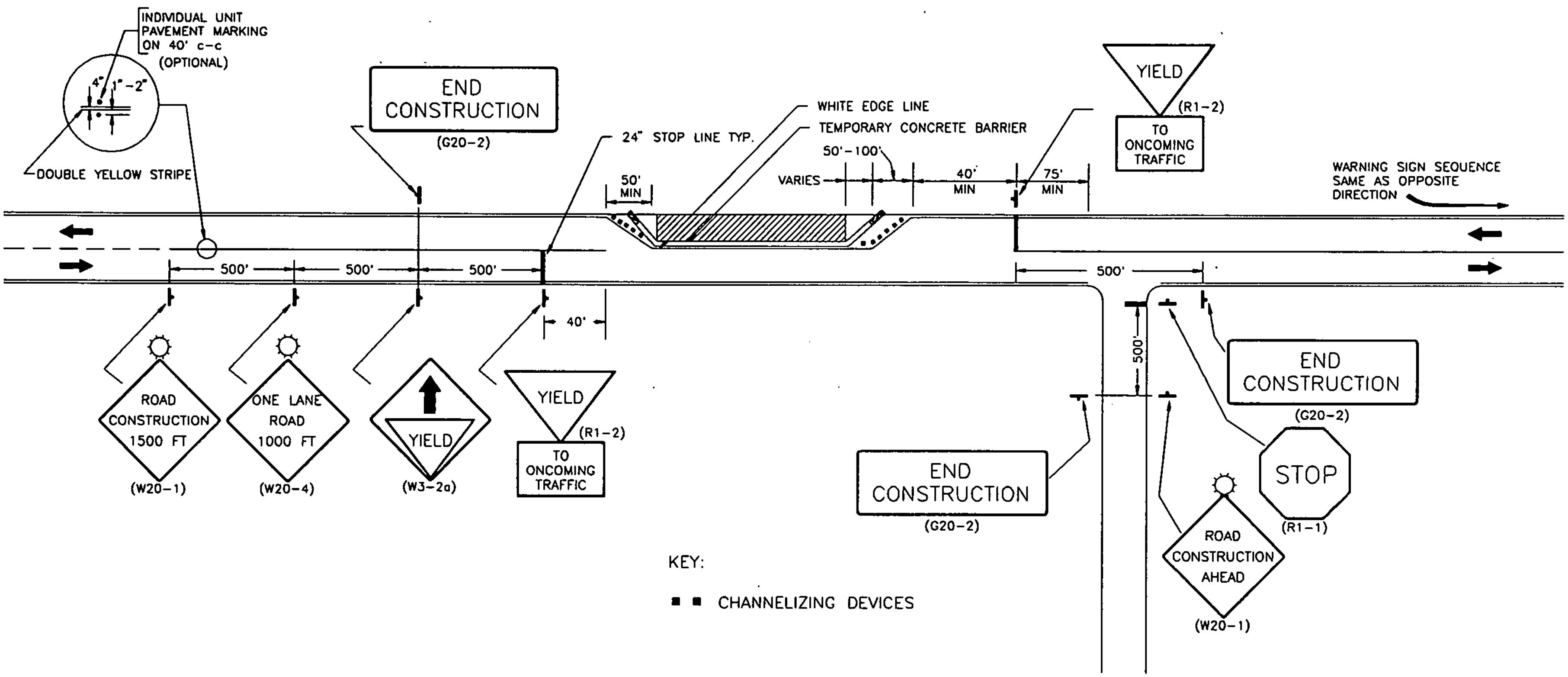


Figure 3.32. Typical application for yield control where work activity area is on opposite side of and 115 ft or more upstream from intersecting roadway.

NOTE:

1. Barrier end treatments should be selected based upon guidelines given in Chapter 4 of the User's Manual.

2. All traffic signal and control equipment shall meet the applicable standards and specfications prescribed in Part IV of the Manual on Uniform Traffic Control Devices.

3. The Type A flashing warning lights should be used to call attention to the advance warning signs.

4. Adequate area illumination to clearly identify both ends of the work area at night shall be provided.

5. Twenty-four (24) inch stop lines shall be installed at each intersection approach. No passing lines shall be added where they are not already in place. Existing conflicting pavement markings and retroreflective raised pavement markers between the work area and the stop line shall be removed.

6. When the signal is changed to a flash condition, red shall be flashed to all approaches.

7. The horizontal or vertical alignment of the roadway may require adjustments in the location of the advance warning signs (the distance shown for advance warning sign spacings are minimums). The vertical alignment of the roadway may require adjustments in the height of the signal heads (Clearances must be 15 - 19 feet).

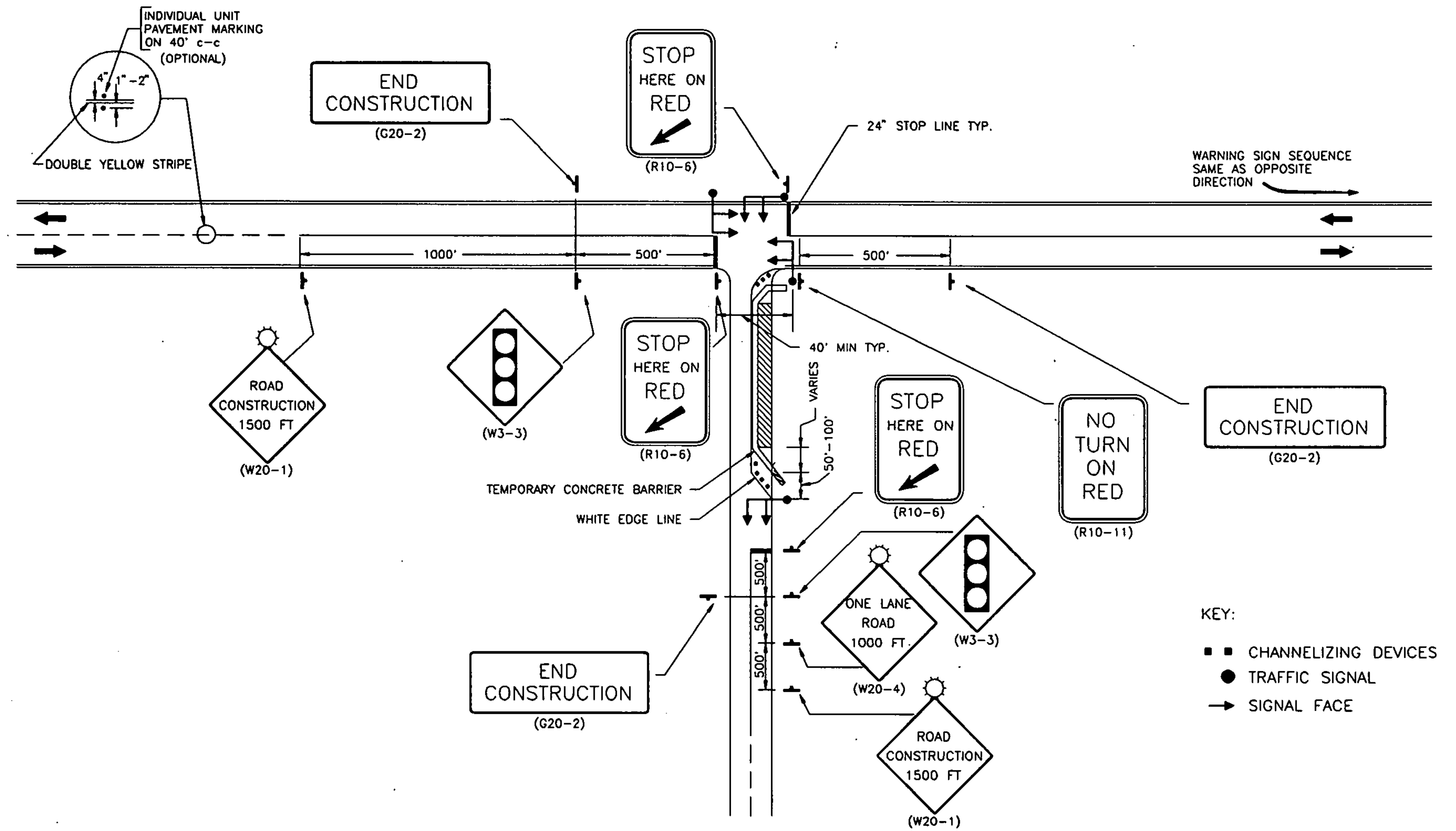


Figure 3.33. Typical application for signal control where work activity area is on approach of intercepted leg of and less than 50 ft from T- intersection.

NOTE:

1. Barrier end treatments should be selected based upon guidelines given in Chapter 4 of the User's Manual.
2. All traffic signal and control equipment shall meet the applicable standards and specfications prescribed in Part IV of the Manual on Uniform Traffic Control Devices.
3. The Type A flashing warning lights should be used to call attention to the advance warning signs.
4. Adequate area illumination to clearly identify both ends of the work area at night shall be provided.
5. Twenty-four (24) inch stop lines shall be installed at each intersection approach. No passing lines shall be added where they are not already in place. Existing conflicting pavement markings and retroreflective raised pavement markers between the work area and the stop line shall be removed.
6. When the signal is changed to a flash condition, red shall be flashed to all approaches.
7. The horizontal or vertical alignment of the roadway may require adjustments in the location of the advance warning signs (the distance shown for advance warning sign spacings are minimums). The vertical alignment of the roadway may require adjustments in the height of the signal heads (Clearances must be 15 – 19 feet).

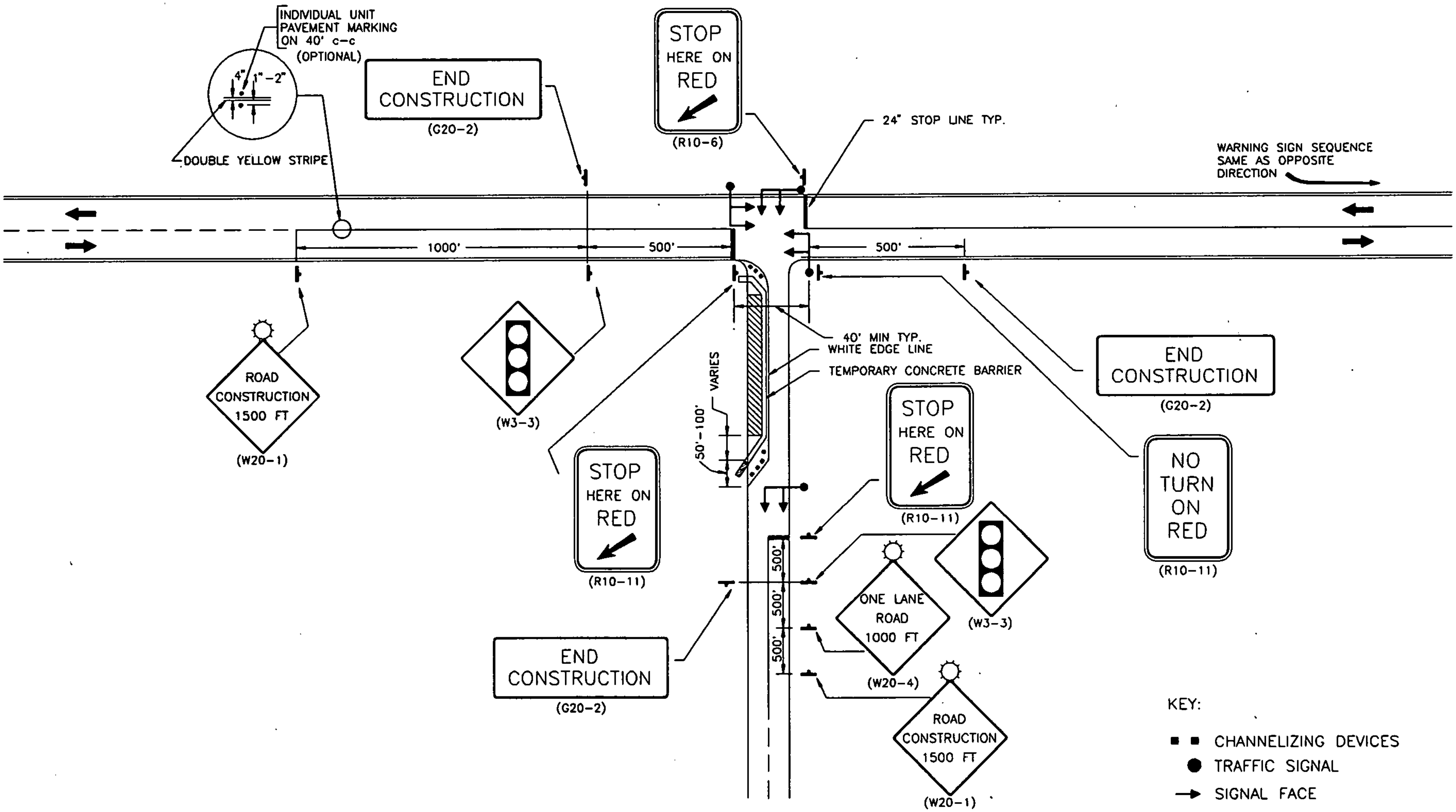


Figure 3.34. Typical application for signal control where work activity area is on departure of intercepted leg of and less than 50 ft from T-intersection.

NOTE:

1. Barrier end treatments should be selected based upon guidelines given in Chapter 4 of the User's Manual.
2. All traffic signal and control equipment shall meet the applicable standards and specfications prescribed in Part IV of the Manual on Uniform Traffic Control Devices.
3. The Type A flashing warning lights should be used to call attention to the advance warning signs.
4. Adequate area illumination to clearly identify both ends of the work area at night shall be provided.
5. Twenty-four (24) inch stop lines shall be installed at each intersection approach. No passing lines shall be added where they are not already in place. Existing conflicting pavement markings and retroreflective raised pavement markers between the work area and the stop line shall be removed.
6. When the signal is changed to a flash condition, red shall be flashed to all approaches.
7. The horizontal or vertical alignment of the roadway may require adjustments in the location of the advance warning signs (the distance shown for advance warning sign spacings are minimums). The vertical alignment of the roadway may require adjustments in the height of the signal heads (Clearances must be 15 – 19 feet).

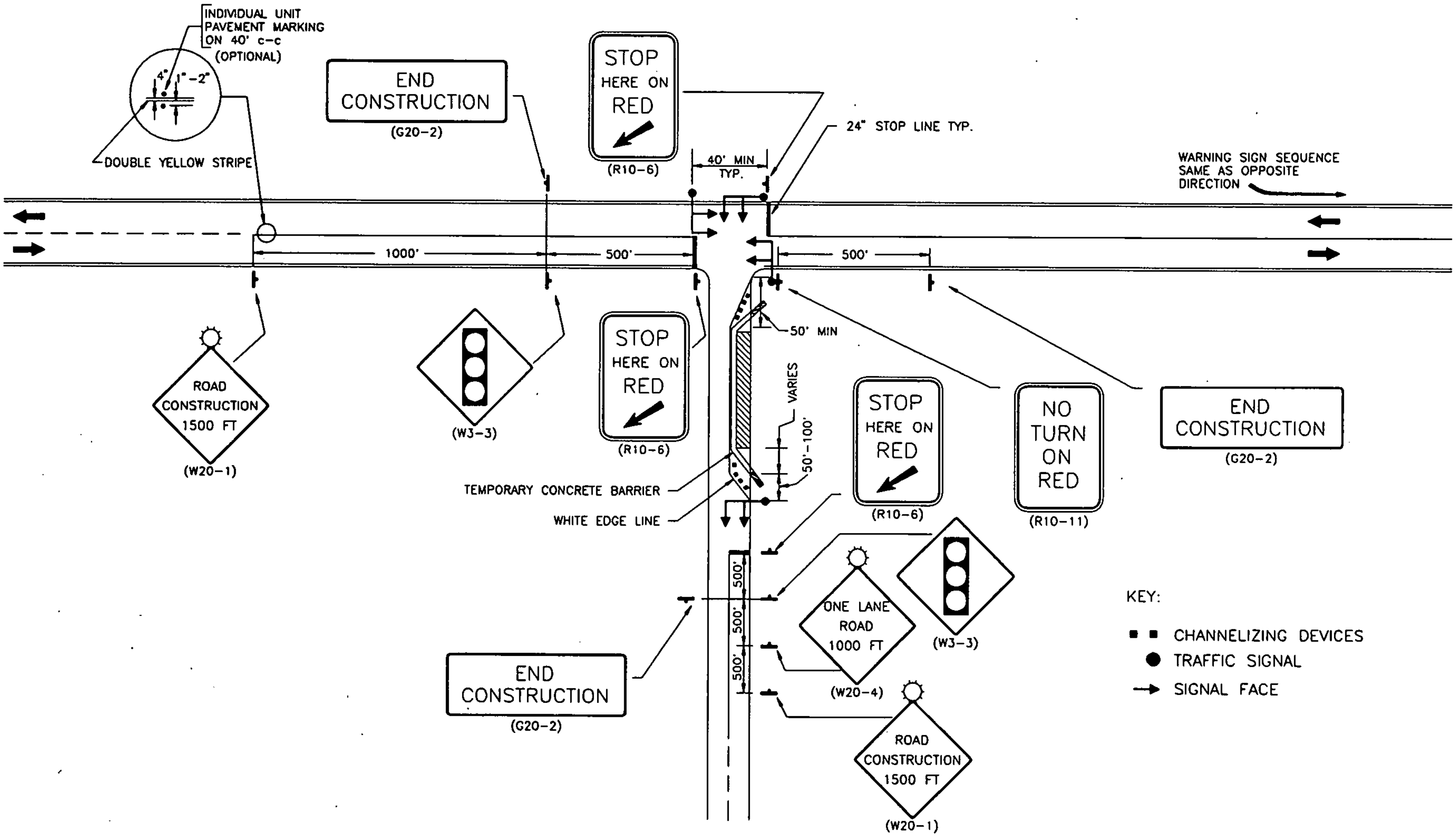


Figure 3.35. Typical application for signal control where work activity area is on approach of intercepted leg of and 50 ft or more from T-intersection.

NOTE:

1. Barrier end treatments should be selected based upon guidelines given in Chapter 4 of the User's Manual.

2. All traffic signal and control equipment shall meet the applicable standards and specfications prescribed in Part IV of the Manual on Uniform Traffic Control Devices.

3. The Type A flashing warning lights should be used to call attention to the advance warning signs.

4. Adequate area illumination to clearly identify both ends of the work area at night shall be provided.

5. Twenty-four (24) inch stop lines shall be installed at each intersection approach. No passing lines shall be added where they are not already in place. Existing conflicting pavement markings and retroreflective raised pavement markers between the work area and the stop line shall be removed.

6. When the signal is changed to a flash condition, red shall be flashed to all approaches.

7. The horizontal or vertical alignment of the roadway may require adjustments in the location of the advance warning signs (the distance shown for advance warning sign spacings are minimums). The vertical alignment of the roadway may require adjustments in the height of the signal heads (Clearances must be 15 – 19 feet).

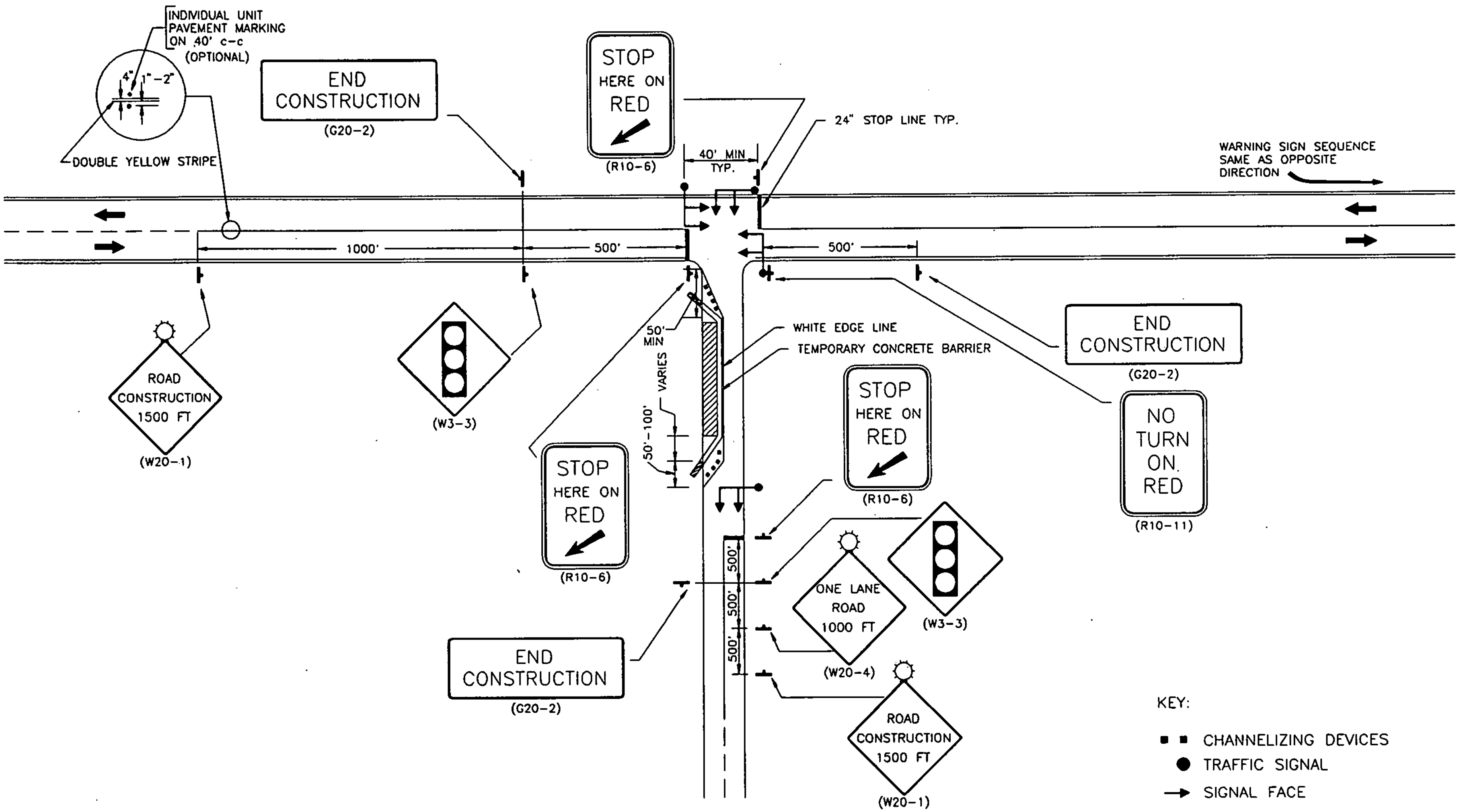


Figure 3.36. Typical application for signal control where work activity area is on departure of intercepted leg of and 50 ft or more from T-intersection.

Figure 3.37. Temporary concrete barrier placed along roadway at a Case C restricted work zone. (Note: Treatments shown in Figures 3.37 and 3.39 are not necessarily recommended.)

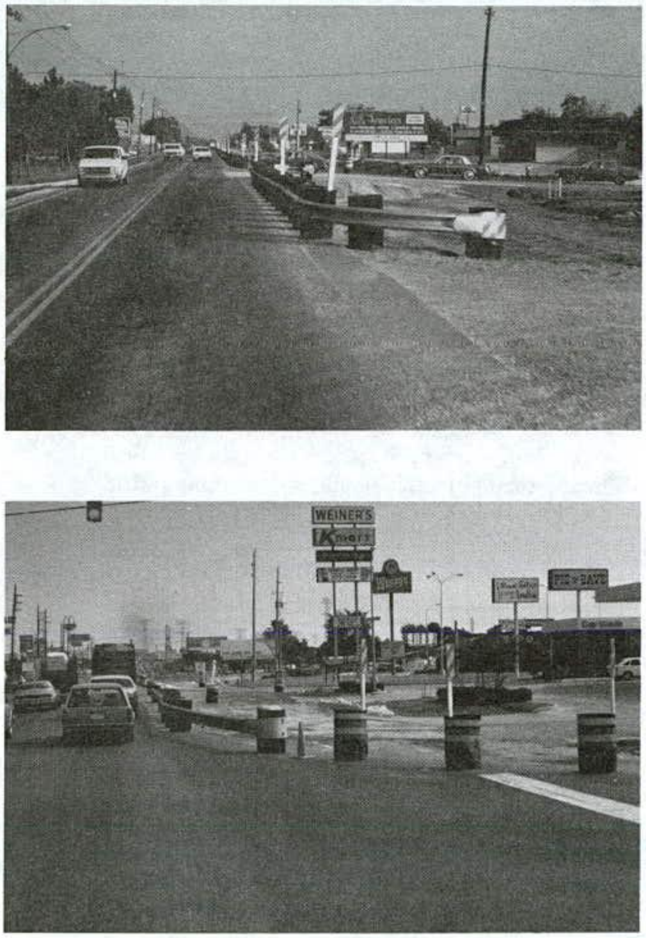


Figure 3.38. W-beam-on-barrels "wrapped around" at access drives and roadways.

Figure 3.39. Use of barrels at a Case C restricted work zone.

3.3.2 Design Considerations

This section discusses several factors that should be considered during the planning, design, and implementation of the traffic control plan for Case C restricted work zones. Sight-distance issues related to barrier openings and the delineation treatments for barriers are presented.

3.3.2.1 Sight-Distance Issues

Proper sight distances in accordance with AASHTO (*8*) design criteria should be provided at Case C restricted work zones. Adequate sight distance at the barrier openings is essential to minimize vehicle conflicts and accidents. Although not specifically stated in the AASHTO (*8*) design policy, design and field engineers should ensure that the driver's line of sight is not restricted by the barrier or other traffic control devices. At night, drivers entering the arterial from the barrier openings should be able to see the headlights of approaching vehicles. Measures should be taken to ensure that drivers have a clear and unobstructed view of approaching vehicles at night and during adverse weather conditions.

Access drives to abutting properties at barrier openings are usually located in an area where earth excavation is ongoing. Sight distance problems could result if access drives are lower in elevation than the roadway so that the driver eye height is lower than the height of the barrier. One way to increase sight distance is to keep the elevation of the access drive as high as possible. This method may require additional temporary construction activities but may minimize the probability of vehicle accidents.

3.3.2.2 Barrier Delineation

An important design consideration at Case C restricted work zones is the delineation of the barrier. Adequate delineation is necessary to minimize the probability of motorists striking the barrier. The intended vehicle path should be clearly defined and the barrier properly delineated using standard delineation treatments. Standard barrier delineation treat-

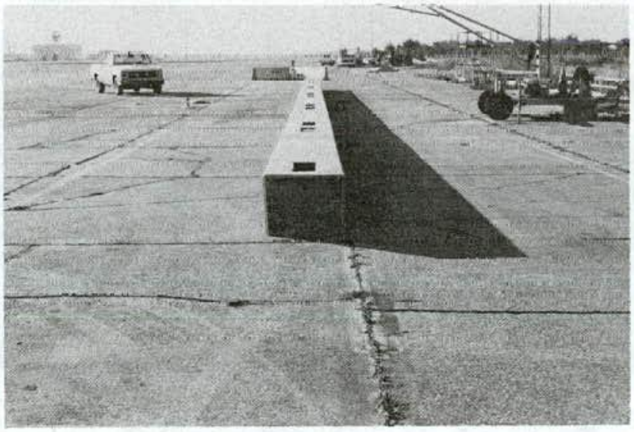


Figure 3.40. Low-profile barrier at test site (26).

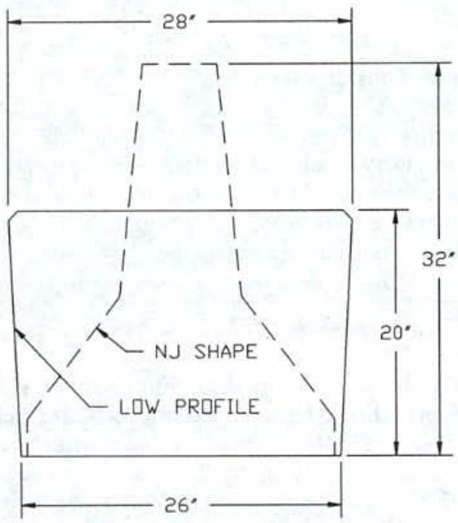


Figure 3.41. Cross-section of low-profile barrier (26).

ments include Type C steady-burn warning lights on top of the barrier, retroreflective devices on the top or side of the barrier, vertical panels placed on top of the temporary concrete barrier or W-beam-on-barrels, reflective pavement markings on the side of the barrier, and edgelines placed on the pavement parallel to the barrier.

At Case C restricted work zones, the selection of barrier delineation treatments may be further complicated by the need to maintain adequate sight distance for traffic entering the arterial from the barrier openings. Therefore, low-profile delineation treatments such as steady-burn lights on the top of the barrier or retroreflective devices on the top or side of the barrier should be considered. In addition, edgelines placed on the pavement at the base of the barrier are desirable.

3.3.3 Low-Profile Barrier as a Potential Treatment

A potential solution to many of the problems at Case C restricted work zones is a low-profile concrete barrier devel-

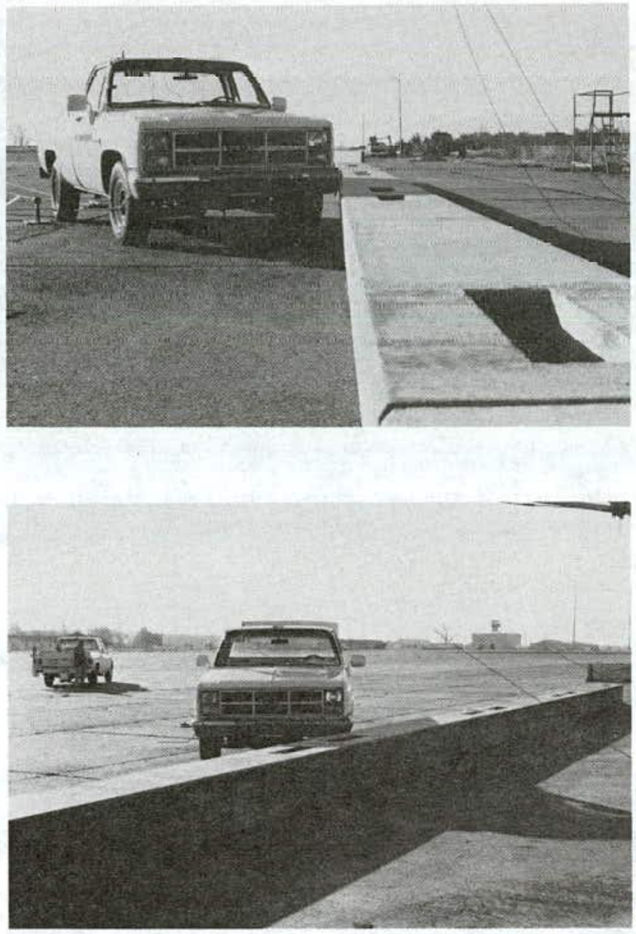


Figure 3.42. Vehicle/barrier geometrics (26).

oped at the Texas Transportation Institute (TTI) (*26*). The barrier was developed in response to sight-distance problems common to work zones on urban arterials where openings in the barrier for access to adjoining businesses are required. The problem was especially acute at night because drivers had difficulty seeing the headlights of oncoming traffic.

The low-profile barrier passed crash tests designed to evaluate extreme impact conditions expected on urban arterials. At the time of this writing, TTI researchers were developing end treatment designs that could be used with the low-profile barrier.

Figure 3.40 shows the low-profile barrier at the test site. The cross section of the barrier is given in Figure 3.41. The outline of the New Jersey concrete median barrier is also presented for comparison purposes. Figure 3.42 illustrates the vehicle/barrier geometrics. It is important to mention that the low-profile barrier is short enough so that vehicle headlights are visible over the barrier.

The low-profile barrier directly addresses sight-distance problems common to Case C restricted work zones. The primary advantage of the barrier is that it provides protection for motorists and workers without interfering with the visibility of drivers entering the arterial from access drives.

CHAPTER 4

BARRIER END TREATMENTS FOR RESTRICTED WORK ZONES

4.1 INTRODUCTION

Guidelines are presented for the selection and placement of barrier elements in a restricted work zone, once it has been established a positive barrier is warranted. It was not within the scope of this project to develop warrants or needs guidelines for work zone barriers.

The guidelines were developed for and are applicable to the precast concrete safety-shaped barrier (CSSB). Their use for other types of work zone barriers is not recommended without further analysis. The guidelines were developed for and are applicable to two- or four-lane rural arterials with speed limits of 55 mph or less and two- or four-lane urban arterials with speed limits of approximately 45 mph or less. However, in the absence of more definitive data, the guidelines may also be used for rural local and collector roadways with speed limits of 55 mph or less and urban local and collector roadways with speed limits of approximately 45 mph or less. Their use for other roadway types is not recommended without further analysis. The guidelines are based on the assumption that the barrier at a given site will be in place for 1 year or less. Their use for longer durations is not recommended without further analysis.

While the shape of the precast CSSB is essentially standard, there are a variety of precast CSSB systems in use throughout the United States. Segment length, segment-to-segment joint design, the amount and placement of reinforcing steel, and the manner in which the segments are anchored, if at all, are the primary elements that vary from state to state. It has been found that most states use 10-ft segments and the vast majority of states use a pin-and-loop joint design (*27*). The segments are typically not anchored unless placed near the edge of a drop-off. Segments placed along the edge of a bridge rehabilitation work activity are typically anchored.

The guidelines are applicable to any precast CSSB design, with or without anchorage, with one proviso; the design should satisfy service level 2 impact performance recommendations of *NCHRP Report 230* (*28*). Tests of a widely used precast CSSB were made in the present project. It had 10-ft segments and a pin-and-loop joint design, and it was unanchored. To be noted is that the system tested has one of the weakest joint designs of those used. Although the tests showed the design would not meet service level 2 recommendations, minor changes in the joint's features would likely strengthen it sufficiently to meet service level 2 recommendations (see discussion in Section IV-C-1 of the final report). Reference may be made to the literature for methods to improve joint design and actual designs that provide good connections (*27,29*).

A barrier in a restricted work zone can typically be characterized by three components, as illustrated in Figure 4.1: a tangent section placed adjacent to the work activity area, a run-out section at the upstream and downstream ends of the tangent section that is flared away from traffic, and a terminal treatment placed on the ends of the barrier. Three basic elements of a work zone barrier system are addressed in the guidelines: 1) flare rate of the run-out section, 2) the lateral offset of the end of the barrier, and 3) the terminal treatment used at the end of the barrier. As described in following sections, selection of these elements will depend on site conditions.

It was also necessary to assume that barrier placement will be sufficient to provide adequate shielding of the work activity area. For permanent barriers, this is referred to as the "length of need" (LON). In other words, it was assumed the barrier layout will prevent essentially all vehicular penetrations into the work activity area, other than very low probability events and those predicted to occur when the capacity of the CSSB is exceeded. The LON for a barrier depends on dimensions of the work activity area, offset of the end of the CSSB, and longitudinal distance from the end of the CSSB to the work activity area. Based on site surveys, it is surmised that the LON for most restricted work zones can be achieved if the end of the CSSB, or associated terminal treatment, is offset to the edge of the travelway or greater.

Note that "work activity area" as used herein may include a "buffer space." According to Reference 1, "A buffer space is an optional feature in the activity area that provides a recovery space for errant vehicles and separates traffic flow from the work activity or a potential hazard. No work activity should occur and no equipment and materials should be stored within this space."

In summary, these guidelines are applicable for the following conditions:

(a) Four roadway types:

- Two-lane rural arterial.
- Two-lane urban arterial.
- Four-lane rural arterial.
- Four-lane urban arterial.

In the absence of more definitive data, the guidelines may also be used for rural and urban local and collector roadways. Their use for other roadway types is not recommended without further analysis.

(b) Any CSSB that meets service level 2 recommendations of *NCHRP Report 230* (*28*).

(c) Sites where the barrier will be in place for approximately one year or less.

(d) Placement of the barrier is such that the work activity area is properly shielded.

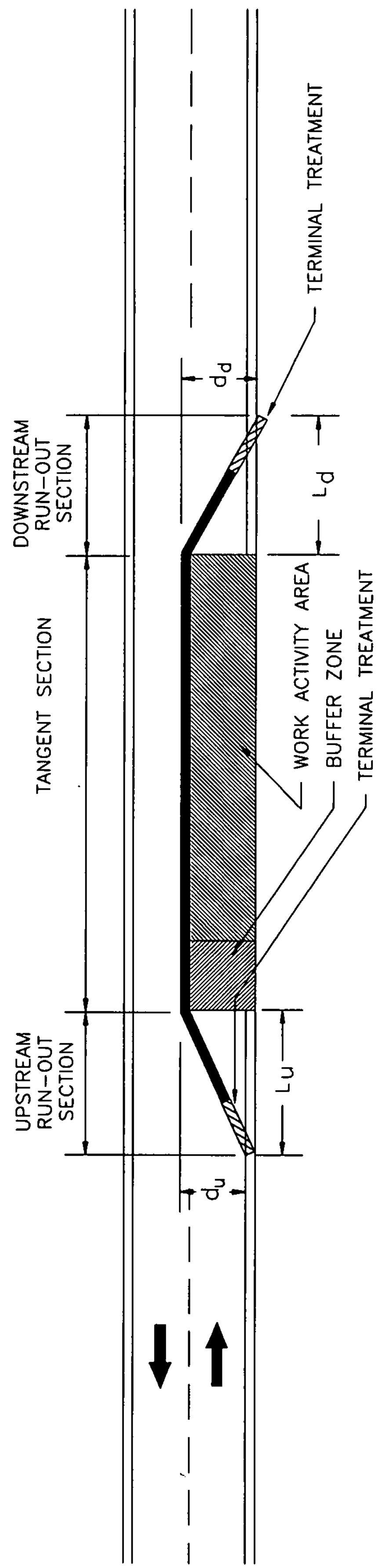


Figure 4.1. Barrier components.

Furthermore, these guidelines should be used in conjunction with the recommended traffic control treatments given in Chapter 3.

As discussed in Chapter 5 of the final report, these guidelines were developed through the application of a benefit/cost (B/C) analysis program. It is important to note that the B/C program, although state of the art, has certain limitations. These limitations do not concern the methodology itself; rather, they relate primarily to the input data. For example, in the absence of statistically valid accident data for work zones, it was necessary to estimate the nature of vehicular accidents in work zones based on encroachment data for roadways free of construction activities. The reader should be aware of limitations and assumptions made in developing the guidelines. These are discussed in Section V-B of the final report. Further research is planned by the Federal Highway Administration to address key data needs of the B/C methodology. Subject to the findings of these efforts, it may be necessary to update the guidelines. The guidelines may also need updating as new and cost-effective barrier terminal treatments become available.

Finally, site and traffic conditions obviously vary from one work zone to the next and, in fact, conditions vary within a given work zone as the work progresses. Consequently, these guidelines should be construed as general in nature, not all inclusive or absolute. It is imperative that they be used in conjunction with sound engineering judgment to effect the most appropriate plan for a given site, for a given stage of the work activity.

4.2 TREATMENTS AT END OF CSSB

Five options were evaluated for treating the end of the CSSB: (1) a baseline option of leaving the blunt end untreated, (2) a conventional sloped-end treatment (CSET), (3) the inertial crash cushion (ICC), (4) the GREAT$_{cz}$, marketed by Energy Absorption Systems, Inc. (*30*), and (5) the ADIEM, marketed by Syro Steel Company (*31*).

The option 2 design is shown in Figure 4.2. Dimensions selected for the sloped end are believed to be representative of many in-service installations. As discussed in Section IV-D-2 of the final report (*32*), more overturns can be expected for shorter taper lengths, consequently benefits would be reduced. While the propensity for overturn will decrease for greater taper lengths, added costs and increasing handling problems can be expected as the length of the sloped end increases.

Three ICC designs were evaluated, namely a 60 mph full-array design, a 45 mph full-array design, and a 45 mph single-row design. In addition, two orientations of each design were evaluated. The analysis indicated the single-row design was not cost beneficial for any circumstances considered. The other two designs and two orientations of each, along with important dimensions, are shown in Figures 4.3 through 4.6. Note the following:

(a) Two orientations were evaluated for the full-array designs: one with the cushion's centerline parallel to the travelway, or a 0 deg alignment, and one with the cushion's centerline aligned at an angle of 10 deg with the travelway. Depending on the

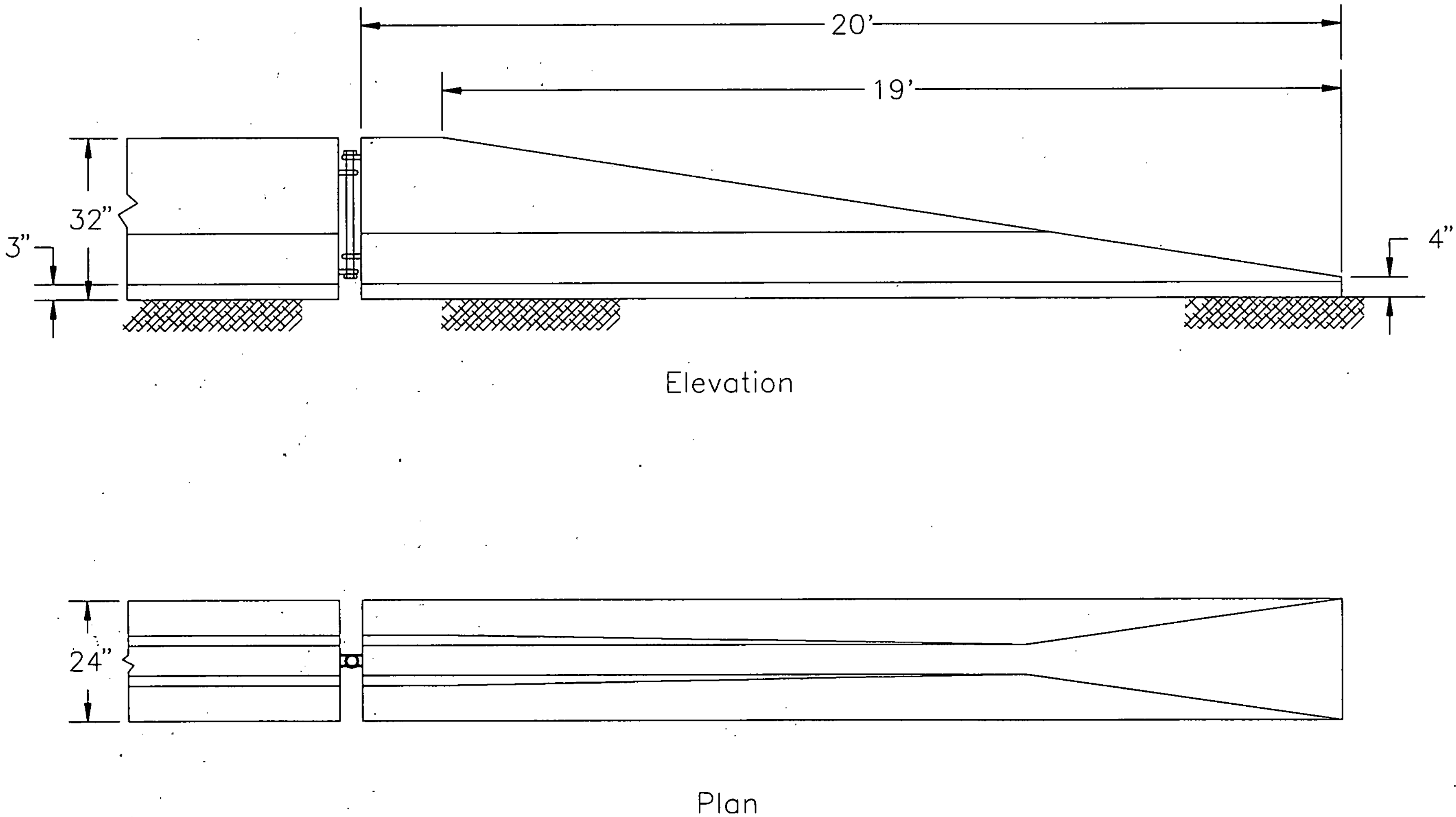


Figure 4.2. Conventional sloped-end treatment.

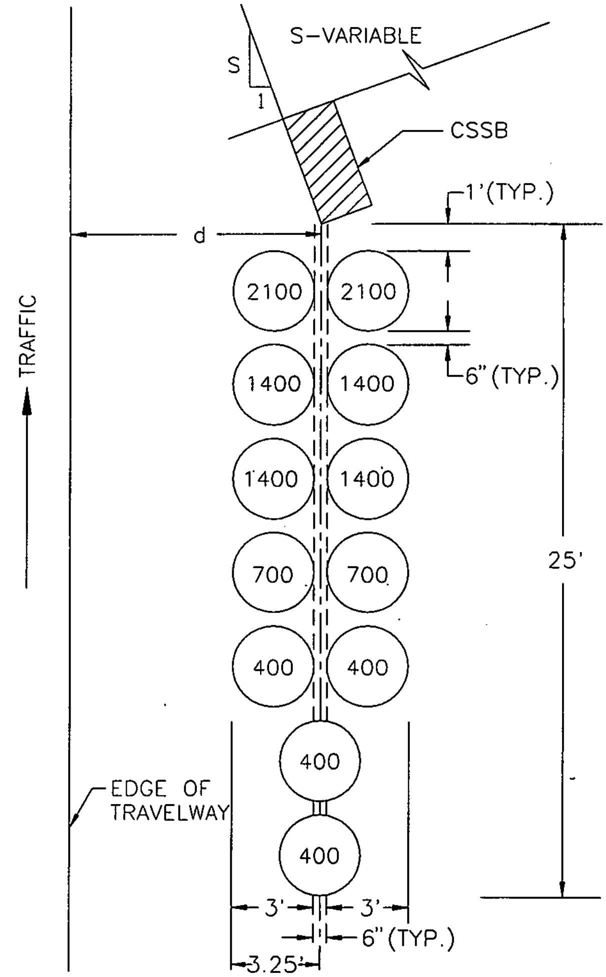


Figure 4.3. Design and orientation of 60 mph inertial crash cushion for 5.25′ ≤ d ≤ 8.25′.

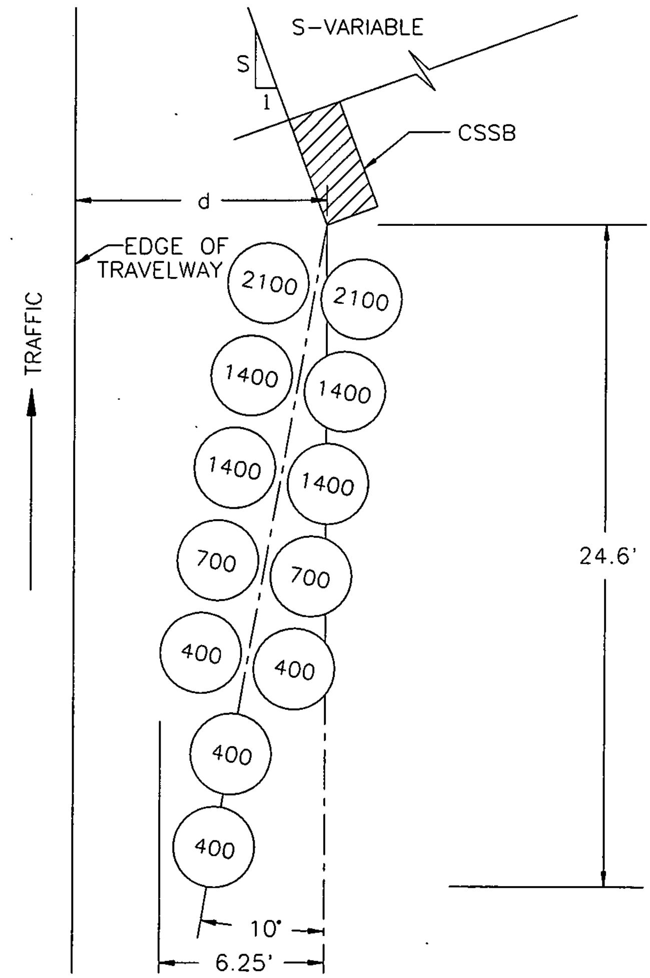


Figure 4.4. Design and orientation of 60 mph inertial crash cushion for d ≥ 8.25′.

offset, "*d*," of the end of the CSSB, one of the two orientations is selected. Note that ranges of *d* for which the orientations are recommended are based on the assumption that no part of the cushion would be placed closer than 2 ft from the travelway. For values of *d* between the ranges given for the 0 deg alignment, additional safety benefits could be realized by aligning the cushion somewhere between 0 deg and 10 deg. The actual angle would depend on the value of *d*. The cushion should not be aligned at an angle in excess of 10 deg or less than 0 deg.

(b) As shown, it is recommended *(30,33)* that the spacing between modules be 6 in. and that the spacing between the last modules and the hazard be 1 ft.

Two $GREAT_{cz}$ designs were evaluated: a 60 mph design and a 45 mph design. The 60 mph design is shown in Figure 4.7. Note its length is 20.75 ft and its width is 2.5 ft, whereas the 45 mph design has the same width and its length is 11.75 ft. The analysis indicated the 45 mph design was not cost beneficial for any circumstances considered.

Two ADIEM designs were evaluated: a 60 mph design and a 45 mph design. The 60 mph design is illustrated in Figure 4.8. Note its length is 30 ft and its width is approximately 24 in., whereas the 45 mph design has the same width and its length is 18 ft. The analysis indicated the 45 mph design was not cost beneficial for any circumstances considered.

Note that the analysis was based on the assumption that the sloped-end treatment, the $GREAT_{cz}$, and the ADIEM were attached to the end of the CSSB and were aligned at the same flare rate as the CSSB in the run-out section. Assumed alignment of the ICC options was as previously described.

4.3 DETERMINATION OF RECOMMENDED FLARE RATE, BARRIER END OFFSET, AND TREATMENT AT END OF CSSB

To determine a recommended flare rate for the run-out sections, lateral offset of the ends of the barrier, and treatment for the barrier ends, the following procedure should be used:

(1) Identify roadway type.
(2) Determine the current ADT of the roadway.
(3) Determine the maximum permissible lateral offset of the barrier including the terminal treatment at the upstream

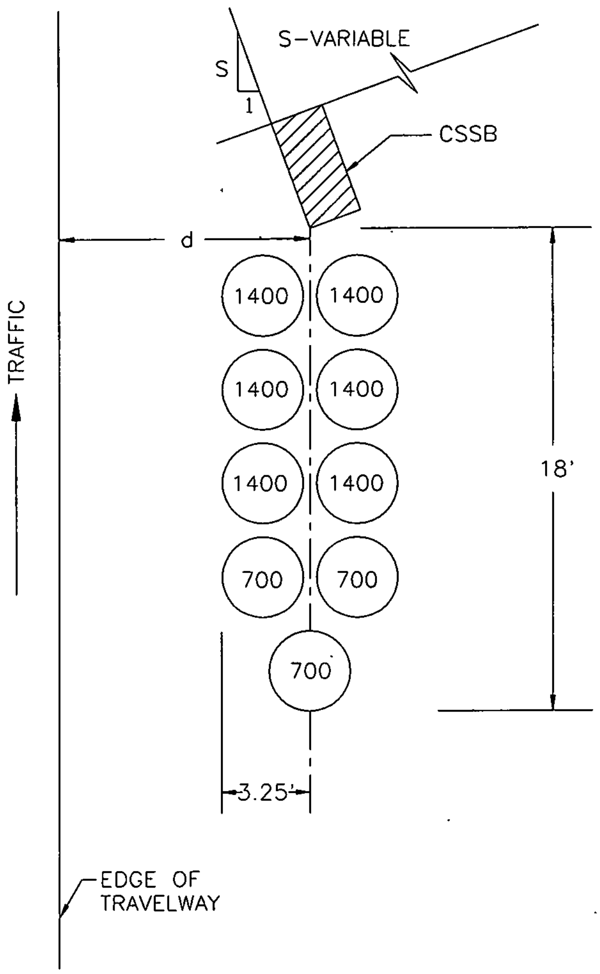


Figure 4.5. Design and orientation of 45 mph inertial crash cushion for 5.25′ ≤ d ≤ 7.8′.

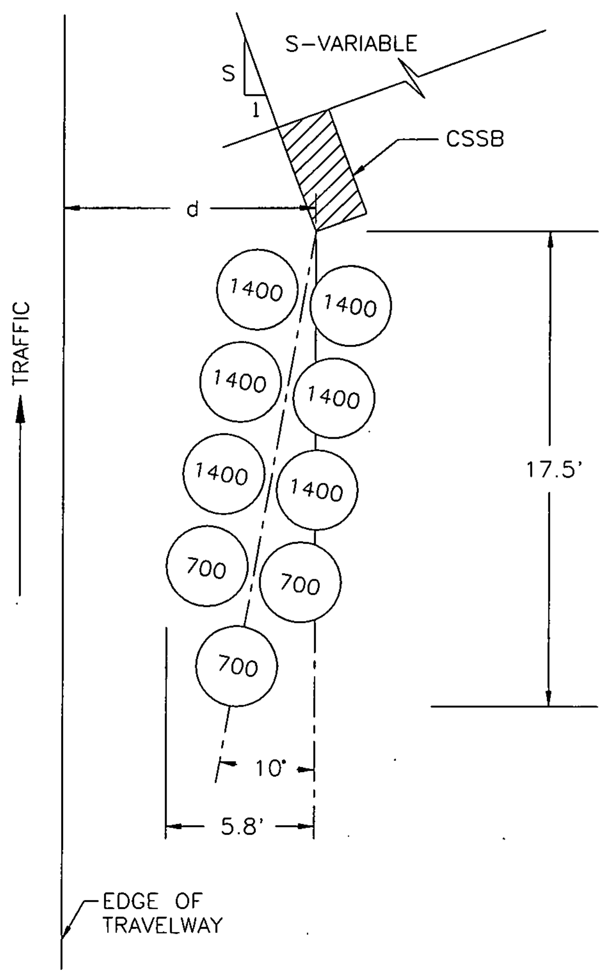


Figure 4.6. Design and orientation of 45 mph inertial crash cushion for d ≥ 7.8′.

and the downstream end of the run-out sections. With reference to Figure 4.1, these are denoted d_u and d_d, respectively. Both ends of the barrier should be offset laterally from traffic, a distance sufficient to provide proper shielding of the work activity area, recognizing access must be maintained to the work zone. As a general rule, access to the work zone should be through the downstream end of the run-out section, if practical, so as to permit maximum offset of the upstream end. Also, for work zone activities that close off a lane(s) of traffic, it is desirable that the ends of the barrier be offset at least to the shoulder.

(4) With information in items 1, 2, and 3, select the recommended flare rate from Figures 4.9 through 4.16, whichever is appropriate, for the upstream and downstream run-out sections. These are denoted R_u and R_d, respectively.

(5) With information in items 1, 2, and 3, select the recommended terminal treatment from Figures 4.17 through 4.24, whichever is appropriate. Determine the space requirements for the terminal treatment from Figures 4.2 through 4.8, whichever is appropriate. Note that Figure 4.7 is for the 60 mph GREAT$_{cz}$ and the length of the 45 mph design is 11.75 ft; Figure 4.8 is for the 60 mph ADIEM and the length of the 45 mph design is 18 ft.

(6) Compute the required longitudinal distance for the upstream and downstream run-out sections. These are denoted L_u and L_d, respectively, and are computed as follows:

$$L_u = (R_u) \times (d_u) + L_{eu}$$
$$L_d = (R_d) \times (d_d) + L_{ed}.$$

where L_{eu} and L_{ed} are the length requirements in the longitudinal direction of the upstream and downstream end treatments. Note that with the exception of the ICCs, these lengths are zero.

NOTE: Depending on the length of the segments used in the CSSB, it may or may not be possible to obtain the precise barrier layout as recommended by the above procedures. However, to the extent practicable, deviations should be kept as small as possible.

(7) The selection procedure is complete if the recommended flare rate of the run-out sections and the recommended end treatments can be accommodated within available space. In some restricted conditions, this may not be possible—in which case the next step should be followed.

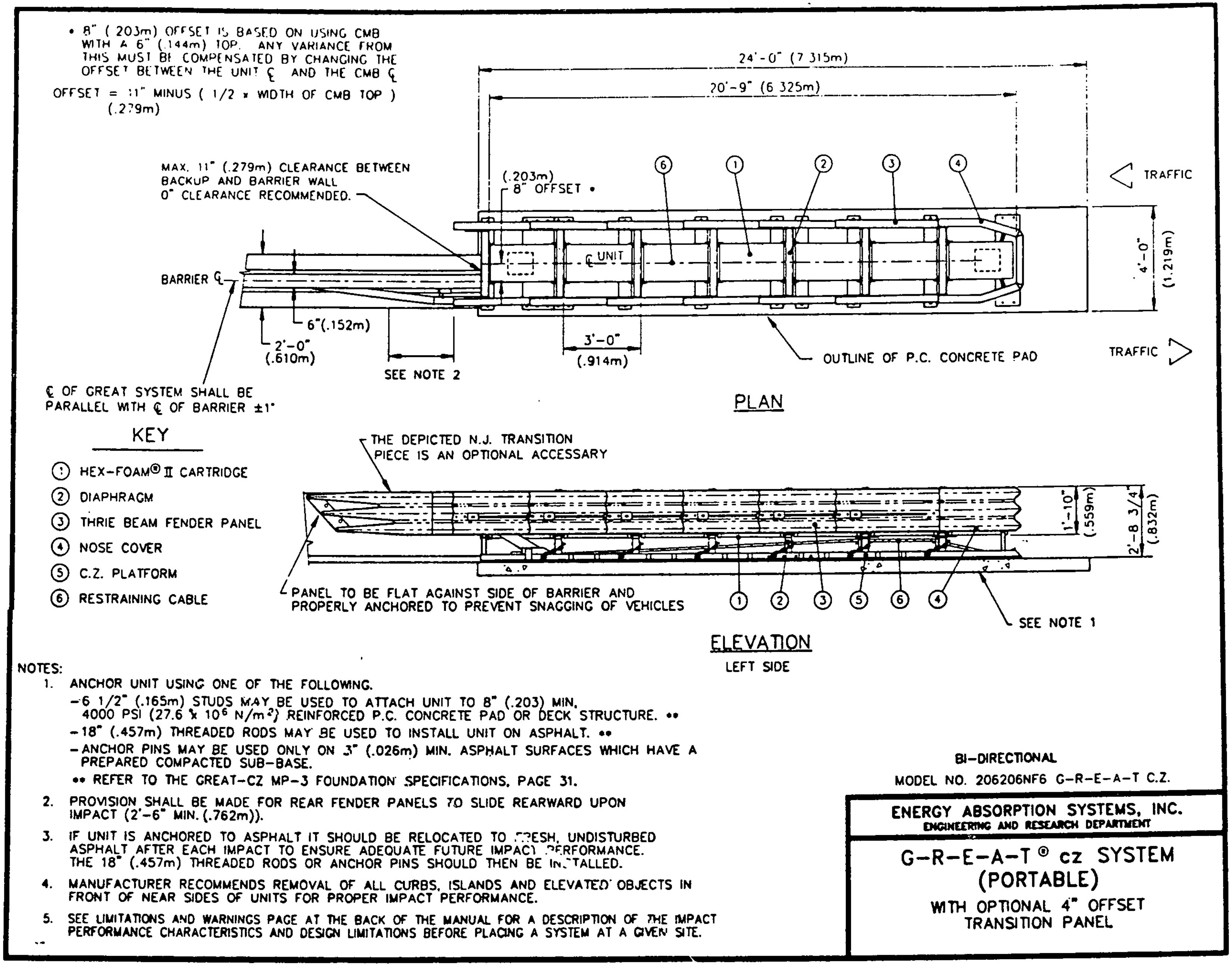


Figure 4.7. 60 mph GREAT$_{cz}$ design (30).

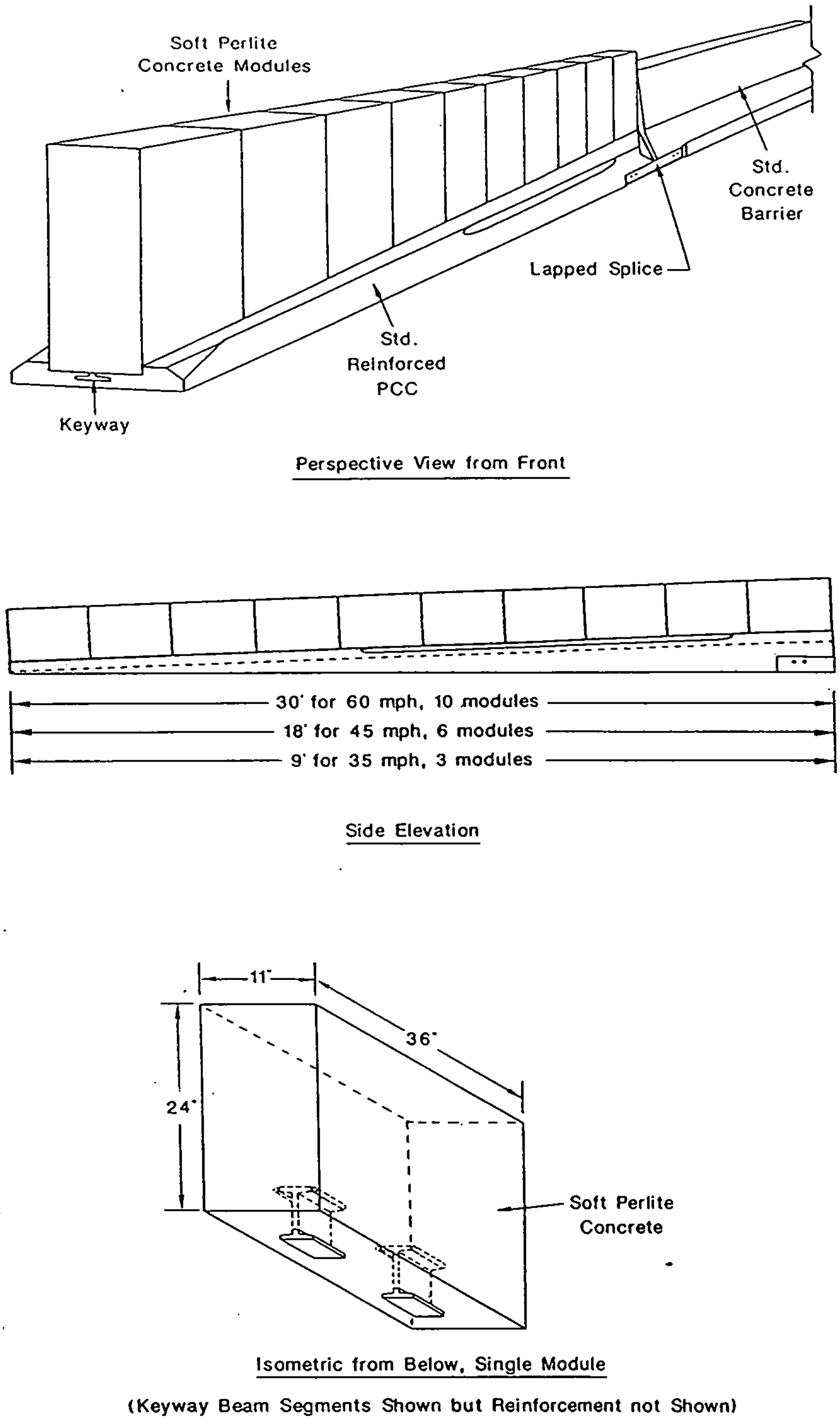


Figure 4.8. 60 mph ADIEM design (52).

(8) For those sites at which the above cannot be accommodated the following is recommended:

(a) If the recommended terminal treatment is *other* than one of the four ICC designs, go to part b. If the recommended end treatment is one of the ICC designs, determine an alternate terminal treatment. Determination of the next best end treatment is made by referring to the appropriate terminal treatment selection criteria (Figures 4.17 through 4.24) and selecting the recommended treatment directly below the original recommendation. This process is repeated until a terminal treatment is found that can be accommodated

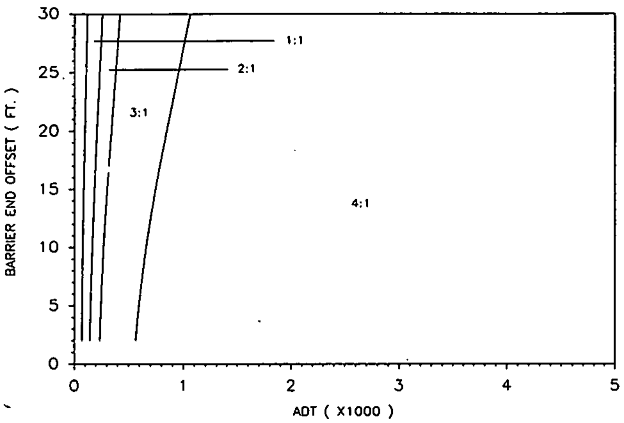


Figure 4.9. Recommended flare rates for two-lane rural arterials, low ADTs.

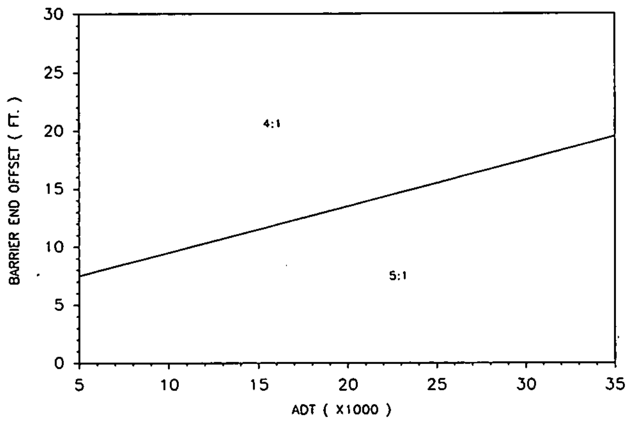


Figure 4.12. Recommended flare rates for two-lane urban arterials, high ADTs.

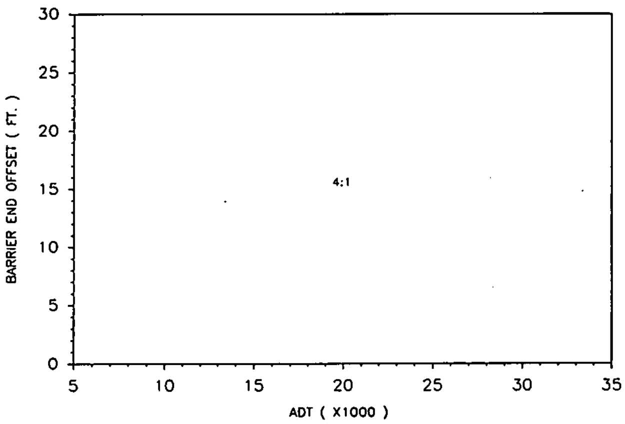


Figure 4.10. Recommended flare rates for two-lane rural arterials, high ADTs.

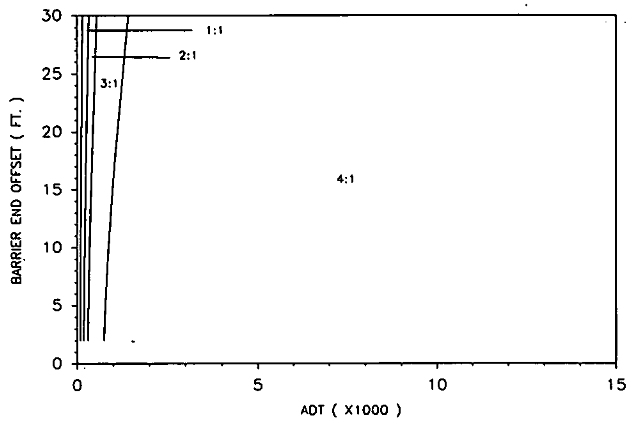


Figure 4.13. Recommended flare rates for four-lane rural arterials, low ADTs.

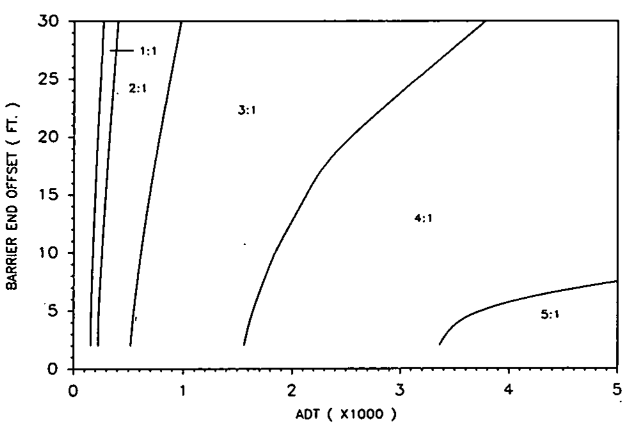


Figure 4.11. Recommended flare rates for two-lane urban arterials, low ADTs.

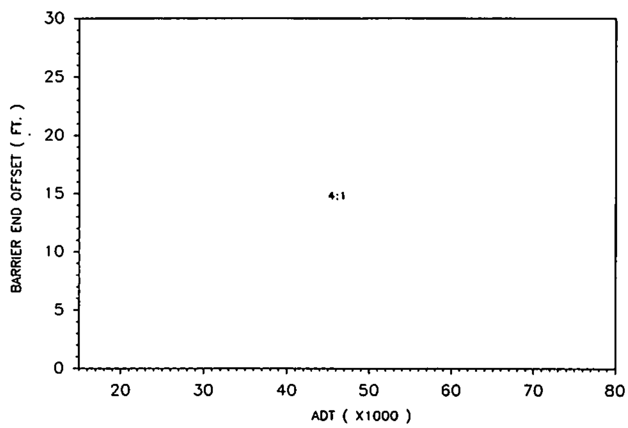


Figure 4.14. Recommended flare rates for four-lane rural arterials, high ADTs.

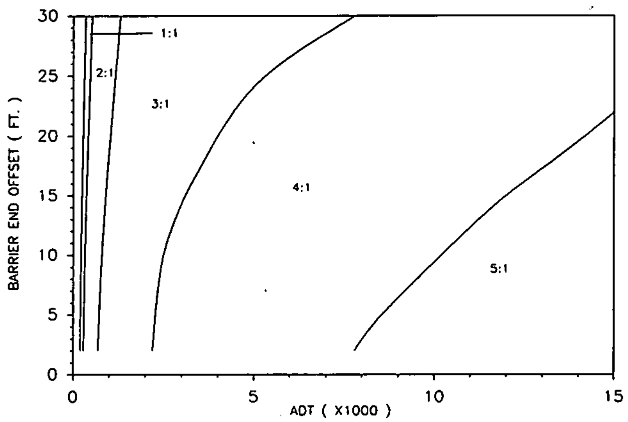


Figure 4.15. Recommended flare rates for four-lane urban arterials, low ADTs.

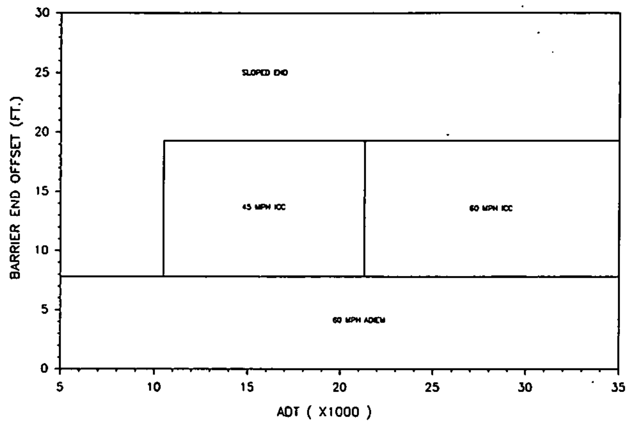


Figure 4.18. Recommended terminal treatment for two-lane rural arterials, high ADTs.

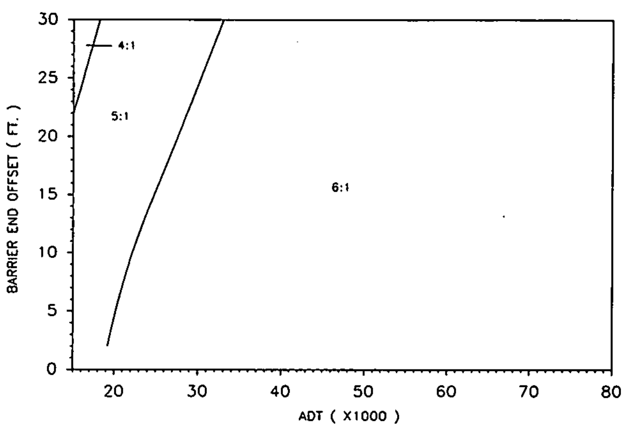


Figure 4.16. Recommended flare rates for four-lane urban arterials, high ADTs.

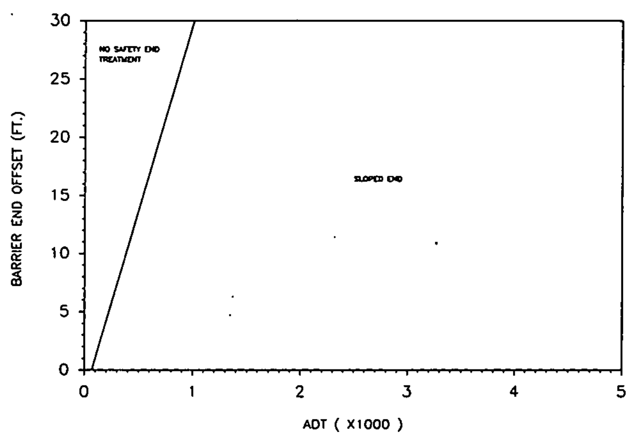


Figure 4.19. Recommended terminal treatment for two-lane urban arterials, low ADTs.

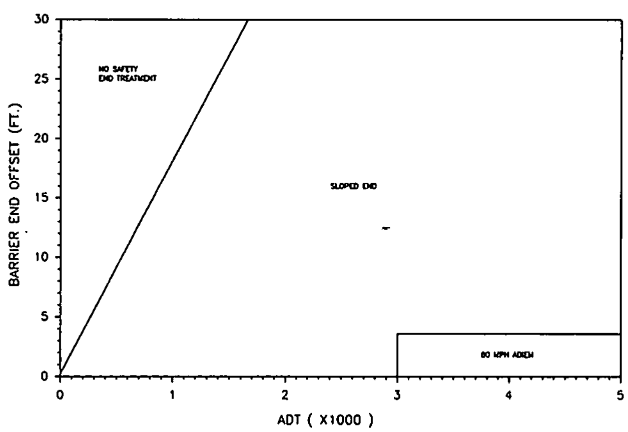


Figure 4.17. Recommended terminal treatment for two-lane rural arterials, low ADTs.

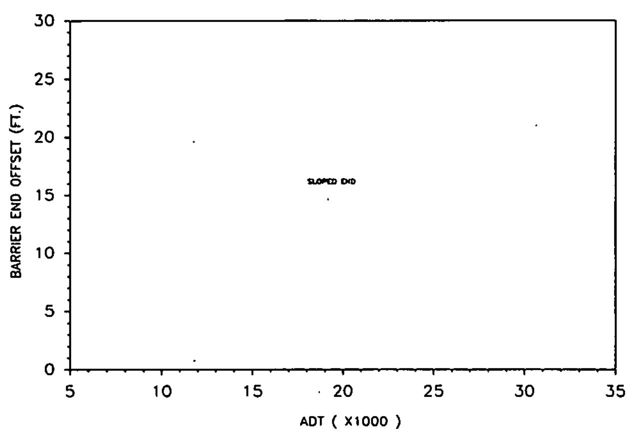


Figure 4.20. Recommended terminal treatment for two-lane urban arterials, high ADTs.

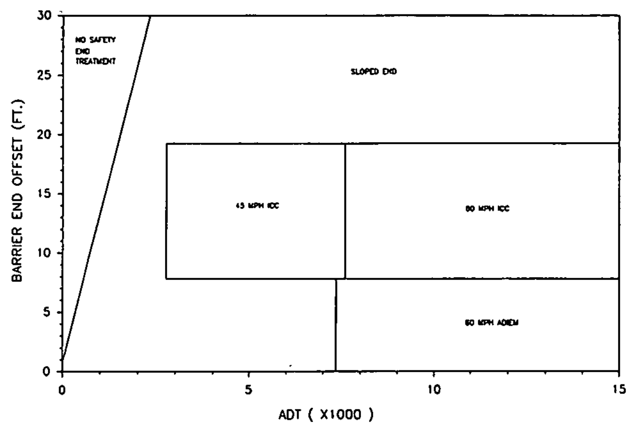


Figure 4.21. Recommended terminal treatment for four-lane rural arterials, low ADTs.

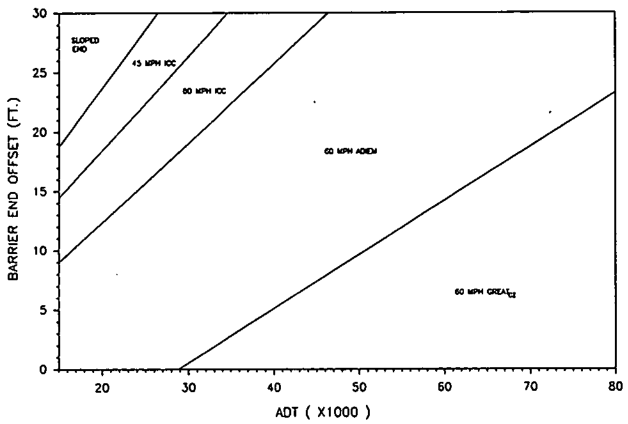


Figure 4.22. Recommended terminal treatment for four-lane rural arterials, high ADTs.

within the available space or it is determined that none of the terminal treatments can be accommodated. For the latter case, proceed to the next step.

(b) The barrier should be flared at the flattest rate possible and the end should be offset as far from traffic as possible. The reader should refer to the note in Section 5.2.8 for a discussion of problems that can occur

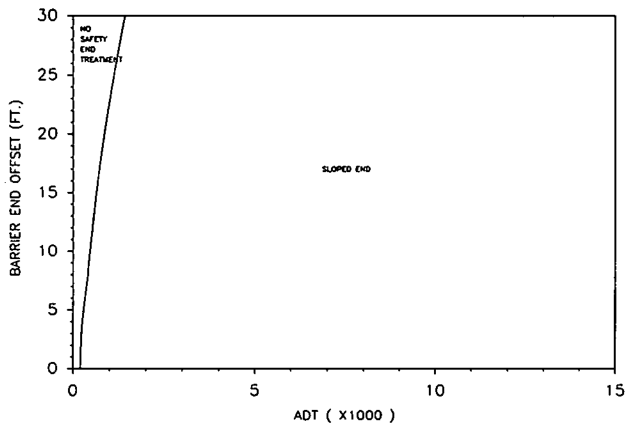


Figure 4.23. Recommended terminal treatment for four-lane urban arterials, low ADTs.

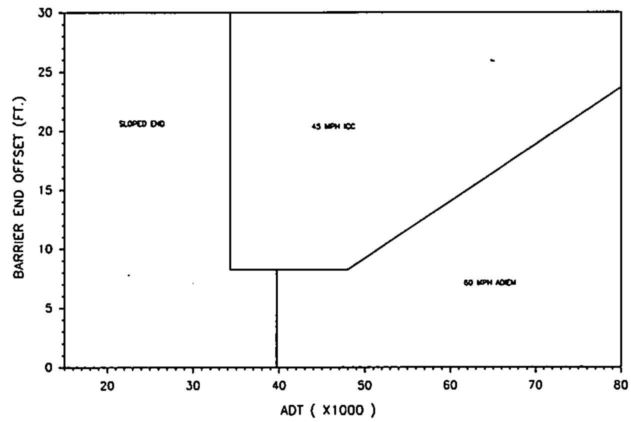


Figure 4.24. Recommended terminal treatment for four-lane urban arterials, high ADTs.

in this situation and how these problems may be addressed.

Examples to illustrate the use of these guidelines are given in Chapter 5. In addition, the examples illustrate the recommended traffic control treatments for use in conjunction with the barrier treatments.

CHAPTER 5

EXAMPLES TO ILLUSTRATE THE USE OF GUIDELINES

5.1 GENERAL

Each work zone has its own unique characteristics and attendant problems, and these characteristics and problems can change rather frequently during the course of the work. Restricted work zones, as defined herein, present especially difficult problems. It is not possible to formulate precise, absolute criteria for traffic control measures and barrier treatments in these situations. This chapter presents several hypothetical work zone situations and recommendations as to how they could be treated using the procedures and guidelines developed in the project. However, it must be emphasized that it does not necessarily follow that sites with characteristics similar to those used in the examples should, or can, be treated precisely as has been recommended in the examples. It is essential that these guidelines be used in conjunction with sound engineering judgment to reach the best solution for the given set of conditions. The examples follow the traffic control and barrier end treatment selection process outlined in Figure 1.1.

5.2 EXAMPLE 1

5.2.1 Site Inventory

Example 1 involves a bridge reconstruction project on a two-lane rural arterial with 12-ft lanes and 2-ft shoulders. The ADT is 3,000 vehicles per day. The posted speed limit is 45 mph. An intersecting roadway located near the end of the bridge creates a Case A restricted work zone situation. The ADT on the intersecting roadway is 500 vehicles per day. A K-factor of 15 and a directional distribution of 2/3 in the peak direction is assumed.

The bridge will be reconstructed one half at a time. As Figures 5.1 and 5.2 illustrate, Phase 1 involves the half of the bridge on the near side of the roadway and Phase 2 involves the half on the far side of the roadway. The work activity area is 90 ft long; this length includes the bridge, buffer area, equipment storage area, and work space. The distance from the end of the work activity area to the intersecting roadway is 40 ft.

5.2.2 Select Traffic Control Option

The roadway cross section is too narrow to maintain two-lane, two-way operations while reconstructing half of the bridge. It is assumed that topography makes it unfeasible to relocate the intersecting roadway or to construct an on-site detour and that no suitable alternative route is available for an off-site detour; hence, the only traffic control option is alternating one-way traffic operations.

5.2.3 Select Traffic Control Treatment

Table 3.1 indicates that because the distance x from the intersecting roadway to the work activity area is less than 115 ft, signal control is the only feasible traffic control method. Table 3.6 indicates that for Phase 1 the traffic control treatment should be based upon Figure 3.13; for Phase 2, Figure 3.14 is the appropriate typical application.

5.2.4 Evaluate Traffic Impacts

For alternating one-way traffic, Table 3.2 indicates that the delay element to consider is the delay due to temporary stoppage of traffic flow. To determine the magnitude of delays, the mean clearance interval (MCI) must be estimated using Figure 3.9. Figure 3.9 requires the length of one-lane operation, which can be estimated from Figures 3.13 and 3.14 to be at least 310 ft. Then, from Figure 3.9 the MCI can be estimated as 9 sec.

The peak-hour two-way volume on the main roadway can be estimated at 450 vehicles per hour based upon the specified ADT and K factor. Given the directional distribution, the approach volumes are estimated at 150 and 300 vehicles per hour. Similarly, the peak-hour approach volume on the intersecting roadway can be estimated at 50 vehicles per hour.

Table 3.3 can be used to estimate the total delay during the peak hour given the demand and MCI. Interpolating yields an estimated total delay of 2.8 hours.

5.2.5 Are the Traffic Impacts Acceptable?

The 2.8 hours of total delay during the peak hour correspond to an average delay per arriving vehicle of approximately 20 sec per vehicle. According to the 1985 *Highway Capacity Manual*, this average delay represents level of service C, which would generally be considered acceptable.

5.2.6 Select Barrier End Treatments

5.2.6.1 Determine Maximum Permissible Barrier End Offsets

It is assumed that contractor access to the work area can be maintained through the downstream end of the barrier for both phases. It is assumed that material will be added near the shoulder, if necessary, at the downstream end of the barrier for access. It is assumed that maximum permissible barrier end offsets for both phases are as follows:

$$d_u = 14 \text{ ft (upstream offset)}$$

$$d_d = 10 \text{ ft (downstream offset)}$$

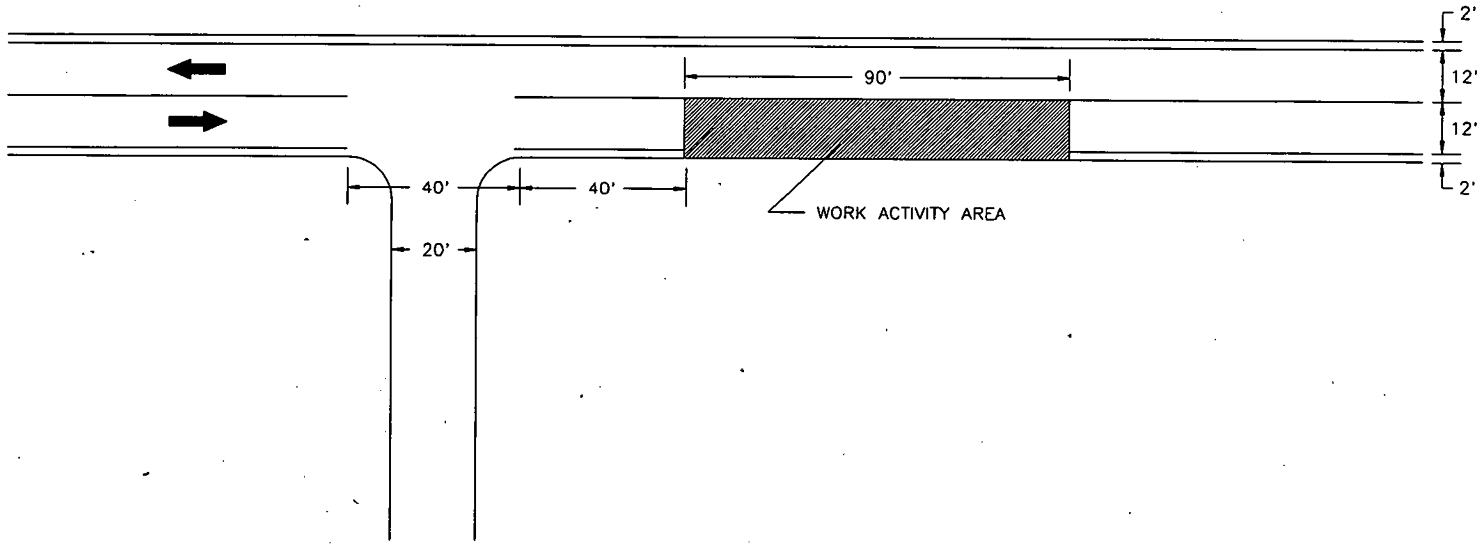


Figure 5.1. *Site conditions, example 1, phase 1.*

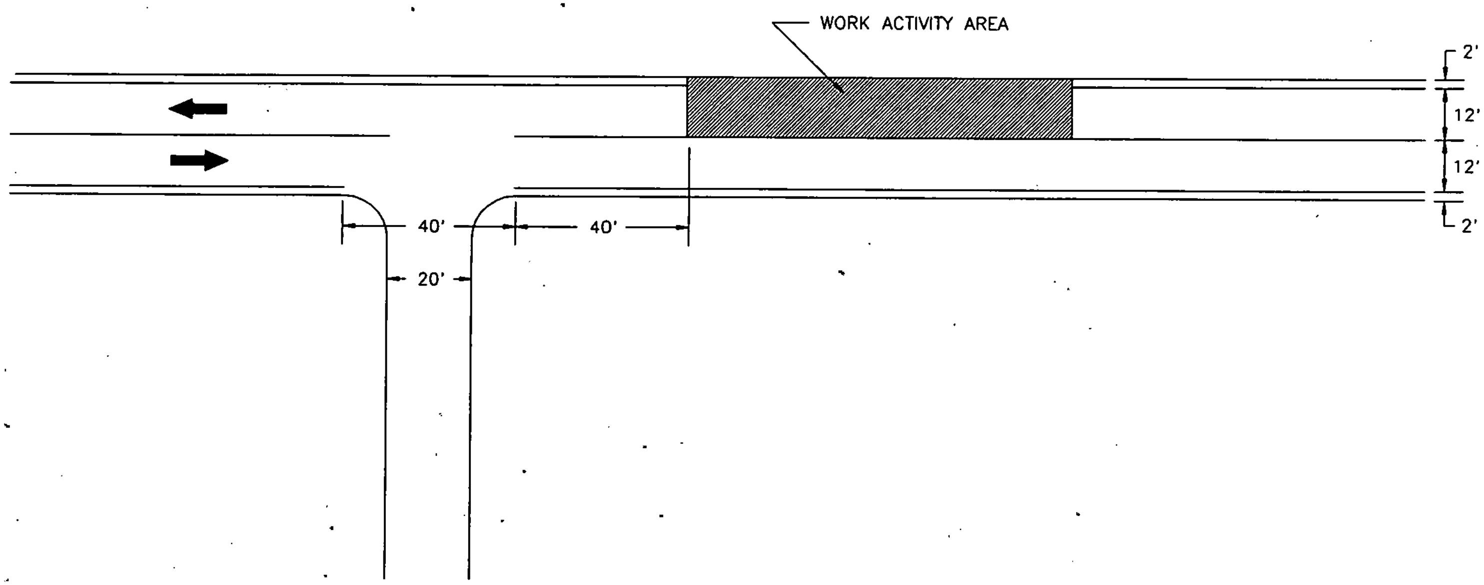


Figure 5.2. *Site conditions, example 1, phase 2.*

5.2.6.2 Determine Recommended Flare Rates

From Figure 4.8, with the above offsets and an ADT of 3,000 the recommended flare rates for both phases are as follows:

$$R_u = 4{:}1$$
$$R_d = 4{:}1 \; .$$

5.2.6.3 Determine Recommended Barrier Terminal Treatments

From Figure 4.16, with the above offsets and an ADT of 3,000, the recommended terminal treatments for both the upstream and downstream ends of the barrier during both phases are sloped ends (see Figure 4.2).

5.2.6.4 Determine Required Longitudinal Distances

The required longitudinal distances for both phases are as follows:

$$L_u = (4/1) \times (14) = 56 \text{ ft}$$
$$L_d = (4/1) \times (10) = 40 \text{ ft}$$

5.2.7. Do Recommended Barrier End Treatments Fit Within Available Space?

From Figure 5.1 for Phase 1 it can be seen that the downstream end of the work zone has sufficient space to accommodate the recommended flare rate but the upstream end does not. From Figure 5.2 for Phase 2 it can be seen that adequate space is available at both ends of the work zone to accommodate the recommended barrier layout.

5.2.8 Adjust Recommended Barrier End Treatments

During Phase 1, the barrier on the upstream end should be flared as flat as possible to fit within available space and to accommodate the recommended traffic control treatment based on Figure 3.13. The recommended barrier layouts for Phases 1 and 2 are shown in Figures 5.3 and 5.4, respectively.

NOTE: This example illustrates problems that may exist within certain restricted work zones. First, the joint design of most CSSBs used in work zones is such that the maximum relative angle that can be achieved between adjoining segments is 12 to 15 deg. The angle between the tangent section and the flared section on the upstream end of the work zone for this example, as shown in Figure 5.3, is approximately 22 deg. Second, as the flare rate increases (approximately 2.5:1 in this example), benefits of a safety terminal treatment diminish, and at some flare rate it will become more beneficial to leave the end untreated. Third, for relatively short run-out sections (approximately 38 ft in this example for the upstream end) where the 20-ft long sloped-end treatment comprises a significant portion of the section, the redirectional effectiveness of the section is diminished. Vehicular redirection can be expected for most impacts into the side of the sloped-end treatment for impact points between the mid-length and the full-height end.

Potential ways that these items can be addressed are as follows:

(a) Depending on the joint design and the segment length, it may be possible to transition from the tangent section to the recommended flare rate within the first two or three barrier segments without greatly affecting the basic recommended barrier layout. Where this is not possible, consideration may be given to positioning the first segment in the run-out section at the necessary flare rate, with no connection to adjoining segment in the tangent section if necessary, and rigidly anchoring both of these segments to the surface on which they are supported. Care must be used in orientating the adjoining ends of the anchored segments so as to minimize the potential for vehicular snagging. It is also important that segments joining the rigidly anchored segments be properly connected, and in fact, it is important that all segments be properly connected. Reference should be made to the discussion in Section 4.1 regarding joint designs for the CSSB.

(b) There are no objective criteria to identify the flare rate at which a safety terminal treatment is no longer cost beneficial. It is surmised that terminal treatments lose most of their effectiveness as a redirective barrier if the flare rate is 1:1 or steeper. However, depending on impact conditions, effective protection of workers can be provided for flare rates steeper than 1:1.

(c) The decision as to whether to use the sloped-end treatment on relatively short run-out sections should depend, in part, on how much buffer space is available between the sloped end and the work space (where workers and equipment are located) and the lateral offset of the end of the sloped-end treatment. The concern diminishes as the length of the buffer space increases. Moreover, if the supplementary taper is used as part of the traffic control plan, the probability of an errant motorist entering the work activity area should be very small, and the importance of the terminal treatment will also be reduced.

5.2.9 Finalize Traffic Control Plan

Figures 5.5 and 5.6 show the recommended traffic control treatments for Phases 1 and 2, respectively. These figures incorporate minor adjustments to the dimensions shown on Figures 3.13 and 3.14. To finalize the traffic control plan, a number of details would need to be resolved, including the types of channelizing devices, barrier delineation, and pavement markings. The need for reduced speed zoning should also be evaluated because of the steeper than recommended flare rate that is used during Phase 1.

5.3 EXAMPLE 2

5.3.1 Site Inventory

Example 2 has the same site conditions as example 1, except the work activity area is 200 ft long and is located 120 ft from

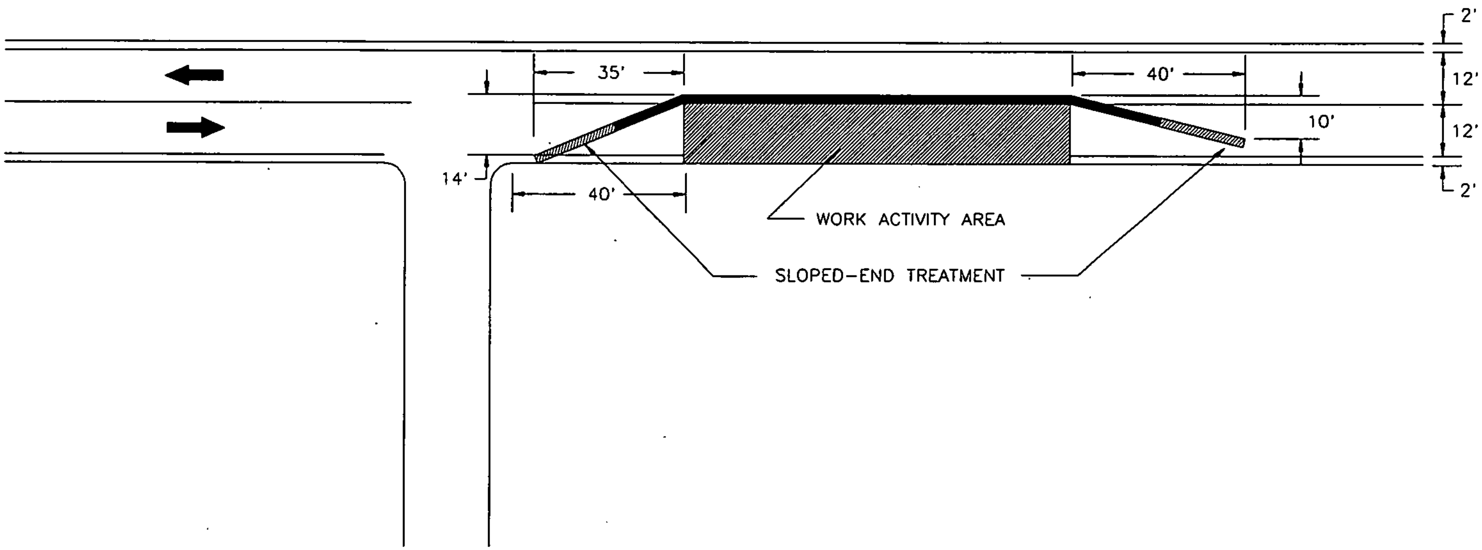


Figure 5.3. Recommended barrier layout, example 1, phase 1.

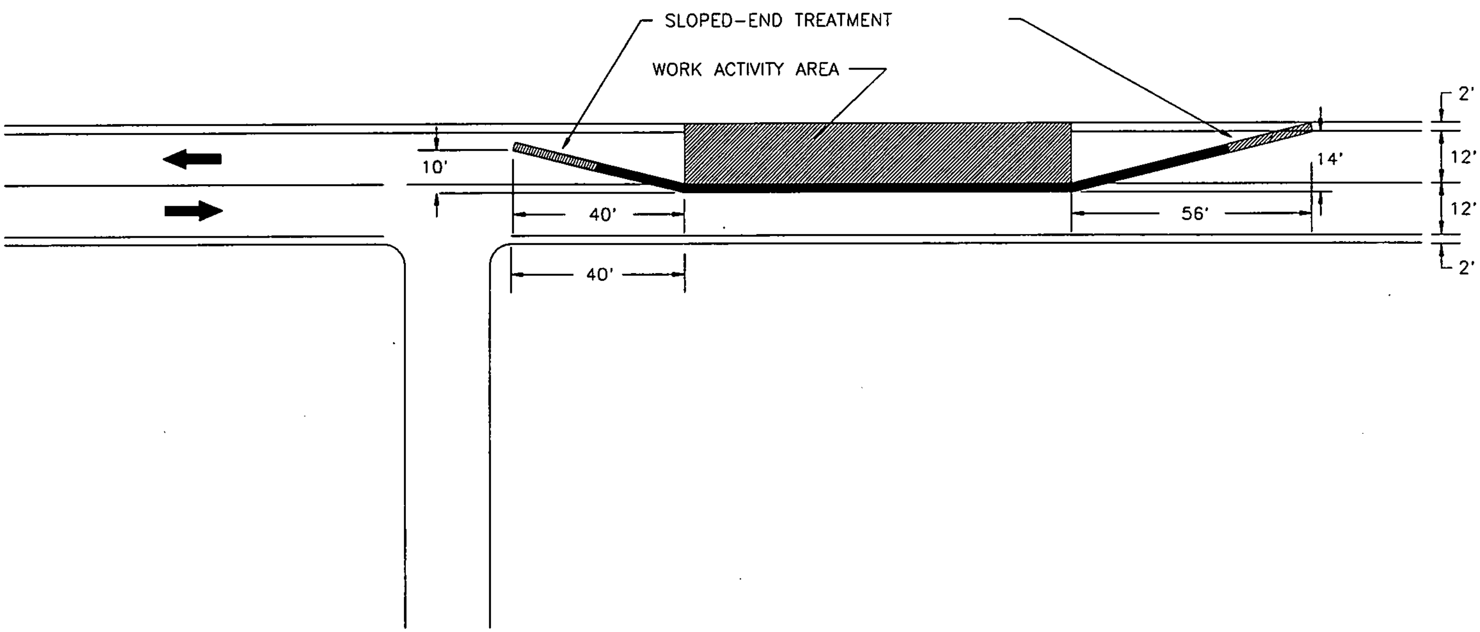


Figure 5.4. Recommended barrier layout, example 1, phase 2.

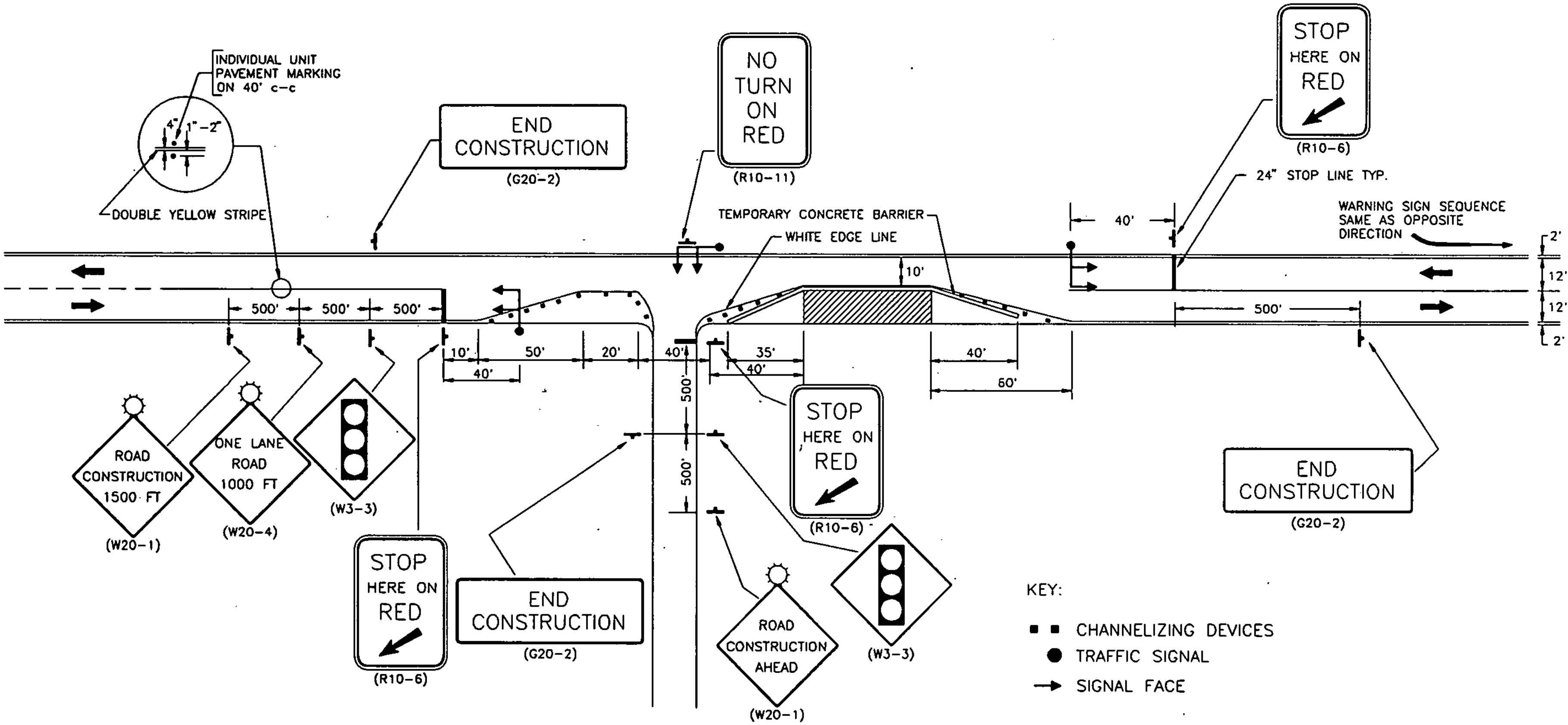


Figure 5.5. Recommended traffic control treatment, example 1, phase 1.

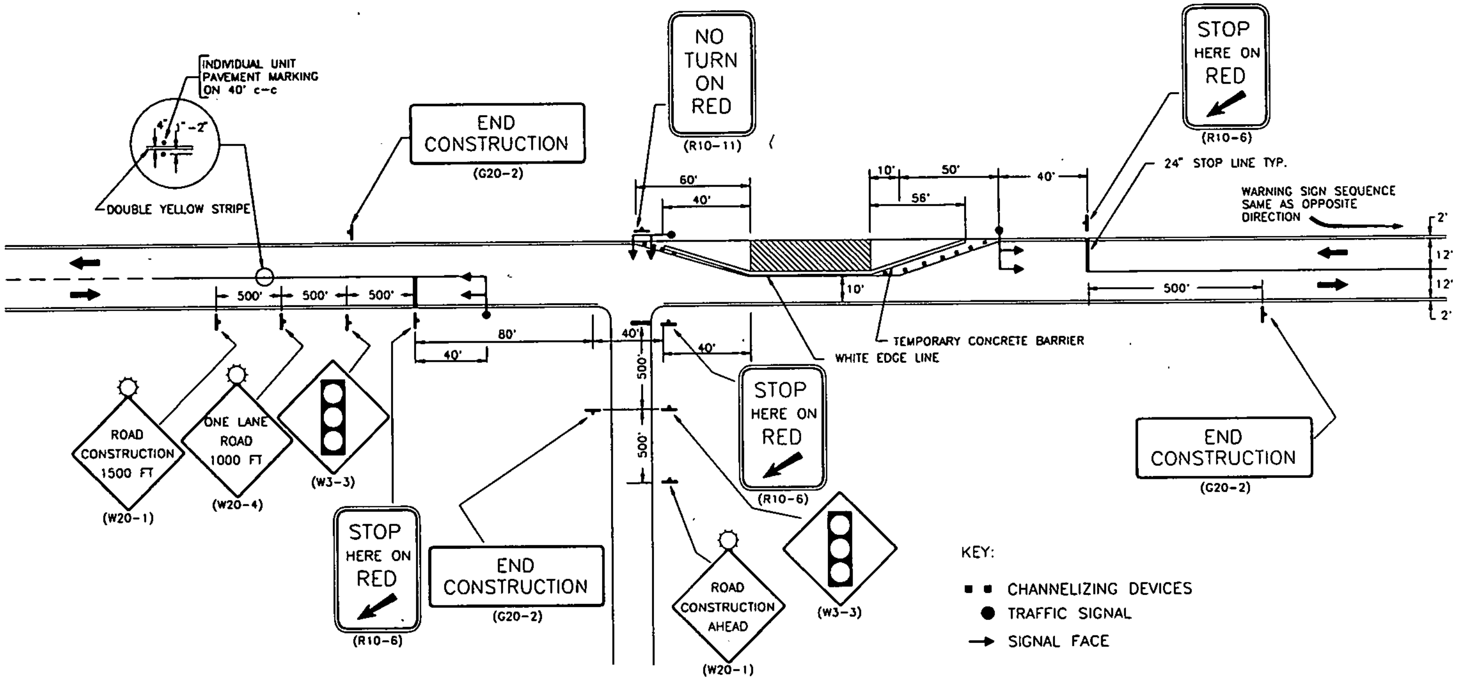


Figure 5.6. Recommended traffic control treatment, example 1, phase 2.

the intersecting roadway. Site conditions are illustrated in Figures 5.7 and 5.8 for Phases 1 and 2, respectively.

5.3.2 Select Traffic Control Option

The roadway cross section is too narrow to maintain two-lane, two-way operations while reconstructing half of the bridge. It is assumed that topography makes it unfeasible to relocate the intersecting roadway or to construct an on-site detour and that no suitable alternative route is available for an off-site detour; hence, the only traffic control option is alternating one-way traffic operations.

5.3.3 Select Traffic Control Treatment

Table 3.1 indicates that because the distance x from the intersecting roadway to the work activity area is greater than 115 ft, traffic from the intersecting roadway could be merged into the through roadway so that the one-lane section would have only two approaches. Therefore, stop, yield, and signal control are all feasible. In selecting among the three types of control, consideration should be given first to sight distance. It is imperative that the line of sight between the stop lines be unobstructed to use either stop or yield control.

If sight distance is adequate, then consideration should be given to traffic delays and user costs. Yield control is generally used only with very low volumes and short one-lane sections; in this example, the ADT is probably too high and the one-lane section too long for yield control.

Figure 3.10 may be used as a guide for selecting between stop and signal control based upon minimizing total delays. This figure requires estimates of the approach volumes and MCI. The approach volumes were estimated in Example 1 to be 150 and 300 vehicles per hour for the two approaches. To estimate the length of one-lane section, assumptions must be made about the traffic control treatment. Table 3.6 indicates that the appropriate typical application will be either Figures 3.17 and 3.18 for signal control or Figures 3.19 and 3.20 for stop control. These figures suggest that the length of one-lane section (between stop lines) will be at least 385 ft (including the 200-ft work activity area). The MCI corresponding to a 385-ft one-lane section and an assumed speed limit of 45 mph is 10 sec. Then from Figure 3.10 for a 10-sec MCI and the estimated approach volumes, one would conclude that signal control would minimize delays. Therefore, the appropriate typical applications on which the traffic control plan should be developed would be Figure 3.17 for Phase 1 and Figure 3.18 for Phase 2.

5.3.4 Evaluate Traffic Impacts

For alternating one-way traffic, Table 3.2 indicates that the delay due to temporary stoppage of traffic flow should be estimated. Table 3.3 can be used to estimate the total delay during the design hour given the previously estimated MCI of 10 sec and approach volumes of 150 and 300 vehicles per hour. Interpolating in Table 3.3 yields an estimated total delay of approximately 1.8 hours.

5.3.5 Are the Traffic Impacts Acceptable?

The total delay of 1.8 hours corresponds to an average delay of approximately 14 sec per arriving vehicle. According to the 1985 *Highway Capacity Manual*, this average delay corresponds to level of service B, which is acceptable. Therefore, alternating one-way traffic with signal control appears to be a reasonable traffic control treatment.

5.3.6 Select Barrier End Treatments

5.3.6.1 Determine Maximum Permissible Barrier End Offsets

It is assumed that contractor access to the work area can be maintained through the downstream end of the barrier for both phases. It is assumed that material will be added near the shoulder, if necessary, at the downstream end of the barrier for access. It is assumed that maximum permissible barrier end offsets for Phase 1 are as follows:

$$d_u = 12 \text{ ft (upstream offset)}$$

$$d_d = 10 \text{ ft (downstream offset)}$$

It is assumed that maximum permissible barrier end offsets for Phase 2 are as follows:

$$d_u = 14 \text{ ft (upstream offset)}$$

$$d_d = 10 \text{ ft (downstream offset)}$$

Note that the upstream offset for Phase 1 is limited by the requirements of the traffic control treatment for Phase 1 (see Section 5.3.9).

5.3.6.2 Determine Recommended Flare Rates

From Figure 4.8, with the above offsets and an ADT of 3,000, the recommended flare rates for both phases are as follows:

$$R_u = 4{:}1$$

$$R_d = 4{:}1$$

5.3.6.3 Determine Recommended Barrier Terminal Treatments

From Figure 4.16, with the above offsets and an ADT of 3,000, the recommended terminal treatments for both the upstream and downstream ends during both Phases 1 and 2 are sloped ends.

5.3.6.4 Determine Required Longitudinal Distances

The required longitudinal distances for Phase 1 are as follows:

$$L_u = (4/1) \times (12) = 48 \text{ ft}$$

$$L_d = (4/1) \times (10) = 40 \text{ ft}$$

The required longitudinal distances for Phase 2 are as follows:

$$L_u = (4/1) \times (14) = 56 \text{ ft}$$

$$L_d = (4/1) \times (10) = 40 \text{ ft}$$

5.3.7 Do Recommended Barrier End Treatments Fit Within Available Space?

From Figures 5.7 and 5.8 it can be seen that adequate space exists at both the upstream and downstream ends of the work zone for both phases to accommodate the recommended barrier layouts. The recommended barrier layouts for both phases are shown in Figures 5.9 and 5.10.

5.3.8 Adjust Recommended Barrier End Treatments

Because the recommended barrier end treatments fit within the available space, no adjustments are required.

5.3.9 Finalize Traffic Control Plan

Figures 5.11 and 5.12 show the recommended traffic control treatments for Phases 1 and 2, respectively. Only minor adjustments were made to the typical applications in Figures 3.17 and 3.18. To finalize the traffic control plan, a number of details would need to be resolved, including the type of channelizing devices, barrier delineation, and pavement markings.

5.4 EXAMPLE 3

5.4.1 Site Inventory

Example 3 involves a bridge repair on a two-lane rural arterial with 12-ft lanes and 10-ft shoulders. Site conditions are shown in Figure 5.13. The ADT is 6,000 vehicles per day. The posted speed limit is 55 mph. An intersecting roadway located near the end of the bridge creates a Case A restricted work zone situation. The ADT on the intersecting roadway is 500 vehicles per day. A K-factor of 15 and a directional distribution of 2/3 in the peak direction is assumed.

The half of the bridge being repaired is on the near side of the roadway. The work activity area is 90 ft long; this length includes the bridge, buffer area, equipment storage area, and work space. The distance from the end of the work activity area to the intersecting roadway is 30 ft.

5.4.2 Select Traffic Control Option

The roadway cross section is wide enough to maintain two-lane, two-way operations while closing half of the bridge for repair. This option would be preferred given the relatively high traffic volumes. Consideration might be given to an off-site detour to avoid the need to squeeze a barrier end treatment into the limited distance between the work activity area and the intersecting roadway. In this example it will be assumed that a suitable alternative route is not available and, therefore, an off-site detour is not feasible.

5.4.3 Select Traffic Control Treatment

Figure 3.12 provides the appropriate typical application for maintaining two-lane, two-way traffic by shifting traffic to the shoulder while closing one half of the roadway.

5.4.4 Evaluate Traffic Impacts

Because it is possible to maintain two-lane, two-way traffic, albeit on a restricted cross section, and because a detour route is not available, a detailed evaluation of traffic impacts is not necessary. There would be some reduction in capacity through the restricted cross section: the 1985 *Highway Capacity Manual* estimates that the capacity of a two-lane highway with a 20–22-ft cross section would be only 75–82 percent of the capacity with 12-ft lanes and 10-ft shoulders.

5.4.5 Are the Traffic Impacts Acceptable?

Some reduction in speed and associated delays would result from this capacity reduction. Clearly, however, these delays would be less than with any other traffic control option.

5.4.6 Select Barrier End Treatments

5.4.6.1 Determine Maximum Permissible Barrier End Offsets

It is assumed that contractor access to the work area can be maintained through the downstream end of the barrier. It is assumed that material will be added near the shoulder, if necessary, at the downstream end of the barrier for access. It is assumed that maximum permissible barrier end offsets for both phases are as follows:

$$d_u = 18 \text{ ft (upstream offset)}$$

$$d_d = 12 \text{ ft (downstream offset)}$$

5.4.6.2 Determine Recommended Flare Rates

From Figure 4.8, with the above offsets and an ADT of 6,000, the recommended flare rates for both phases are as follows:

$$R_u = 4{:}1$$

$$R_d = 4{:}1$$

5.4.6.3 Determine Recommended Barrier Terminal Treatments

From Figure 4.17, with the above offsets and an ADT of 6,000, the recommended terminal treatments for both the upstream and downstream ends of the barrier are sloped ends.

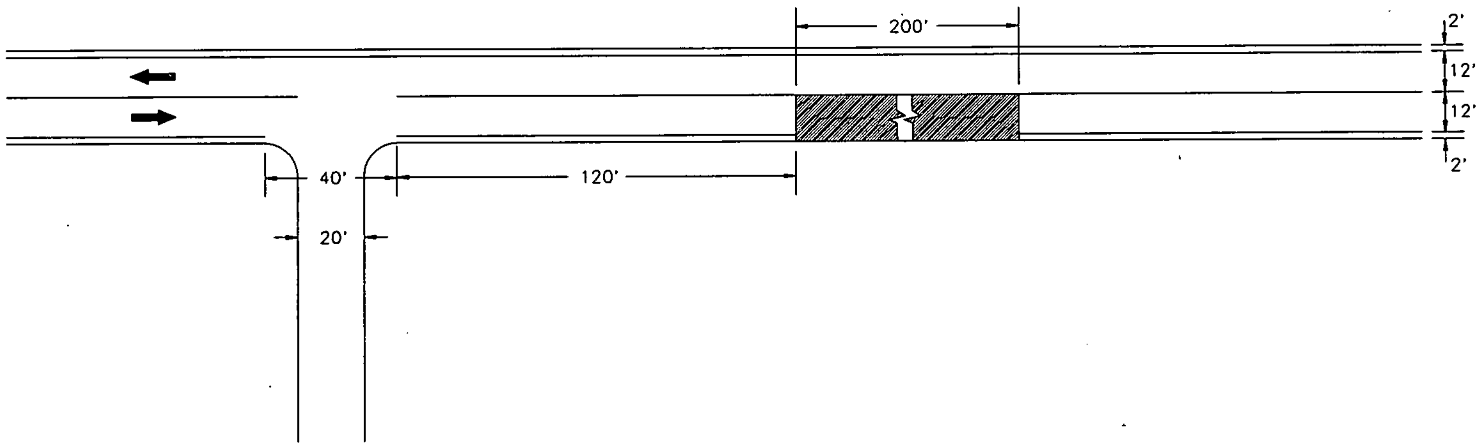


Figure 5.7. Site conditions, example 2, phase 1.

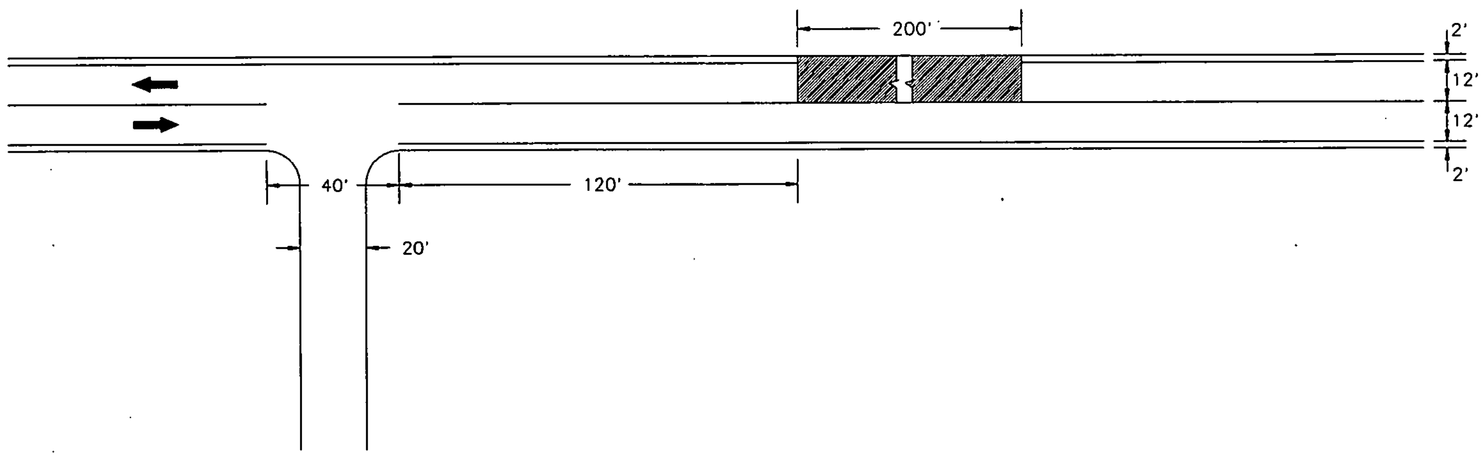


Figure 5.8. Site conditions, example 2, phase 2.

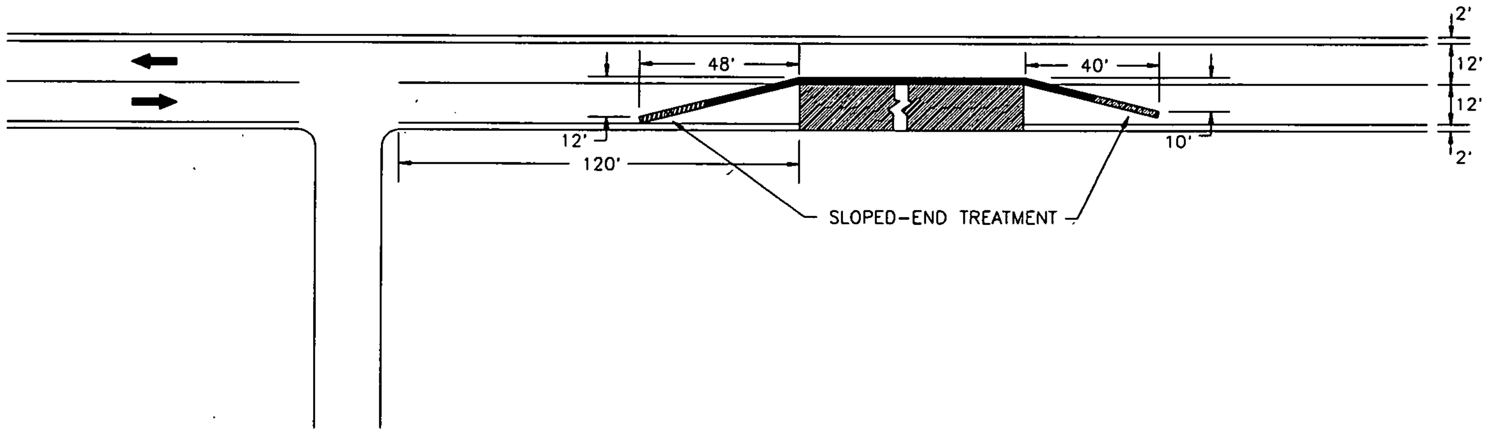


Figure 5.9. Recommended barrier layout, example 2, phase 1.

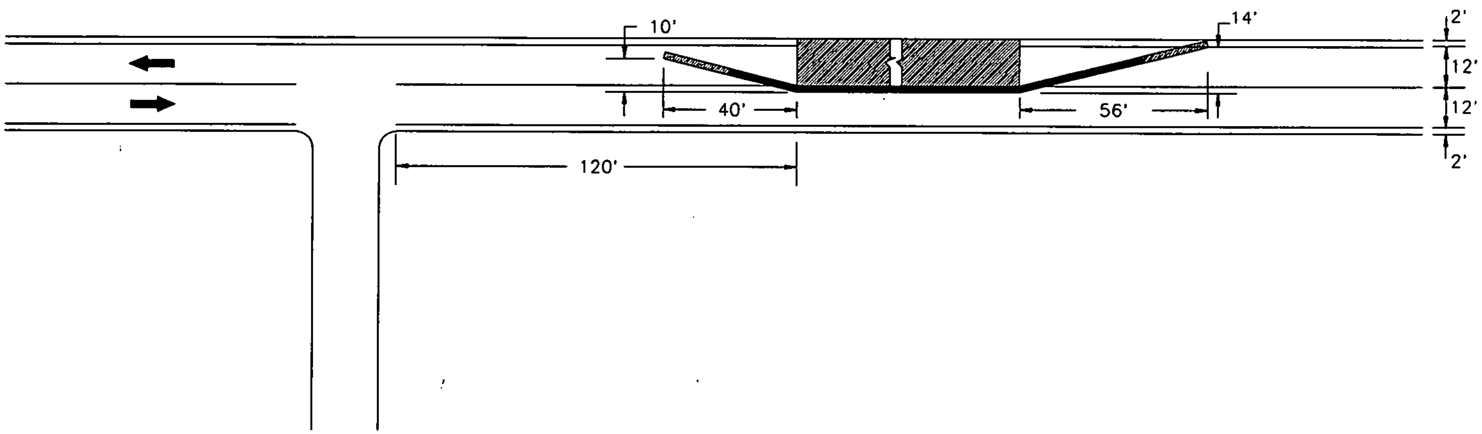


Figure 5.10. Recommended barrier layout, example 2, phase 2.

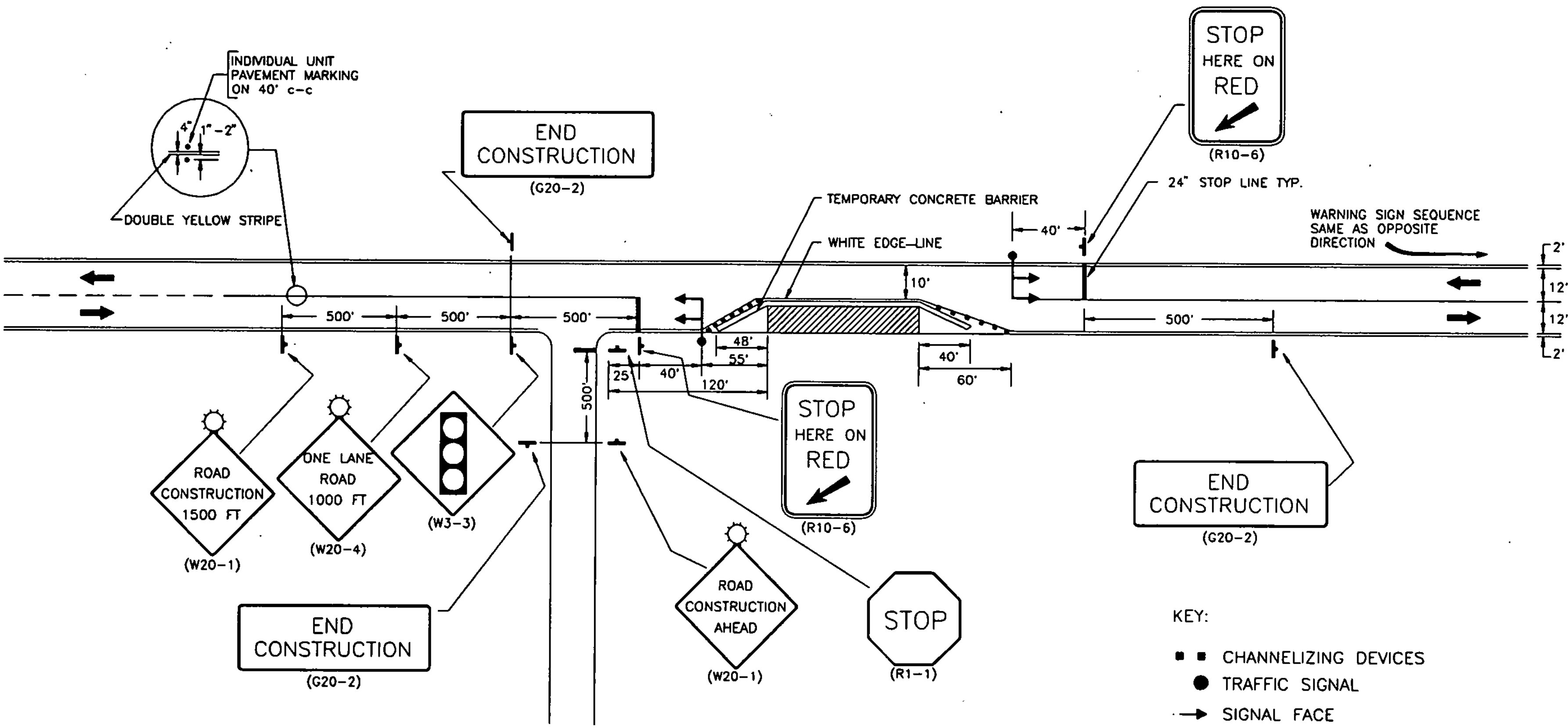


Figure 5.11. Recommended traffic control treatment, example 2, phase 1.

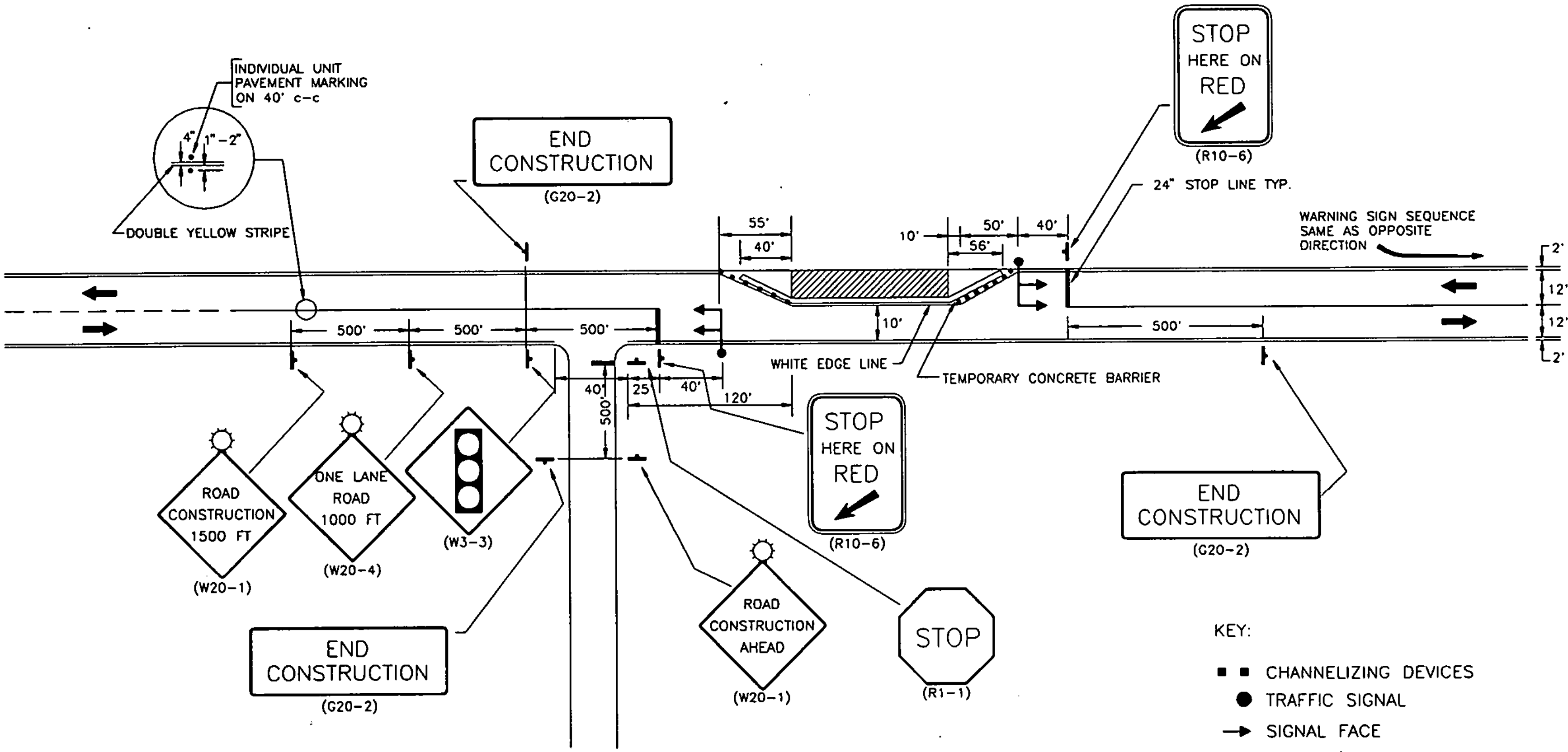


Figure 5.12. Recommended traffic control treatment, example 2, phase 2.

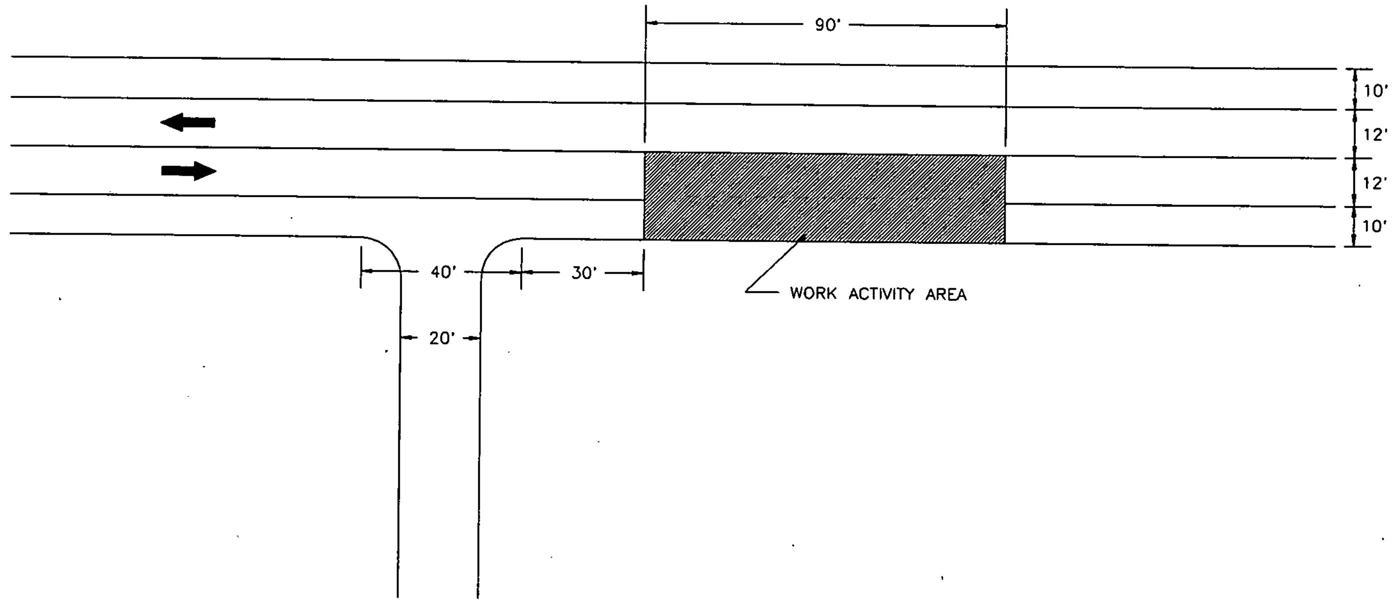


Figure 5.13. Site conditions, example 3.

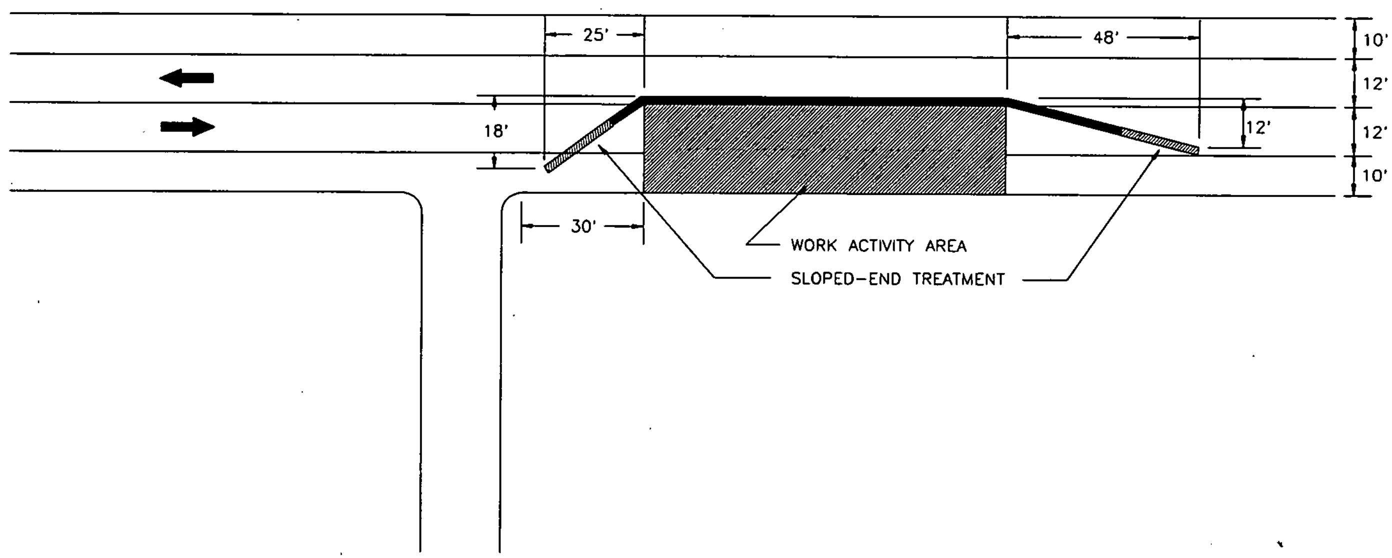


Figure 5.14. Recommended barrier layout, example 3.

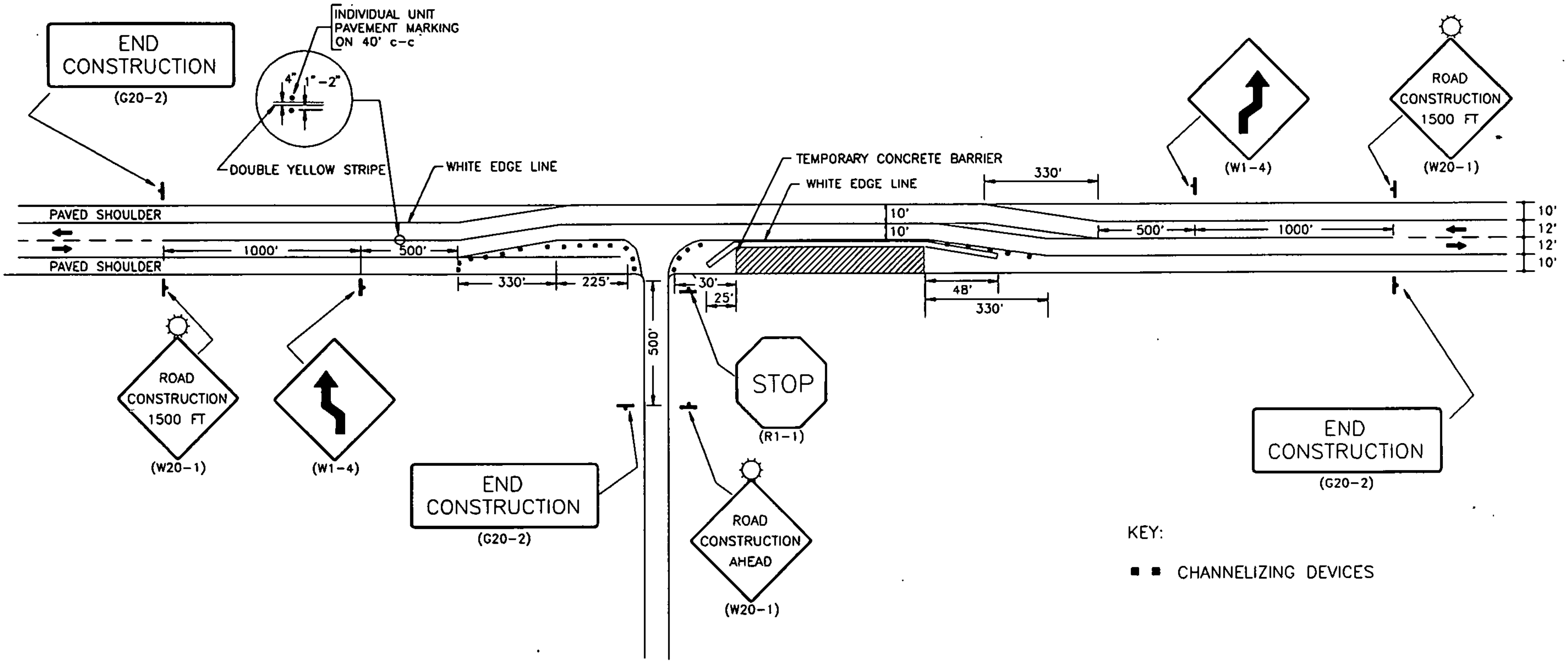


Figure 5.15. Recommended traffic control treatment, example 3.

5.4.6.4 Determine Required Longitudinal Distances

The required longitudinal distances for both phases are as follows:

$$L_u = (4/1) \times (18) = 72 \text{ ft}$$

$$L_d = (4/1) \times (12) = 48 \text{ ft}$$

5.4.7 Do Barrier End Treatments Fit Within Available Space?

From Figure 5.13, it can be seen that the downstream end of the work zone has sufficient space to accommodate the recommended flare rate but the upstream end does not.

5.4.8. Adjust Recommended Barrier End Treatments

The barrier on the upstream end should be flared as flat as possible to fit within available space and to accommodate the recommended traffic control treatment based on Figure 3.12. The recommended barrier layout is shown in Figure 5.14. Reference should be made to the note in Section 5.2.8 for a discussion of problems and potential solutions associated with the steeper flare rates.

5.4.9 Finalize Traffic Control Plan

Figure 5.15 shows the recommended traffic control treatment for this example. This figure incorporates minor adjustments to the dimensions shown in Figure 3.12. To finalize the traffic control plan, a number of details would need to be resolved, including the types of channelizing devices, barrier delineation, and pavement markings. When selecting the type of channelizing devices for the taper upstream of the intersecting roadway, consideration should be given to providing adequate sight distance for vehicle approaching on the intersecting roadway.

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APPENDIX A

CHAPTER THREE

BARRIER TERMINAL TREATMENT DESIGNS

III-A. General

Work zone barriers are designed to be installed and removed quickly and are usually in place for relatively short periods of time. Operating speeds in the work zone may be reduced and available shoulder widths may be small so that the barrier must be placed near the edge of the travelway. For these situations, probable impact speeds and angles are reduced. Due to these special conditions, construction zone barriers are often designed to a lower performance level than permanent barriers. Similarly, work zone barrier end treatments are often designed for a reduced performance level.

It was found through surveys of typical restricted work zones, described in Chapter II, that the precast concrete safety-shaped barrier (CSSB) was the dominant design used to shield errant motorists from the work zone and to shield workers from errant motorists. At least one state makes wide use of both the CSSB and a W-beam-on-barrel barrier. The barrier is typically placed along a tangent to the roadway in the work zone area and then, depending on available space, may be flared away from traffic in the run-out area upstream and downstream from the work zone. Depending on available space, various treatments are used to shield the end of the barrier.

The survey also showed operating speeds in a large majority of restricted work zones were 45 mph or less. In view of this finding and in view of the sparsity of designs and design criteria for this speed range, it was concluded a major part of Project 17-8 should focus on barrier run-out flare rates and end treatments for lower speed conditions.

As part of the Phase I effort, a review was made of widely used end treatments for work zone barriers. New end treatment designs were also conceptualized and evaluated as part of the Phase I effort. This chapter summarizes the results of this part of the study; reference should be made to the Phase I Interim Report (1) for full details.

The original work plan for the project called for full-scale testing in Phase II of promising end treatment designs developed in Phase I. However, upon completion of Phase I it was determined that the crash test effort should focus on a determination of the impact performance of the sloped-end treatment and the effects of flare rate of the CSSB on impact performance for impacts speeds believed to be representative of restricted work zones.

III-B. Existing Terminal Treatments

As noted in Chapter II, there are several commonly used end treatment designs for barriers in restricted work zones. These include the sloped-end concrete section for the end of the CSSB, a single-row inertial crash cushion (ICC), a full-array ICC, and flared ends with and without safety end treatments. In at least one state a W-beam-on-barrel system is occasionally used with an end treatment utilizing the same structural elements.

III-B-1. Sloped-End Treatments

Many states use a sloped-end section, illustrated in Figure III-1, to treat the end of the CSSB for both temporary and permanent applications. This design is referred to herein as the conventional sloped-end treatment (CSET). Sloping the barrier to the ground eliminates the hard point associated with the barrier end. However, crash tests have demonstrated that these end treatments can cause rollover during high-speed impacts. It is noted that according to the evaluation criteria of NCHRP Report 230 (10), a vehicle must remain upright during and after collision. A modified sloped-end treatment, shown in Figure III-2, is used extensively in at least one state. This design is referred to herein as the New York sloped-end treatment (NYSET). Note that the section is warped to reduce the ability of a vehicle's tires to ride directly up the slope.

Preliminary evaluations of the impact performance of these two sloped-end treatments were made in Phase I of the study using the HVOSM computer program (3). Subsequently, the designs were subjected to full-scale testing and additional computer analysis, as described in Chapter IV.

III-B-2. Single-Row Inertial Crash Cushion

A single-row ICC, illustrated in Figure III-3, is another commonly used end treatment for the CSSB. Such an end treatment can safely attenuate head-on impacts, but it has limited capacity to redirect a vehicle impacting from the side. Depending on impact

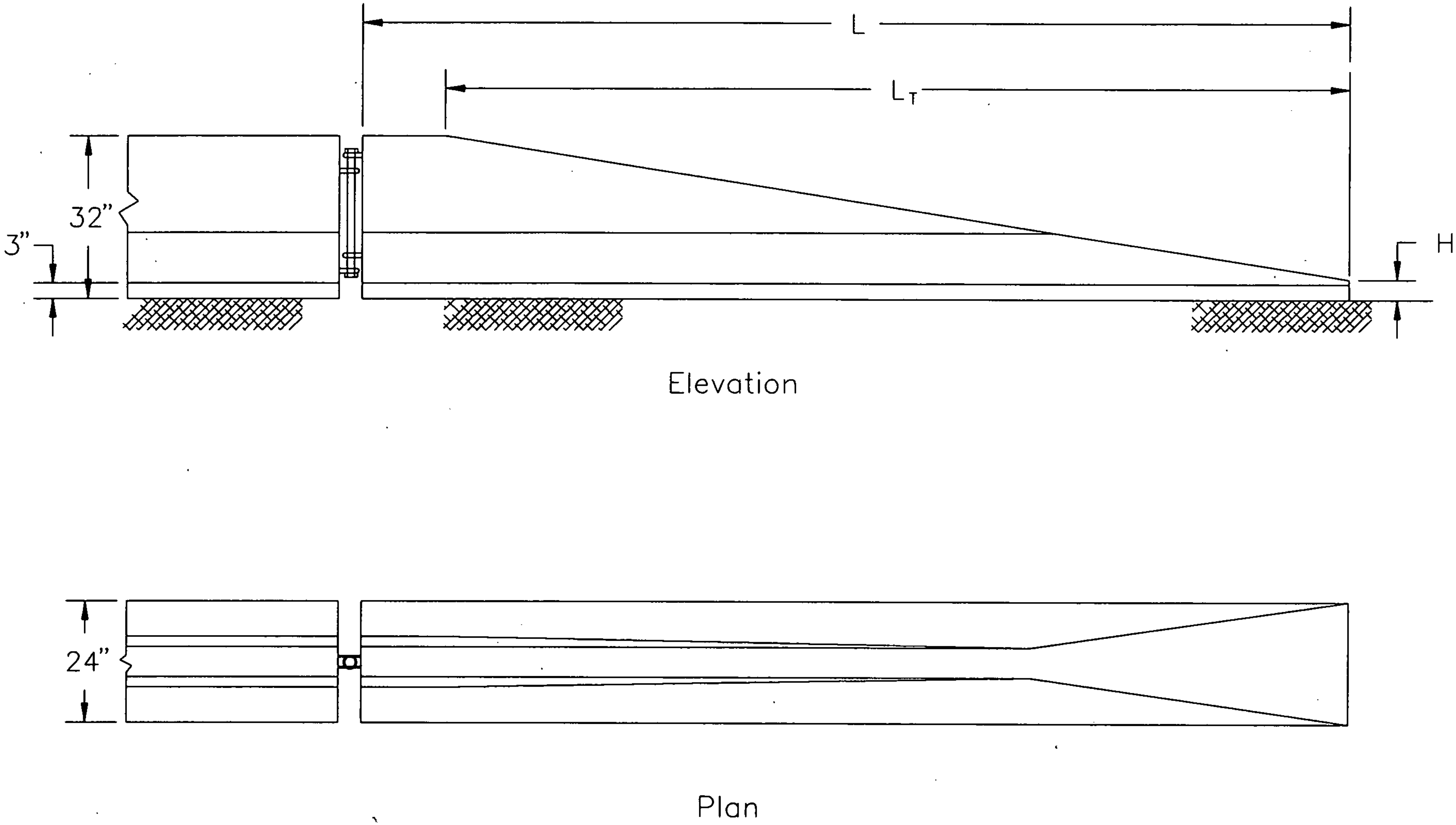


FIGURE III-1. CONVENTIONAL SLOPED-END TREATMENT

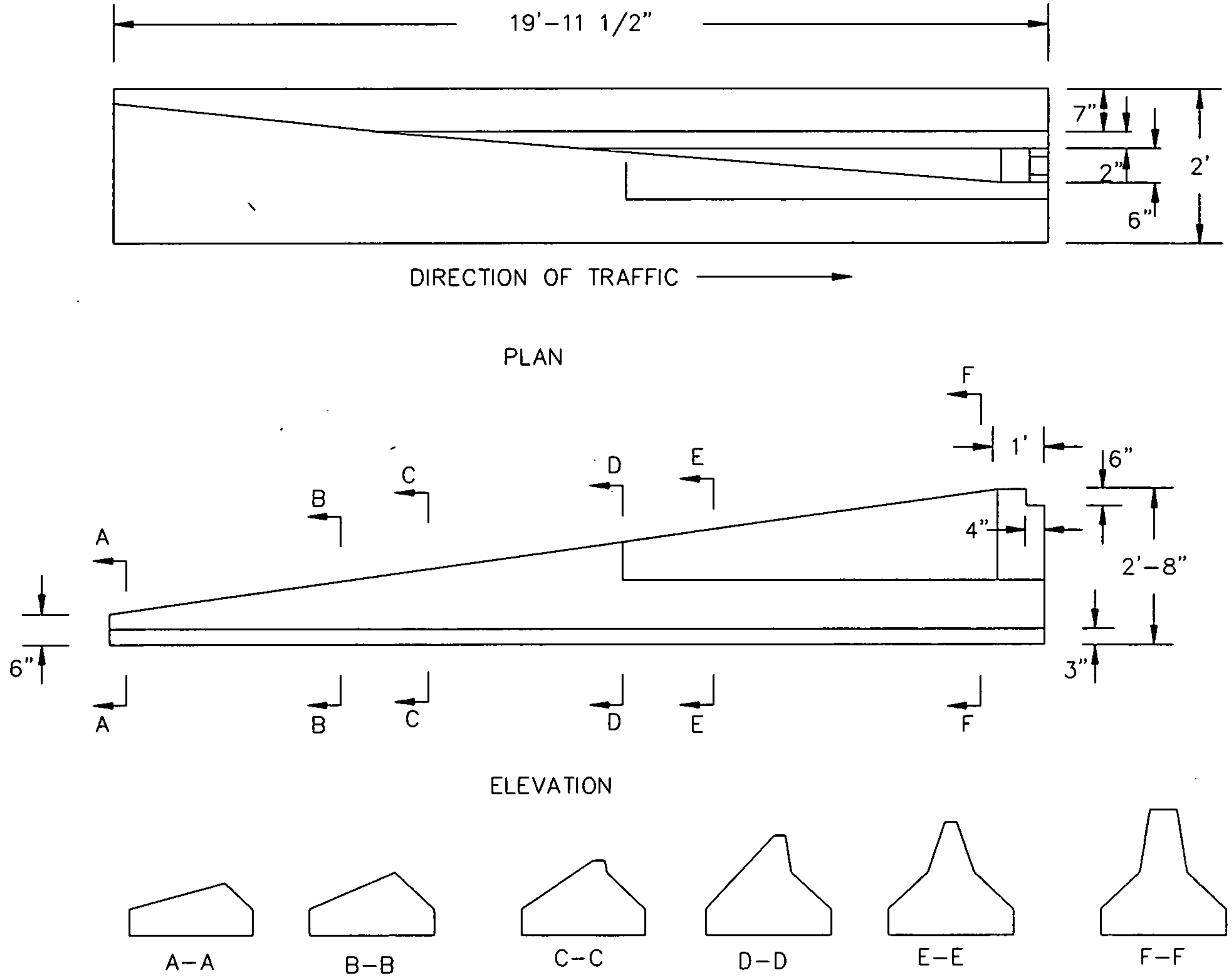
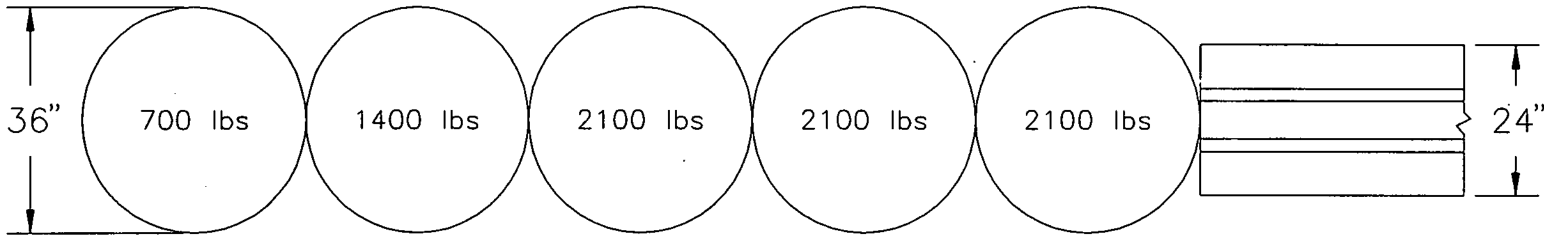
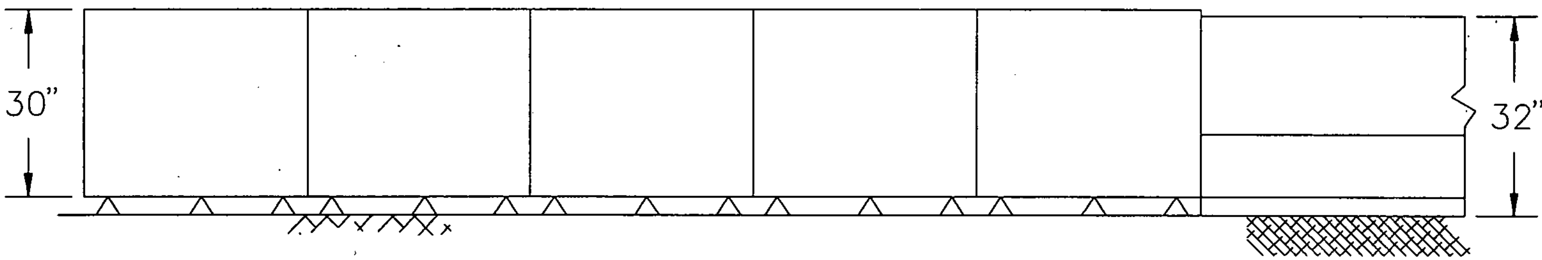


FIGURE III-2. NEW YORK SLOPED-END TREATMENT



TOP VIEW



ELEVATION

FIGURE III-3. SINGLE-ROW INERTIAL CRASH CUSHION conditions, it may or may not meet performance requirements for an angled impact along the side of the cushion or near the rear of the cushion. However, as discussed in Chapter V, the system does not appear to be a cost effective alternative for restricted work zone sites.

III-B-3. Other Designs

Some states use a full-array ICC to shield ends of barriers in restricted work zones provided adequate space is available. These cushions can be designed to meet performance requirements for permanent cushions, as recommended in NCHRP Report 230 (10) (tests 50, 52, 53, and 54), or for a reduced performance. Variations of full-array ICC's are given in Figures V-1 through V-4.

Another treatment used to shield the end of a CSSB is the GREAT$_{cz}$ system marketed by Energy Absorption Systems, Inc. (11). It can be designed to meet requirements for 60 mph or less impacts. A 60 mph design is shown in Figure V-7. Potential applications of this system in restricted work zones are discussed in Chapter V and in the User's Manual.

Development of the Advanced Dynamic Impact Extension Module (ADIEM) was completed the latter part of 1991 (52). General details of the design are shown in Figure V-8. Complete details and specifications of the ADIEM are given in reference 52. ADIEM is marketed by Syro Steel Company (53). Energy absorption elements are lightly reinforced, ultra low strength Perlite concrete. The redirection element (for angled impacts into the side of the system) is a heavily reinforced, conventional concrete, variable height curb with an automobile hub-height pipe rail. While it has had limited in-service exposure to date, ADIEM has been tested and evaluated in accordance with nationally recognized evaluation criteria (10), and has met the recommended performance criteria. Evaluation of the ADIEM as a candidate treatment for ends of the CSSB is discussed in Chapter V and in the User's Manual.

For the W-beam-on-barrel system a special end treatment has been designed and tested (12). It consists of a flared end section and a leading barrel to which the W-beam is anchored.

III-C. New Concepts

Several brainstorming sessions were held during the course of the study and a number of new end treatment concepts were developed. A general discussion of the operation and potential performance of the most promising concepts is presented in the following section. Reference should be made to the Phase I report for a more in-depth evaluation of these systems.

III-C-1. Sloped-End/Inertial Crash Cushion End Treatment

The sloped-end/ICC end treatment, illustrated in Figure III-4, is a combination of the sloped-end concrete treatment and the single-row ICC. This concept involves transitioning the standard concrete shape to a vertical wall with a width between 24 to 30 in. to provide a surface for placement of sand tubs. As illustrated in Figure III-4, the height of the barrier could be reduced somewhat in the transition section to decrease the taper rate. The tapered section of the barrier would be stair stepped to accommodate placement of the plastic tubs. Length of the tapered section and the number of sand drums can be selected to minimize the end treatment's destabilizing effect on impacting vehicles.

This system offers potentially significant improvements over the sloped-end treatment or the single-row ICC that are now widely used in construction zones. It does not have the rigid "coffin corner" end associated with the single-row ICC and, therefore, will not cause snagging during side impacts. Further, the sand tubs should slow impacting vehicles and thereby reduce the potential of the system for causing rollover when compared to the sloped-end treatment. A disadvantage of the system is the impairment to sight distance it would create in certain restricted work zones.

It is anticipated that this concept could be designed to attenuate most head-on impacts at speeds up to 45 mph. Further, a vehicle impacting the side of the terminal at a speed of 45 mph or less and an angle of 15 deg or less would likely be redirected if the concrete barrier is 12 in. high or taller at the point of impact. A vehicle impacting the side of the terminal at a point before the concrete shape reaches a 12 in. height may roll over and/or experience relatively high decelerations resulting from impacting heavy sand barrels for impact speeds of 45 mph. These potential problems notwithstanding, this system would

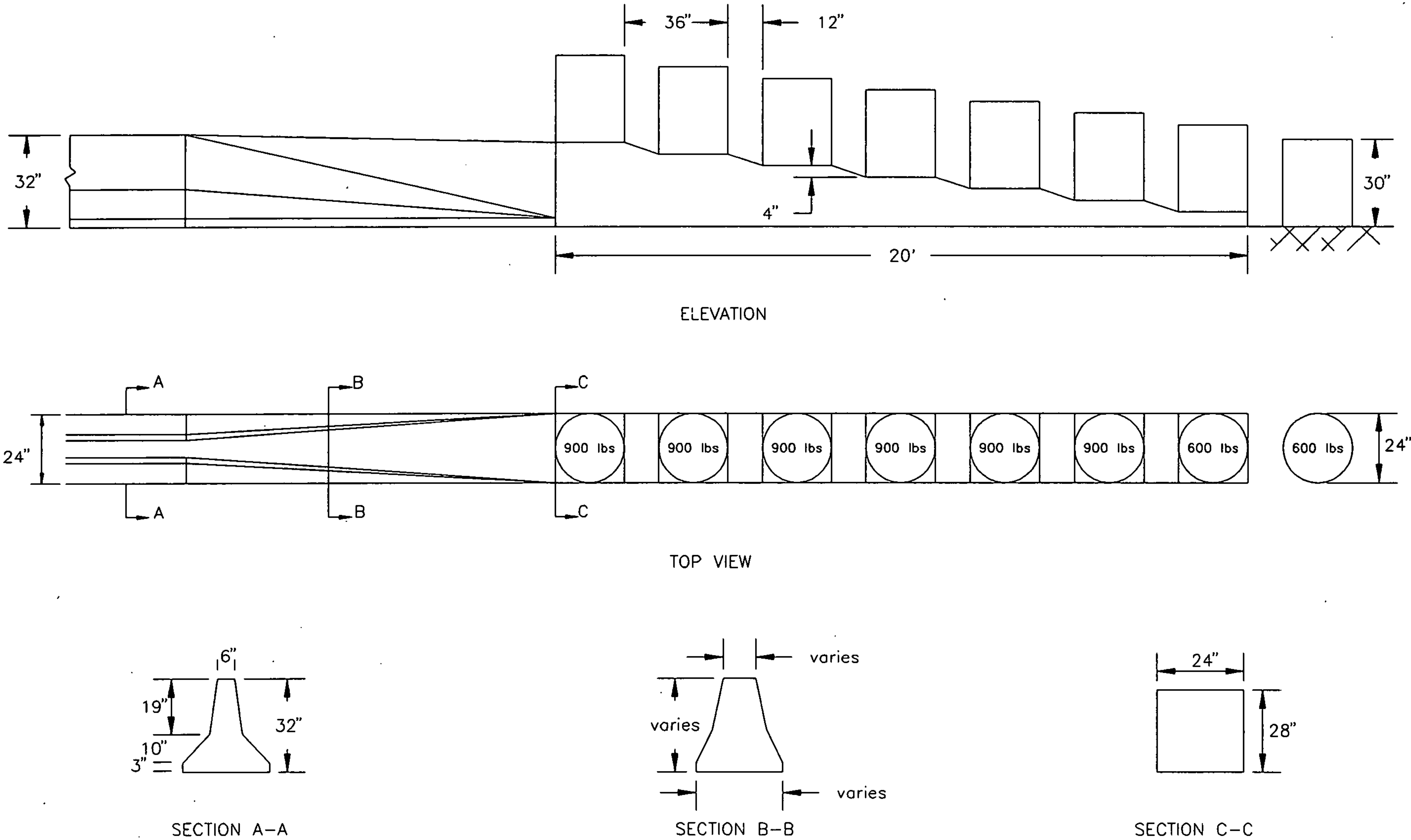


FIGURE III–4. SLOPED–END/INERTIAL CRASH CUSHION END TREATMENT greatly reduce the "window of vulnerability" for vehicular impacts present in each of the two component systems.

III-C-2. Rubber Cylinder End Treatment

This concept involves attaching cylindrical, rubber energy-absorbing elements to the end of a concrete barrier section. Elements of this type have been used in the design of a permanent end treatment (13). The permanent design required steel diaphragms and fender panels to provide redirection capacity. These items make the design relatively expensive, but its low repair costs offset some of the increases in initial costs. Although the high initial cost may prevent the permanent design from finding applications in the work zone environment, a reduced performance device should merit consideration. A reduced performance rubber end treatment would involve elimination of steel diaphragms and fender panels, illustrated in Figure III-5. Such a design should be capable of safely attenuating 45 mph head-on impacts.

III-C-3. Composite Beam Concept

This concept involves incorporating fiber-reinforced plastic (FRP) composite beams for energy-absorbing elements. Tests of composite beams have indicated that these elements can reliably dissipate large amounts of energy (1), and structural composite beams are now widely available and relatively inexpensive. Redirection capacity would be provided by W-beam fender panels and a breakaway post, illustrated in Figure III-6. Light weight and excellent bending characteristics enable long composite beams to function as energy dissipation elements. Further, the energy dissipation rate of these beams can be varied along the length to improve the efficiency of using long attenuation elements. Such long attenuation elements should allow a low speed end treatment to be designed with only one bay, thereby greatly reducing costs associated with providing diaphragms and fender panels. Note that a cable passed through the breakaway post and attached to the end of the concrete barrier would prevent the device from deflecting laterally during angular impacts on the nose. Further, attaching the end treatment to free standing barriers should reduce loadings on fender panels during side impacts, thereby facilitating the longer bay design.

Various shaped beams were experimentally evaluated during the Phase I effort. Static and dynamic pendulum tests were conducted. As a result of these tests and initial analysis, it was concluded this concept could be designed to safely attenuate head-on impacts as well as providing adequate redirective capacity for impact speeds of 60 mph. A 45 mph design would probably require only one bay while a 60 mph design would require additional and shorter bays to withstand the more severe side impacts.

III-C-4. Friction End Treatment Concept

The friction end treatment concept is similar to the composite beam design except energy is dissipated through sliding friction, generated by friction bands attached to fender panels, as illustrated in Figure III-7. This system would work best with a single long bay, which would also be advantageous from a cost standpoint. However, the energy dissipation rate for this system is constant for each bay, thereby reducing its efficiency. Preliminary analysis indicated this concept could be designed to accommodate impact speeds up 60 mph.

III-C-5. Extruder End Treatment Concept

The extruder end treatment concept is an adaptation of the recently developed guardrail extruder terminal (14) for treating the ends of a W-beam roadside barrier. The concept is illustrated in Figure III-8. Energy is dissipated by the flattening and bending of the W-beam as the extruder is pushed forward by the impacting vehicle. Guardrail elements provide redirection capacity for the system as well as serving as attenuation elements. Note that the system must be limited to a single bay, but intermediate breakaway posts could be used to provide additional support for side impacts. Initial analysis indicates this concept could be designed to accommodate impacts up to 45 mph. If higher performance levels are desired, it would be necessary to use a different beam element with a section modulus less than the standard W-beam to properly manage the energy dissipation of two beams for high-speed impacts.

III-D. Summary

Shown in Table III-1 is a summary of the estimated performance level and cost of the existing systems, discussed in Section III-B, and the new concepts, discussed in Section

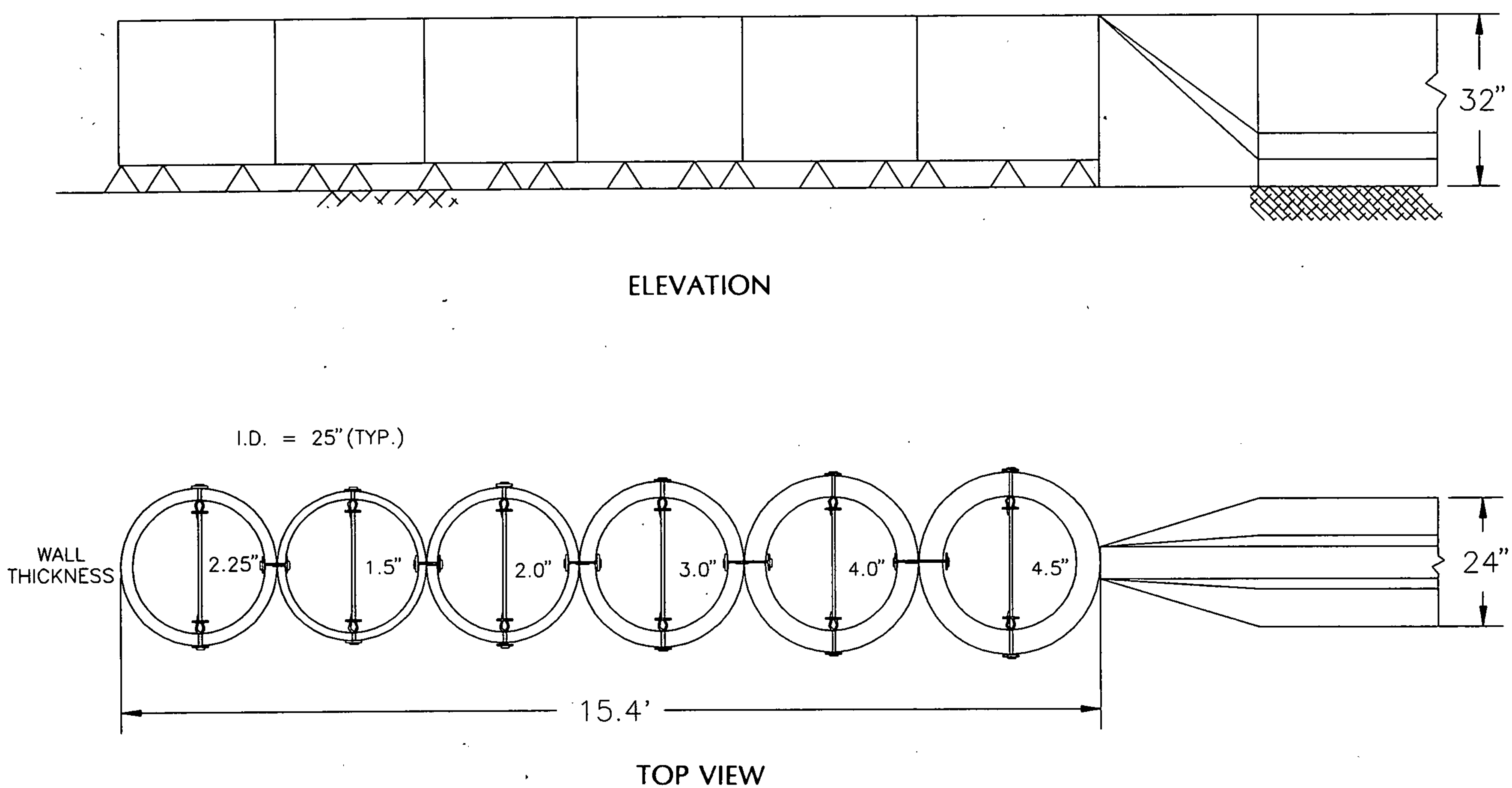


FIGURE III–5. REINFORCED RUBBER CYLINDER

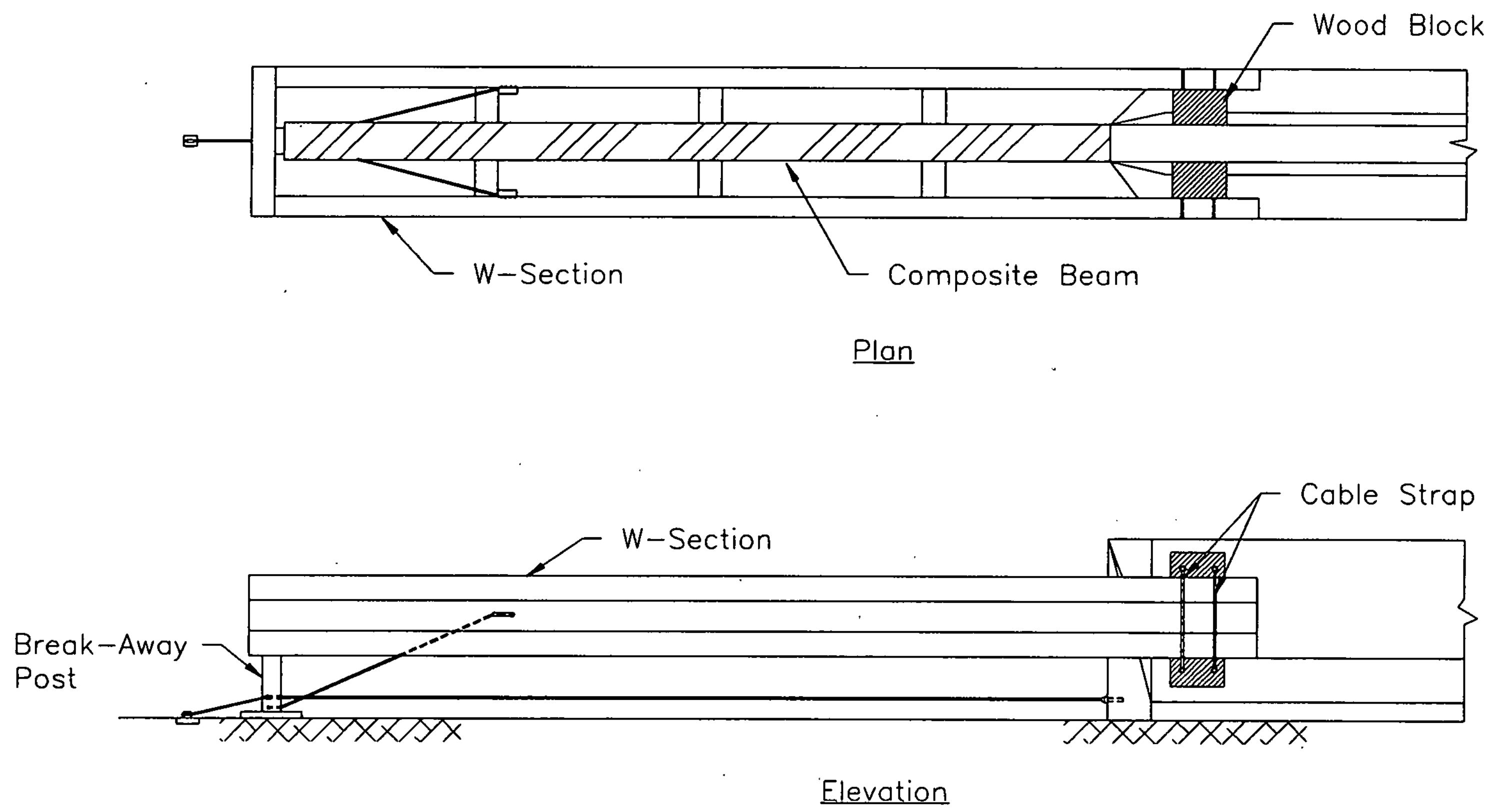


FIGURE III–6. COMPOSITE BEAM END TREATMENT

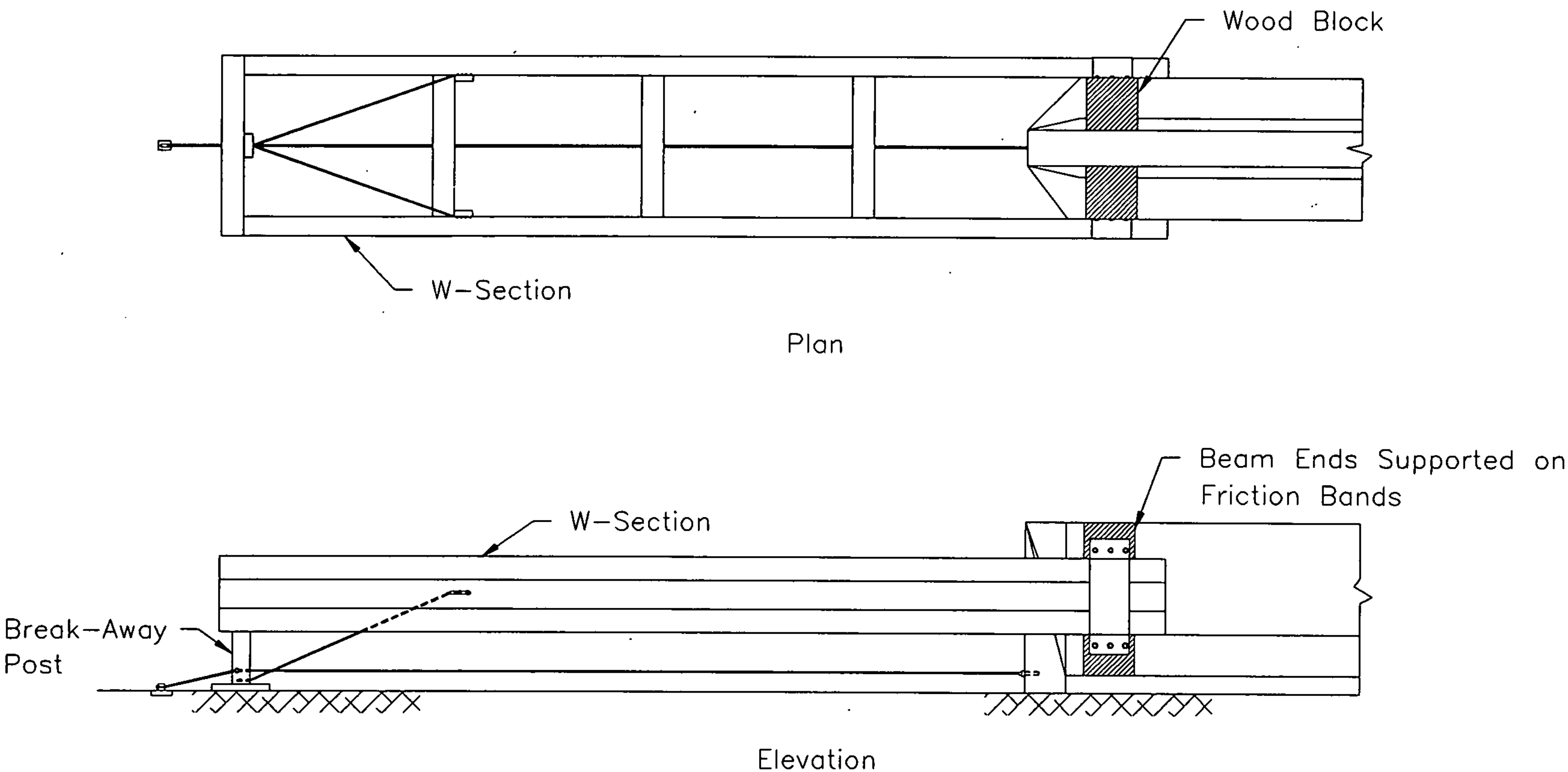


FIGURE III–7. FRICTION END TREATMENT

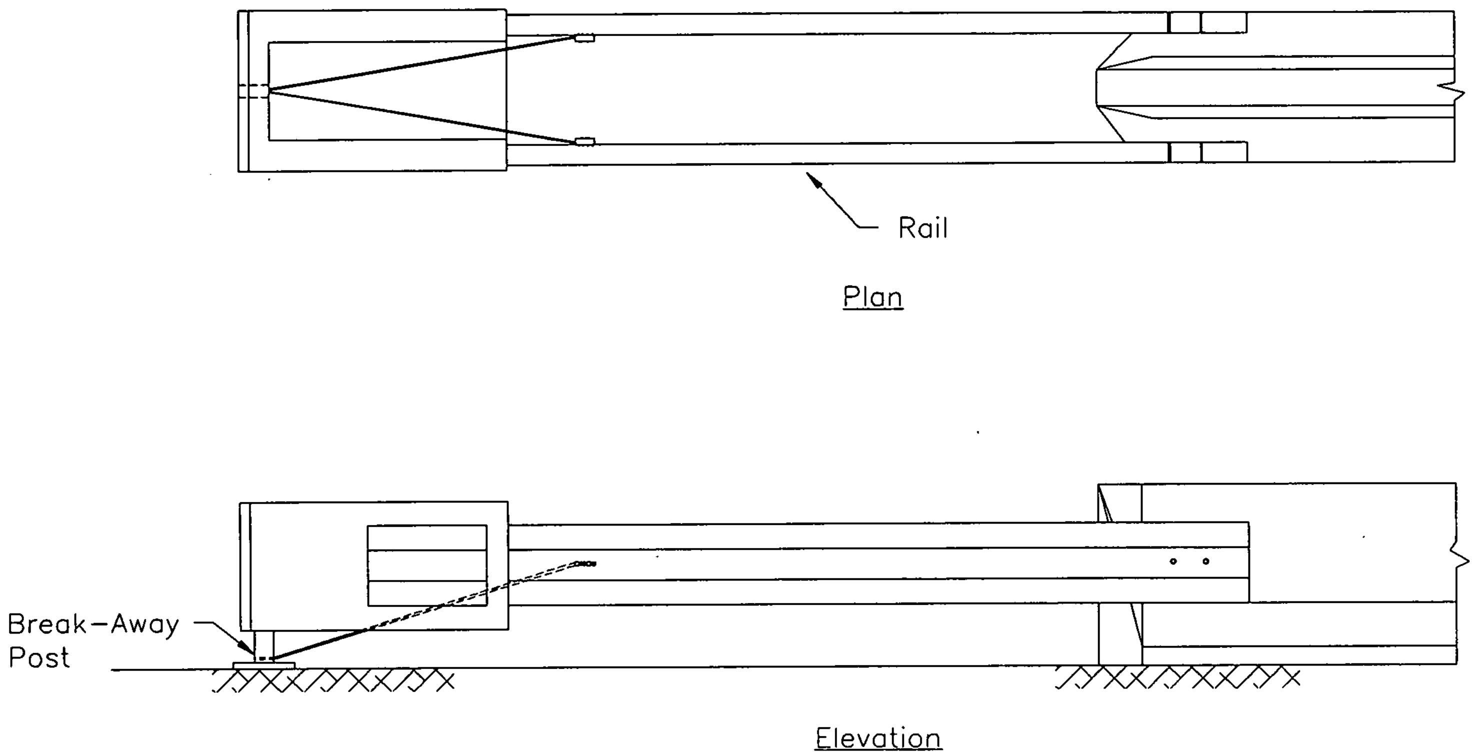


FIGURE III-8. EXTRUDER END TREATMENT

III-C. Note that Chapter IV reports on further testing and analysis of the sloping-end treatments and that Chapter V reports on a B/C analysis of various candidate barrier treatments.

TABLE III-1. ESTIMATED PERFORMANCE AND COST OF EXISTING AND NEW TERMINAL TREATMENT CONCEPTS FOR WORK ZONE BARRIERS

Description	Estimated Performance Level	Estimated Cost ($)
EXISTING DESIGNS		
A. Conventional Sloped-End	(a)	600
B. New York Sloped-End	(a)	600
C. Single-Row Inertial Crash Cushion	(b)	1000
D. 60 mph Full-Array Inertial Crash Cushion	(c)	2,400
E. 45 mph Full-Array Inertial Crash Cushion	(d)	1,800
F. 60 mph $GREAT_{cz}$ System	(c)	12,500
G. 45 mph $GREAT_{cz}$ System	(d)	7,500
H. 60 mph ADIEM System	(c)	5,000
I. 45 mph ADIEM System	(d)	3,500
NEW CONCEPTS		
J. Sloped-End/Inertial Crash Cushion	(e)	1,650
K. Rubber Cylinders	(b)	4,000
L. 60 mph Composite Beam	(c)	3,000
M. 45 mph Composite Beam	(d)	1,850
N. Friction Concept	(d)	1,850
O. Extruder Concept	(d)	2,750

[a] For a taper length of approximately 20 ft this system meets recommended performance criteria (10) for head-on impacts up to about 45 mph and for side impacts up to about 30 mph.
[b] Meets recommended performance criteria (10) for head-on impacts up to about 45 mph. Side-hit capabilities are limited.
[c] Meets all recommended performance criteria (10) for impact speeds up to 60 mph.
[d] Meets all recommended performance criteria (10) for impact speeds up to 45 mph.
[e] Performance between b and d.

APPENDIX B

CHAPTER FOUR

TEST AND EVALUATION OF BARRIER ELEMENTS

IV-A. General

Results of the Phase I effort indicated run-outs of the concrete safety-shaped barrier (CSSB) used in restricted work zones could be safely and cost-effectively flared at an angle considerably larger than permitted by current standards for permanent barriers (2). Larger angles, or steeper flare rates, could eliminate or mitigate many of the problems now faced in restricted work zones. Note that run-out lengths are inversely proportional to the flare rate. A significant effort was therefore directed toward the testing and evaluation of the effects of flare rate for a widely used temporary, precast CSSB. The purpose of these tests was to determine effects of flare rate on vehicular impact performance and occupant risk. Note for a given vehicular encroachment angle from the travelway, the impact angle increases as the flare rate increases.

Many states use a concrete, sloped-end section to terminate the end of a CSSB. It is relatively inexpensive, durable, portable, reusable, and requires minimal space. Although it is known to have poor impact performance for high-speed impacts, its performance at speeds common to most restricted work zones was largely unknown. Due to its wide use and the attributes just mentioned, it was concluded that further testing and analysis for lower-speed impacts were warranted. Consequently, tests and evaluation of two different concrete sloped-end treatments were made.

A total of fourteen full-scale crash tests were budgeted for the project; eight were used to study the effects of flare rate and associated factors, and six were used to evaluate sloped-end treatments. The fourteen tests were used to the extent possible to experimentally determine impact performance of the respective treatments. Crash tests are unfortunately quite expensive, which limits the number that can be conducted. A modified version of the HVOSM computer program (3) was therefore used to supplement and fill voids in crash test results.

IV-B. Test Articles

IV-B-1. Precast CSSB Used to Evaluate Flare Rate

It was desirable that a widely used precast CSSB system be used in the crash test program to evaluate effects of flare rate. A study by Loumiet, et. al., (15) found the "pin and rebar" and the "pin and wire rope" are by far the most widely used connection designs for precast CSSB systems in the United States (41 states use one or the other of these designs). Of these two types, which are similar in design and performance, the pin and rebar is dominant. Segment lengths for these types of connections vary from 10 ft to 20 ft, but the 10 ft length is used by a large majority of states.

The precast CSSB system selected for testing is shown in Figure IV-1. It is a pin and rebar design with a segment length of 10 ft. To be noted is the pin size (1 in. nominal diameter, steel pin) is typical for this connection design (15). Photos of the design are shown in Figure IV-2.

IV-B-2. Sloped-End Treatments for CSSB

Two types of concrete sloped-end treatments for the CSSB are used in the United States. The first, and by far the most dominant, is what is referred to herein as the conventional sloped-end treatment (CSET). Figure III-1 shows the basic parameters used to describe the CSET. Based on a review of current practice the "H" and "L_T" dimensions were selected to be 4 in. and 19 ft, respectively, for crash test evaluation. As described subsequently, a parametric study was conducted with a computer program to examine other values of L_T and impact conditions not covered by the crash tests. Figure IV-3 shows the dimensions of the CSET and the manner in which it was anchored for each of the crash tests. Photos of the as-tested CSET are shown in Figure IV-4.

The other sloped-end treatment examined is shown in Figure III-2. It is widely used in the state of New York and is referred to herein as the New York sloped-end treatment (NYSET). As can be seen in Figure IV-5, the NYSET was anchored in the same manner as was the CSET. Photos of the as-tested NYSET are shown in Figure IV-6.

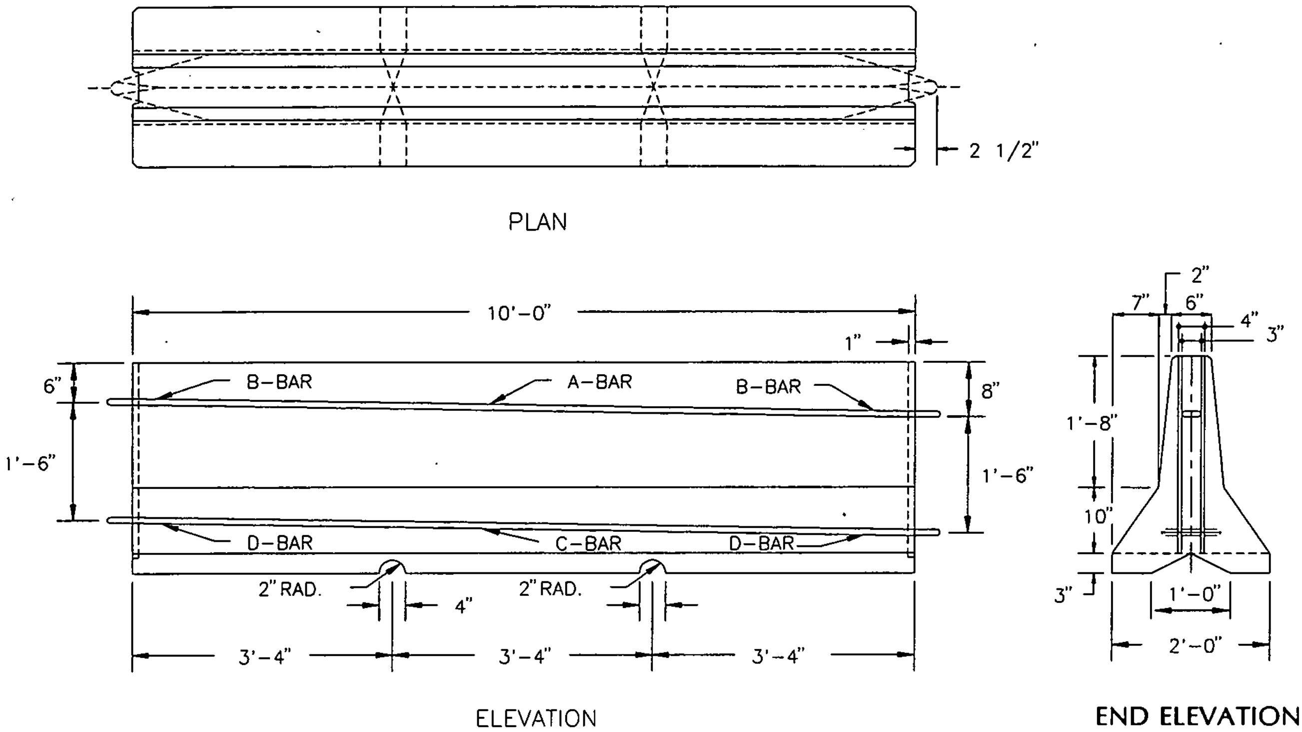


FIGURE IV-1. PRECAST CSSB USED IN TEST PROGRAM

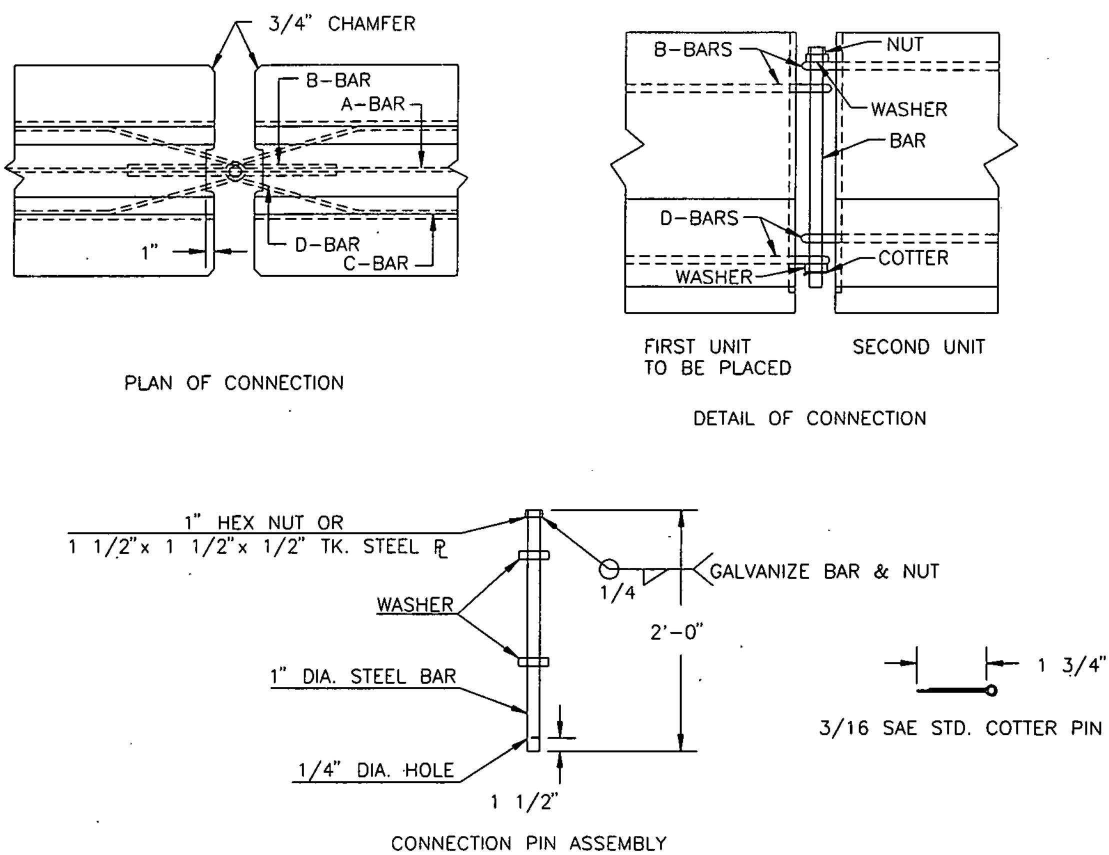
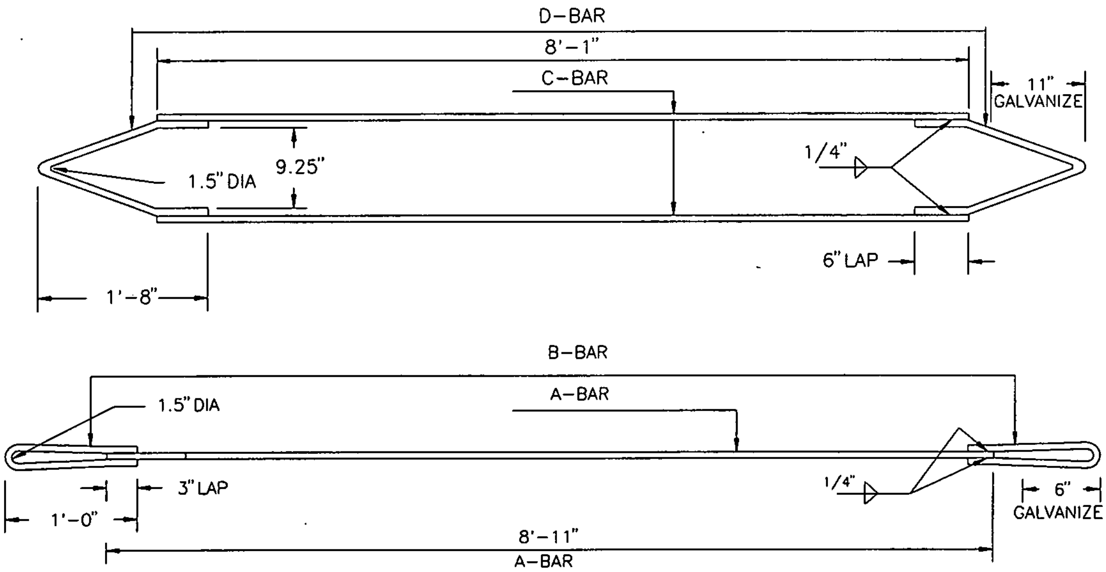


FIGURE IV-1. PRECAST CSSB USED IN TEST PROGRAM (CONTINUED)



BAR LIST				
MARK	SIZE	NO. BARS	SHAPE	LENGTH
"A"	#6	1	STRAIGHT	8'-11"
"B"	3/4" SMOOTH	2	BENT	2'-2"
"C"	#6	2	STRAIGHT	8'-11"
"D"	3/4" SMOOTH	2	BENT	3'-7"

FIGURE IV-1. PRECAST CSSB USED IN TEST PROGRAM (CONTINUED)

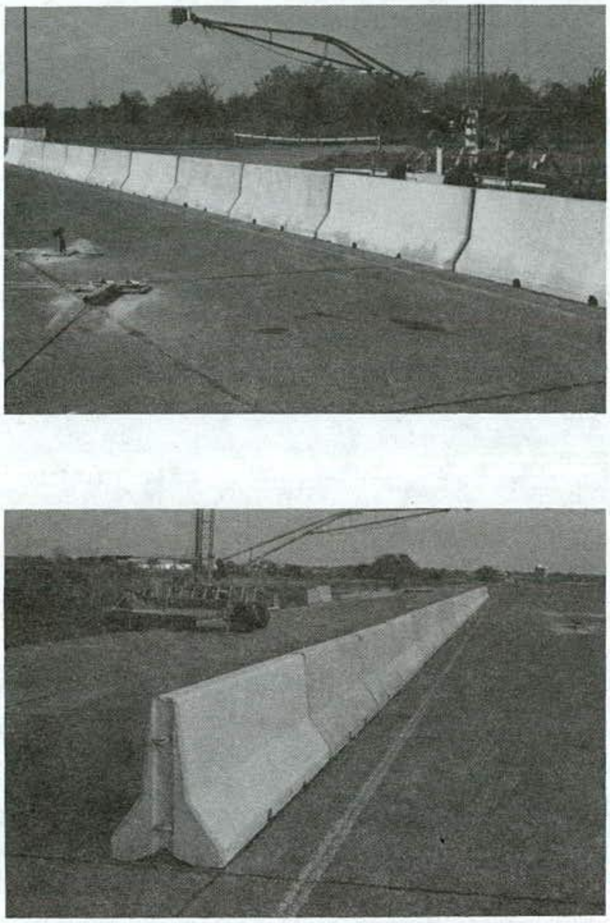


FIGURE IV-2. PHOTOS OF PRECAST CSSB USED IN TEST PROGRAM

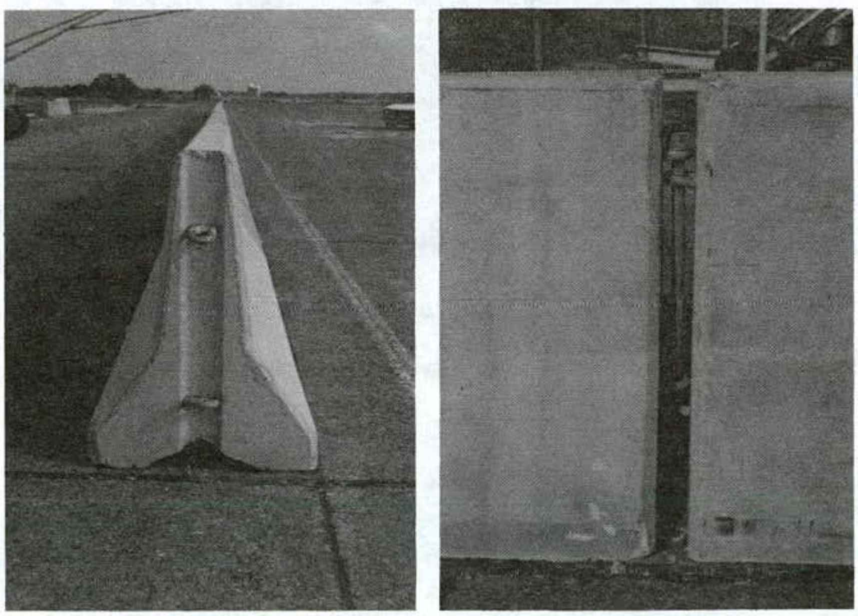


FIGURE IV-2. PHOTOS OF PRECAST CSSB USED IN
TEST PROGRAM (CONTINUED)

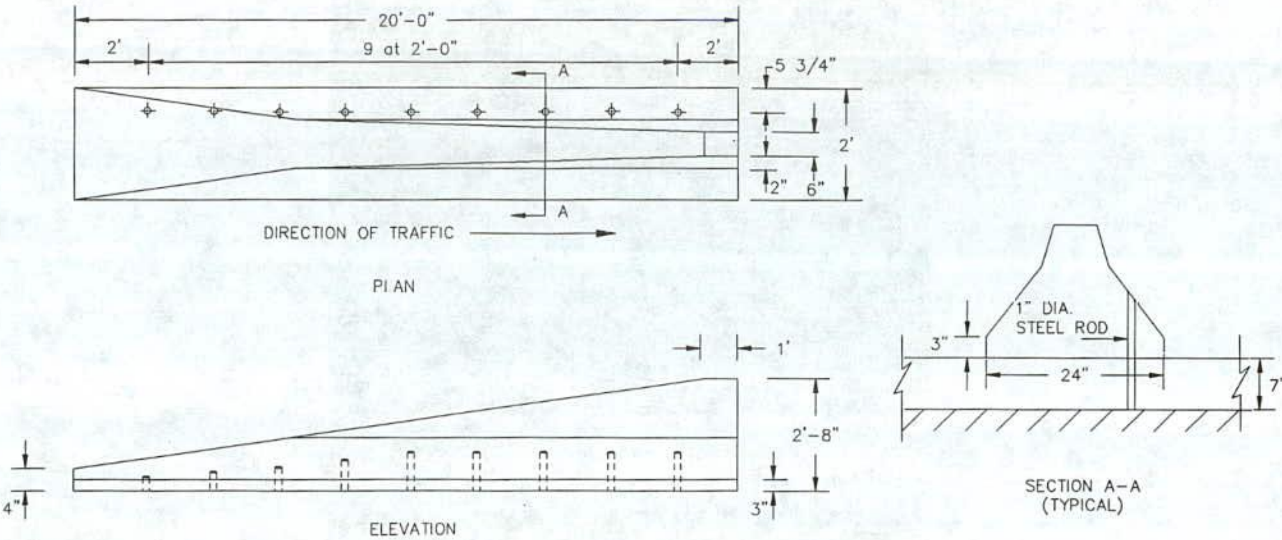


FIGURE IV-3. CSET DETAILS

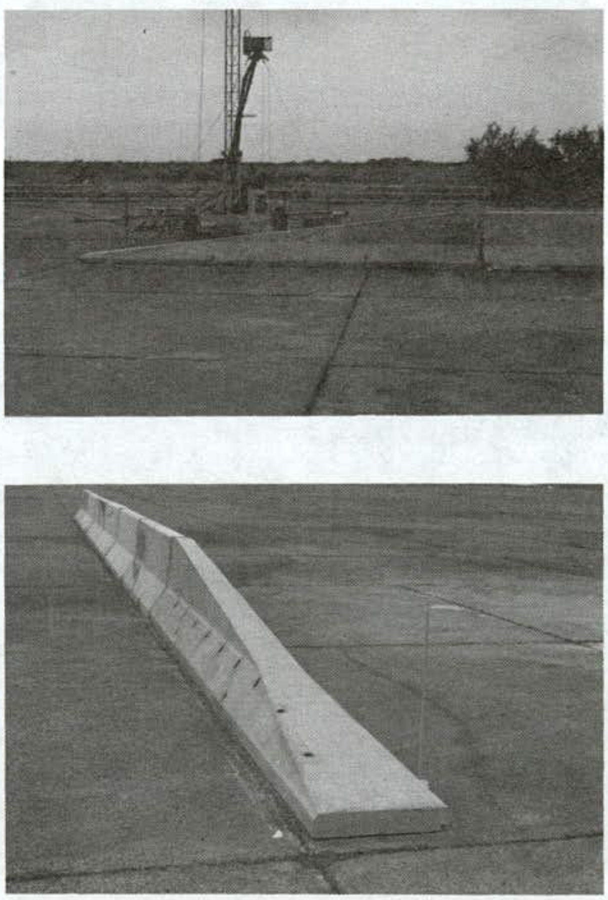


FIGURE IV-4. PHOTOS OF CONVENTIONAL SLOPED-END TREATMENT USED IN TEST PROGRAM

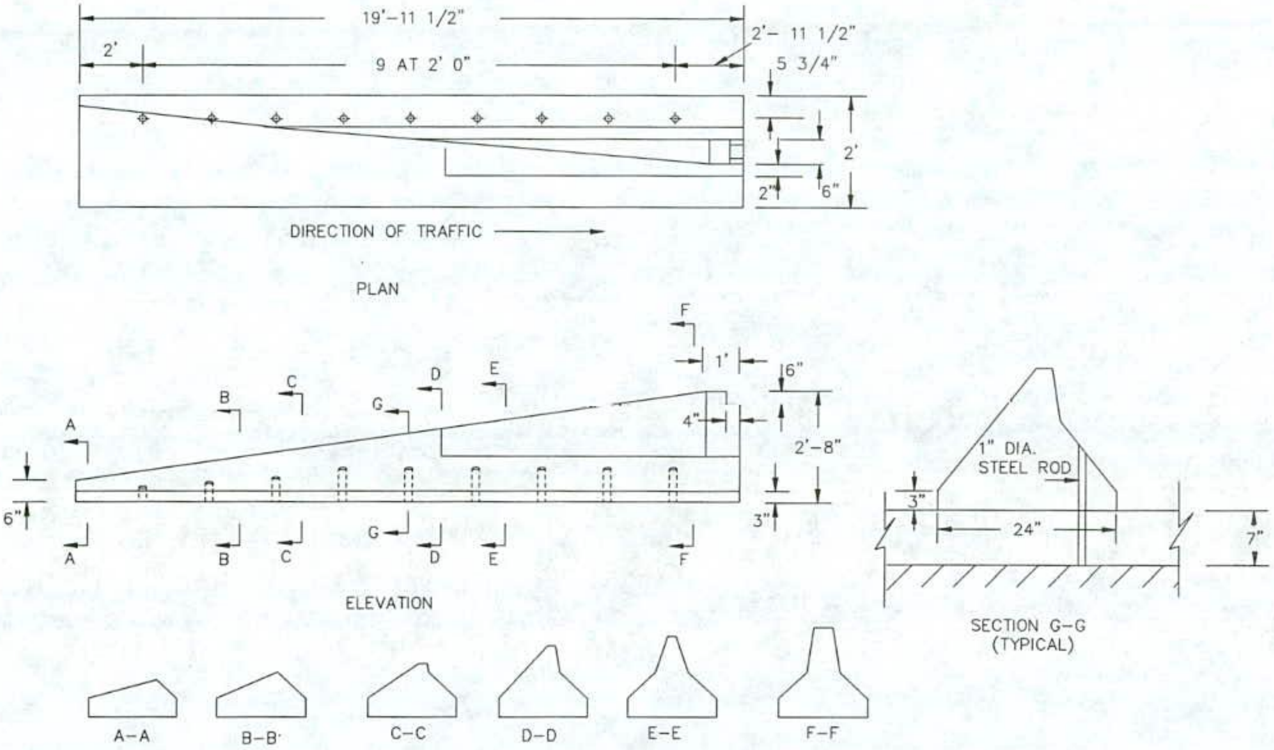


FIGURE IV-5. NYSET DETAILS

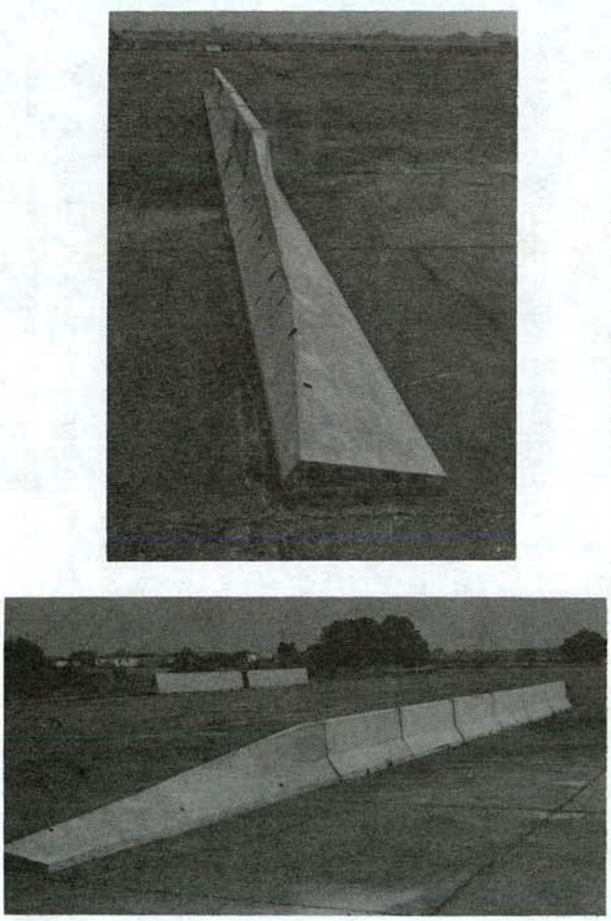


FIGURE IV-6. PHOTOS OF NEW YORK SLOPED-END TREATMENT USED IN TEST PROGRAM

IV-C. Test Conditions and Results

As a result of surveys of typical restricted work zones, as described in Chapter II, it was determined that operating speeds through a large majority of these zones were 45 mph or less. In view of this finding and in view of the sparsity of designs and design criteria for this speed range, it was concluded that a major part of the effort should be directed at barrier treatments for 45 mph or lower speeds. Test and evaluation guidelines contained in NCHRP Report 230 (10) were used to the extent possible; Report 230 does not specifically address testing of work zone barriers for reduced speed (less than 60 mph) conditions. To be noted is that an update to Report 230, currently under preparation (16), will address the test and evaluation of work zone barriers and will include guidance for 45 mph tests.

Tests were conducted with small cars weighing approximately 1,800 lb and large sedans weighing approximately 4,500 lb in accordance with Report 230. The small car is used primarily to evaluate occupant risks and the large car is used primarily to evaluate structural adequacy of the barrier. Results of the tests were assessed in terms of the evaluation criteria of Report 230.

IV-C-1. Tests to Evaluate Flare Rate

A total of eight full-scale crash tests were conducted to evaluate various design factors related to the flared portion of a precast CSSB. Details of the precast CSSB were described in Section IV-B-1. A summary of conditions and results of these tests are given in Table IV-1. Complete details of the tests are given in Appendix A.

Tests 7110-1 and -2 were conducted with the barrier in a free-standing condition, i.e., it was resting on a paved surface but with no anchorage. As shown in Figure IV-7, the barrier was assembled along a straight line. These tests were selected to evaluate a baseline flared configuration. Note the impact point was purposely selected near the middle of the assembled barrier to avoid the influence of end effects. The impact conditions were also selected to represent a rather extreme impact. If, for example, a barrier was flared at a 6-to-1 rate (an angle of approximately 9.5 deg with respect to the travelway), a vehicle would have to approach the barrier at an angle (with respect tot the travelway) of about 20.5 deg to reach a 30 deg impact angle. For most restricted work zones where the barrier is

TABLE IV-1. SUMMARY OF TESTS TO EVALUATE FLARE RATE

Test No.	Test Article	Impact Conditions			Occupant Risk Criteria				Vehicle Stable?	Barrier Deflection (in.)
					Impact Velocity (ft/sec)		Ridedown Accel. (G's)			
		Veh. Wt (lb)	Speed (mph)	Angle (deg)	Long.	Lat.	Long.	Lat.		
7110-1	Free-Standing Precast Barrier, 10 ft Segments	1,970[a]	44.6	28.0	20.5	16.1	3.7	4.3	Yes	17
7110-2	Free-Standing Precast Barrier, 10 ft Segments	4,500	46.8	30.0	18.0	12.7	6.9	6.0	Marginal	55
7110-3	Rigid Safety-Shaped Barrier	1,967[a]	45.4	28.5	21.3	22.6	3.4	3.6	Yes	0
7110-4	Rigid Safety-Shaped Barrier	4,500	48.1	29.0	26.7	20.8	6.2	5.4	Yes	0
7110-7	Free-Standing, Kink	4,500	45.1	30.1	12.9	12.3	3.5	3.6	Yes	56
7110-10	Anchored, Kink	4,500	44.4	31.3	13.1	13.3	6.4	7.7	Yes	48.5
7110-13	Rigid Safety-Shaped Barrier	1,970[a]	47.5	40.1	33.6	28.4	5.8	6.4	Yes	0
7110-14	Rigid Safety-Shaped Barrier	4,500	47.9	40.5	26.1	25.0	6.3	9.0	No (Overturn)	0

[a] Includes weight of 170 lb dummy.

Note: Dummy not used in 4,500 lb test vehicle.

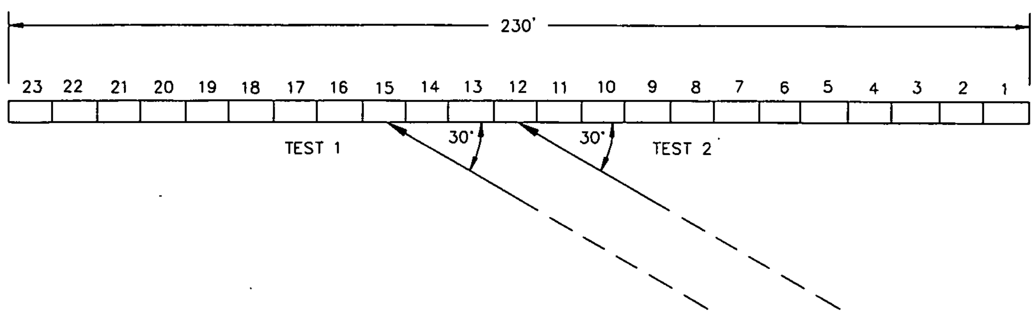


FIGURE IV-7. IMPACT CONDITIONS – TESTS 7110-1 AND 7110-2 typically placed in close proximity to traffic, a 45 mph/20 deg approach to the barrier would be a low probability event. The target impact speed and angle for these tests were 45 mph and 30 deg; the actual speed and angle are given in Table IV-1.

In test 1 the car was redirected and remained stable after impact and occupant impact velocities and ridedown accelerations were below recommended limits of reference 10. Maximum barrier deflection was approximately 17 in.

In test 2 the car was redirected but almost overrode the barrier. Maximum barrier deflection was 55 in. and one of the barrier joints separated due to failure of the 1-inch pin. Occupant impact velocities and ridedown accelerations were below recommended limits of reference 10. It was obvious the limit of performance of the free-standing barrier had been reached in test 2. In other words, the 4,500 lb car could be expected to penetrate the barrier at impact conditions more severe than 45 mph/30 deg. It should be noted, using current indicators of loading on a barrier, as given by the impact severity, IS, (see discussion of impact severity, IS, in Section V-B-4) that the impact loading on the barrier in test 2 was about 85 percent of that expected from a 60 mph/25 deg impact. Most permanent barriers are designed to contain and redirect the 4,500 lb test vehicle at 60 mph/25 deg (10).

It was apparent upon inspection of the barrier after test 2 that the 1 in. diameter, steel pin was the weak link in the barrier system (see photos of test results in Appendix A). In test 2 several of the pins underwent large deformations and one actually pulled free of the rebar hoop. The pin pulled free partially as a result of the lack of a bolt/washer combination at the bottom of the pin. The design tested had a washer and a cotter key at the lower end of the pin. It is believed that the impact performance of the system tested could be improved significantly by use of a positive bolt/washer combination by increasing the size of the pin and by using a higher strength steel. This improvement should increase the barrier's capacity to that required of a permanent barrier. The reader should refer to the literature (15,17) for ways to optimize the design of the pin and rebar connection and for capacities of other connection designs.

The test article for tests 7110-3, -4, -13, and -14 was the same as that in tests 1 and 2 except it was fixed to prevent movement of any kind. The barrier was placed against an existing 32-in. high vertical concrete wall and braced to prevent lateral, longitudinal and rotational movements. In this manner the barrier represented a rigidly anchored precast concrete barrier. Photos of the barrier for these tests are given in Figure IV-8.

Vehicle weights and target impact conditions for tests 3 and 4 were the same as tests 1 and 2, respectively. Table IV-1 gives the actual impact speed and angle. Both cars redirected in a stable manner with no tendency to overturn. Occupant impact velocities and ridedown accelerations were within recommended limits of reference 10. It is noted that the lateral occupant impact velocity in both tests exceeded the recommended design or desirable limit of 20 ft/sec but was considerably below the 30 ft/sec limit. As expected, occupant risk values for both cars impacting the rigid barrier were higher than those of the free-standing barrier. Also as expected, the heavy car was contained in a more stable manner upon impact with the rigid barrier than with the free-standing barrier.

Target speed and angle for tests 13 and 14 were 45 mph and 40 deg. The actual impact speed and angle are given in Table IV-1. The small car was contained and redirected in a stable manner and the occupant risk values were within recommended limits of reference 10. However, the longitudinal and lateral occupant impact velocities exceeded the recommended design limit. The large car almost overrode the barrier before returning to the impact side of the barrier. Upon returning to the pavement, it overturned and came to rest on its top, causing extensive crush to the roof. Occupant risk values were within recommended limits during the initial impact. However, the occupant flail-space model of reference 10 is not intended for use in evaluating occupant risk associated with an overturn. In any case it was apparent that the overturn would have been a life-threatening event.

In test 14 the right-rear tire contacted the vertical wall (against which the precast barrier was placed) upon the return of the car to the impact side of the barrier. Upon review of the high-speed test film, it was concluded that this did not have a significant effect on the response of the vehicle. It was concluded that the car would have returned to the impact side and that it would have overturned, regardless of the right-rear contact.

In tests 7110-7 and -10 the test article was the same as that in tests 1 and 2 but the layout or barrier orientation was different. As shown in Figure IV-9, the purpose of these tests was to evaluate the structural adequacy of a typical temporary barrier system in the transition or "kink" area. Both tests were with a 4,500 lb car impacting at 45 mph at the

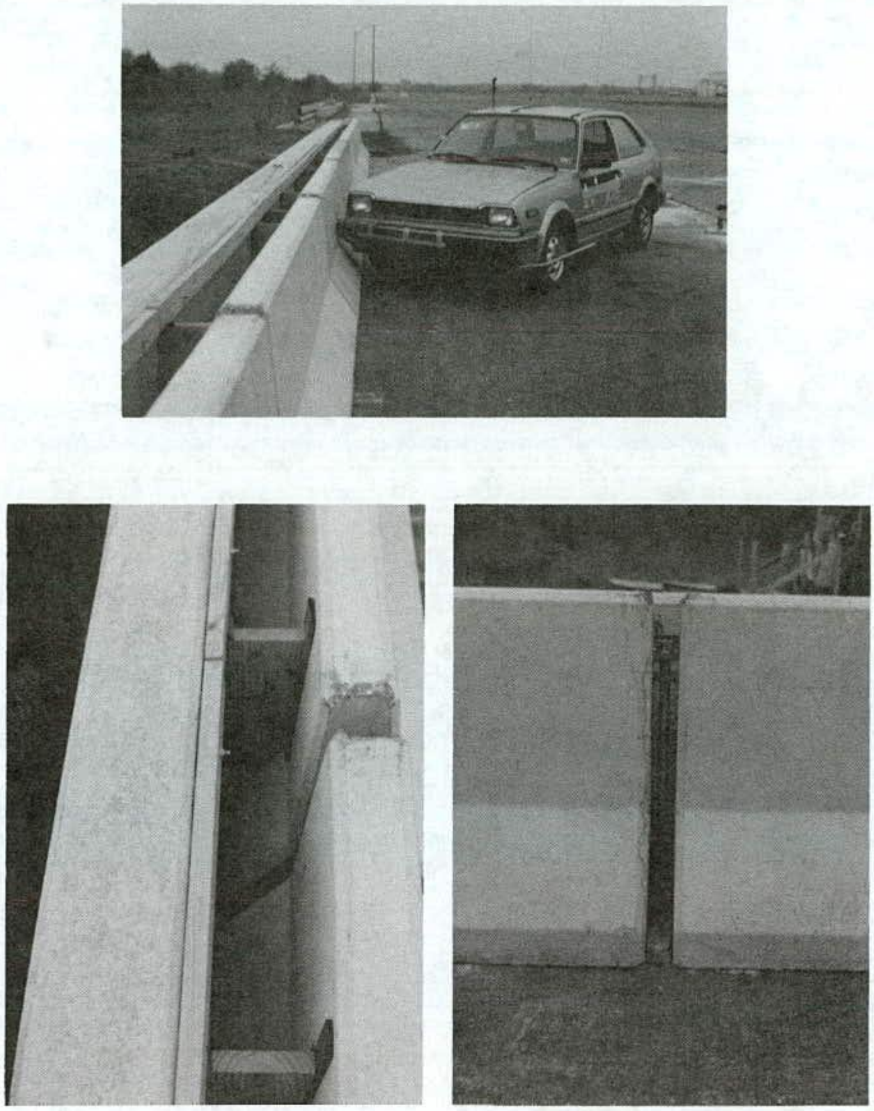


FIGURE IV-8. PHOTOS OF CSSB FOR TESTS 7110-3, -4, -13, AND -14

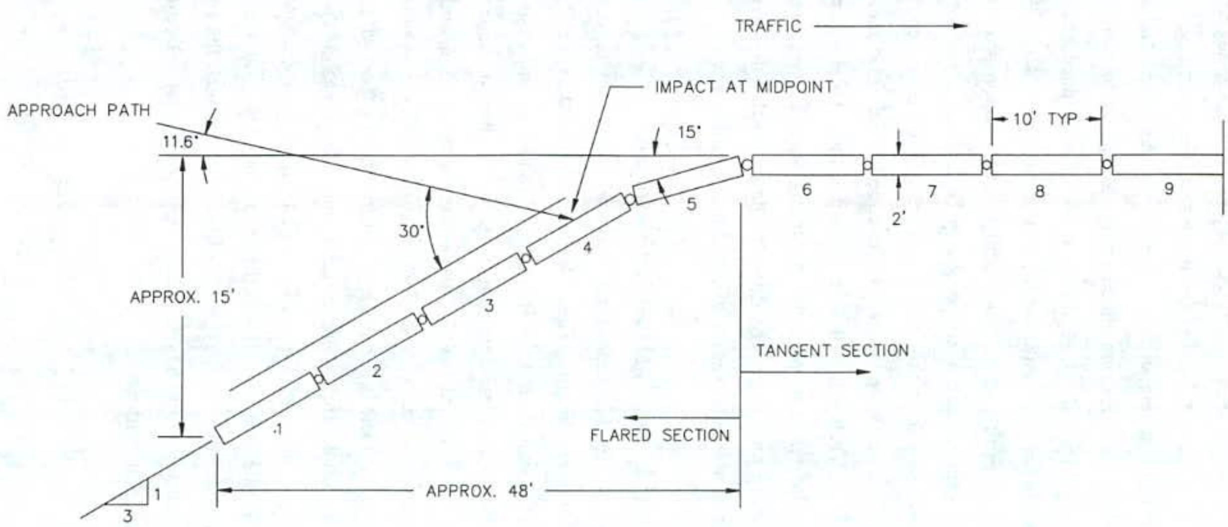


FIGURE IV-9. BARRIER LAYOUT FOR TESTS 7110-7 AND 7110-10 approach angle, indicated on Figure IV-9. Although not shown on Figure IV-9, there were ten barrier segments in the tangent section, i.e., segments 6 through 15.

In test 7 the entire barrier was free-standing, i.e., the segments were not anchored to the concrete surface. The car was contained and redirected and occupant risk values were below recommended limits. Maximum barrier movement was 56 in.

In test 10, segments 1 and 6 were anchored. This is believed to be a typical anchorage configuration for certain work zone activities, e.g., bridge rehabilitation. To be noted is that in an actual bridge rehabilitation project all of the barrier elements in the tangent section would probably be anchored, but for purposes of the crash test it was necessary to anchor only segment 6. The car was contained and redirected and occupant risk values were below recommended limits. Maximum barrier movement was 48.5 in.

Tests 7 and 10 were conducted since it was assumed that an impact in the "kink" area would result in vehicular pocketing and/or snagging and, consequently, would be more severe than elsewhere along the flared portion of barrier. Results of tests 7 and 10 when compared with results of test 2 proved otherwise.

IV-C-2. Tests of Sloped-End Treatments

Six full-scale crash tests were conducted to evaluate two different sloped-end treatment designs. These designs, referred to as the CSET and the NYSET, are described in Section IV-B-2. A summary of conditions and results of these tests are given in Table IV-2. Complete details of the tests are given in Appendix A.

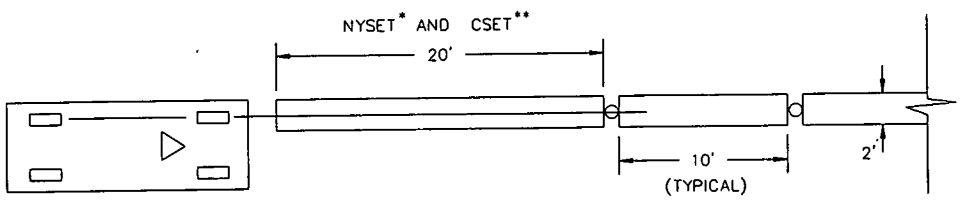
Note the NYSET was evaluated in tests 5, 6, and 12 and the CSET was evaluated in tests 8, 9, and 11. Also note that the small car was used in each of these tests. Overturn of the vehicle is the primary concern for an impact with a sloping-end treatment and a small car is inherently more unstable than a large car for an impact of this type.

In tests 5 (NYSET) and 8 (CSET) the car approached head-on at 45 mph with the left side tires aligned with the centerline of the end treatment, as illustrated in Figure IV-10. The car did not overturn in either test, although the roll angle reached a maximum value between 40 and 50 deg in both tests. Occupant risk criteria were well below recommended limits in both tests.

TABLE IV-2. SUMMARY OF TESTS TO EVALUATE SLOPED-END TREATMENTS

Test No.	Test Article	Impact Conditions			Occupant Risk Criteria[b]				Vehicle Stable?	Barrier Deflection (in.)
					Impact Velocity (ft/sec)		Ridedown Accel. (G's)			
		Veh. Wt (lb)	Speed (mph)	Angle (deg)	Long.	Lat.	Long.	Lat.		
7110-5	NYSET	1,965[a]	45.0	0	6.7	7.6	0.6	1.6	Marginal	0
7110-6	NYSET	1,968[a]	45.5	30.2	10.4	5.5	0.9	2.1	No (Overturn)	0
7110-8	CSET	1,970[a]	45.8	0	5.5	4.1	3.9	4.7	Marginal	0
7110-9	CSET	1,970[a]	45.3	29.6	14.3	8.2	3.5	3.6	No (Overturn)	0
7110-11	CSET	1,968[a]	30.4	31.2	17.3	10.6	3.6	7.0	No (Overturn)	0
7110-12	NYSET	1,970[a]	30.1	29.1	8.1	7.1	1.1	11.2	No (Overturn)	0

[a] Includes weight of 170 lb dummy.
[b] Determined prior to ground contact by vehicle.



PLAN VIEW

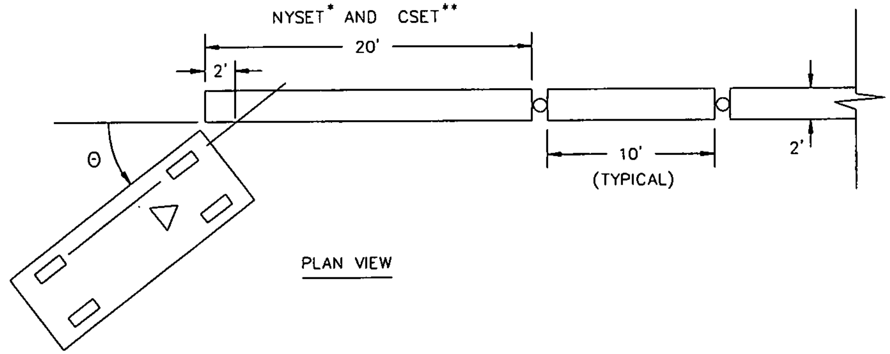
* TEST 7110-5
** TEST 7110-8

FIGURE IV-10. IMPACT CONDITIONS - TESTS 7110-5 AND 7110-8

Upon careful review of the high-speed film of tests 5 and 8, it was noted that a guide plate attached to the right-front wheel for directing the vehicle into the test article made contact with the pavement just prior to wheel contact. This induced a sudden clockwise steer input, tending to steer the vehicle to the right. This appeared to have the effect of neutralizing the clockwise roll motion of the vehicle, probably preventing an overturn. An HVOSM simulation of the impact without the effects of the plate predicted overturn, whereas simulation with the effects of the plate predicted no overturn.

In tests 6 (NYSET) and 9 (CSET) the target speed and angle were 45 mph and 30 deg with the left front tire contacting the end treatment 2 ft from the leading end, as illustrated in Figure IV-11. The actual impact speed and angle are given in Table IV-2. In test 6 (NYSET) the car became airborne, went through a 180 deg roll and landed squarely on its top, causing extensive roof crush. In test 9 (CSET) the car became airborne and rolled in excess of 90 deg before coming down on the driver's side. It then continued to roll through another 270 deg, coming to rest on its wheels. Damage to the vehicle was moderate.

In tests 11 (CSET) and 12 (NYSET) the target speed and angle were 30 mph and 30 deg with the left front tire contacting the end treatment 2 ft from the leading end, as illustrated in Figure IV-11. The actual impact speed and angle are given in Table IV-2. In test 12 (NYSET) the car became airborne and went through approximately a 90 deg roll before coming down on the driver's side. It then continued to roll another 90 deg, coming to rest on its roof. The car sustained light to moderate damage. In test 11 (CSET) the car became airborne, rolled approximately 90 deg and landed on the driver's side. It then continued to roll another 90 deg, coming to rest on its roof. Damage to the vehicle was light.



* TESTS 7110-6 AND 7110-12
** TESTS 7110-9 AND 7110-11

FIGURE IV-11. IMPACT CONDITIONS - TESTS 7110-6,9,11,12

IV-D. Computer Simulations

A modified version of the HVOSM computer program (3) was used to supplement crash test data described in Sections IV-C-1 and -2. Modifications were made to improve HVOSM'S capabilities relative to (1) the simulation of impacts with fixed or rigidly anchored CSSB's and sloped-end treatments, and (2) the simulation of impacts with free-standing, precast CSSB's. Details of these modifications including their theoretical basis, validation efforts, and coding documentation are given in Appendices C and D.

IV-D-1. CSSB Simulation

Impact performance of a precast CSSB depends, among other factors, on (1) segment length, (2) manner in which segments are joined, and (3) manner in which segments are anchored. Since existing versions of HVOSM assumed the CSSB was rigidly anchored, the program was modified to account for sliding and articulation that occurs in a free-standing, precast CSSB. Changes were also made to improve simulations of impacts with rigidly anchored barrier elements.

Based on application of the modified program and on crash test results, it was found, as expected, an impact with a rigidly anchored CSSB resulted in higher occupant risks than an impact with a free-standing barrier for similar impact conditions, provided the vehicle was contained and remained upright. As discussed in Chapter V, the key to containment in a precast, free-standing system is proper design of the segment-to-segment connection.

In-depth evaluations of moveable precast systems were not pursued with the modified HVOSM program. It was concluded that in the interest of simplicity and generality the guidelines developed in Chapter V should be developed irrespective of barrier anchorage. The guidelines were therefore developed assuming the CSSB was rigidly anchored. Further, while good correlation was achieved between simulation and test results for small car impacts with the CSSB, satisfactory correlation for the large car was not achieved, primarily for severe impact conditions where the large car tended to climb on top of the barrier.

Shown in Table IV-3 are results of HVOSM simulations of impacts by an 1,800 lb car with a rigid CSSB for a range of speeds and angles. As expected, severity of impact increases with speed and angle of impact and, at higher speed/angle combinations, impacts become life threatening. Although overturns are not predicted, high roll angles are indicative of major instability at the high-speed/angle combinations. Considering ideal conditions assumed in the simulations, overturn would not be uncommon under in-service conditions. Results of the simulation study were used to develop severity index relationships for the CSSB, as discussed in Appendix B. Severity index relationships were used in the benefit/cost analysis of Chapter V.

TABLE IV-3. HVOSM RESULTS OF IMPACTS BY 1,800 LB CAR WITH RIGIDLY ANCHORED CSSB

Impact Conditions		Occupant Risk Criteria		
Speed (mph)	Angle (deg)	Max. Impact Velocity (ft/sec)	Max. Ridedown Accel.(G's)	Vehicle Stable?
30	10	7.2[a]	0.8[a]	Yes
	20	11.9[a]	2.0[a]	Yes
	30	15.7[a]	2.1[a]	Yes
	40	21.9[b]	2.1[a]	Yes
	50	29.6[b]	0.4[a]	Yes
40	10	10.7[a]	1.2[a]	Yes
	20	13.3[a]	5.8[a]	Yes
	30	18.4[a]	6.3[a]	Yes
	40	25.9[b]	3.3[a]	Yes
	50	37.8[b]	2.9[b]	Yes
50	10	14.0[a]	2.1[a]	Yes
	20	16.8[a]	6.8[a]	Yes
	30	23.1[a]	7.6[a]	Yes
	40	31.4[b]	5.1[a]	Marginal
	50	48.3[b]	3.9[a]	Yes
60	10	16.6[a]	2.7[a]	Yes
	20	20.3[a]	9.8[a]	Yes
	30	27.8[a]	10.8[a]	Yes
	40	37.9[b]	7.9[a]	Marginal
	50	57.7[b]	7.8[b]	No

[a] Lateral component
[b] Longitudinal component

IV-D-2. Sloped-End Treatment Simulations

Modifications made to HVOSM to simulate sloped-end treatments are discussed in Appendix C, along with efforts to validate the modified version. These modifications enabled the researchers to simulate impacts with the CSET (see Figure III-1) and the more complex NYSET (see Figure III-2).

Based on results of the crash tests and HVOSM simulations, it was concluded there were no major differences in impact performance of the CSET and the NYSET. Consequently, all simulations were made with the CSET.

Shown in Table IV-4 are results of simulations of impacts with the CSET by an 1,800 lb car. Impacts at speeds of 30, 37.5, and 45 mph and angles of 0, 15, and 30 deg were simulated. Figure IV-10 shows the approach orientation of the vehicle for the "head-on" impact angle. Figure IV-12 shows the impact point of the right front tire for the 15 deg and 30 deg impact angles. Note that simulations were made for impacts at values of "x" equal to $0.1L_T$, $0.2L_T$, and $0.3L_T$, where L_T was the length of the taper. Four taper lengths were considered, namely 10, 15, 20, and 25 ft.

The primary concern in an impact with a sloped-end treatment is vehicular overturn. Consequently, maximum vehicular roll angles are given in Table IV-4 unless overturn was predicted. These results indicate the following:

(a) At a 30 deg impact angle, vehicular overturn can be expected at all impact conditions for all four taper lengths simulated. This could be of concern since the sloped-end treatment is commonly flared away from traffic at some angle. If, for example, a 10 deg flare was used, a 20 deg encroachment angle from the travelway would create a 30 deg impact angle.

(b) The vehicle will either overturn or climb on top of the barrier for almost all impacts at 0.3L or less with sloped ends having a taper length of 10 ft.

(c) Only slight improvements are seen in vehicular behavior for the 15 ft taper length in comparison to the 10 ft taper length.

(d) In comparison to the 10 ft and 15 ft taper lengths, measurable improvements in vehicular performance is seen for the 20 ft and 25 ft taper lengths.

(e) Considering the added length and handling problems for a sloped end with a 25 ft taper length compared to a 20 ft length and considering the relatively insignificant

TABLE IV-4. MAXIMUM ROLL ANGLES (DEG) FOR 1,800 LB CAR IMPACTING CSET

Impact Angle (deg)	Impact Point	Impact Speed (mph)	Taper Length (L)			
			10'	15'	20'	25'
0 Head On	RF Tire on C_L	30	Overturn	Overturn	50	44
		37	Overturn	Overturn	55	49
		45	Overturn	Overturn	Overturn	53
15	0.1 L_T	30	Climbs	25[2]	34[2]	33[1]
		37.5	Climbs	43[1]	Overturn	Overturn
		45	24[1]	38[1]	Overturn	Overturn
	0.2 L_T	30	Climbs	31[2]	39[3]	44[3]
		37.5	49[2]	Overturn	40[2]	Climbs
		45	Climbs	50[2]	50[2]	51[2]
	0.3 L_T	30	36[2]	39[3]	49[3]	50[3]
		37.5	Overturn	Overturn	Climbs	Climbs
		45	Overturn	Overturn	37[1]	40[2]
30	0.1 L_T	30	Overturn	Overturn	Overturn	Overturn
		37.5	Overturn	Overturn	Overturn	Overturn
		45	Overturn	Overturn	Overturn	Overturn
	0.2 L_T	30	Overturn	Overturn	Overturn	Overturn
		37.5	Overturn	Overturn	Overturn	Overturn
		45	Overturn	Overturn	Overturn	Overturn
	0.3 L_T	30	Overturn	Overturn	Overturn	Overturn
		39.5	Overturn	Overturn	Overturn	Overturn
		45	Overturn	Overturn	Overturn	Overturn

[1] Runs over to the back side
[2] Rides along the back side
[3] Redirects

improvement in performance for the 25 ft taper length, the 20 ft taper length appears to be the better choice of the two.

(f) Although not shown in Table IV-4, the simulations predicted the vehicle would redirect for each taper length for each impact condition provided impact occurred at 0.5 L_T or greater.

Data from Table IV-4 along with data from the crash tests were used to develop severity index values for the sloped-end treatment which in turn were used in the B/C analysis of Chapter V.

IV-E. Impact Performance of Inertial Crash Cushion

The sand-filled plastic drum crash cushion, or inertial crash cushion, has proven to be a cost effective safety feature. Its relatively low cost, ease of installation, simplicity of design and analysis, and proven impact performance are its main attributes. Its primary disadvantage is its lack of redirectional capability for side impacts. However, as shown in Appendix B, the "window of vulnerability" for side hits is not as significant as had been previously thought.

It has been shown through crash testing (18) that the full-array inertial cushion meets current impact performance guidelines for permanent installations (10). In fact, the referenced test program showed that the cushion performed above expectations for side impacts by an 1,800 lb car. Although no known tests have been conducted on an inertial cushion for design speeds less than 60 mph, a well established and validated procedure is available to design the cushion for any speed. The procedure is based on the principle of conservation of momentum, documentation of which can be found in the literature (19). Reference should be made to Section V-B-1 for the types of inertial cushions evaluated in the present project, and reference should be made to Appendix B for the procedure used to determine impact performance of these designs and results therefrom.

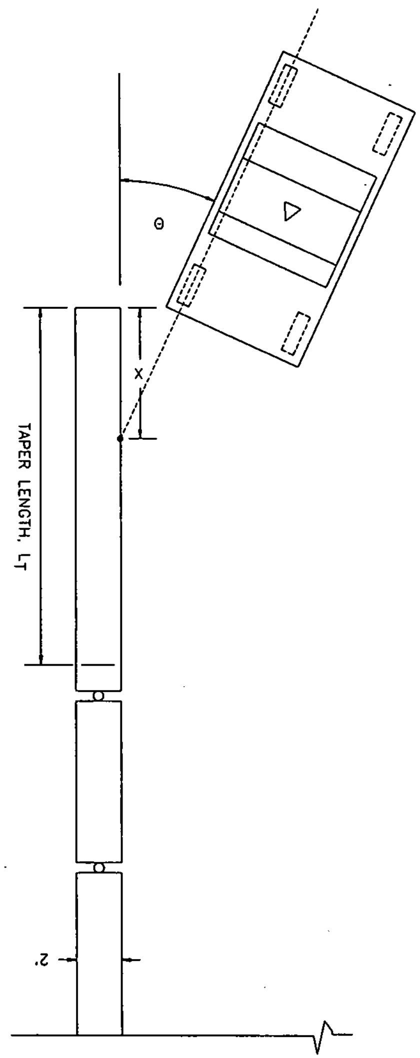


FIGURE IV-12. APPROACH FOR ANGLED IMPACTS WITH CSET SIMULATED BY HVOSM

APPENDIX C

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