Traffic Control Strategies in Work Zones with Edge Drop-Offs

CTRE Project 97-15

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

Pavement and shoulder edge drop-offs commonly occur in work zones as the result of overlays, pavement replacement, or shoulder construction. The depth of these elevation differentials can vary from approximately one inch when a flexible pavement overlay is applied to several feet where major reconstruction is undertaken. The potential hazards associated with pavement edge differentials depend on several factors including depth of the drop-off, shape of the pavement edge, distance from traveled way, vehicle speed, traffic mix, volume, and other factors.

This research was undertaken to review current practices in other states for temporary traffic control strategies addressing lane edge differentials and to analyze crash data and resultant litigation related to edge drop-offs. An objective was to identify cost-effective practices that would minimize the potential for and impacts of edge drop crashes in work zones.

Considerable variation in addressing temporary traffic control in work zones with edge drop-off exposure was found among the states surveyed. Some states base traffic control plans on only one factor—the depth of the drop-off. Other states consider additional issues such as the expected duration of exposure, posted speed limit, average annual daily traffic, and the lateral distance from the traveled way to the drop-off. All of the states surveyed indicated that edge drop-off treatment is initiated before a depth of three inches is encountered. The elevation differential warranting the use of temporary traffic barriers varies from two inches to two feet, depending on individual state policy.

Crashes related to pavement edge drop-offs in work zones do not commonly occur in the state of Iowa, but some have resulted in significant tort claims and settlements. No major deficiencies were identified in the current temporary traffic control procedures used by the Iowa Department of Transportation for work zones that include pavement edge differentials. Prudent drivers apparently travel through Iowa work zones without excessive difficulty or significant speed reduction.

The use of a benefit/cost analysis may provide guidance in selection of an appropriate mitigation and protection of edge drop-off conditions. While not as compelling as the need for adequate safety, economic analysis does offer an objective, quantifiable rationale for preliminary decision making for selection of temporary traffic control. Development and adoption of guidelines for design of appropriate traffic control for work zones that include edge drop-off exposure, particularly identifying effective use of temporary barrier rail, may be beneficial in Iowa.

1. INTRODUCTION

1.1. Project Objectives

The Iowa Department of Transportation (Iowa DOT) has adopted several standards for implementing traffic control through work zones. These guides address road closures, lane restrictions, and uneven pavement elevations that may occur between lanes, between travel lane and shoulder, and beyond the shoulder. It was not known how these procedures compare to policies and practices used by other states or how edge differentials relate to crash incidence.

To assist the Iowa DOT in evaluating current practices and to identify areas where modification would be beneficial, the goals of this research were established as follows:

- Review literature on the effects of edge differentials in work zones and for current policies and practices used to address these potential hazards.
- Compare practices of states on issues related to pavement drop-offs.
- Review and analyze Iowa's crash and litigation experience regarding edge differentials in work zones.
- Evaluate several active Iowa DOT projects that feature edge drop-offs to assess the effectiveness of temporary traffic control being used.
- Develop recommendations for any identified improvements in control strategies in work zones where pavement or shoulder edge drop-offs may occur.

Current literature addressing the unique safety concerns of pavement edge differentials as well as some related safety issues in work zones is reviewed in Chapter 2 of this report. This chapter also defines terminology used throughout this report. In Chapter 3, an extensive description of the methodology used in this research is provided. Chapter 4 explains how the data were analyzed and also illustrates the techniques used to perform a benefit/cost analysis. Chapter 5 summarizes the results of the research and offers recommendations for mitigation of edge drop-offs in work zones. Suggestions for future research on the topic of pavement edge differentials are also presented in Chapter 5.

This research should assist the Iowa DOT in the process of refining a policy that provides safe traffic flow through work zones while maintaining acceptable levels of risk for road users and workers.

1.2. Problem Description

From the 1950s through completion of the interstate highway system, the transportation industry was dominated by the construction of new highways, freeways, and other facilities. Today, however, transportation improvements are primarily focused on the rehabilitation and maintenance of the existing infrastructure. In consideration of road user convenience, most roadways remain open to traffic during work activities. The combination of work activities and vehicle traffic creates potential safety exposures for both the workers and road users. Workers are not only exposed to the hazards associated with the construction work itself, but also to the additional possibility of being struck by an errant vehicle. Road users traveling through a work zone have to deal with features such as lane closures, reduced lane widths, slower traveling speeds, increased congestion, more merging movements, and potential exposure to travel lane edge drop-offs.

The magnitude of travel lane drop-off that can occur in work zones varies by the type of work being accomplished. If an improvement involves an overlay of an existing road, a lane edge differential between two and four inches may result. Warning of this drop-off is generally addressed by placing warning signs and other devices in advance and throughout the work zone and by incorporating an earth, granular or asphalt wedge along the edge of the higher elevation surface. When the project involves replacement of a full depth pavement or shoulder, an edge drop-off from ten inches to two feet may result. A drop-off of this magnitude is generally considered more hazardous than the lesser differentials, and therefore may warrant the use of more extensive temporary traffic control measures such as barricades or barriers to supplement warning signs. Drop-offs greater than two feet can also be referred to as trenches and are generally the result of structure work. To reduce hazard exposure, trenches are usually filled in, covered, or protected by portable barriers throughout and at the end of each workday. Some work areas may involve two or more types of drop-off conditions, requiring more complex temporary traffic control and management procedures. Because of the wide variation in drop-off conditions that can occur during a road or street improvement, the resultant potential hazards presented to road users are difficult to characterize.

A significant percentage of crashes can be classified as road departure (single direction run off road, head-on, and opposite direction sideswipe). On the average, about 22,000 such crashes occur each year across the nation. In Iowa, rural ran-off-road crashes often make up approximately 35%–40% of the total. Considering this fact, adequate warning and protection for pavement edge drop-offs is necessary.

1.3. Overview of Traffic Control Measures at Work Zones with Drop-Offs

While common hazards resulting from work zone activities are safely and effectively mitigated by consistent and standardized traffic control and management procedures, the occasional exposure to pavement edge drop-offs presents unique concerns. A common measure used to protect road users and workers from the hazards that occur in work zones is effective use of temporary traffic control that include such devices as advance warning signs, channelizing devices, portable traffic barriers, warning lights, and temporary pavement markings.

The traffic control strategy selected to warn of an edge differential is dependent on several factors. It is accepted that the height of the edge drop-off as well as the shape of the pavement edge—rounded, sloped, or vertical—can impact the relative safety for road users. Other characteristics of the work zone such as the lateral distance from the travel lane to the drop-off, speed and volume of traffic, and length and duration of the project may also influence the level of hazard associated with a lane edge differential. The impact and interaction of these factors has not been determined and therefore a uniform set of criteria from which to select an appropriate traffic control strategy does not currently exist.

Before a safe and effective temporary traffic control and management plan can be established, the potential hazards associated with pavement edge drop-offs should be analyzed. Two adverse effects for errant vehicles presented by permanent and/or temporary edge drop-offs are (1) the possibility of a vehicle to be over-steered into oncoming traffic and (2) the potential for vehicle rollover. When a vehicle leaves the edge of the road and its tires drop down two or three inches, the driver's instinct is to steer immediately back onto the pavement. In some instances, the driver over-steers, causing the vehicle to be redirected into or across the adjacent lane(s). If another vehicle is traveling in the opposite direction, a serious or fatal collision may result. In situations where a vehicle passes over an edge drop-off of one foot or more, a rollover is likely since the forces acting on the vehicle become unbalanced. A vehicle rollover can be very significant in severity as well as property damage; therefore some type of positive barrier is usually recommended to protect the drop-off. Protective rigid barriers, however, can also present a significant hazard if impacted. A benefit/cost analysis could be completed considering barrier cost and comparative crash severity to determine quantitatively whether a barrier or a drop-off would theoretically present the greater potential hazard for road users and workers. Installation of protective barriers at permanent roadside hazard locations can also be evaluated in this manner. The *Roadside Design Guide,* published by the American Association of State Highway and Transportation Officials (AASHTO), is a standard resource to assist engineers in evaluating traffic and roadway conditions, using estimated crash severity indices, in decision making for possible permanent barrier installations (*1*). When a potential hazard is only temporary, as with drop-offs in reconstruction and maintenance projects, a life-cycle benefit/cost analysis is less appropriate because the number of crashes that may occur in a temporary situation is much less than those that might be predicted to occur over the service life of a barrier. Instead, only an allocation of those costs could be considered. A quantitative analysis to assess the potential impacts of an exposed edge drop-off versus providing barrier protection is quite challenging.

1.4. Summary of Results

The need for standard procedures for mitigating pavement drop-offs has been recognized for many years. For example, in a 1986 memorandum the Federal Highway Administration urged states to develop policies addressing drop-offs in work zones, particularly those exceeding two inches in height. The current study recommends that, if possible, highway agencies adopt a uniform policy for design and maintenance of traffic control in work zones. To avoid misunderstandings of appropriate temporary traffic control measures for pavement edge differentials between the contracting agency and contractor, a high-quality, easy-to-interpret traffic control plan could be incorporated into project documents.

A definitive and fully reliable strategy for selecting the safest and most cost-effective temporary traffic control measures to be used in work zones with edge drop-offs is difficult to develop. Although benefit/cost analysis for short-term applications may seem to yield imprecise results, this practice could be used as guidance in strategy selection and as a basis for future studies.

One factor complicating analysis of the most effective and efficient temporary traffic control measures in Iowa is that in recent years crashes associated with edge drop-offs in work zones have not occurred in significant numbers. However, crash records do not always accurately indicate that a pavement edge differential was a contributing factor. Nationally, the proximity of a work zone is not always identified in crash records (*2*). Not only are the number of crashes where edge drop-offs are contributory often underreported, but costs of these crashes are also underestimated. A major factor in underestimated costs is the lack of data for legal implications from these crashes. A settlement of several thousand dollars in legal litigation for one crash resulting from an edge drop-off is quite possible. For example, in a recent Louisiana case, the state department of transportation and the project contractor were ordered to pay a combined total of over $1,100,000 in damages to the widow and daughter of a motorist who died of injuries received in a work zone edge drop-off related crash that occurred in November 1995 (*3*).

Though crashes related to work zone edge drop-offs do not appear to be common in the state of Iowa, but some were identified from Iowa's crash records database. A few of these crashes have resulted in significant tort claim filings and settlements. Crashes resulting in legal claims filed over the six-year period from 1995 through 2000 were reviewed. A cost analysis for short-term exposure was attempted using a predicted number of crashes, the estimated cost of these crashes, and an estimated cost of typical traffic control measures. The information obtained from this analysis may not be used directly; however, it can be compared to data collected from the literature review, other state surveys, crash analysis, and project site reviews to develop proposed guidelines.

Research on pavement edge drop-offs has only begun to identify the issues that impact temporary traffic control management in the work zone. It has been discovered that considerable variation exists from one state to another in the procedures used to warn of and protect edge differentials in work zones. Some states base temporary traffic control on only one factor, the magnitude of drop-off. Other states select traffic control measures not only considering depth of the drop-off but also the expected duration of the project, posted speed limit, average annual daily traffic (AADT), and lateral distance from the traveled way to the edge differential. One state requires that temporary traffic barriers be used to shield an edge drop-off if a depth of two inches is exceeded. Another state does not require the use of rigid barriers until the drop-off exceeds a depth of five feet. While none of the states has identical procedures for addressing pavement edge differentials in work zones, all employ specific temporary traffic control measures for drop-offs exceeding three inches. This magnitude of differential has been generally accepted as the limit at which a significant percentage of drivers will begin to experience control difficulties when attempting to steer back onto the pavement surface (*4*).

States that have adopted and follow a policy to address the potential hazards of an edge drop-off in work zones have a strong defense against legal claims. If, on the other hand, an agency does not adopt or follow a standard policy, defending against liability could prove to be quite problematic.

Although some minor variations from recommended practice were observed, no major deficiencies were identified in current temporary traffic control measures used by the Iowa DOT to mitigate pavement edge differentials in work zones. Road users pass through work zones in Iowa without much difficulty while not significantly reducing travel speeds.

2. LITERATURE REVIEW

This chapter summarizes identified literature associated with the safety issues of lane and pavement edge differentials as well as that related to temporary traffic control practices in work zones. The materials reviewed for general practices include research on work zone safety records, methods to warn road users of potential hazards, and driver behavior in work zones. Some of these topics may not relate directly to edge drop-off conditions.

2.1. Definitions of Terms

To comprehend the details of this report, a basic understanding of the terminology used in the transportation-construction industry is desirable. The following terms are defined, unless otherwise noted, according to Part 6 of the *Manual on Uniform Traffic Control Devices* (MUTCD), millennium edition (*5*).

Temporary Traffic Control Zone

A temporary traffic control zone is the area of a highway where road user conditions are changed because of a work zone or incident through the use of temporary traffic control devices, police, or other authorized officials, generally beginning with the first advance warning device and ending with the last traffic control device, where traffic returns to the normal path and conditions. Most temporary traffic control zones can be divided into four areas: advance warning area, transition area, activity area, and termination area, plus buffer space (see Figure 1).

Advance Warning Area: The section of highway where road users are informed about an upcoming work or incident area. It is generally located 500 feet to one half-mile or more before the transition area and may consist of flashing lights on a vehicle, a single sign, or a series of signs.

Transition Area: The section of highway where road users are redirected out of the normal path of travel. The proper use of channelization is required.

Activity (Work) Area: The section of highway where the work activity takes place, comprised of work area, traffic space, and one or more buffers.

Buffer Space: The portion of the activity area, either lateral and/or longitudinal, that separates road user flow from the work space or hazardous area, and may provide a recovery area for errant vehicles. This space should not be used as a storage area for equipment, vehicles, or material and should be clear of any work activity.

Termination Area: Area used to return road users to their normal travel path, extending from the downstream end of the work area to the END ROAD WORK sign, if used.

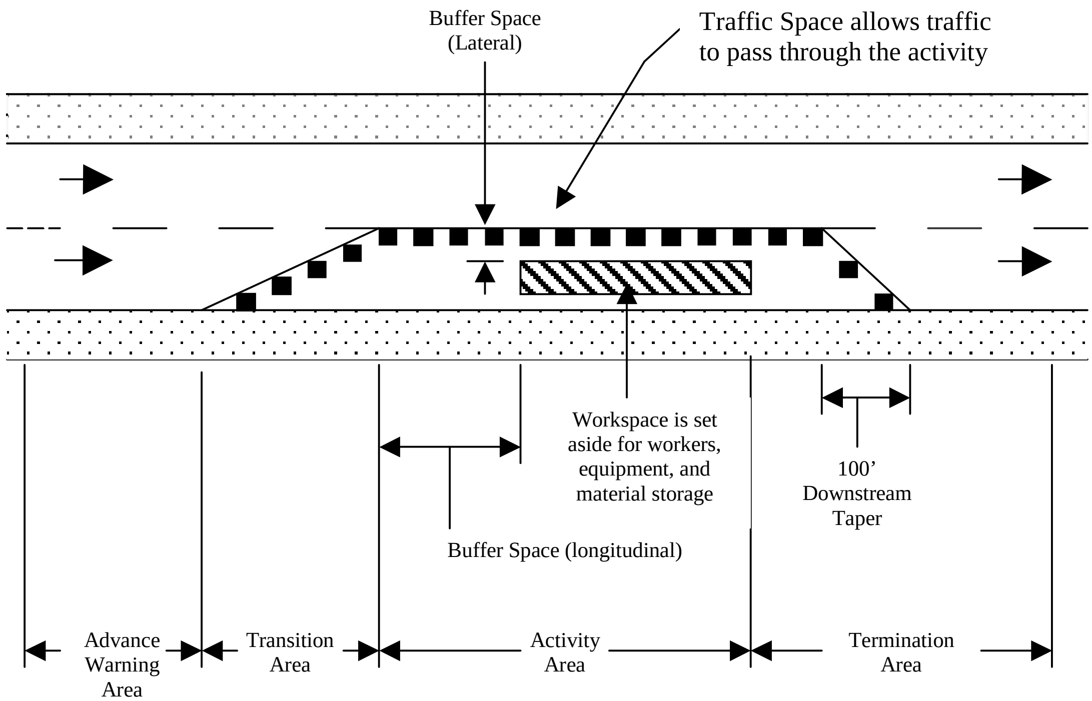


Figure 1. Component Parts of a Temporary Traffic Control Zone *(5)*

Traffic Control Signs

Warning Signs: Temporary traffic control zone warning signs notify road users of specific situations or conditions on or adjacent to the roadway that might not be otherwise apparent. These signs almost always have an orange background with black lettering.

Portable Changeable Message Signs (PCMS): Electronic traffic control devices that can display a variety of messages to fit the needs of road users and authorities.

Arrow Panels: A sign with a matrix of elements capable of either flashing or sequential displays, used to provide additional warning and directional information to assist road users with merging and guidance through or around a temporary traffic control zone.

Barriers and Other Devices

Channelizing Devices: Specially designed devices used in work zones to warn road users of conditions created by work activities in or near the roadway and to provide guidance. They can be used to separate motor vehicle traffic from the work space, pavement drop-offs, pedestrian or bicycle paths, or opposing directions of traffic. Channelizing devices include cones, drums, tubular markers, vertical panels, barricades, and temporary raised islands. See Figure 2.

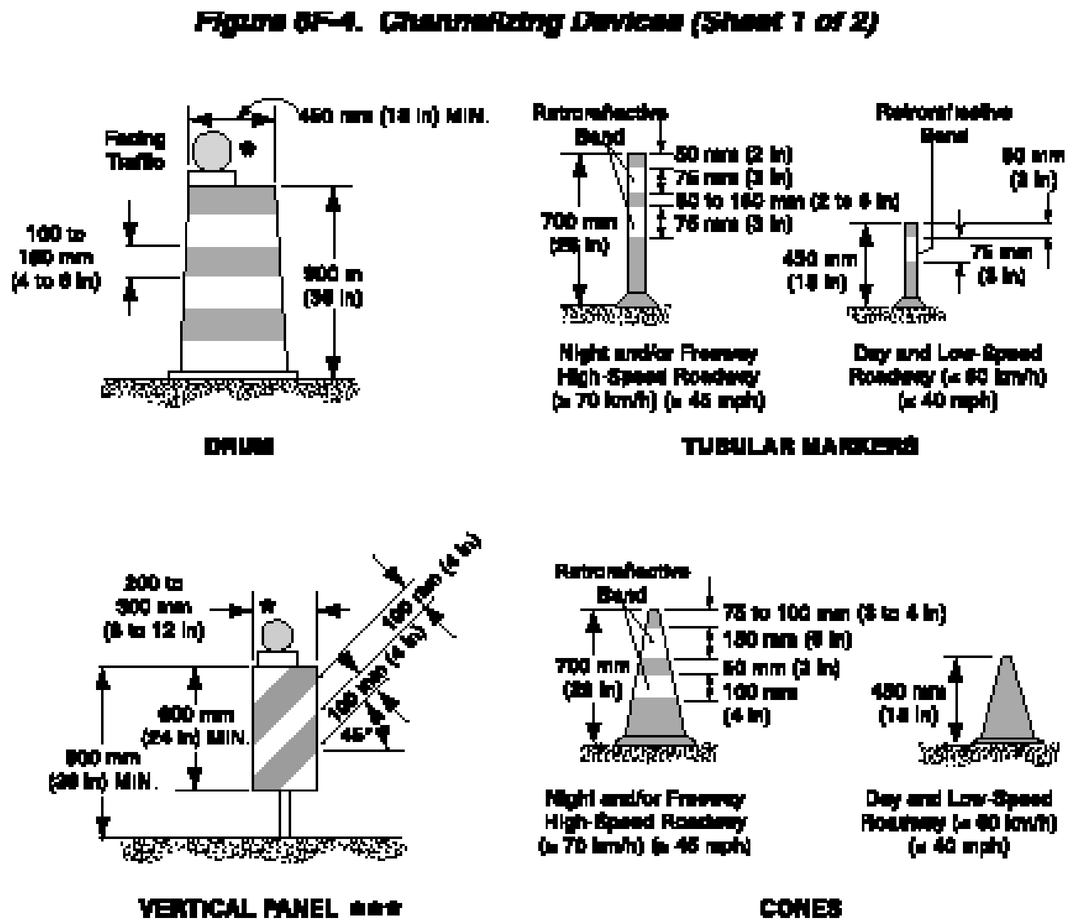


Figure 2a. Channelizing Devices (*5*)

Note: Figures 2a and 2b were taken from Figure 6F-4 at http://mutcd.fhwa.dot.gov; the figures may appear better quality if accessed directly or by viewing a printed copy of the MUTCD.

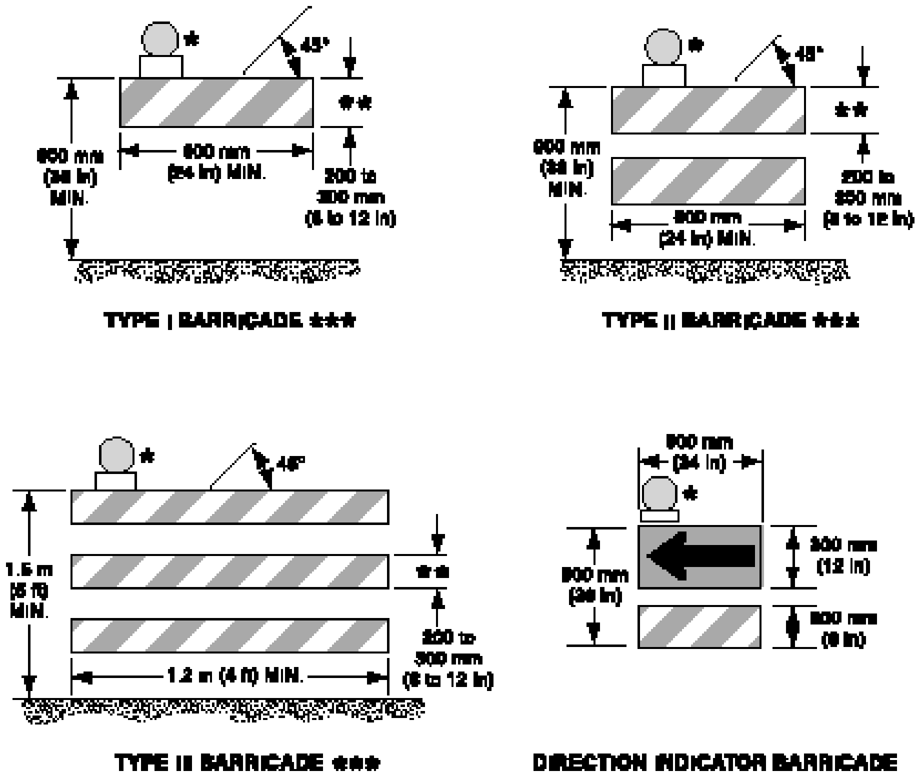


Figure 2b. Channelizing Devices (*5*)

Temporary Traffic Barriers: Devices designed to help prevent penetration by vehicles while minimizing injuries to vehicle occupants, and designed to protect workers, bicyclists, and pedestrians. Although not actually temporary traffic control devices, if used to channelize traffic, temporary traffic barriers are required to be supplemented by standard delineation, pavement markings, or channelizing devices for proper visibility. Use should be based on an engineering study. The MUTCD lists four primary functions of temporary traffic barriers: to keep vehicular traffic from entering work areas; to separate workers, bicyclists, and pedestrians from vehicular traffic; to separate opposing directions of vehicular traffic; and to separate vehicular traffic and other road users from the work area. Typical applications are included in Chapter 6H of the MUTCD.

Portable Concrete Barriers: The *Roadside Design Guide* describes several types of temporary longitudinal traffic barriers including the Iowa temporary concrete barrier shown in Figure 3. These barriers, the most common in use, are freestanding pre-cast concrete sections, each approximately eight to thirty feet in length, and have built-in interconnecting devices. This barrier type is typically used to shield obstacles, false work, excavations, and pavement edges.

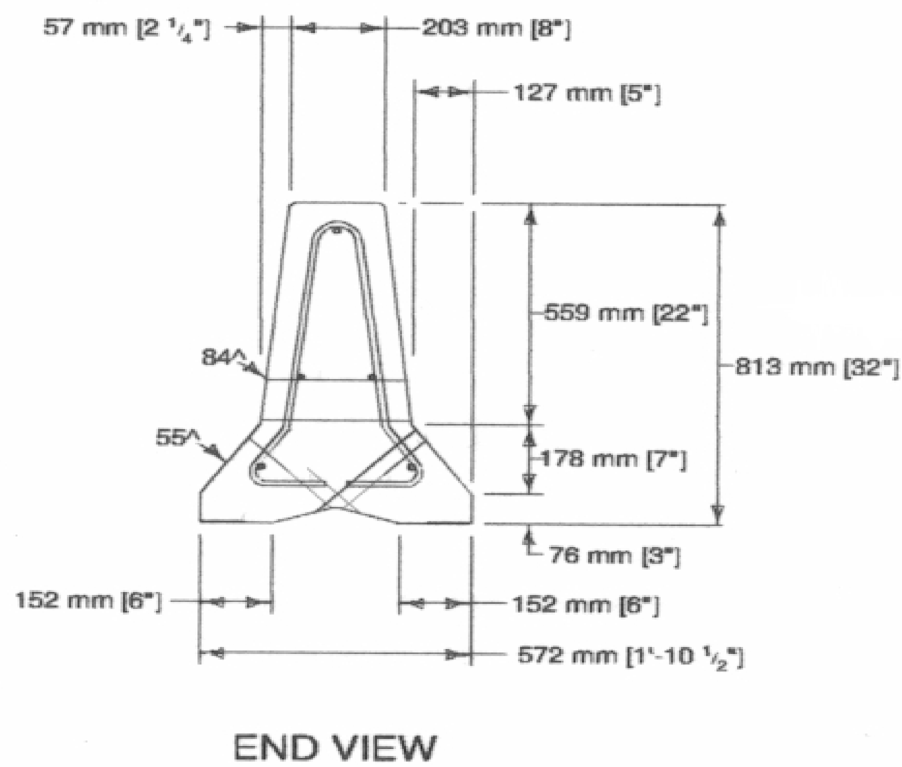


Figure 3. Iowa F-Shape Temporary Barrier Rail (*1*)

Low Profile Barrier System: A portable pre-cast concrete barrier composed of a series of segments with an approximate two-foot-wide base sloping outward at 20:1 to a height of about 20 inches. This barrier system is typically used in urban and suburban work areas where sight distance is deficient.

Other available, mostly proprietary temporary barriers (as described in the *Roadside Design Guide*): "Quickchange" Barrier System, Triton barrier, GUARDIAN safety barrier, and timber barriers. Each has special attributes for use in specific situations. Similar devices are described in the MUTCD under "Longitudinal Channelizing Barricades."

Crash Cushions: These are systems that mitigate the effects of an errant vehicle that strike an obstacle, either by smoothly decelerating the vehicle to a stop, or by redirecting the errant vehicle. Crash cushions used in mobile applications are also known as truck-mounted attenuators (TMAs).

Work Activity Duration

Duration of work activities is a key factor in selecting proper temporary traffic control measures. As defined in Part 6 of the MUTCD (*5*), these are the standard descriptions of work activity durations:

Long-term Stationary Work: Work activities that occupy a location for more than three days.

Intermediate-term Stationary Work: Work activities that occupy a location more than one daylight period up to three days, or any nighttime work lasting more than one hour.

Short-term Stationary Work: Daytime work activities which occupy a location from one to twelve hours.

Short Duration Work: Work activities that occupy a location up to one hour.

Mobile Work: Work activities that move either intermittently or continuously.

2.2. General Work Zone Safety

Many studies have been conducted on the safety concerns associated with work zones. Reports indicate that over 750 fatalities occur in work zones in the United States every year (*6*). More specifically, it has been found that fatalities in work zones nationally have been increasing rapidly from 647 deaths in 1992 to 1,093 deaths in 2000 (*7*). In addition, almost 40,000 persons are injured in work zone crashes each year. According to the Liberty Mutual Research Center, 41 percent of the crashes at work zone sites are rear-end crashes, 11 percent are caused by a collision with barriers, barrels, barricades, or other large objects, and one percent involve an overturned vehicle (*8*). The national crash data, however, may be even lower than the actual number of work zone crashes for three primary reasons. First, many crashes may involve only minor property damages and a crash report is not recorded. Second, an crash that occurs near a work area, such as a rear-end collision at the end of a work zone queue, may not be reported as a work zone crash even though it is work zone related. Third, and most significantly, the crash report may not indicate that the crash occurred in a work zone (*2*).

In Iowa, however, much better crash reporting exists. The Iowa DOT, in cooperation with the many law enforcement agencies in the state, maintains a detailed record of serious crashes that occur in work zones, particularly when a fatality is involved. Iowa records indicate an average of 366 crashes occur each year in work zones, resulting in 8 fatalities and about 136 injuries. Approximately 75 percent of Iowa work zone crashes involve rear-end collisions (*9*).

Past research has presented varying conclusions regarding work zone impacts on highway safety. Most results reveal the number of crashes occurring during work activities is greater than those that occur under non-work conditions. The increase in crash rates in work zones is highly dependent on factors related to traffic conditions, geometry of the roadway, and roadway environment. Wang et al. (*2*) took these factors into consideration during an investigation of highway work zone crashes. In that study, crash data from 1991 and 1992 were analyzed for three sample states. The data available from two of the three states indicated that crash rates on freeways were significantly higher in work zones than in non-work areas. It was also determined that urban work zones have a higher crash frequency than rural work zones, primarily due to limited maneuvering space, more variation in speed, higher traffic volumes, frequent traffic obstructions, and driver distractions (*10*).

A study conducted by AASHTO (*11*) supported these results, finding the crash frequency to be about 70 percent higher in urban than in rural work zones. AASHTO's data also concluded, however, that the number of fatalities are higher in rural work zones, primarily due to higher speeds.

2.2.1. Crash Severity

To investigate the severity of work zone versus non-work zone crashes, Wang et al. (*2*) again analyzed data from 1991 and 1992 for three sample states. The data from one state indicated that work zone crashes were slightly more severe than non-work zone crashes; however, data from the other two states revealed the exact opposite. Since that information could be statistically supported, Wang et al. concluded that work zone crashes are actually less severe than non-work zone crashes (*2*).

A report from AASHTO issued in 1987, however, stated that "… crashes which occur in work zones are generally more severe, producing more injuries and fatalities than the national average for all crashes…" (*1*, p. 9-1). AASHTO determined that injuries and fatalities that occur in work zones are more frequently the result of collisions with fixed objects, such as construction barriers, drums, or barricades, rather than vehicle-to-vehicle collisions. AASHTO also found that approximately half of fixed-object crashes in work zones occur in periods of darkness (*1*).

2.2.2. Crash Types

Wang et al. (*2*) also investigated the types of crashes that occur in work zones. In cooperation with the Liberty Mutual Research Center, the analysis of the same three states indicated that rear-end collisions were involved in a large percentage of work zone crashes. In fact, it was shown that "[t]he percentage of work zone crashes involving a rear-end collision was significantly higher than the percentage of non-work zone crashes involving a rear-end collision" (*2*, p. 57). The majority of these rear-end collisions were concluded to be the result of the speed differentials among vehicles traveling through the work zone. This conclusion agrees well with Iowa's experience referenced earlier.

2.2.3. Speed Modifications

A study conducted by Benekohal and Wang (*10*) examined how drivers modify speeds when traveling through a work zone. The study site, located on Interstate 57 near Matton, Illinois, required the closure of one lane of traffic in each direction for bridge deck repair. The work zone included pavement edge drop-offs. A speed study found that both automobile and truck drivers exhibited a similar speed profile. "As drivers traveled further into the traffic control zone their speeds first decreased, then slightly increased, and finally reached their minimum value at the work space" (*10*, p. 42). Once the actual workspace was passed, drivers continued to increase speeds until attaining similar speeds at which they were traveling before encountering the initial advance warning sign. On average, it was found that automobile drivers reduced speeds by three to thirteen miles per hour (mph) and truckers decreased speeds by three to twelve mph when traveling through the work zone. A small percentage of drivers reduced speeds by a greater degree. Despite the fact that drivers tended to slow down upon entering the work zone, it was found that 65 percent of automobile drivers and 47 percent of truckers were still exceeding posted speed limits. In fact, automobiles and trucks were traveling at an average of five to eighteen mph and one to twelve mph, respectively, above the work zone speed limit (*10*).

Part 6 of the MUTCD (*5*) recommends that reduced speed limits be avoided as much as practical, but if used, the MUTCD further suggests that reductions be no more than 10 mph below posted limits except for unusual circumstances.

The Institute of Transportation Engineers (ITE) *Traffic Control Devices Handbook* (*9*) addresses work zone speed reduction in considerable detail. Recommendations for when to employ reductions, design considerations, and the beneficial use of law enforcement are all discussed.

2.2.4. Crash Costs

Several other studies addressed costs associated with work zone crashes, including societal costs, direct highway agency costs, and legal costs. Societal costs consist of those from fatalities, injuries, and property damage resulting from work zone crashes. Direct agency costs include those resulting from damages to infrastructure and work zone devices. Finally, legal exposure can result from deficiencies in signing, delineation, or other necessary protection in the traffic control zone. During the five year period from 1996 through 2000, the state of Iowa was faced with over 1600 claims totaling more than $156 million for alleged deficiencies on primary roads, many in work zone areas (*12*). In 1996 alone, the state of Iowa agreed to settlements for approximately $1 million.

However, societal impacts of work zone crashes are more significant than legal costs. As stated earlier, in the United States 1,093 people were killed during 2000 in work zone crashes (*7*). In 1988, Minnesota reported that 2,731 crashes occurred on the state's rural and urban highways that were under construction (*13*). During the same year, Oregon reported that during the construction season an average of more than two work zone related fatalities occurred each month (*14*). As was related earlier, over 360 work zone crashes occur each year in Iowa.

Considering these costs resulting from work zone collisions, significant concern has been raised nationally and in the state of Iowa.

2.2.5. Traffic Control Plans

To maximize safety in work zones, proper traffic control and management procedures must be implemented. An effective traffic control plan will not only emphasize safety for all road users, but will also allow for cost effective and time efficient completion of the work activity. Part 6 of the MUTCD (*5*, 2000 edition) provides strong recommendations for developing and utilizing a traffic control plan for all work zones. The plan should be appropriately detailed as required by the complexity of the work and understood by all responsible parties before the work site is occupied. The ITE *Traffic Control Devices Handbook* (*9*) also provides good advice for the development of temporary traffic control plans and in addition discusses the important aspects of implementation, including installation, monitoring of effectiveness, and removal. A detailed traffic control plan is probably justified only in higher volume, speed, and longer duration applications, but flexibility for needed modifications by qualified personnel is also necessary with any implemented plan.

Project Duration

For every roadway activity, an appropriate traffic control plan should be developed based not only on highway classification and traffic conditions, but also considering expected duration of exposure and location of the workspace relative to traffic. For roadway improvements with edge drop-off potential, duration of exposure should be considered when selecting an appropriate level of temporary traffic control. The expected length of time required to complete a project will affect the number, design, and types of devices used in temporary traffic control zones.

With long-term stationary work zones, "… there is ample time to install and realize benefits from the full range of temporary traffic control procedures and devices that are available for use" (*5*). Since long-term operations extend into darkness, traffic control devices must be highly visible at night. Other traffic control procedures that may be efficiently implemented in long-term activities include use of larger devices, temporary roadways, temporary pavement markings, lighting, and temporary traffic barriers.

It may not, however, be feasible or economically practical to implement such procedures with short or intermediate-term projects. The time required to place and remove temporary roadways, pavement markings, and temporary barriers may increase the time road users and workers are exposed to potential work zone hazards. Short-term stationary work operations will often use flaggers to help control and guide traffic. Mobile operations may include moving the advance warning signing with the work. On roadways with high traffic volumes and/or high travel speeds, a truck with an arrow panel should follow the work activities (*5*).

Work Location

"The choice of temporary traffic control needed for a temporary traffic control zone depends upon where the work is located. As a general rule, the closer the work is to road users, the greater the number of temporary traffic control devices that are needed" (*5*). The *MUTCD* lists five locations where work activities can take place: (1) outside of the shoulder, (2) on the shoulder with no encroachment, (3) on the shoulder with minor encroachment, (4) within the median of a divided highway, or (5) within the traveled way. Generally if the work area is located away from the edge of the shoulder, only minimal or no traffic control devices are required. As the work moves closer to the traveled way, however, higher levels of temporary traffic control are needed. For example, when work takes place on the shoulder, advance warning signs and channelizing devices are needed to warn road users of the closed area, to guide traffic, and to make the workspace visible. In some instances, temporary traffic barriers may be warranted to protect road users and workers by preventing errant vehicles from encroaching into the workspace. When work is located in the median of a divided highway, traffic control devices may be required for both directions of traffic. Work that takes place just adjacent to or on the traveled way presents the most potential hazard for road users and workers, therefore requiring a high level of temporary traffic control. Roadway activities that present pavement and/or lane elevation differentials fall into this category.

2.2.6. Work Zone Safety Enhancement

While the provisions in the MUTCD form the basis for uniform traffic control across the nation, defining details to address every application is not possible. Engineering judgment must be applied when selecting proper temporary traffic control in each unique situation. Research has shown that some common deficiencies noted in work zones include the use of misleading markings and signs, excessive edge drop-offs, use of unconnected or unanchored temporary traffic barriers, and improper flagging techniques (*11*). Mitigation of these deficiencies is relatively obvious, but not all work zone hazards are so easily addressed. Part 6 of the MUTCD (*5*) does offer guidance (termed "fundamental principles") for enhancing the safety of road users and workers in temporary traffic control zones, including the following:

- "Road user and worker safety in temporary traffic control zones should be an integral and high-priority element of every project from planning through design and construction."
- General plans or guidelines should be developed to provide safety for all road users.
- Road user movement should be inhibited as little as practical.
- Any traffic control devices inconsistent with intended travel paths through temporary traffic control zones should be removed or covered.
- Traffic control elements should be routinely inspected day and night to ensure acceptable levels of operations.

- Work equipment, workers' private vehicles, materials, and debris should be stored in such a manner to reduce the probability of impact by errant vehicles.

The MUTCD further suggests that reduced speed limits be used only where necessary to maintain safe conditions and, even then, only reductions of 10 mph from posted speeds are recommended.

While Part 6 of the MUTCD contains a considerable volume of information to establish and maintain safe conditions in work zones, only a few references are made regarding pavement edge drop-offs and no specific recommendations are included for temporary traffic control to address these conditions. These references to pavement edge drop-offs can be found in Part 6 of the MUTCD:

- It is suggested that a lateral buffer area be used to better separate traffic from excavations and pavement drop-offs.
- SHOULDER DROP-OFF signs (W8-9a) are required when a shoulder drop-off, adjacent to the travel lane, exceeds 3 inches and is not protected with portable barriers.
- LOW SHOULDER signs (W8-9) may be used when a elevation difference is less than 3 inches.
- UNEVEN LANES signs (W8-11) are recommended for use during operations that create a difference in elevation between adjacent lanes.
- Channelizing devices are suggested for various uses, including separating motor vehicle traffic from pavement drop-offs.

The use of temporary traffic barriers is described in several sections of the MUTCD, and one particular function is listed as keeping motor vehicle traffic from entering work areas, such as excavations or material storage sites. The use of temporary traffic barriers is also mentioned in several typical applications, but a requirement for specific use to protect excavations and drop-offs is not included. Use of an engineering study and exercise of engineering judgment is urged for any application of these barriers. Other resources are also available as references in quality temporary traffic control.

2.2.7. Lane Width Reduction

Research from France, published by the Organisation [sic] for Economic Co-Operation and Development (OECD), stated that it was preferable to reduce the width rather than number of available traffic lanes (*15*). This recommendation applies primarily to applications where the geometry of the roadway is altered and/or where traffic congestion is a concern. Kemper et al. (*16*) also studied the impacts of reduced width traffic lanes. That research examined how safety was affected when an existing road with two 12-foot lanes and 10-foot shoulders was modified during construction to two 11-foot lanes with 9-foot shoulders, and a 4-foot median. According to the 1976 study, "[c]apacity and travel times through the narrow lanes were comparable with capacity and travel times at construction sites where standard lanes had been used" (*16*). It was estimated that traffic delays could have quadrupled if the traffic control plan had not implemented the use of narrow lanes. The only deficiency Kemper et al. found with the narrow lane plan was that the number of crashes doubled during the construction period. The use of narrowed lanes was defended by pointing out that the increase in crashes that occurred at the narrow lane study site was less than the increase in crashes that occurred at other major construction sites during the same time period (*16*).

2.2.8. Night Work

Part 6 of the MUTCD (*5*) suggests off-peak hour scheduling or night work be considered when traffic volumes are high. The OECD report (*15*) listed some of the advantages and disadvantages of performing work activities at night. Advantages include less congestion and delay due to reduced traffic interference and for road users, and safer, more productive working hours. However, disadvantages include restricted nighttime visibility for road users and workers. Edge drop-offs may present increased safety concerns at night and adequate visibility of temporary traffic control is imperative. Auxiliary lighting, necessary for work activities at night, can be distracting for drivers. These factors must be considered when night work on projects with edge drop-offs is anticipated.

2.2.9. Comparison of Temporary Traffic Control Devices

When designing temporary traffic control for a work zone, a comparison of the effectiveness of available devices is helpful. This may be particularly true for edge drop-off applications where consideration might be given to the use of temporary barrier rail for protection. Several studies of this topic have been completed.

One study of urban work zones by Garber and Woo (*17*) found that a combination of cones, arrow panels and flaggers had the most positive effect in reducing crash rates on multi-lane roads while for two-lane highways, the most effective combination was found to be a flagger supplemented by cones, static signs, and/or barricades (*17*).

A more generalized study was conducted by Pain et al. (*18*) to evaluate the effectiveness of cones, tubular markers, barricades, drums, and vertical panels in rural freeway work zones. Observations included variable detection among individual drivers, particularly at night, lane change differentials, and speed reduction impacts. Pain et al. also noticed that regardless of the device used, drivers tended to shift laterally away. Other general characteristics Pain et al. observed include the following; speed reduction is most affected by the size of device during the day and the amount of retroreflective surface at night, the size and visible area of a device had greater impact on driver behavior than did the shape of the object, and only arrow or chevron markers, not diagonal stripes, successfully conveyed a sense of direction. With these observations in mind, Pain et al. concluded that most of the devices were effective for every work zone application and devices could be interchanged without reducing effectiveness. In one last observation, Pain et al. pointed out that "[m]otorists do not respond to a single channelization device, but to the path that is defined by the array" (*18*).

A third study, published by OECD (*15*), compared various traffic control devices based on four selection criteria: maintenance characteristics, ease of installation and removal, overall costs, and ability to provide proper guidance. According to the OECD report, cones and tubular markers have four major advantages, presenting minor impediments to regular traffic flow, they can be struck by an errant vehicle without being severely damaged, road users can easily recognize and understand the meaning, and both cones and tubular markers are easy to store, transport, set up, and remove. The major disadvantages of tubular markers and cones are that they command less respect from road users since they are easy to penetrate, knock over, or displace. The OECD, like the MUTCD, recommends using tubular markers to separate traffic when lateral space is limited. For drums, the OECD concluded that the larger size increases visibility and commands more respect.

The results and recommendations from these studies are useful in selecting temporary traffic control measures. When protecting drop-off conditions, for example, use of larger, more imposing devices will result in increased driver respect and less propensity to steer near the devices and subsequent hazard.

2.2.10. Barrier Selection

Many road improvements that present significant road surface edge differentials warrant consideration for use of temporary traffic barriers. Several studies have been conducted to determine which type of barrier provides maximum safety for road users and workers.

As mentioned in Section 2.1, AASHTO's *Roadside Design Guide* (*1*) provides some typical uses for several types of barrier. The portable concrete barrier (PCB) is typically used in high volume and speed applications to shield various obstacles, pavement edges, and false work for structures. The low profile barrier system can be beneficial in urban and suburban areas where sight distance is a concern. Several proprietary barrier systems provide excellent portability when changing or emergency traffic control measures are needed. The Quickchange barrier system, Triton barrier, and GUARDIAN safety barrier are available choices when high portability is desired.

A study conducted by Ross et al. (*19*) discusses some problems that could be encountered when using barriers in restricted work zones. The report examines three basic examples of restricted work zones primarily characterized by intersecting roadways near the work activity restricting space available for barrier end treatments and work zones with a need for openings within the run of barrier. In the report, Ross et al. describe some methods to mitigate potential hazards of using barriers within restricted work zones that go beyond the scope of this research; however, it is important to recognize that location of the work site can influence the type, placement, and end treatment of the selected temporary barrier (*19*).

Definitive documentation recommending the type of barrier most appropriate under specific conditions is not available. The *Roadside Design Guide* does provide some guidelines for permanent barrier selection; however, these criteria are not easily transferred to temporary applications. Permanent installations can be more readily analyzed using crash history and life-cycle costs. These factors may not be accurately assessed in temporary situations for several reasons principally dealing with relatively short exposure durations.

Revisions in the MUTCD may require consideration of continuous barriers or barricades particularly in urban areas where these devices are used to channelize pedestrians, as detectability by users of long canes is required.

2.2.11. Driver Behavior

The final area of general work zone safety that was reviewed focused primarily on road user attitudes and behavior. In a study conducted by Benekohal et al. (*20*) drivers were asked to complete a survey addressing various aspects of a ten-mile construction project on a rural section of Interstate 57 in Illinois. Survey results indicated 77 percent of motorists paid more attention to road signs after entering the work zone than prior. After observing a lower speed limit sign, approximately 91 percent of drivers reported reducing travel speeds. Approximately five percent of the motorists, however, reported not even seeing the speed reduction sign. The survey also reported that even after reducing speeds, 34 percent of the drivers admitted to driving over the posted limit while traveling through the work zone. Other survey responses indicated that 54 percent of motorists felt work zones were more hazardous than non-work areas and approximately 22 percent of drivers reported work zones made them feel uncomfortable. The drivers who reported feeling uncomfortable traveling through the work zone opined that drums were placed too close to the travel lane. These drivers also reported that the presence of an edge drop-off and excess material left on the shoulders added to the discomfort (*20*).

Another study related to attitudes and behavior indicated that unless workers are visible, motorists would generally not slow down as they traveled through the work area (*21*).

Finally, in agreement with previous reports, Popp pointed out in a study of Minnesota construction projects that it was evident that motorists need a repetition of warning signs to remind them of the potential hazards of work zones (*22*).

Recognition of human characteristics and behavior is becoming more common in design of temporary traffic control for work zones. These factors are even more important because of the potential hazards of edge drop-offs.

2.3. Safety and Liability Issues Concerning Edge Drop-Offs

Travel lane edge drop-offs are common occurrences in work zones, ranging in magnitude from as minimal as one inch to depths of several feet. Pavement/ shoulder drop-offs can present both a safety and liability concern for road agencies. Three of fourteen states responding to a nationwide survey indicated that excessive pavement edge drop-offs were one of the most frequent liability problems (*23*).

The state of Nebraska identified a specific 1992 claim where negligence was found for failing to require the "… contractor to properly place edge marking devices to warn of shoulder drop-off during construction" (*23*).

On May 1, 1992, a tanker truck driver received injuries as result of overturning the truck after crossing over a pavement edge drop-off in a construction zone. The driver sued an Alabama construction company for failing to place LOW SHOULDER warning signs along the construction site. Although the trial court found for the claimant, an appeals court reversed the decision stating there was insufficient evidence to prove the construction company failed to provide adequate warning (*24*).

Between 1988 and 1995, the Louisiana DOT was sued for three work zone edge drop-off related crashes. The first case, which occurred in October 1988, involved a motorist who in an attempt to return to the paved roadway after crossing over a drop-off in a highway construction zone blew a tire, resulting in a rollover. In this case, an appeals court found the Louisiana DOT 70 percent at fault for creating a drop-off hazard and failing to adequately warn drivers. The Louisiana DOT paid $41,940 to the claimant (*25*). The second case, which took place in January 1989, the driver entered the interstate median in a construction zone while passing another vehicle. As the driver attempted to return to the highway, he lost control of his vehicle, crossed the right shoulder and overturned. The driver sued the Louisiana DOT claiming that a drop-off between the median and the left lane created by the construction activities caused him to lose control of the vehicle. In this case, since there were warning signs, traffic barrels, and a lower posted speed limit throughout the work zone, the court found the driver to be solely at fault (*26*). In the third case, the Louisiana DOT and the contractor were ordered to pay a combined total of over $1,100,000 in damages to the widow and daughter of a motorist who died of injuries received in a work zone edge drop-off related crash that occurred in November 1995. Apparently there were warning signs at the beginning and end of the project; however, there were no signs or edge striping to warn motorists of the drop-off and the centerline stripes were partially obscured (*3*).

In July 1990, the South Carolina DOT was found completely at fault for a crash that occurred as the result of an edge drop-off located in a work zone (*27*).

Iowa has also experienced tort liability resulting from work zone deficiencies, including edge differentials. Discussion of Iowa litigation history is contained in Section 4.2.1 of this report.

2.3.1. Vehicle Stability Over Drop-Offs

"Pavement Edges and Vehicle Stability: A Basis for Maintenance Guidelines" (*28*) discusses a series of tests conducted to determine how various factors affect the relative safety of an edge drop-off. In their study, Zimmer and Ivey (*28*) expanded on prior research conducted in the mid-

1970s. Testing was conducted using three edge drop heights (1.5 inches, 3 inches, and 4.5 inches) and three edge shapes (1.5-inch radius, 0.75-inch radius, and a 45-degree slope). Other variables considered were vehicle type (passenger car versus pickup truck), driver skill (professional, semi-professional, typical male, or typical female), and vehicle position (scrubbing versus non-scrubbing). Under scrubbing conditions the tire rubs against the pavement edge creating a resistance force that inhibits the vehicle from easily remounting the higher surface. Under non-scrubbing conditions, both right front and rear wheels ride on the lower surface, little resistance force is created, and the vehicle can easily return to the roadway.

Each test condition was evaluated at three vehicle speeds: 35 mph, 45 mph, and 55 mph. For each test run, three forms of data were collected: electronic, photographic, and subjective. The subjective data were obtained from drivers' rating of the severity of each test condition on a scale of 1 (no detectable effects) to 10 (total loss of control).

Upon evaluating the results of the tests, the researchers noticed that under non-scrubbing conditions there was very little difference in the level of severity between 3-inch and 4.5-inch drop-offs. Under scrubbing conditions, however, a pronounced increase in severity was observed when the edge drop increased from 3 inches to 4.5 inches. It was also noted that, under scrubbing conditions, when the 4.5-inch rounded edge drop-off was modified to a 45-degree slope a marked reduction in the severity level was reported by drivers. When evaluating speed effects on safety, a nearly linear increase in severity associated with each edge height was observed as speed increased. In agreement with past studies, Zimmer and Ivey concluded that an edge differential of 4.5 inches was a potentially unsafe condition even at a speed of 35 mph. A summary of the effects the three edge shapes have on relative degree of safety is illustrated in Figure 4 (*28*).

The level of safety associated with the pavement edge drop-offs as based on drivers' opinions can be described by one of these definitions (*28*):

Safe: No matter how impaired the driver or defective the vehicle, the pavement edge will have nothing to do with a loss of control. (This includes the influence of alcohol or other drugs and any other infirmity or lack of physical capability.) The term includes the subjective severity levels 1 through 3."

Reasonably Safe: A prudent driver of a reasonably maintained vehicle would experience no significant problem in traversing the pavement edge. The term includes subjective severity levels 3 through 5.

Marginally Safe: A high percentage of drivers could traverse the pavement edge without significant problems. A small group of drivers might experience some difficulty in performing the scrubbing maneuver while remaining in the adjacent traffic lane. The term includes subjective severity levels 5 through 7.

Questionable Safety: A high percentage of drivers would experience significant difficulty in performing the scrubbing maneuver while remaining in the adjacent traffic lane and full loss of control could occur under some circumstances. The term includes subjective severity levels 7 through 9.

Unsafe: Almost all drivers would experience great difficulty in returning from a pavement edge scrubbing condition and loss of control would be likely. The term includes subjective severity values 9 through 10.

From other tests, it was found that, regardless of whether tires rubbed against the edge of pavement or not, drivers at all four skill levels responded similarly while traversing a 3-inch drop-off. It was also concluded that vehicle type had very little influence on degree of safety associated with an edge drop-off, but edge shape, particularly a 45 degree slope did (*28*).

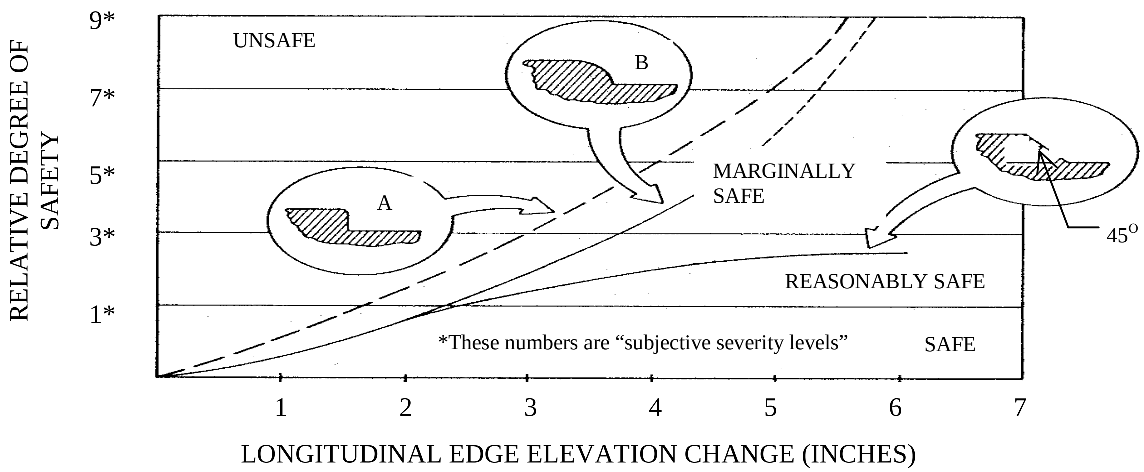


Figure 4. Relationship Between Edge Geometry and Safety for Scrubbing Conditions (*28*)

2.3.2. Analytical Model of Vehicle Behavior

In 1986, Ivey and Sicking published a report titled *Influence of Pavement Edge and Shoulder Characteristics on Vehicle Handling and Stability* (*29*). This report developed an analytical approach to predict the steer angle required for a vehicle to mount an edge differential under conditions where the tire is rubbing against the edge of the pavement. The following is an excerpt describing the importance of steer angle:

> Consider an automobile with one set of wheels off the pavement edge but with the inside of those wheels brushing that edge as shown in Figure [5]. As the driver turns the steering wheel in an effort to mount the edge to return to the paved surface, the steering angle of the front wheels, α, is gradually increased. As α gets larger, the vehicle will finally climb the edge when the front wheel reaches the critical value of α, α_c. Further, the right rear tire will finally mount the edge when

the yaw of the vehicle has increased to approximately α_c. The vehicle speed, yaw, and yaw rate at this predictable vehicle position, along with the driver's reaction time and counter steering capability will then dictate whether the vehicle can be successfully controlled. The critical steer angle, α_c, is therefore of major importance in predicting vehicle controllability.

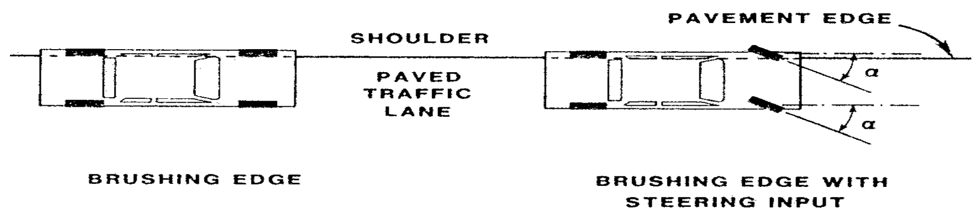


Figure 5. Vehicle Gradually Turning Toward a Pavement Edge (*29*)

The steer angle is dependent on several factors including effective edge height. "The effective edge height is defined as the height above the lower surface (usually considered the shoulder surface) at which the tire makes predominant contact with the edge" (*29*). The effective edge height equals total edge height for a 90-degree vertical face. If the edge shape is more rounded, and/or the slope is more gradual, the effective edge height decreases. Effective edge heights for different shapes and slopes are illustrated in Figure 6. The effective edge height can be used to explain "… in simple geometric terms the resistance a tire (or vehicle) encounters in traversing edges of the same total height but of quite different shape" (*29*).

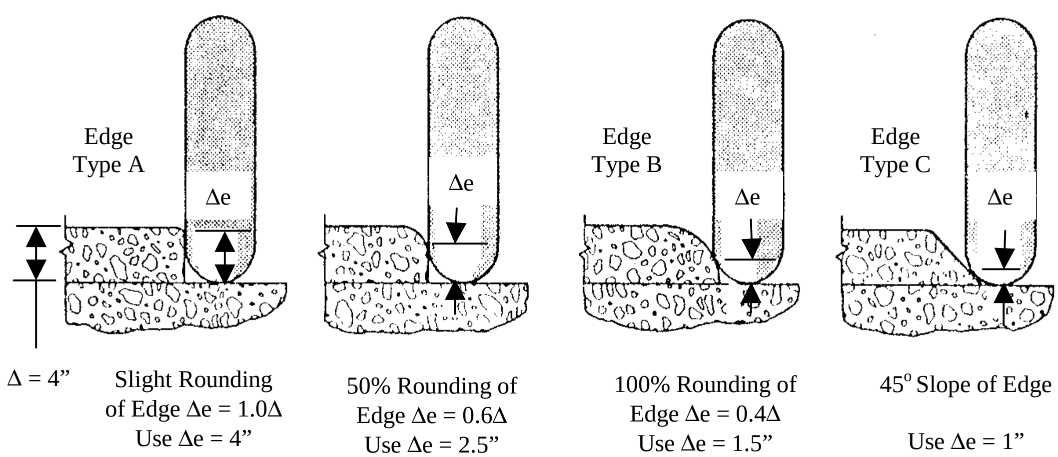


Figure 6. Effective Edge Heights for Different Edge Slopes (*29*)

After a formula for calculating steer angle was determined, the relative degrees of safety for nine different edge conditions were evaluated in research using the Highway Vehicle Object Simulation Model (HVOSM) (*30*). But before the HVOSM could be used, driver control characteristics were input for each test run. Based on previous research, it was assumed that "… the driver would start moving the steering wheel 0.5 sec after the right front tire mounted the edge from a scrubbing condition, and the rate of wheel movement would be 16 degrees per sec" (*29*). An analysis of edge rounding influence on vehicle action determined that a sharp, four-inch high edge could result in complete loss of control. As the edge is progressively rounded however, that reaction is rapidly reduced. Another investigation found that safety with a 45-degree sloped edge progressively increased as edge height was decreased from six to two inches. A final analysis determined how varying edge slopes influence relative safety of a four-inch drop-off. It was shown that "[a]s the slope is reduced from 45 to 15 degrees, the margin of safety, as illustrated by how much of a 12-ft lane is needed for the maneuver, becomes progressively larger" (*29*).

2.3.3. Vehicle Interaction at Pavement Edge Drops

Pavement Edge Drop (*31*), a report published by the University of Michigan Transportation Research Institute in 1986, discusses in significant detail an investigation conducted to determine the performance of ordinary (naïve) drivers on their first encounter with a pavement edge drop-off. The study evaluated how edge drop height affected the "… extent to which the vehicle intruded beyond its own lane during the recovery process" (33). The independent variables evaluated included edge shape (vertical face versus 45-degree beveled edge), shoulder surface type (solid versus soft), and vehicle size and type (front-wheel drive versus rear-wheel drive). It was found that naïve drivers could not recover from a vertical face edge drop of 4.5 inches without traveling beyond the adjacent lane at any of the speeds tested (minimum of 20 mph). Naïve drivers of large passenger cars were generally able to recover from a scrubbing condition experienced when passing over a vertical edge drop-off of three inches at a speed of 30 mph. However, tests with a professional driver operating a small car on the same three-inch vertical drop-off "… suggest that the safe speed would have to be lower, probably between 20 and 25 mph" (*31*). Tests conducted on varying edge heights with 45-degree beveled edges revealed that all subjects, naïve and professional, were able to recover from the scrubbing condition at speeds up to 55 mph without intruding beyond the adjacent lane of travel. "Tests run on soft shoulders by a professional driver indicate that it is the height of the edge to be climbed, not the nature of the material at the edge, that affect the ease with which the edge can be mounted" (*31*). Soft materials, however, may allow a vehicle's wheels to sink in to some degree, thus increasing the effective edge height that the vehicle would have to mount. In-vehicle measurements recorded for each test indicated that a higher edge drop results in a higher average steer angle. Comparisons of performance for front-wheel and rear-wheel drive cars indicated that front-wheel drive vehicles perform slightly better than rear-wheel drive for a 4.5-inch drop. The reverse was found to be true for an edge drop of three inches (*31*).

References to an earlier study indicated "… there is a simple linear relationship between edge drop height and normal velocity required to climb until the edge drop height reaches about four inches. From that point on the velocity required to climb increases very rapidly" (*31*).

2.3.4. Effects of Pavement Drop-Offs on Highway Safety

"Effect of Pavement/Shoulder Drop-Offs on Highway Safety" (*32*), an article in the 1987 NCHRP *State of the Art Report 6*, synthesizes the safety of pavement/shoulder drop-offs. According to Glennon (*32*), there are seven possible outcomes that can occur when a driver inadvertently crosses over a pavement edge drop-off. These results are dependent on the degree of vehicle departure angle and the driver's initial response (see Figure 7). As Figure 7 illustrates, "[i]f the departure angle is high, recovery is quite unlikely, and a collision of some type on the roadside is probable (Outcome 7). If the departure angle is shallow to moderate, the driver has some potential to respond with a recovery attempt (Outcomes 1–6)" (*32*). Glennon recognizes scrubbing re-entries, where a resistance force is created from the interaction of tire and pavement edge, as the primary hazard associated with pavement edge differentials. When a driver traverses a significant drop-off at a relatively high speed and scrubbing occurs, the vehicle is likely to either encroach on the adjacent travel lane or spin out of control (*32*).

Glennon referenced several prior research studies. One of these illustrated that a drop-off exceeding about three inches requires a high steering angles for the vehicle to mount the pavement surface. Once the vehicle re-mounts, that steering angle forces a rapid lateral move into the adjacent lane. This phenomenon helps explain why scrubbing re-entries are so potentially hazardous. Glennon expanded on this research and developed a graph (Figure 8) to illustrate the maximum re-entry angle that could be attempted before a safe recovery would no longer be possible (*32*).

Glennon also developed a graph (Figure 9) to illustrate the minimum safe re-entry angle after traversing edge drop-offs of various heights. "For any combination of vertical-face drop-off height and lane width, the upper and lower boundary conditions shown in Figures [8] and [9] can be combined to depict the range of safe reentry angles for any vehicle speed" (*32*).

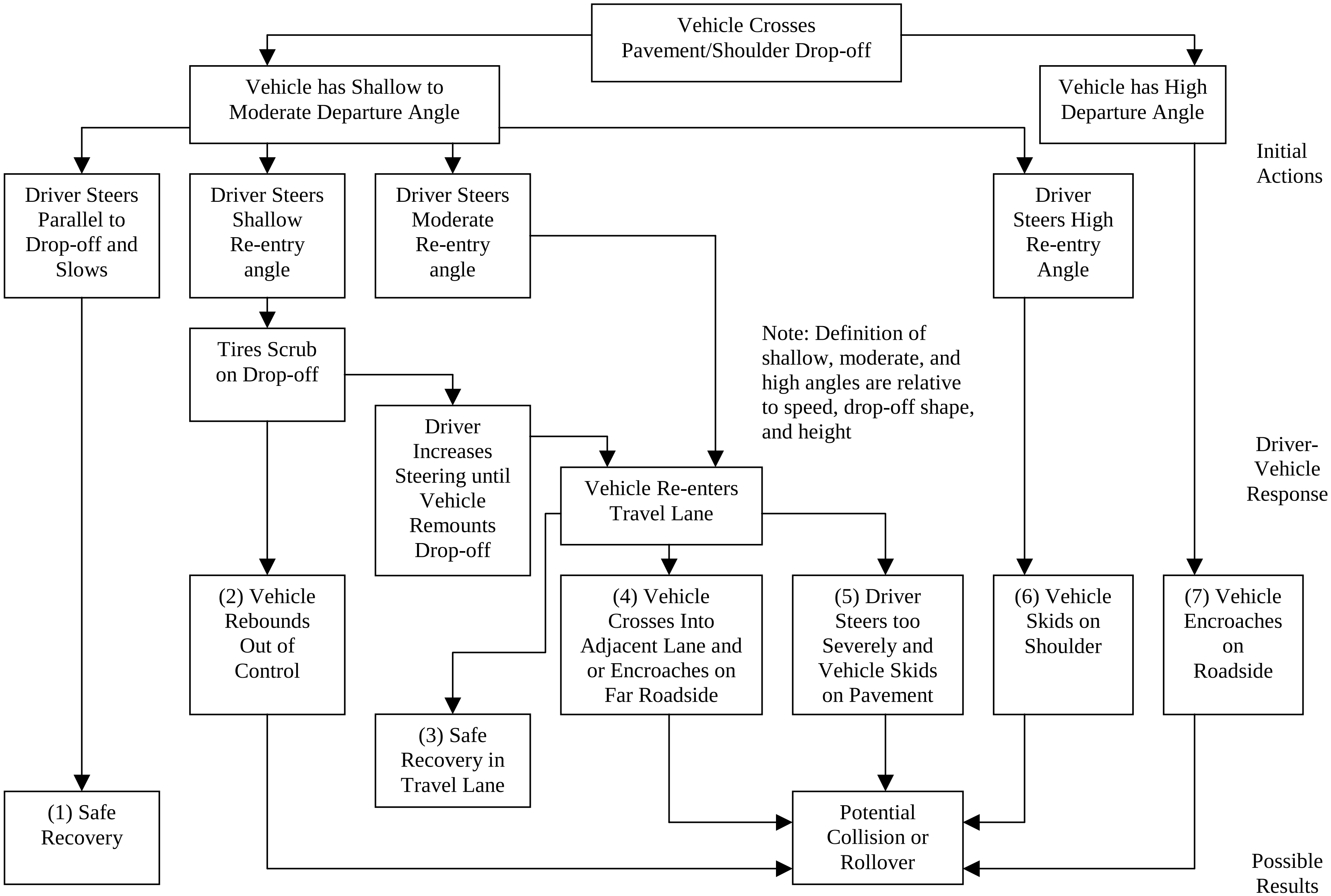


Figure 7. General Characterization of Pavement/Shoulder Drop-Offs (*32*)

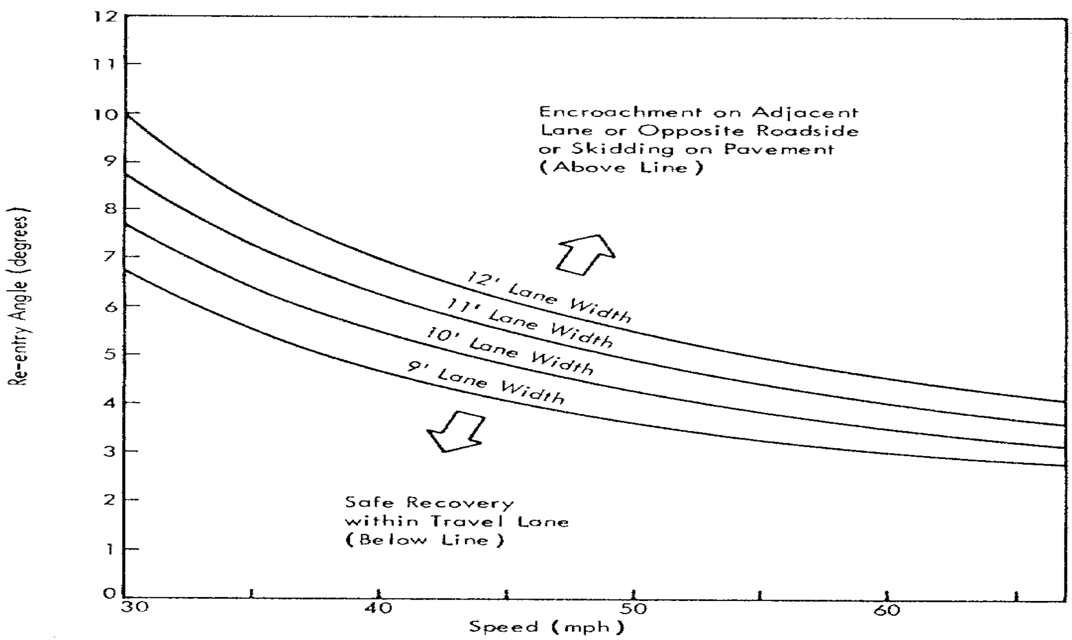


Figure 8: Maximum Safe Reentry Angle for Shoulder Traversal (*32*)

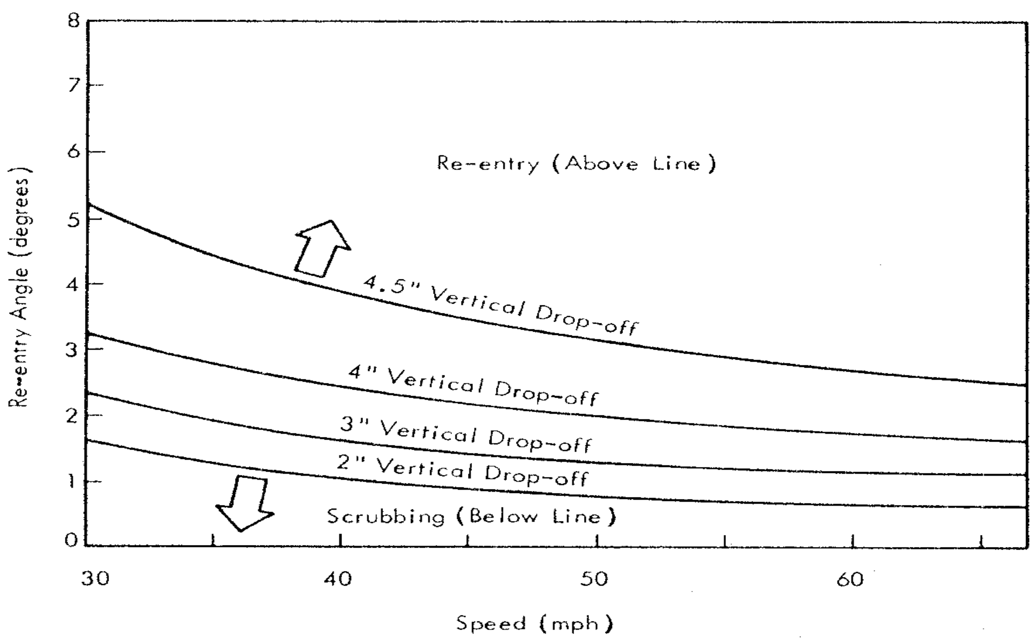


Figure 9. Minimum Safe Reentry Angle for Traversal of Vertical Face Pavement/Shoulder Drop-Off (*32*)

Glennon developed the following general conclusions regarding safety of pavement/shoulder drop-offs (*32*):

- The most obvious hazard associated with pavement/shoulder drop-offs occurs when a driver tries to recover from a scrubbing condition.

- The probability of a scrubbing reentry at a pavement/shoulder drop-off increases as (a) the drop-off face approaches a full vertical edge and (b) the drop-off height increases.

- The probability of a successful recovery from a drop-off maneuver decreases as (a) the drop-off face approaches a full vertical edge, (b) the drop-off height increases, (c) the vehicle speed increases, and (d) the lane width decreases.

- The severity (yaw velocity, lateral encroachment, etc.) of a scrubbing reentry maneuver increases as the drop-off shape approaches a full vertical edge and as the drop-off height and vehicle speed increase.

- A 5-inch drop-off height is a practical maximum to prevent hazardous undercarriage contact on most vehicles.

Based on the above conclusions, Glennon developed provisional guidelines (Figure 10) for determining whether or not an edge drop-off would be tolerable. These guidelines were developed primarily for use with resurfacing, rehabilitation, and restoration (3R) highway improvements. If the data in Figure 10 indicate that a pavement/shoulder drop-off is intolerable at highway speeds, Glennon recommends implementing one of the following two mitigation measures. “First, material (preferably stabilized) can be added to raise the shoulder elevation to a tolerable level (preferably flush). Second, the edge shape can be changed to more closely approximate a 40 to 60 degree continuous taper by either adding an asphalt wedge or grinding the existing edge” (*32*). Glennon also recommends the use of warning signs in situations where a tolerable pavement edge drop-off is allowed to remain.

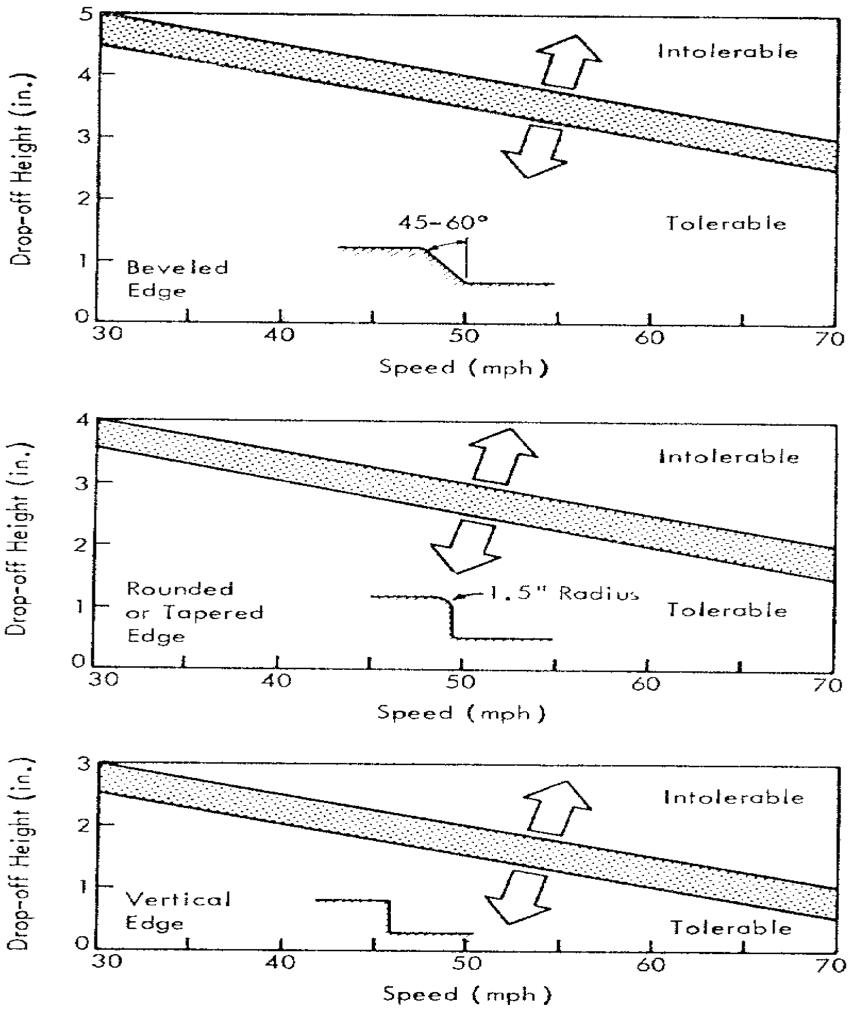


Figure 10. Suggested Guidelines for Determining Tolerable Pavement/Shoulder Drop Heights (*32*)

2.3.5. Driver Behavior, Vehicle Behavior, and Economic Analysis

"Safety in Construction Zones Where Pavement Edges and Drop-Offs Exist" (*4*) defines four levels of vehicle interaction with pavement edges: nibbling, scrubbing, dragging, and rolling.

The first level of interaction, nibbling, is generally associated with edge drop-offs of not more than one inch. The term nibbling "… comes from the idea that a tire rolling immediately adjacent to a longitudinal pavement edge or 'seam' of low height nibbles at the edge until it gets a good bite, and then the tire-edge interaction forces pull the tire up onto the higher-level pavement" (*4*). The nibbling phenomenon is illustrated in Figure 11. Nibbling does not usually affect safety, but rather can cause driver irritation. A possible exception to this however, may occur when the shallow edge drop of one inch or less is located within four to nine feet laterally from a more significant drop-off. In this case the driver, in an attempt to avoid the irritation of the nibbling edge, may cross the more severe edge drop-off, possibly colliding with a construction barrier or channelizing device.

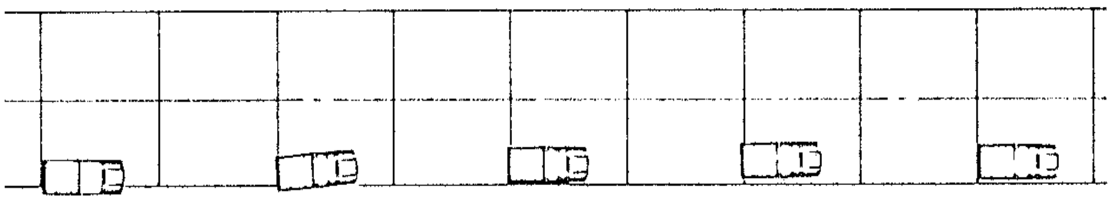


Figure 11. The Nibbling Phenomenon (*4*)

The second level of interaction, scrubbing, occurs with pavement edge differentials between one and five inches. Unlike nibbling, scrubbing is recognized as a significant potential hazard. With scrubbing, a resistance to steering back onto the higher level occurs, which could result in a loss of vehicle control. The following is a list of events that can occur with scrubbing conditions (*4*):

- A vehicle is under control in a traffic lane adjacent to a pavement edge where an unpaved shoulder is lower than the pavement.

- Because of inattention, distraction, or some other reason the vehicle is allowed to move so that the right wheels are on the unpaved shoulder and just off the paved surface.

- The driver then carefully tries to steer the vehicle gently to bring the right wheels gradually back up onto the paved surface without reducing speed significantly.

- The right front wheel encounters the pavement edge at an extremely flat angle and is prevented from moving back onto the pavement. The driver further increases the steering angle to make the vehicle regain the pavement. However, the vehicle continues to scrub the pavement edge and does not respond. At this time there is equilibrium between the cornering force to the left and the edge force acting to the right, as shown in Figure [12-1a].

- The driver continues to increase the steering input until the critical steering angle is reached and the right front wheel finally mounts the paved surface. Suddenly, in less than one wheel revolution, the pavement edge force has disappeared and the cornering force of the right front wheel may have doubled because of increases in the available friction on the pavement and the increases in the right front wheel load caused by cornering (see Figure [12-1b]).

- The vehicle yaws radically to the left, pivoting about the right rear tire, until that wheel can be dragged up onto the pavement surface. The excessive left turn and yaw continues, and it is too rapid in its development for the driver to prevent penetration into the oncoming traffic lane (Figure [12-1c]).

- A collision with oncoming vehicles or spin-out and possible vehicle roll may then occur.

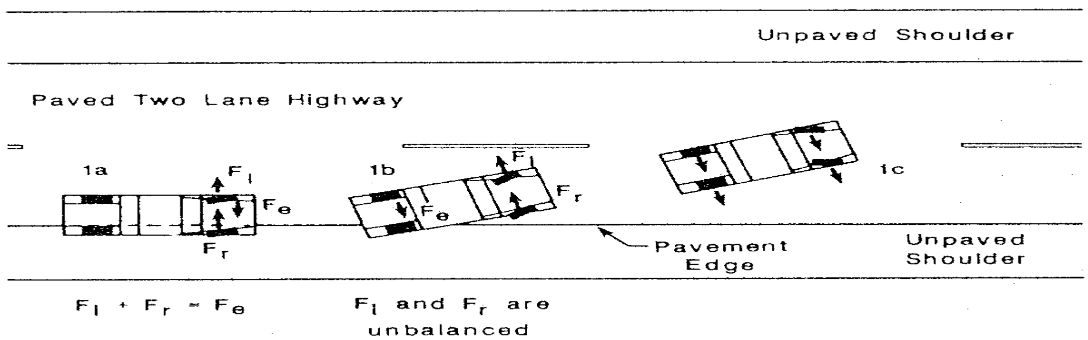


Figure 12. Pavement Edge Influence on Vehicle Stability: The Scrubbing Phenomenon (*4*)

The third level of vehicle interaction with pavement edges is known as drag. Dragging occurs when the height of the drop-off exceeds the clearance under a vehicle. It was found that 75 percent of the vehicles evaluated had a clearance of 4.8 to 6.4 inches. Dragging, for the most part, only causes damage to the undercarriage of a vehicle and therefore, is not considered as significant a safety concern as scrubbing. When the drag forces act to the right of a vehicle's center of gravity as depicted in Figure 13a, however, the vehicle is brought to a fairly abrupt stop. Although the rate of deceleration may be tolerable for occupants of the vehicle, it generally occurs too fast for a driver following closely behind to react. For this reason, drag conditions can result in rear-end collisions (*4*).

In some situations, departure angle, speed, or combination of these factors could cause the drag force to act on a line to the left of the vehicle's center of gravity. In this scenario, the vehicle would rotate counter clockwise, as shown in Figure 13b. The result of this drag condition is loss of vehicle control and possible roll (*4*).

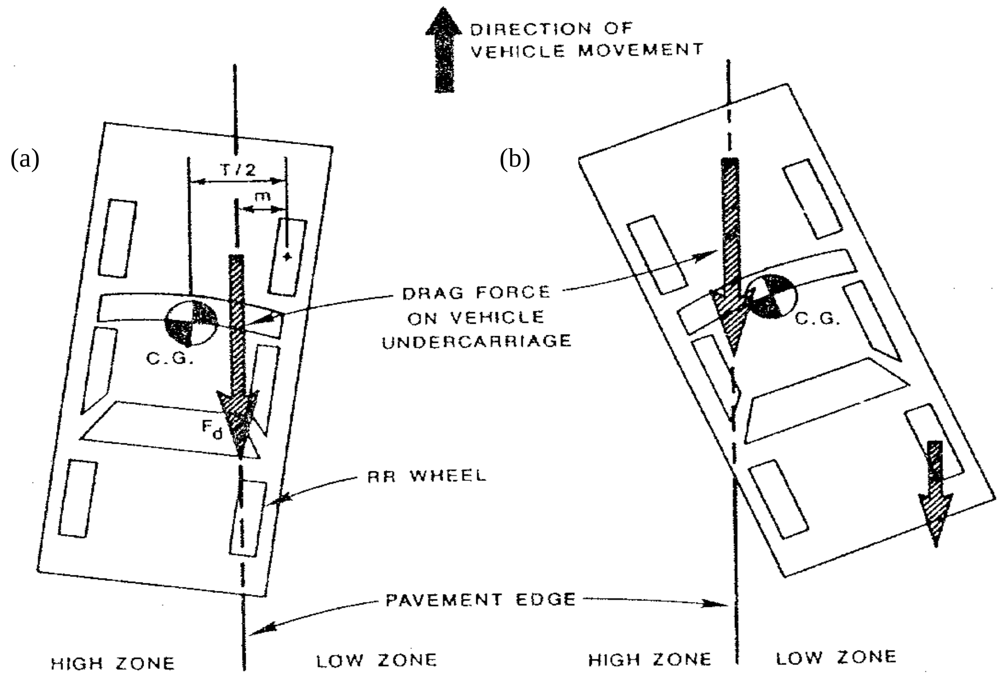


Figure 13. Vehicle Movements in Response to Drag Force: (a) Drag Force to Right of Center of Gravity; (b) Drag Force to Left of Center of Gravity (*4*)

The fourth level of interaction is identified as roll which is generally associated with edge differentials in excess of one foot, a very significant safety concern. When one side of a vehicle moves abruptly to a lower elevation, as is the case when a vehicle traverses a drop-off, the center of gravity moves outward with respect to the right side. This shift in the center of gravity, combined with any cornering effect induced by the driver's attempt to steer back onto the higher surface, produces an overturning moment. The critical height at which the overturning moment will cause a vehicle to roll varies by type and size of vehicle. A typical tractor-trailer can traverse an edge differential of up to 17.3 inches before rolling; a typical automobile can cross an edge drop as high as 26 inches and remain upright (*4*).

After identifying some of the safety concerns associated with edge drop-offs, Ivey et al. (*4*) developed a benefit-cost analysis that could be used to justify use of a specific countermeasure to protect an edge drop-off of a given height. To formulate the benefit-cost procedure, it was necessary to determine the cost of crashes associated with pavement/shoulder drop-offs. "The determination of crash costs requires the estimate of the number of crashes that are expected to occur and the severity of those crashes" (*4*). The method Ivey et al. used to predict the probability and severity of a hazardous event follows the concepts of the 1977 *Traffic Barrier Guide* and the 1989 *Roadside Design Guide*.

The benefit/cost analysis was not fully described in that report; however, a detailed description of the procedures can be found in a 1987 report titled *Assuring Appropriate Levels of Safety in*

Construction Zones Where Pavement Edges and Drop-Offs Exists (*33*). In this report, Ivey, Mak, and Cooner developed a method to estimate the probability of a vehicle crossing an edge drop-off located a given lateral distance from the travel lane. This probability was related to the average daily traffic (ADT). Next, the percentage of those vehicles that would be subjected to the scrubbing condition was estimated based on the magnitude of drop-off, vehicle speed and indirectly related to the angle of approach. Then the percentage of scrubbing vehicles that would encroach into the adjacent travel lane was estimated, again dependent on vehicle speed and depth of drop-off. Finally the researchers developed formulas to predict a severity index (SI) for a crash depending on whether the errant vehicle was predicted to nibble, scrub, drag, or roll.

Referring to the Ivey et al. report "Safety in Construction Zones Where Pavement Edges and Drop-offs Exist" (*4*), severity indices (SI) were used to calculate crash costs. These costs, in 1986 dollars, associated with each crash severity index used in the benefit-cost analysis are shown in Table 1. Specific conditions Ivey et al. used to predict the costs of the crashes are shown in Table 2. Table 3 lists some of these predicted crash costs "… for the most critical situation investigated, the four-lane undivided highway" (*4*). Ivey et al. used these predicted crash costs to develop graphs that could be used to economically analyze use of a temporary traffic barrier in a work zone with barrier costs per month of two, five, or ten dollars per foot. The graph developed for a barrier cost of five dollars per foot per month is shown in Figure 14. The initial cost of the barrier may be significantly higher than these approximations, but "[i]f a highway department buys a portable barrier and uses it for several years, the ultimate cost per month of use may be only a fraction of the original cost" (*4*). It should be noted that this benefit-cost analysis developed by Ivey et al. did not consider "… the crash costs of colliding with the barrier instead of interacting with the edge" (*4*).

Table 1. Crash Costs for Various Severity Index Levels (*4*)

Severity Index	**Crash Costs (1986 dollars)**
0	$2,120
1	$4,290
2	$6,450
3	$8,620
4	$18,230
5	$49,450
6	$103,020
7	$238,500
8	$463,340
9	$604,820
10	$723,970

Table 2. Conditions Used to Predict Crash Cost (*4*)

Highway Type	**ADT**	**Edge Height (inches)**	**Lateral Position (feet)**
Two-lane, undivided	1,000 to 30,000	1 to 24	0 to 20
Four-lane, undivided	10,000 to 200,000	1 to 24	0 to 20
Six-lane, undivided	25,000 to 225,000	1 to 24	0 to 20

Table 3. Representative Crash Costs for 1,000 Feet of a Specified Edge Condition in a Construction Zone (*4*)

Lateral Clearance (feet)	**Drop-Off Height (inches)**	**Crash Cost (per month/1,000 feet of drop-off)**
ADT = 10,000		
0	5	$30
5	5	$28
20	5	$13
0	24	$639
5	24	$587
20	24	$263
ADT = 100,000		
0	5	$442
5	5	$402
20	24	$182
0	24	$9,302
5	24	$8,539
20	24	$3,833
ADT = 200,000		
0	5	$4,493
5	5	$1,370
20	5	$615
0	24	$31,498
5	24	$28,851
20	24	$12,949

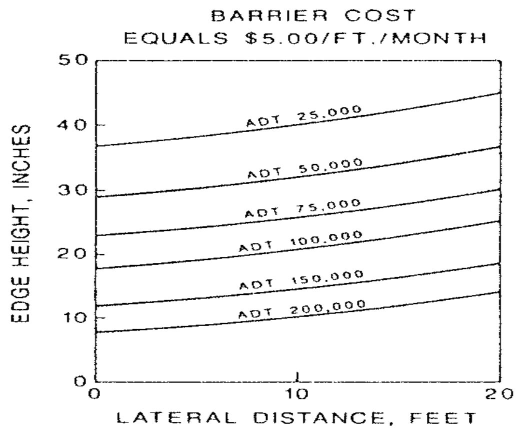
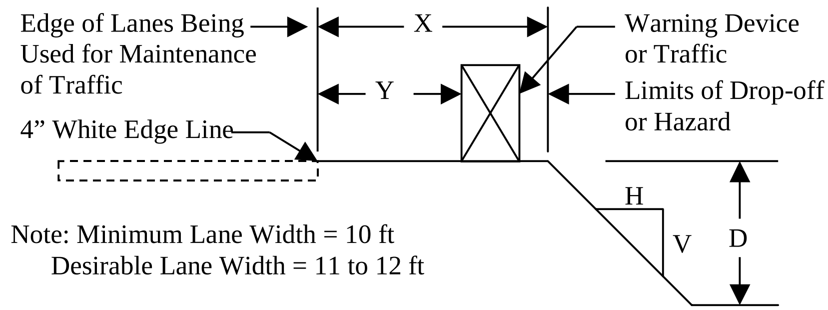


Figure 14. Edge Height and Lateral Distance Conditions Related to Cost Effectiveness of Concrete Barrier Rail (at $5.00/feet/month) (*4*)

From the results of their study, Ivey et al. formulated guidelines for selection of warning and protective devices in work zones. "The type of warning device and/or protective barrier selected depends on several factors including traffic volume, lateral distance from the edge of travel lane to hazardous condition, depth of drop-off, duration of the hazardous condition, and shape of the edge or slope of the drop-off" (*4*). In developing the guidelines, project duration was assumed to extend overnight or longer. Figure 15 illustrates pertinent dimensions and terms referenced throughout those guidelines.



1. Distance “X” (lateral clearance) is to be the maximum practical under job conditions

2. Distance “Y” is to be a minimum of 2 feet if feasible.

3. Warning devices must not encroach on lanes required for maintenance of traffic at any time.

4. When optional devices are specified, the contractor may select the type to be used. If distance “X” must be less than 3 feet use of positive barrier (e.g., concrete traffic barrier, metal beam guard fence, barrel mounted guard fence) may not be feasible. If in this case a positive barrier is needed according to Figure 19, considerations should be given to moving the lane of travel laterally to provide the needed space or to providing an edge slope such as Condition I.

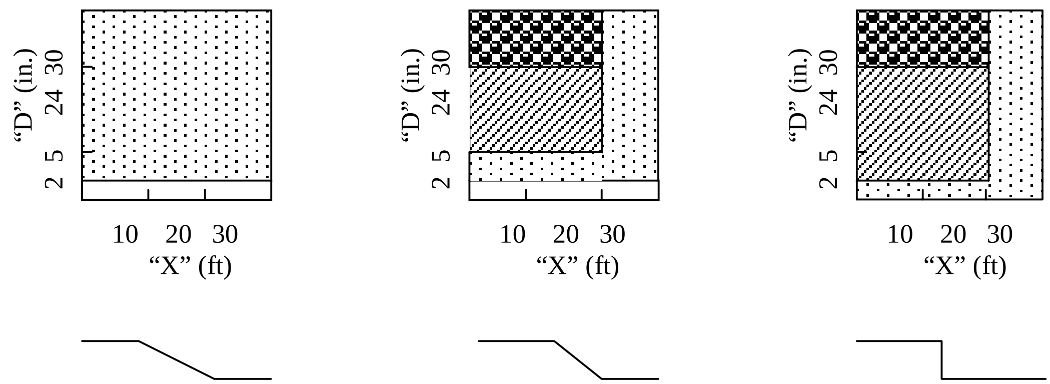
Figure 15. Definition of Terms (*4*)

Figure 16 provides definitions and treatments for different zones with various edge conditions as described below. These factors should be considered when selecting the appropriate treatment for each edge condition (*4*).

- **Edge Condition I:** Most vehicles are able to traverse an edge condition with a slope rate of 3:1 or flatter.

- **Edge Condition II:** Most vehicles are able to traverse this edge as long as D [depth of edge drop-off] does not exceed 5 inches. Undercarriage drag on most automobiles will occur as D exceeds 6 inches. As D exceeds 24 inches, the possibility of rollover will be greater for most vehicles.

- **Edge Condition III:** Edges where D is greater than 2 inches can present a problem to drivers if not properly treated. In the zone where D is 2 to 24 inches, different types of vehicles have safety-related problems at various edge heights. Automobiles have more difficulty in the 2- to 5-inch zone. Trucks, particularly those with high loads, have more difficulty in the 5- to 24-inch zone. As D exceeds 24 inches, the possibilities of rollover will be greater for most vehicles.



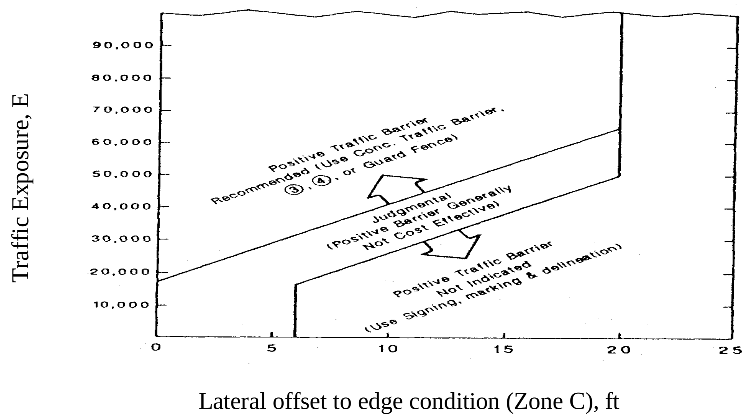
Edge Condition I: 3:1 or flatter   Edge Condition II: 2.99:1 to 1:1   Edge Condition III: 0.84:1 to 0:1

Zone	Usual Treatment
A	SHOULDER DROP-OFF or UNEVEN LANES signs plus vertical panels.
B	SHOULDER DROP-OFF or UNEVEN LANES signs plus drums with steady burn lights. Where restricted space precludes the use of drums, use vertical panels. An edge fill may be provided to change the edge slope to that of the preferable Edge Condition I.
C	Check indications for positive barrier. Where positive barrier is not indicated, the treatment shown above for zone B may be used after consideration of all other applicable factors.

Figure 16. Definition of Treatment Zones and Treatment Selection Guidelines for Various Edge Conditions (*4*)

It is also recommended that when traffic may cross either Edge Condition I or II, height of edge drop-off be limited to 1.5 inches. Any edge differentials from 1.5 to 3 inches should be treated with a 3:1 or flatter sloped asphalt fillet if traffic may cross it (*4*).

To determine when a temporary traffic barrier may be justified to shield an edge drop-off, Ivey et al. developed Figure 17. The use of a temporary barrier is related to traffic volume and lateral distance from the drop-off to the traffic lane. These guidelines as developed by Ivey et al. were reviewed and accepted by the Federal Highway Administration (*4*).



Notes:

1) E = ADT * T, Where ADT is that portion of the average daily traffic volume traveling within 20 feet (generally two adjacent lanes) of the edge dropoff condition and, T is the duration time in years of the dropoff condition.
2) Primarily applicable to high speed conditions only.
3) Barrel Mounted Guard Fence may be used in lieu of CTB where speeds of 45 mph or less and impacting angles of 15 degrees or less are anticipated.
4) An approved end treatment should be provided for any positive barrier end located within a lateral offset of 20’ from the edge of the travel lane.

Figure 17. Conditions Indicating Use of Positive Barrier (*4*)

Another study for effective use of temporary barriers for edge drop-off protection is *Guidelines for Positive Barrier Use in Construction Zones* by Sicking (*34*). In this report, Sicking recognized the need for definitive guidelines in selecting temporary barrier use and provided a benefit/cost methodology and selection recommendations. Several situations were analyzed including bridge widening, roadway widening, adjacent structure construction, and two-lane, two-way operations on normally four-lane roadways. Guidelines were developed and presented in graphical form for these applications, primarily relating to operating speed and traffic volumes. It was concluded that temporary barrier use could be warranted economically with quite low traffic volumes for structure work, but roadway widening situations would require much higher volumes and long exposure times to justify temporary barrier deployment, if predicted crash costs are the major consideration. Sicking also presented recommendations for barrier end treatment by flaring the approach end to avoid a potential hazard for oncoming traffic.

2.3.6. Elimination or Mitigation of Hazards

The report *The Elimination or Mitigation of Hazards Associated with Pavement Edge Drop-Offs During Roadway Resurfacing* (*35*), published by the University of Tennessee’s Transportation Center in 1994, discusses some of the safety issues dealing with vehicle interaction with pavement edge drop-offs (see Section 2.3.3). The report also discusses some of the possible mitigation strategies that can be used to decrease potential hazards associated with travel lane drop-offs. The relative degrees of safety associated with edge drop-offs are again described as safe, reasonably safe, marginally safe, questionably safe, and unsafe, with the same definitions as listed in Section 2.3.1. Adding a 45-degree fillet along a lane differential enables a driver to more easily return to the road surface without over-steering into the oncoming traffic lane. Figure 18 illustrates this premise by showing the influence various edge shapes have on a vehicle's path of re-entry. The report also points out that "[a]s the tire size (height) increases, pavement edge drop-off has less influence on the ability of the tire to mount the pavement. Likewise, a larger vehicle uses momentum and sheer weight to overcome the resistance force of the pavement edge" (*35*).

The Tennessee researchers indicated that pavement edge drop-offs may be even more hazardous than previously realized. "In addition, pavement edge drops are a common source of tort claims against highway agencies" (*35*). To determine the best mitigation methods for lane edge drop-offs, common practices with resurfacing projects were reviewed. It was found that in some states shoulder work is not included in the resurfacing contract. It then is incumbent on the governmental agency to perform the shoulder restoration, which may not be competed for several weeks or months. In the interim, public travel on the roadway continues the edge drop-off is exposed to traffic. The most effective method to address this concern is simply to include shoulder work as part of all resurfacing contracts. If shoulder work is not incorporated into the resurfacing contracts, the Tennessee researchers recommended "… that a 45-degree-angle asphalt fillet be installed as part of the roadway resurfacing, along the edge of the roadway" (*35*). The asphalt fillet can be formed along the edge of the pavement concurrent with overlay placement by attaching a device known as a "molding shoe" to the paving machine. "The molding shoe not only forms the shape of the asphalt fillet, but also reduces the amount of handwork required to finish the pavement edge" (*35*). The cost associated with placement of this asphalt fillet is minimal compared to exposure of public traffic to drop-offs.

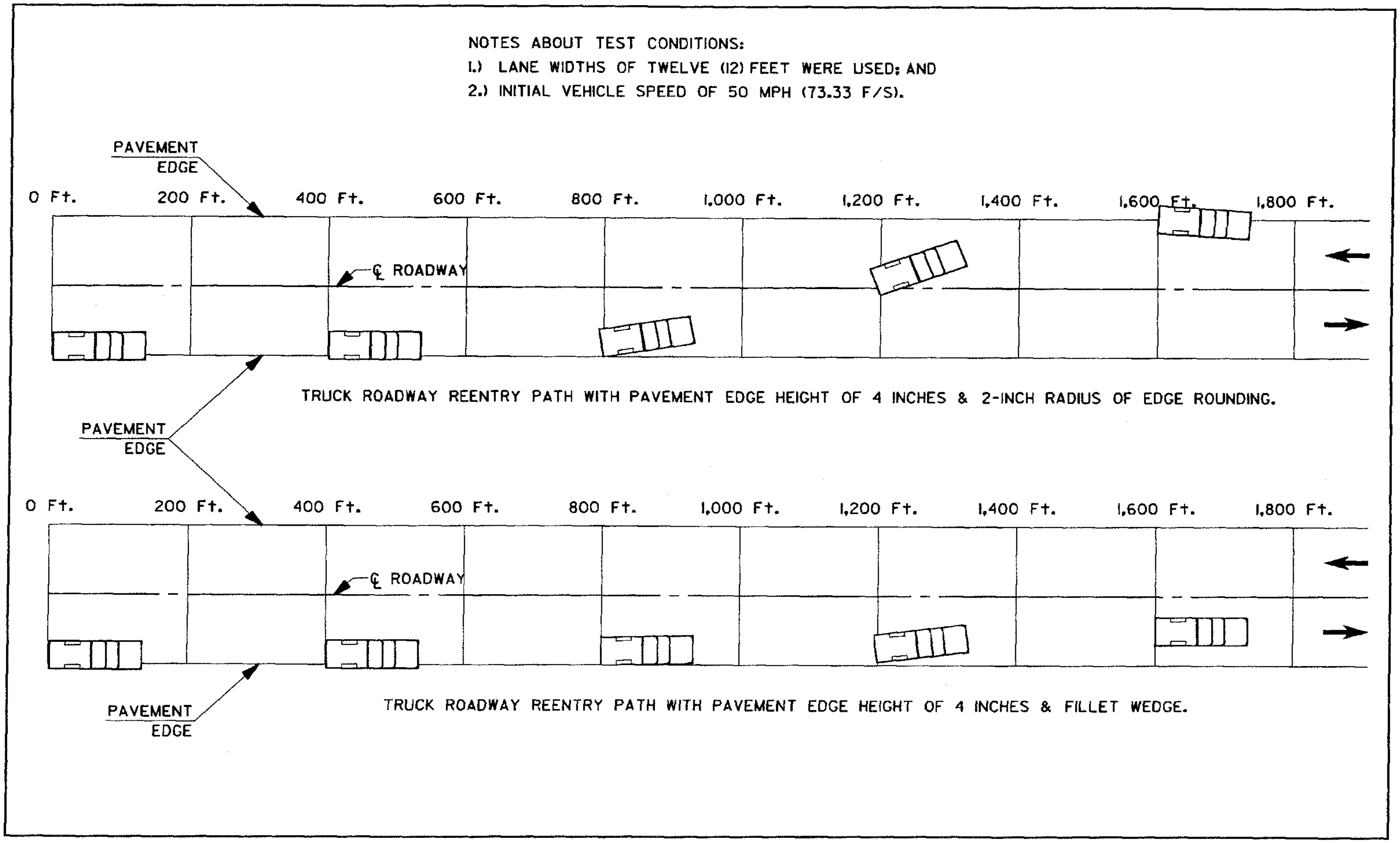


Figure 18. Influence of Different Pavement Edges on Vehicle Reentry Path (*35*)

2.3.7. Guidelines for Mitigating Pavement Edge Drop-Offs

An additional resource reviewed was Chapter 9 of AASHTO's 2002 *Roadside Design Guide* (*1*). According to this design guide, "[d]esirably, no vertical differential greater than 50 mm [two inches] should occur between adjacent lanes" (*1*). Since this may not always be possible, the design guide also suggests some mitigating measures. These measures can depend on several factors including project duration, traffic volume and speed, geometry of the roadway, relative location of opposing traffic, shape of the vertical edge, longitudinal length of the differential, and lateral location of the differentials to center-line, lane line, and/or edge-of-traveled-way. The guide notes that loss of control could occur when traversing an edge drop-off at speeds greater than approximately 30 mph if an attempt to quickly return to the traffic lane is made by over-steering to overcome scrubbing resistance. It was stated that edge differentials could be mitigated satisfactorily with a 45-degree or flatter edge face. It was also recommended that drop-offs greater than three inches immediately adjacent to open traffic lanes not be left overnight. Several mitigating measures are suggested if overnight exposure cannot be avoided:

- Place a wedge of material along the face of the drop-off. The wedge should consist of stable material placed at a 45-degree or flatter slope. Warning signs should be placed in advance and throughout the treatment. Pavement markings are useful in delineating the edge of the travel lane.

- Place channelizing devices along the traffic side of the drop-off and maintain, if practical, a 1-m [three foot] wide buffer between the edge of the travel lane and the drop-off. Warning signs should be placed in advance and throughout the treatment.

- Install portable concrete barriers or other acceptable positive barriers with a buffer between the barrier face and the traveled way. An acceptable crashworthy terminal or flared barrier should be installed at the upstream end of the section. For nighttime use, standard delineation devices must supplement the barriers.

- Where a trench exists adjacent and parallel to the pavement edge, place steel plates to cover an excavation or trench, if feasible. A wedge of material around the cover may be required to ensure a smooth transition between the pavement and the plate. Steel plates shall be held in place with pins adjacent to the paving material to prevent lateral movement. Warning signs should be used to alert motorists of the presence of steel plates and that they may be slippery, particularly when the plates are on the travel lanes.

2.3.8. Other Mitigation for Pavement Edge Differentials

In 2001 the Center for Transportation Research and Education at Iowa State University completed a study for the Iowa DOT, *Paved Shoulders on Primary Highways in Iowa: An Analysis of Shoulder Surfacing Criteria, Costs, and Benefits* (*36*). Although this study did not focus directly on edge drop-offs, the conclusions and recommendations include findings of potential importance to the subject. In comparing crash histories and other states' experiences and reviewing pertinent research, it was found that roads with paved shoulders generally exhibit lower crash rates than those without paved shoulders. The recommendations included specific width paved shoulders be included in design of new and restorative improvements on many Iowa highways. This action, particularly with resurfacing projects, would contribute directly to eliminating a drop-off adjacent to open traffic lanes and would laterally shift any remaining differential away from those lanes, a positive safety step.

2.4. Literature Conclusion

The resources related to general work zone safety provide an excellent background for pertinent issues of concern. Although some variation in severity data for work zone crashes was found, all reviewed materials indicated that frequency of crashes is greater in work zones compared to non-construction areas. It was also generally agreed that rear-end collisions are the most frequent type of work zone related crash.

Several common methods to decrease crash rates in work zones were also identified. Road users must be provided with advance warning of road and traffic conditions ahead, unnecessary speed reductions should be avoided, and the width of travel lanes should be narrowed before reduction of available lanes is considered. The literature results found that overall safety of a work zone is highly dependent on an effective traffic control plan and quality of traffic control devices used throughout the activity. Reports indicated that project duration influences the selection of proper traffic control; however, information relating duration and/or project length to overall safety in work zones could not be identified. The materials also did not clearly define how the existence of an edge drop-off increases the degree of hazard associated with work zones.

All reviewed studies recognize pavement edge differentials as potentially serious hazards, with most significant safety concerns occurring when a differential of three inches or more is reached. Although a precise speed at which loss of control for a given edge differential varies slightly among reports, all studies support the hypothesis that relative severity of an edge drop-off increases as vehicle speeds increase. The use of a 45-degree or flatter beveled edge is strongly recommended in several reports.

Some research studies have addressed selection of appropriate temporary traffic control measures using a benefit cost approach considering the effects of such factors as traffic volumes and speed, dimensions of drop-off, and lateral clearance to the hazard.

Other factors that may affect potential hazards not thoroughly addressed in the reviewed literature include the following:

- length of the roadway exposed to an edge drop-off

- duration of time of traffic exposure to a drop-off

- beneficial effects to worker safety and productivity with temporary barrier use

- quantification of road user safety and convenience comparing use of an off-site detour to traveling through active work zones

These issues may be topics for future research efforts.

3. METHODOLOGY

The scope of this research features four basic objectives, briefly described below along with an explanation of the methodology used to achieve each goal:

1. Determine how the policies and practices used to mitigate the potential hazards of edge drop-offs in work zones compare or differ among Iowa and other states.

2. Analyze Iowa's crash and litigation experience with respect to edge drop-offs in work zones.

3. Evaluate current Iowa DOT projects that include edge drop-offs to assess the effectiveness of the temporary traffic control. This objective also involves a subjective evaluation of how drivers modify behavior in response to various traffic control measures in those areas.

4. Recommend criteria that could be used to select the safest and most cost-effective strategy to manage and control traffic through work zones where pavement or shoulder edge drop-offs are present.

3.1. Comparison of State Practices

The Iowa DOT was interested in comparing policies and procedures for controlling and managing traffic through work zones that feature edge differentials with those of other states. To obtain this information, a preliminary questionnaire was developed to inquire about temporary traffic control practices used. The questionnaire asked the states to identify factors that influence temporary traffic control selection for work zones where edge drop-offs may occur. The states were asked to submit a copy of current written policies or department procedures used in development of traffic control strategies for that type of activity.

Several states in the general region of Iowa were selected for analysis based on the premise that these states would have similar environmental conditions that would allow the variable of weather to be eliminated. The states of Michigan, Minnesota, North Dakota, and South Dakota responded to the survey. Michigan, however, did not have current specific guidelines for addressing edge drop-offs in work zones. In a telephone contact, Wisconsin also indicated that specific policies for mitigating pavement/shoulder edge differentials in work zones had not been adopted. Several other states were also contacted by telephone but did not furnish copies of current guidelines. The Ohio Department of Transportation was conducting a similar study and information on the policies and procedures used by a sampling of other states from across the country were obtained from that source. Information about temporary traffic control procedures used by the Florida Department of Transportation to protect edge drop-offs in work zones was identified during the literature review and extensive research on pavement edge drop-offs in work zones conducted in the state of Texas was discovered. The practices used by the Texas Department of Transportation to mitigate edge drop-offs were also reviewed. The state of West

Virginia, where an edge drop-off policy had been recently adopted, also completed a survey questionnaire.

Much of the data presented for other states' practices was obtained indirectly and from web site sources. Only a few states were contacted directly. The information presented in this discussion is thought to be current and factual, but further, direct contact with individual state sources may be warranted if details of policy are questioned.

3.2. Crash and Liability Analysis

The Iowa DOT also desires to consider past experience with crash history and resultant litigation, relating to edge drop-offs in work zones. To analyze possible safety concerns, work zone crash history over a three-year period from 1998 through 2000 was reviewed. Tort claim filings and legal settlements of claims from 1995 through 2000 were analyzed. Reports of work zone crashes that were submitted to the Iowa DOT central office as potential liability claims were also reviewed.

3.3. Evaluation of Active Projects

The construction engineer in each of the six DOT districts in Iowa was contacted to identify current projects that might involve edge drop-offs in one or more of the construction stages. Initially only Iowa DOT work activities were to be reviewed; however, during the course of this research, projects managed by the city of Ames, Iowa, were found to involve pavement edge drop-offs and these were also evaluated in addition to the Iowa DOT projects. The projects evaluated were located in or near Ames, Ankeny, and Des Moines and included four rural and four urban locations.

An Iowa State University research staff member drove through each of the identified sites, making notes of existing temporary traffic control devices, location and maintenance. The speed of other traffic was assessed by pacing vehicles through the work zone. Each project site was also recorded on videotape.

3.4. Development of Traffic Control Plan Selection Criteria

A major goal of the Iowa DOT was to analyze the effectiveness of temporary traffic control procedures compared to the cost of implementation. To make this assessment, the report by Ivey, Mak, and Cooner (*33*) detailing a benefit/cost analysis for temporary traffic control in work zones, including barrier usage, as discussed in Section 2.3.5 of this report, was reviewed. For various reasons, however, that analysis could not be replicated for this study. Instead, the computer software program ROADSIDE 5.0 (*37*) was used to analyze various temporary traffic control options. While application of this program is primarily anticipated for permanent roadside conditions and features, it can be modified to also provide valuable analysis data for temporary applications. The software will only be briefly described in this report; however, a detailed description can be found in Appendix A of the 1996 *Roadside Design Guide* (*1*).

To analyze the effectiveness of various temporary traffic control options related to the cost of implementation, ROADSIDE 5.0 was used to predict the work zone crash costs associated with a certain set of circumstances. ROADSIDE 5.0 automatically establishes severity index-cost relationships shown in Table 4. These values can be modified, but for the purpose of this analysis, current crash loss values used in Iowa were accepted. The default encroachment angles assigned to each design speed, as shown in Table 5, were also used for this analysis. It should be noted that the program uses metric units, and therefore all of the evaluation data will be expressed in metrics. The basic work screen prompts for information about traffic, highway, and economic data for each case study being evaluated. For each of three basic situations, influences of highway type, traffic volume, and traffic speed were investigated.

Table 4. Severity Index–Cost Relationships (*37*)

Severity Index	Cost (2001 Dollars)
0.0	$0
0.5	$600
1.0	$1,405
2.0	$3,025
3.0	$15,525
4.0	$42,200
5.0	$100,425
6.0	$214,475
7.0	$348,100
8.0	$542,500
9.0	$777,700
10.0	$1,000,000

Table 5. Encroachment Speed Relationships Angle Combinations (*37*)

Design Speed (km/hour)	Encroachment Angle Degree
50 (31 mph)	13.0
60 (37 mph)	12.8
70 (43 mph)	12.4
80 (50 mph)	12.0
90 (56 mph)	11.6
100 (62 mph)	11.1
110 (68 mph)	10.7
120 (75 mph)	10.3

For this project, three basic conditions were evaluated. The first scenario evaluated several situations with an unprotected edge drop-off. The second scenario evaluated using a 3:1 (horizontal: vertical) sloped earth wedge in conjunction with 152 mm (6 inch) and 254 mm (10 inch) of edge differentials. Finally, the use of a temporary concrete barrier to shield the drop-off was evaluated. For each of the three basic scenarios, influences of highway type, traffic volume, speed, and offset distance were explored. Two different types of highways were used in the analysis: a two-way, two-lane undivided highway and a four-lane divided facility. Daily traffic volumes of 2000, 6000, and 10,000 were assigned to the two-way, two-lane highway, while daily traffic volumes of 10,000, 30,000 and 50,000 were used for the four-lane road. Average traffic speeds of 70 km/hour (43 mph) and 90 km/hour (56 mph) were assigned to the two-lane two-way highway. For the four-lane highway, traffic speeds of 90 km/hour (56 mph) and 110 km/hour (68 mph) were used. Offset distances of zero meters and 3.6 meters (12 feet) were used to replicate drop-offs immediately adjacent to the edge of the traveled way and differentials located one lane away, respectively. Finally, the predicted cost of crashes per week was determined from the computer program ROADSIDE 5.0. Predicted crash costs were then compared to traffic control implementation costs to achieve a benefit/cost representation.

A positive benefit cost is expressed in the number of weeks required to be more cost effective to install an earth wedge or temporary barrier rail compared to an unprotected drop-off. To determine positive benefit cost (in weeks) for providing these options the following formulae were used:

$$P_W = \frac{W}{C_W - C_U}$$

where

P_W = positive benefit cost (weeks) for using a 3:1 sloped wedge
W = cost of wedge
C_W = cost of crashes per week when wedge is used
C_U = cost of crashes per week when drop-off is unprotected

$$P_B = \frac{B}{C_B - C_U}$$

where

P_B = positive benefit cost (weeks) for using a temporary concrete barrier
B = cost of barrier
C_B = cost of crashes per week when barrier is used
C_U = cost of crashes per week when drop-off is unprotected

The following assumptions were made in this analysis:

- Crash loss costs for Iowa were considered as follows:
  - Fatality = $1,000,000
  - Major injury = $150,000
  - Minor injury = $10,000
  - Possible injury = $2,500
  - Property damage only 1 = $2,500
  - Property damage only 2 = $600

- Default global encroachment angles were applicable to this analysis. These angles were determined through the use of a computer program that calculates encroachment angles based on a variety of design vehicles and speeds.

- A default swath width of 3.6 m (12 feet) was used. According to the *Roadside Design Guide*, a value of 3.6 m is intended to represent a non-tracking passenger car skidding toward the hazard.

- It was assumed that traffic volumes flowed equally in each direction.

- Traffic growth rate = 0 because small periods of time were considered.

- This activity area was flat.

- The activity was tangent to the roadway.

- Default encroachment multiplication factors were used.

- Severity indices from Appendix A in the *Roadside Design Guide* were used.

- A project life of one year was assumed.

- The yearly crash cost obtained from ROADSIDE 5.0 occurred uniformly throughout the year, and weekly costs were prorated as follows:

$$C = \frac{C_Y}{52 \text{ weeks}}$$

where

C = cost of crashes per week
C_Y = cost of crashes per year

- Present worth values were used.

For the first condition, an unprotected drop-off, crash costs were assessed by evaluating the severity indices associated with drop-off dimensions 152 mm (six inches) and 254 mm (ten inches). The severity indices associated with each drop-off depth were determined from Table A.13.2 of the *Roadside Design Guide* (*1*) for a vertical foreslope without the presence of water. The relationship of the SI values for each differential was assumed to be linear. In a similar manner, the SI values associated with a vehicle crossing an edge drop-off with a 3:1 sloped wedge were determined from Table A.13.1 of the *Roadside Design Guide* for a 3:1 foreslope. Once again, the relationship between the severity indices associated with various drop-off dimensions was assumed to be linear. For this analysis, surface condition B, a smooth surface subject to rutting by errant vehicles half of the year was assumed. The severity indices associated with a vehicle collision with a temporary traffic barrier, the third basic scenario, were selected directly from Table A.13.8 of the *Roadside Design Guide*.

The crash severity for every example was examined when the hazard, vertical drop-off, 3:1 sloped wedge, or temporary traffic barrier, was located directly adjacent to the travel lane and at 3.6 meters (12 feet) laterally. The influence of project length on estimated crash costs was evaluated by analyzing two length exposures: 30 meters (100 feet) and 400 meters (1/4 mile).

The minimum project life considered by the ROADSIDE 5.0 program is one year. However, most edge drop-offs occurring in work zones exist for much shorter periods; therefore, lesser durations needed to be evaluated. Human behavior studies indicate that a road user's first reaction to a change in the operating environment is different from the response after long-term exposure. It is expected that as drivers become more comfortable with changed conditions over longer project durations, behavior and performance would improve and therefore crash rates should be reduced over longer exposures. However, specific data for these expectations could not be established and it was therefore assumed that crashes predicted to occur during one year would occur in a uniform manner. Therefore, the predicted weekly crash rates would be equivalent to the predicted yearly crash rates divided by 52. A similar assumption was made for crash costs.

Since all treatment options were assumed to require similar traffic control devices, the costs of these warning devices were not considered in this analysis. With either an unprotected vertical drop-off or a 3:1 sloped wedge, cones, drums, vertical panels, and/or other channelizing devices may be used. These devices may not all be necessary with a temporary barrier rail installation. Possible placement of temporary edge line markings was also not considered in this cost analysis.

To evaluate costs for a 3:1 sloped earth wedge treatment or shielding with a temporary traffic barrier, the *Summary of Awarded Contract Prices for 2001* (*38*) from the Iowa DOT was used. The total daily cost to construct the wedge was assumed to be approximately equivalent to earth embankment grading, including labor, equipment, and water required for spreading, shaping, and compacting. Finish shaping was not considered in the calculations because the wedge would only be a temporary feature. Removal costs were assumed to be one half of placement costs. Sample calculations can be found in the appendix.

The average bid price for furnishing and placing temporary traffic barrier listed in the *Summary of Awarded Contract Prices for 2001* (*38*) was used to estimate the complete cost associated with providing a temporary barrier to protect an edge drop-off. For the purpose of this analysis, it was assumed that any maintenance costs were included in the installation price. It was also assumed that a contractor would fully salvage the barrier for use on other projects. Sample calculations can be found in the appendix.

Other costs not considered in this analysis include road user costs for off-site detours if this option is studied as an option to performing work on a road open to traffic. Also the beneficial impacts to worker safety and productivity with temporary barrier use are problematic to quantify, but should be taken into account when judgment is exercised for selection of the most appropriate temporary traffic control measures in a given situation.

4. DISCUSSION OF RESULTS

4.1. Common State Practices

Information on the policies and practices used to control, manage, and guide traffic through work areas involving lane edge differentials was obtained from several states in addition to Iowa. Beginning with the state of Iowa and through the other states alphabetically, individual state guidelines are described in the following discussion.

4.1.1. Iowa Practice

The Iowa DOT places strong emphasis on proper traffic control and general work zone safety issues. For example, the Iowa DOT Office of Design includes a chapter entitled “Traffic Control” in their *Design Manual*; the chapter specifically requires a traffic control plan to be developed for all projects. This manual also includes guidelines for traffic control with several applications for two-lane and multilane roads as well as discussion of proper uses of temporary barrier rail.

Specific to edge differentials, Article 1107.08 of the Iowa DOT *Standard Specifications* admonishes contractors to minimize the length and degree of edge drop-off created by shouldering work. In addition, Article 1107.09 of those *Standard Specifications* also list special temporary warning signs, markings, and edge fillet placement to warn, guide, and mitigate potential hazards when edge differentials may occur. The precise treatment is predicated on the magnitude and location of those differentials. At the time of this report, the Iowa DOT was considering revision of this specification to clarify and strengthen the intent.

Based on the primary factors of degree of drop-off, location with respect to open traffic lanes, and classification of highway where work occurs, the Iowa DOT has also developed several toad standards that address edge drop-offs or lane elevation differentials.

For two-lane roads, Standard Road Plan RS-2 addresses traffic control for work within 15 feet of an open traffic lane, including possible edge drop-offs. This standard requires certain warning signs, SHOULDER DROP-OFF or NO SHOULDER, depending on the magnitude of differential between 2 and 10 inches. Placement of channelizing devices is stipulated and temporary pavement edge markings required if the drop-off occurs over night. No drop-off exceeding 10 inches is permitted during non-working hours. Also for two lane roads, Standard Road Plan RS-6 illustrates single lane traffic control with signals. Note 10 in this standard requires all full-depth openings to be eliminated or covered during non-working hours.

For lane or edge differentials that commonly occur with asphalt resurfacing improvements, the Iowa DOT has developed three road standards. RS-17A, in addressing differentials of 2 inches or less, requires placement of UNEVEN LANES warning signs, a temporary granular fillet at the shoulder, and a 1:1 tapered asphalt fillet at centerline. Refer to Figure 19 for an illustration.

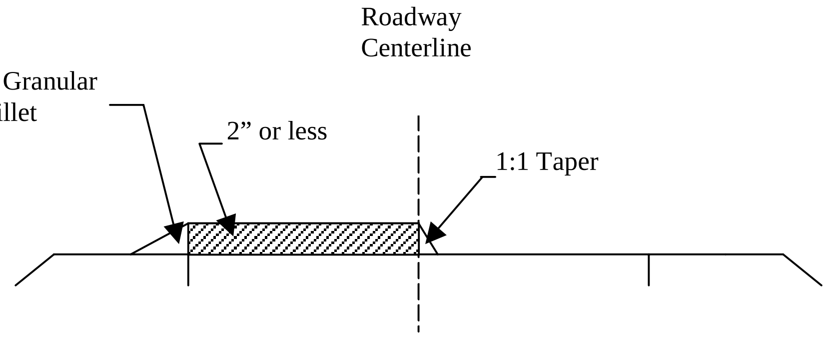


Figure 19. RS-17A

For differentials greater than 2 inches, the Iowa DOT uses Standard Road Plans RS-17B and RS-17C. These standards also require placement of the special warning signs, UNEVEN LANES, and a granular fillet at the shoulder. However, centerline treatment varies, from a 3:1 tapered asphalt fillet for drop-offs up to 3 inches, to temporary pavement markings and specific channelizing devices for differentials exceeding 3 inches. Please see Figures 20 and 21 for more information.

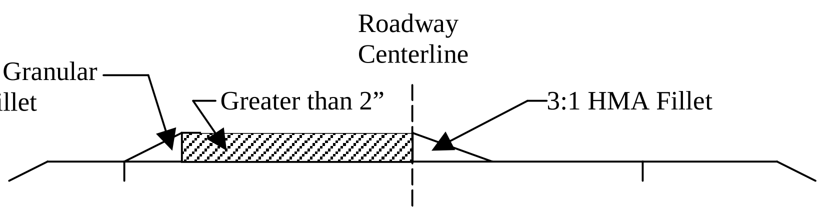


Figure 20. RS-17B

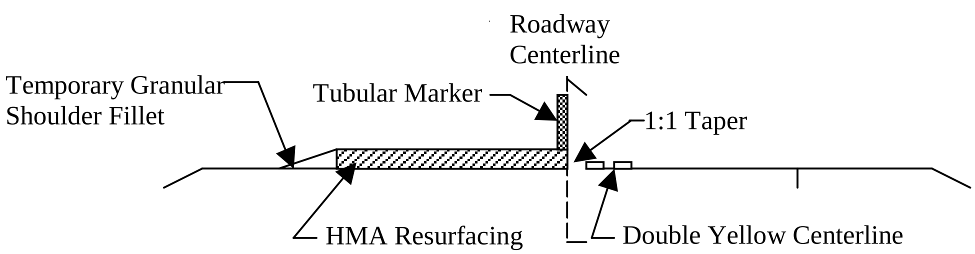


Figure 21. RS-17C

For possible pavement edge drop-offs adjacent to multilane roads, several road standards provide temporary traffic guidance. RS-62 requires placement of SHOULDER DROP-OFF warning signs and channelizing devices for drop-offs between 2 and 6 inches. Lane closures are required if the differential exceeds 6 inches. Road Standards RS-63A, RS-63B, RS-64A, and RS-64B are used in short-term applications for lane closures on divided and undivided highways. All require reduced spacing of channelizing devices for differentials exceeding 2 inches. For unplanned overnight exposure to differentials exceeding 3-1/2 inches, contractors are required to place either temporary pavement edge markings or drums to delineate the traveled lane.

Other road standards of pertinence include RS-80 that addresses the use of temporary barrier rail, although no specific mention of drop-offs is listed. RS-81 and RS-82 both refer to closure of more than one lane of multilane roadways and both require placement of additional class II barricades where open holes from patching activities occur.

In addition, Iowa has utilized informal guidelines to establish reasonable levels of temporary traffic control relating to depth of differential and lateral distance to open traffic lanes, as listed in Table 6.

Table 6. Iowa DOT Depth of Differential to Treatment

Differential	Treatment
2 to 6inches	Use standard traffic control per Road Standard RS-2
6 to 10 inches	Add temporary pavement markings per RS-2
10 inches to 2 feet	Use temporary barrier rail (less than 10 feet offset)
2 feet or greater	Use temporary barrier rail (less than 15 feet offset)

Although not specifically for work zones, Iowa DOT maintenance standards also have established procedures for mitigating edge differentials at the pavement/shoulder interface when the magnitude exceeds 1-1/2 inches for both paved and unpaved shoulders.

4.1.2. Arkansas Practice

The practices implemented by the state of Arkansas to mitigate the hazards of pavement edge drop-offs in work zones are influenced primarily by two factors: the magnitude of the differential and the lateral distance to open traffic lanes. In general, vertical panels or drums are used to delineate the edge of drop-offs less than five feet in depth. For increased safety, a 2:1 taper is constructed along the edge of the drop-off. When drop-offs exceed five feet, temporary rigid barriers are installed. Warning signs are erected in accordance with MUTCD *(5)* guidelines. Either SHOULDER DROP-OFF or LOW SHOULDER warning signs are used when a shoulder drop-off exceeds three inches, and UNEVEN LANES warning signs are used when a difference in elevation between adjacent travel lanes is encountered.

When an edge differential adjacent to an open traffic lane exceeds four inches, the Arkansas DOT restricts the length of project work to approximately one mile. Arkansas also places restrictions on time duration for traffic exposure to drop-offs. Table 7 lists allowable exposure times for various magnitudes and locations of vertical differentials. At no time is traffic exposed to a drop-off for more than 30 calendar days and never to a vertical differential greater than three inches in depth located at centerline or lane line.

Table 7. Arkansas's Restrictions on Traffic Exposure Time to Vertical Differentials

Height of Vertical Differential	Location of Differential	Time Limit for Shoulder Backfill or Adjacent Pavement Construction
1 inch or less	Centerline, lane line, or edge of pavement	None
1 to 3 inches	Centerline or lane line	By next working day
1 to 4 inches	Edge of pavement	Within 30 calendar days
Greater than 4inches	Edge of pavement	Within 7 business days

4.1.3. California Practice

Temporary traffic control procedures for work zones with edge drop-offs in California are influenced by depth and location of the differential. Regardless of location, differentials of less than two inches require no special treatment. California's policy requires all lanes and shoulders to be brought to the same elevation by the end of each work week. Only a drop-off no more extensive than one day's production is allowed to exist at the end of each work day. Traffic is not allowed to cross an edge differential greater than two inches.

For differentials of two inches or greater at street intersections or freeway ramps a minimum 6:1 sloped edge fillet is constructed. For drop-offs between two and three inches along the edge of the traveled way, contractors are required to place a minimum 1:1 sloped edge taper. Differentials adjacent to open travel lanes and greater than three inches are not permitted for extended periods of time.

Vertical edge differentials between two and three inches within eight feet of the edge of a traveled lane are delineated with temporary edge lines or portable delineators spaced at 100 feet or less. LOW SHOULDER warning signs are erected on type II barricades and placed in the excavation area adjacent to the travel lane at a maximum spacing of 2000 feet. When excavations are between three and six inches deep, OPEN TRENCH and NO SHOULDER warning signs are placed on either type II or type III barricades and alternately spaced at 2000 feet or less in the excavation area adjacent to the pavement edge. Channelizing devices a minimum of 36 inches high, placed 2 to 6 feet from the edge, and spaced 100 feet apart delineate the edge of the drop-off. Drop-offs greater than six inches are protected with a rigid temporary barrier rail. If barrier placement is more than two feet from the edge of the traveled way, edge line delineation is required.

Excavations between 3 inches and 2 1/2 feet located between 8 and 15 feet from the edge of the traveled way are marked with OPEN TRENCH warning signs again erected on type II or type III barricades and installed in the excavation area at a spacing of not more than 2,000 feet. To delineate the edge, channelizing devices are spaced at intervals of 200 feet for drop-offs between 3 and 6 inches and at 100 feet for drop-offs between 6 inches and 2 1/2 feet deep. All channelizing devices are placed within two feet of the edge of the drop-off. Special engineering consideration is required for all excavations deeper than 2-1/2 feet.

Drop-offs located more than fifteen feet away from the edge of the travel lane do not require treatment unless more than 6 inches deep. Drop-offs between 6 inches and 2-1/2 feet deep are marked with delineators spaced at 200 feet and OPEN TRENCH warning signs spaced at a maximum of 2,000 feet. Once again, excavations greater than 2.5 feet deep require special engineering consideration.

4.1.4. Florida Practice

Florida also considers depth and location of differential in selecting the best mitigation procedure. Florida requires special treatment for drop-offs of 3 or more inches located in the clear zone. A temporary concrete or water-filled barrier, a temporary guardrail, or in urban locations, a barrier curb, can be used to protect these drop-offs, although a 4:1 wedge may be used in lieu of a barrier. When the drop-off conditions extend for less than one day, warning signs alone may provide adequate protection. Drop-offs exceeding 5 feet within the clear zone require temporary barrier rail.

4.1.5. Illinois Practice

Three factors; depth of drop-off, lateral location with respect to traffic, and traffic speed form the basis of Illinois's guidelines for addressing vertical edge differentials in work zones. No special treatment is required for any differential less than or equal to two inches. An elevation difference greater than two inches, however, is not allowed when located between adjacent open travel lanes. The Illinois DOT also limits the length of the project with a drop-off to four miles, unless the hazard associated with the drop-off is reduced by either completing adjacent shoulder construction, providing delineation with barricades or vertical panels, or constructing a temporary earth fillet along the edge.

Edge differentials greater than 3 inches within 3 feet of the traveled way require edge line delineation. Either type I or type II barricades or vertical panels are used to delineate the edge of the drop-off. If the speed limit on the roadway is less than 45 mph, these devices are spaced 100 feet apart. If the speed limit is 45 mph or greater, spacing is increased to 200 feet. Traffic control surveillance is conducted at least once every four hours during non-working periods when excavations greater than three inches and are located adjacent to an open traffic lane.

When the engineer considers the drop-off to be hazardous, barricades spaced 50 feet apart are provided. Flashing warning lights are installed on the barricades during night hours. When the hazard is more than 100 feet in length, steady burn warning lights replace the flashing lights. If the drop-off extends more than 250 feet, spacing of barricades may be increased to 100 feet.

4.1.6. Minnesota Practice

The Minnesota DOT has established guidelines for treating edge differentials in work zones considering two primary factors, depth of the drop-off and location with respect to traffic. However, duration of the work, traffic volume and speed are also used in selecting the most appropriate temporary traffic control measures.

Minnesota offers several options for addressing edge differentials in work zones, as described below.

For milling and overlay operations, a standard plan note requires contractors to assure that travel lane and adjacent shoulder surfaces are level, as directed by the engineer.

Differentials less than 2 inches along the edge or between travel lanes are denoted with LOW SHOULDER or UNEVEN LANES warning signs, spaced at approximately one mile for speeds greater than 30 mph and approximately 1/4 mile for speeds of 30 mph or less. Surface elevations between adjacent travel lanes must be brought to the same level, weather permitting, by the end of the working period. At no time is more than one uneven lane condition between the traffic lanes permitted. For milling operations, provisions are offered for use of HIGH SHOULDER signs and also wedges, when differentials exceed 2 inches.

When differentials of 2 inches to 4 inches occur at the edge or between traffic lanes, a 3:1 compacted wedge and UNEVEN LANES or LOW SHOULDER signs are provided, although on some rural highways, a 4:1 wedge is required. If a wedge is not placed, the shoulder or adjacent travel lane is closed using drums spaced at 4 times the posted speed and NO SHOULDER warning signs are installed. For lane closures, type III barricades are placed at a maximum of 20 times posted speed.

Shoulder drop-offs from 4 to 12 inches can be treated with a 4:1 edge taper (wedge) and LOW SHOULDER warning signs if left open or a 3:1 edge taper and NO SHOULDER warning signs if the shoulder is closed. When the shoulder is closed, drums or channelizers are placed throughout the length of the drop-off at a maximum spacing of four times speed or two times speed, respectively. Use of portable barriers is also optional.

For differentials of this magnitude, wedges or portable barriers are not required if traffic speed is 30 mph or less in urban areas, or if speeds exceed 30 mph but the work area is less than 50 feet and duration of exposure is less than three calendar days.

Differentials of 4 inches or less between 2 and 8 feet from the edge of the travel lane can also be optionally delineated with a temporary edge line, but no temporary traffic control measures are required if the differential is more than 8 feet from traffic lanes.

For drop-offs exceeding 12 inches, portable barriers are recommended using Minnesota's MUTCD for guidance.

4.1.7. Missouri Practice

The depth and location of edge differentials are also primary factors the state of Missouri considers when designing temporary traffic control for lane edge and shoulder drop-offs in work zones. Special treatment is not required for edge differentials less than two inches. The use of LOW SHOULDER warning signs, however, is considered if the drop-off is located at the pavement edge. When drop-offs at the edge of pavement exceed two inches up to four inches, placement of SHOULDER DROP-OFF signs at a spacing of 1,000 feet is required. In addition, the edge is treated with a 1:1 or flatter tapered wedge during non-work hours. A 3:1 or flatter wedge is required during non-working periods when the drop-off at the pavement edge exceeds 4 inches.

When a differential greater than two inches occurs between adjacent traffic lanes, the edge is treated with a 3:1 or flatter tapered wedge during both working and non-working periods. UNEVEN LANES warning signs are spaced at 1,000 feet.

Alternate treatment methods to those described above include the use of complete or partial lane closures. A partial lane closure utilizes temporary barrier rail, however, if the lane adjacent to the edge differential is completely closed, then either drums or temporary barrier rail may be used (see Figures 22, 23, and 24). With either type of lane closure, no special signs are required to warn of the edge drop-off and pavement edge is not required.

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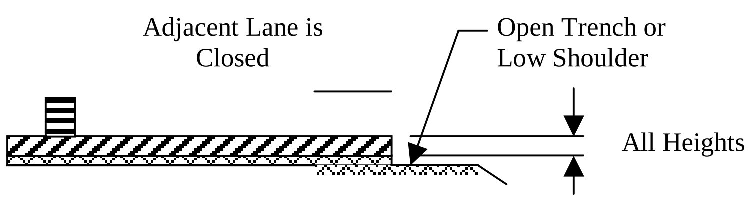

Figure 22. Complete Lane Closure Using Drums (Missouri)

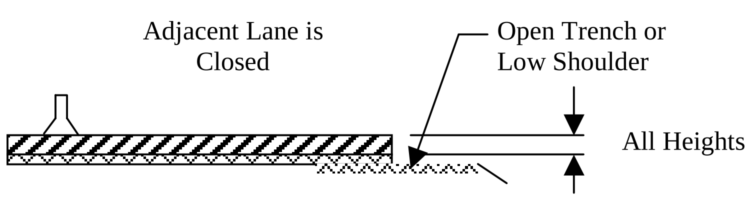

Figure 23. Complete Lane Closure Using Temporary Barrier Rail (Missouri)

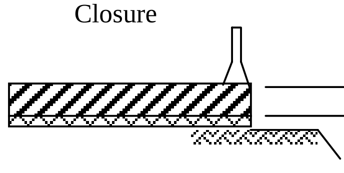

Figure 24. Partial Lane Closure Using Temporary Barrier Rail (Missouri)

Temporary concrete barriers in Missouri are Type "F" section.

4.1.8. Montana Practice

The state of Montana requires all drop-offs within 30 feet from the edge of the traffic lane to be treated with a 3:1 or flatter sloped wedge by the end of each workday, unless the drop-off is shielded by a temporary barrier rail. The Montana DOT has developed a formula to calculate a spacing factor from which the most appropriate type of traffic control device is selected. The formula for the spacing factor is as follows:

spacing factor (feet) = (A*C*W)/(S*D)

where

A = average daily traffic adjustment
C = degree of curvature factor
W = measured width, 4:1 or flatter, in feet from the drop-off to the far edge of the adjacent traffic lane or lanes with the same direction of traffic
S = posted speed limit in miles per hour
D = average drop-off height in inches

When drop-offs are located on the outside of a horizontal curve, Table 8 is used to determine the C factor. When drop-offs are located on the inside of a horizontal curve, the C factor (shown in Table 8) for curves less than two degrees is used. Table 9 is used to determine the ADT adjustment factor, A.

Table 8. C Factor Determination

Degree of Curve	**C**
Less than 2 degrees	5800
2 to less than 4 degrees	5200
4 to less than 6 degrees	4900
Greater than or equal to 6 degrees	4500

Table 9. ADT Adjustment Factor, A

ADT	A
Less than 750	1.50
750 to 1,499	1.30
1,500 to 5,999	1.00
Greater than or equal to 6,000	0.90

When the spacing factor, rounded to the nearest ten feet, is calculated to be 400 feet or greater, flexible guideposts or standard delineators are used to mark the drop-off. If the spacing factor is calculated between 40 to 390 feet, vertical panels are used for delineation. If the spacing factor is determined to be between 20 and 30 feet, vertical panels can again be used for delineation, but the first two panels on the approach end are supplemented with flashing warning lights. When the spacing factor is determined to be less than 20 feet, temporary barrier rail are used to shield a drop-off for exposures exceeding 48 hours. All traffic control devices are spaced at a distance equal to the calculated spacing factor. However, for drop-offs located less than 14 feet from a traffic lane, devices are spaced no greater than two times the posted speed limit in miles per hour. Vertical panels are never spaced closer than 20 feet, however.

4.1.9. Nebraska Practice

The Nebraska DOT requires all drop-offs less than or equal to two inches to be treated with a 1:1 or flatter asphalt wedge. The drop-off area is also denoted with UNEVEN LANES or SHOULDER DROP-OFF warning signs. When a drop-off between adjacent traffic lanes is greater than two inches, construction of a 3:1 or flatter asphalt wedge is required. UNEVEN LANES warning signs are placed throughout the drop-off area. Drop-offs along the pavement edge that exceed two inches are shielded with drums. At night, temporary edge lines are required to delineate the drop-off.

4.1.10. New York Practice

Procedures implemented by the state of New York to treat pavement edge drop-offs in work zones take five factors into consideration: depth of drop-off, anticipated duration of the condition, operating speed of the roadway, traffic volume, and lateral location of the drop-off relative to open traffic lanes. Pavement edge differentials within 10 feet of traffic lanes are treated as shown in Table 10.

Table 10. New York's Required Treatment for Pavement Edge Drop-Offs

Drop-Off Depth (inches)	Anticipated Duration (Calendar Days)	AADT < 7500				AADT ≥ 7500 and All Freeways and Expressways			
		Speed ≤ 45mph		Speed > 45mph		Speed ≤ 45mph		Speed > 45mph	
		Spacing (feet)	Wedge Slope	Spacing (feet)	Wedge Slope	Spacing (feet)	Wedge Slope	Spacing (feet)	Wedge Slope
2 to 6	≤ 7	100	None	150	None	50	None	50	None
2 to 6	8 to 60	100	1:1	200	1:1	50	1:1	100	1:1
2 to 6	≥ 60	100	1:1	200	1:1	50	3:1	200	3:1
6 to 24	≤ 7	50	None	50	None	50	None	50	None
6 to 24	8 to 60	50	None	200	3:1	100	3:1	200	3:1
6 to 24	≥ 60	50	None	200	3:1	100	3:1	200	3:1
≥ 24	≤ 7	50	None	50	None	50	None	50	None
≥ 24	8 to 60	100	3:1	200	3:1	100	3:1	200	3:1
≥ 24	≥ 60	100	3:1	200	3:1	100	3:1	Barrier	None

The spacing indicated in this table is for drums or type III barricades. If other types of channelizing devices are used, the specified spacing is reduced by half. When vertical edge differentials are six inches or less, channelizing devices may be placed in the drop-off area. For drop-offs that exceed six inches, however, these devices are placed on the pavement surface. No device can encroach on the traffic lane such that the lane width is reduced to less than ten feet for roadways for operating speeds of 45 mph or less. That allowable width is reduced to 11 feet for operating speeds greater than 45 mph. Drums or type III barricades are supplemented with LOW SHOULDER or NO SHOULDER signs spaced no farther than 1,000 feet apart when drop-offs are greater than two inches and located within the final shoulder width. The New York DOT also requires two flashing warning lights to be placed at the beginning of each drop-off area.

When vertical differentials are located more than ten feet from the edge of a traffic lane, the sloped wedge specified in Table 10 is not required. All drop-offs located more than 10 feet from the traveled way, even those of a magnitude greater than 24 inches, are protected with drums or type III barricades spaced 100 feet apart. If other channelizing devices are used, the spacing is decreased to 50 feet. When drop-offs exceed six inches, signs and flashing warning lights are provided.

4.1.11. North Dakota Practice

North Dakota has developed guidance for traffic control measures for edge drop-offs in work zones. These recommendations take several factors into consideration: depth of the edge drop-off, lateral location with respect to traffic, traffic speed, and the type of roadway. In general, the guidelines recognize that traffic safety is increased when exposure to drop-offs in minimized, and that action is encouraged.

Appropriate warning signs are placed at a maximum spacing of 1/4 mile for speeds of 30 mph or less, and for speeds greater than 30 mph, sign spacing may be increased to a maximum of one mile. Channelizing devices such as drums, when used to close a shoulder, are spaced at a maximum of 100 feet. When type III barricades are used to close a traffic lane, spacing is a maximum of 1,000 feet.

Elevation differentials between adjacent traffic lanes 1-1/2 inches or less are designated with UNEVEN LANES warning signs. If two adjacent lanes differ in elevation by 1-1/2 inches to 4 inches, a 4:1 sloped wedge is constructed to supplement the warning signs if traffic is allowed to cross the drop-off. If a wedge is not provided, drums and type III barricades are used to close the lower level traffic lane.

For drop-offs adjacent to traffic lanes exceeding 4 inches but less than 12 inches, a 4:1 sloped wedge is constructed and the lower travel lane is closed using drums. If a wedge is not provided, the traffic lane is closed using temporary barrier rail or appropriate traffic control devices. Neither a wedge nor a barrier is required if the drop-off is in an urban area and the speed limit is 30 mph or less. The wedge and barrier may also be eliminated if the drop-off is less than 50 feet long, located on a roadway with a speed limit greater than 30 mph, and is expected to exist for a duration no longer than seven calendar days.

When drop-offs exceed 12 inches, the lane adjacent to the drop-off is closed using appropriate temporary traffic control devices and barrier rail.

For drop-offs at the inside shoulder edge, the guidelines vary slightly, for example a 6:1 wedge is required if traffic to cross the drop-off.

For drop-offs outside the shoulder edge, similar requirements as those described above are used until the shoulder width reaches 8 feet. Then no temporary traffic control measures are required for any drop-off less than 4 inches.

Figure 25 was developed by the North Dakota DOT to provide a visual summary of the previously described guidelines.

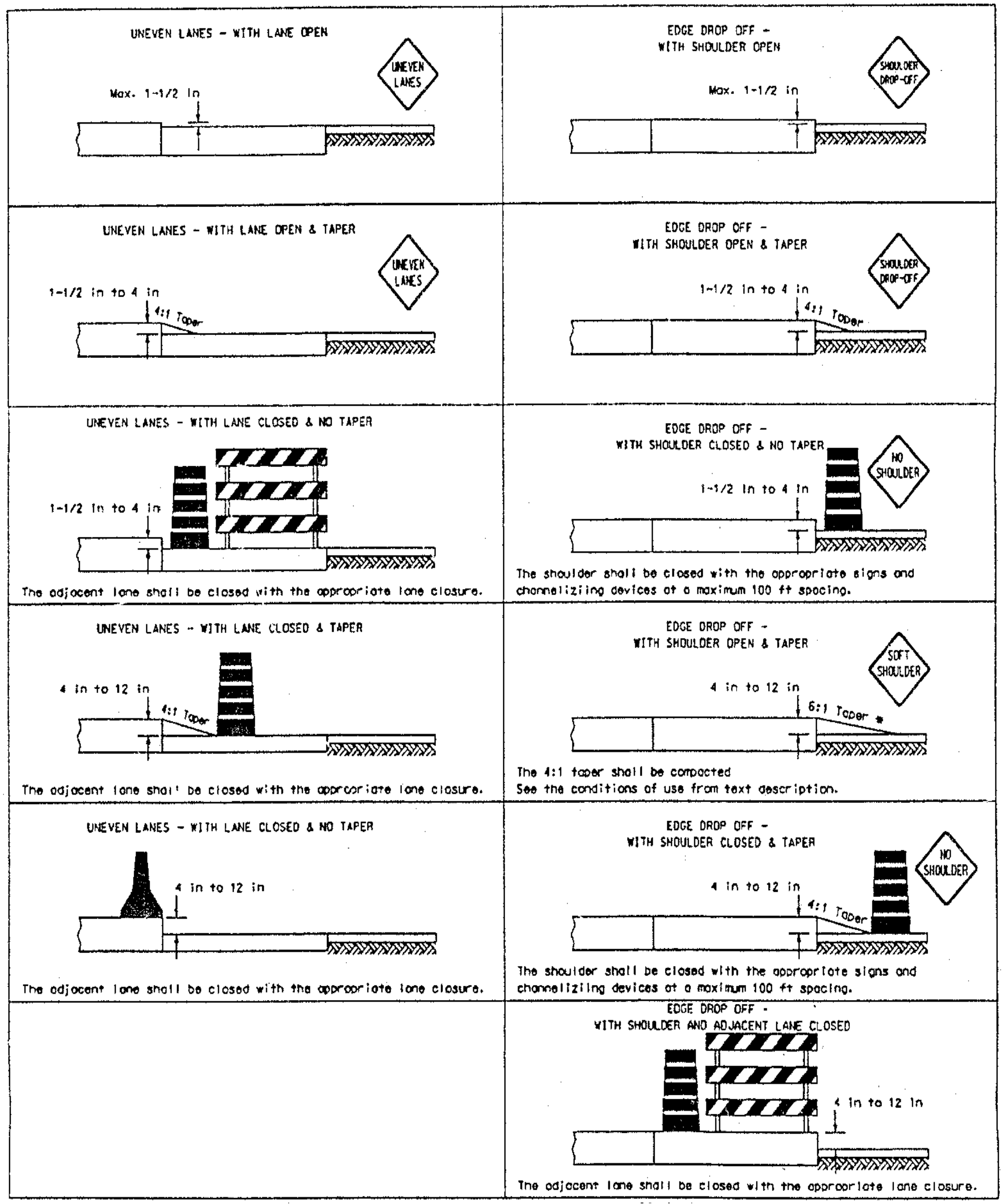

Figure 25. North Dakota's Longitudinal Edge Drop-Off Guidelines

4.1.12. Ohio Practice

The degree of drop-off and three lateral locations relative to traffic form the basis for Ohio's temporary traffic control for elevation differentials in work zones; between traffic lanes, within the shoulder area, and outside the shoulder or back of curb. When edge differentials less than 1-1/2 inches occur between travel lanes, UNEVEN LANES warning signs are erected 750 feet in advance of the drop-off area and at intervals of no more than one mile. Additional signs are placed at all intersections. If the differential between traffic lanes is 1-1/2 to 5 inches, Ohio requires utilization of drums and closure of the lane adjacent to the drop-off. Refer to Figures 26 and 27 for details. For a drop-off of less than three inches, the lanes may be left open if a 3:1 or flatter sloped wedge is placed between the two surfaces and UNEVEN LANES warning signs are erected. If the elevation difference between adjacent lanes exceeds five inches, temporary barrier rail is used to close the lane adjacent to the drop-off.

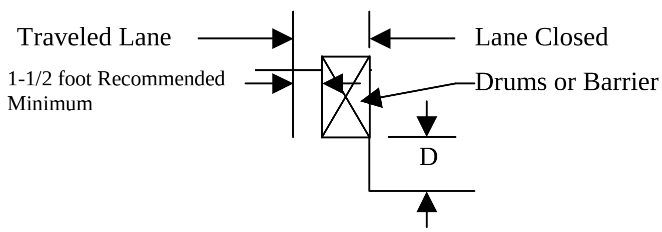

Figure 26. Lower Level Lane Closure (Ohio)

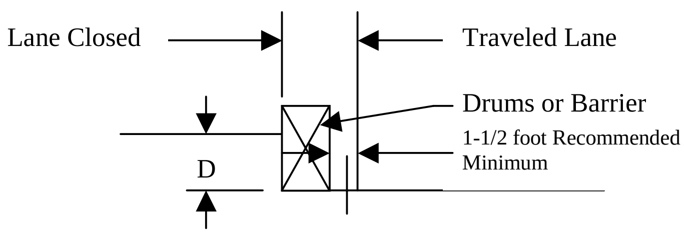

Figure 27. Upper Level Lane Closure (Ohio)

Drop-offs in the shoulder area less than 1-1/2 inches require placement of LOW SHOULDER warning signs in advance and throughout the work area at a maximum spacing of one mile. For a shoulder drop-off between 1-1/2 and 5 inches, three treatment options are available; close the shoulder with drums, use drums to close both the shoulder and adjacent traffic lane, or leave the shoulder open and construct a 3:1 or flatter sloped wedge. A minimum width 10-foot traffic lane is required at all times. If the differential is between five inches and two feet, temporary barrier rail is used to close the shoulder if adequate travel lane width can be allowed. For drop-offs less than twelve inches, drums may be used for closure during daylight hours. For drop-offs exceeding two feet in depth, temporary barrier rail must be used to shield the area.

When addressing drop-offs beyond the shoulder or back of curb, Ohio uses a two-category classification. Category A includes all uncurbed roadways, those with curbs of less than six inches, and any locations having curbs greater than six inches and a speed limit over 40 mph. All other curbed roadways are included in category B. Figure 28 and Table 11 display temporary traffic control for various conditions on category A roads. Figure 29 and Table 12 explain drop-off treatment requirements for category B facilities.

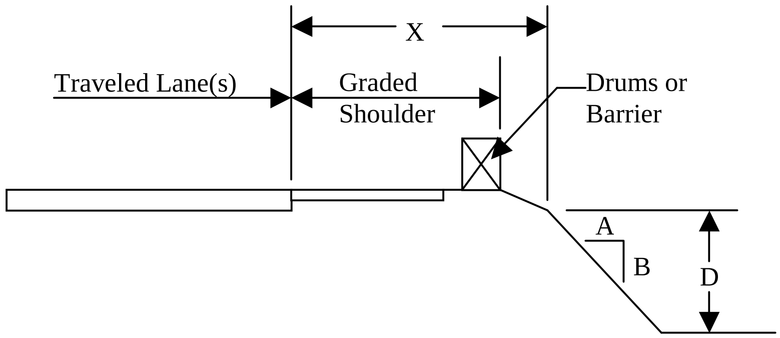

Figure 28. Category A Conditions (Ohio)

Table 11. Edge Treatment for Category A Conditions (Ohio)

X (feet)	D (inches)	A/B	Treatment Required	
			Day	Night
0 to 4	Any	Any	Follow treatment for drop-offs within graded shoulder	
>4 to 30	Any	3:1 or flatter	None	None
>4 to 12	>3	Steeper than 3:1	None	None
>4 to 12	>3 to 12	Steeper than 3:1	Drums	Drums
>4 to 12	>12	Steeper than 3:1	Drums	Barrier
>12 to 20	≤ 12	Steeper than 3:1	None	None
>12 to 20	>12 to 24	Steeper than 3:1	Drums	Drums
>12 to 20	>24	Steeper than 3:1	Drums	Barrier
>20 to 30	≤ 24	Steeper than 3:1	None	Drums
>20 to 30	> 24	Steeper than 3:1	Drums	Barrier
>30	Any	Any	None	None

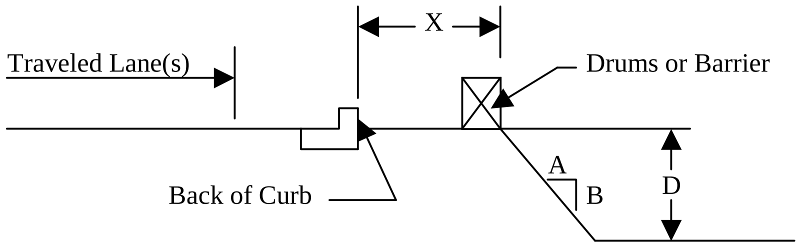

Figure 29. Category B Conditions (Ohio)

Table 12. Edge Treatment for Category B Conditions (Ohio)

X (feet)	D (inches)	A/B	Treatment Required	
			Day	Night
0 to 10	≤12	Any	None	Drums
0 to 10	>12	Any	Drums	Drums
>10	Any	Any	None	None

Ohio intends most of the treatments described above for work zones on higher volume roadways, over 4,000 ADT. For lower volume applications, drums might be substituted for temporary barrier rail, for example. Engineering judgment is urged in selecting most appropriate treatment in all situations.

4.1.13. Oregon Practice

Oregon's temporary traffic control procedures through work areas with drop-offs consider depth of differential and type of highway. When lane or pavement elevations differ by two or less inches, no special treatment is required. Work activities are planned to avoid drop-offs greater than two inches between adjacent traffic lanes during non-work hours. If a drop-off between lanes cannot be totally eliminated by the end of a workday, a wedge of compacted asphalt is placed at a 10:1 or flatter slope. Drop-offs of two to four inches are allowed between traffic lane and shoulder for a maximum of 24 hours. On non-freeway multilane roadways, the edge drop-off is designated with ABRUPT EDGE and DO NOT PASS warning signs spaced alternately every 500 feet. Tubular markers are installed on the lane line throughout the drop-off area at a maximum spacing of 50 feet. Drop-offs on freeways are also denoted with ABRUPT EDGE and DO NOT PASS warning signs installed alternately on both sides of the roadway throughout the drop-off area at intervals of 1,640 feet. On two-lane, two-way roadways, drop-offs are signed in the same manner as for freeways. For lane closures on two-lane, two-way roadways, tubular markers are spaced every 50 feet and flaggers are required to control traffic.

All excavations adjacent to paved shoulders of less than four feet wide are backfilled to the adjacent pavement level by the end of each workday or a temporary wedge of aggregate at a 3:1

or flatter slope may be used. ABRUPT EDGE warning signs on type III barricades are placed throughout the drop-off area at a spacing of 100 feet and tubular markers are installed at a maximum spacing of 50 feet.

4.1.14. Pennsylvania Practice

The Pennsylvania DOT considers depth and location of drop-off as well as speed limit and type of highway when selecting temporary traffic control for edge differentials. No special treatment is required for any drop-off, regardless of location, if less than two inches in depth. When drop-offs located between traffic lanes on multilane highways exceed two inches, lane closure is required. For lane differentials exceeding two-inches on a two-way, two-lane roadway, DO NOT PASS signs are erected throughout the drop-off area at a maximum spacing of approximately one mile and temporary double yellow centerlines are also provided.

When an edge differential exceeding two inches occurs between the traffic lane and shoulder, Pennsylvania requires channelizing devices to be installed throughout the drop-off area, placed at a maximum spacing approximately equal to 1.8 times the posted speed limit. LOW SHOULDER warning signs are also erected at a maximum spacing of approximately one mile.

Drop-offs greater than two inches in or beyond the shoulder are shielded with channelizing devices spaced at approximately 1.8 times the posted speed limit. These devices are not required if the drop-off is located behind a guardrail or curb, outside of the right-of-way, or more than fifteen feet from the edge of the traveled way.

4.1.15. South Dakota Practice

The state of South Dakota references Part 6 of the MUTCD (*5*) for selecting temporary traffic control for drop-offs in work zones. Standard plates are very similar to the typical applications in Chapter 6H of that document.

SHOULDER DROP-OFF warning signs are erected whenever a drop-off greater than three inches exists between shoulder and edge of traffic lane. The warning signs are not required if a temporary barrier rail is used to shield the drop-off. UNEVEN LANES warning signs are erected when a difference in pavement elevation occurs between adjacent traffic lanes. In addition, South Dakota requires a lane closure for edge differentials on a multilane highway.

4.1.16. Texas Practice

The state of Texas has developed basic temporary traffic control options addressing three edge drop-off conditions in work zones, based on procedures developed by Ivey et al. (*4*). These procedures are illustrated in Figures 16, 17, and 18 in Section 2.3.5. The type of device selected is dependent on the depth and lateral location of elevation differential, traffic volume, and duration of exposure. Figure 18 considers potential hazards presented by the drop-off to road users and but require modification to also provide adequate protection for workers. The Texas

DOT notes that recommendation presented in the guidelines are not rigid standards and each situation should be analyzed individually.

Standard plans used by the Texas DOT indicate that edge differentials require no treatment if less than or equal to one inch. When differentials exceed one inch, UNEVEN LANES warning signs must be used to warn of the condition. A drop-off greater than two inches requires the use of SHOULDER DROP-OFF signs or UNEVEN LANES signs with vertical panels. With the above described treatments, a 3:1 or flatter, compacted wedge is placed at the drop-off edge.

For drop-offs exceeding 5 inches, less than 20 feet from an active traffic lane, with an edge slope of 1:1 but less than 3:1, guidelines indicate the use of drums to supplement the treatment used for lesser drop-offs. Flattening the edge slope is also recommended to improve safety.

For drop-offs exceeding 24 inches with an edge slope less than 3:1, the use of positive barriers to protect the drop-off is considered based of traffic volumes, time of exposure, and lateral distance to the differential. An illustration similar to Figure 18 in Section 2.3.5 is used to assist in a decision to use temporary barrier rail. For example, use of a positive barrier would be recommended with a traffic volume of approximately 18,000 ADT with no lateral clearance to the drop-off and a one-year exposure. Use of traffic barriers is primarily applicable to high-speed and high-volume applications. Urban areas with speeds of 30 mph or less would require a lesser need to extensive signing and protection. Providing an adequate lateral clearance or buffer between the edge of open traffic lanes and a drop-off condition is emphasized in Texas' guidelines. If that distance is less than 3 feet, use of a temporary barrier rail may not be possible and narrowing of traffic lanes or edge slope flattening to 3:1 of greater is recommended.

4.1.17. West Virginia Practice

The West Virginia DOT established guidelines for temporary traffic control in work zones that feature elevation differentials considering four major factors: speed of traffic, type of highway, depth of drop-off, and lateral location with respect to traffic. The guidelines describe three circumstances: Case I addresses all drop-off occurrences on multi-lane divided highways with posted speed limits of 45 mph or greater. Case II covers drop-offs on undivided highways with posted speed limits of at least 45 mph. Case III work zone situations cover drop-offs that occur on any highway with a posted speed limit of 40 mph or less.

With Case I, drop-offs less than or equal to two inches between open traffic lanes or between traffic lane and shoulder, channelizing devices are not required, however UNEVEN LANES or LOW SHOULDER warning signs are placed throughout the length of the work. If a drop-off exceeding two inches occurs between traffic lanes on a high-speed multilane divided highway, channeling devices are used to close the lane adjacent to the drop-off. If a drop-off greater than two inches is located between the edge of a lane and shoulder, channelizing devices are installed and LOW SHOULDER warning signs are placed until the elevation difference is eliminated. When Case I drop-offs exceeding three inches occur along the outside edge of a shoulder, channelizing devices and SHOULDER DROP OFF warning signs are utilized. All excavations greater than three inches, whether located in a closed lane, shoulder, or beyond the shoulder but within 30 feet of an open traffic lane, must be filled or covered within 48 hours. Channelizing devices are placed throughout the length of a drop-off unless located behind a guardrail or concrete barrier. If the excavation cannot be filled or covered within 48 hours, temporary barrier rail is used to shield the drop-off. If an excavation of more than three inches is located in a median, channelizing devices are placed at intervals no greater than 50 feet.

Case II conditions, those located on undivided highways with speeds of at least 45 mph, are treated similarly to Case I except flaggers are required when traffic lanes are closed. When drop-offs greater than two inches occur between lanes, channelizing devices are used to separate opposing traffic. When deemed necessary, the lane adjacent to the drop-off is closed and flaggers are used to control traffic. UNEVEN LANES warning signs are required until the drop-off is eliminated. If a drop-off occurs between the traffic lane and shoulder at a depth exceeding two inches, SHOULDER DROP OFF warning signs and channelizing devices are required. Drop-offs over three inches outside of the shoulder (not adjacent to the traffic lane) are denoted with SHOULDER DROP OFF warning signs and channelizing devices. Excavations greater than three inches whether located in a closed lane, shoulder area, or within 20 feet of an open traffic lane must be filled or covered within 48 hours unless the drop-off is behind a guardrail or concrete barrier. Channelizing devices are placed throughout the length of the project. If a drop-off cannot be filled or covered within 48 hours, temporary barrier rail must be used.

When edge drop-offs exist between open traffic lanes for a Case III situation, UNEVEN LANES warning signs are required. If the drop-off between traffic lanes exceeds two inches, channelizing devices are used to separate traffic or to close the lane adjacent to the drop-off. Flaggers are used with lane closures. If a drop-off of three inches or more occurs at the edge of an open lane for a Class III highway, channelizing devices and SHOULDER DROP OFF warning signs are required. All excavations three inches or more located in a closed lane, shoulder area, or within 20 feet of an open lane must be shielded with channelizing devices, but these devices are not required if the drop-off is located behind a guardrail or concrete barrier. When an excavation greater than three inches exists in a median, channelizing devices are spaced at intervals no greater than 40 feet and the excavation must be filled or covered within 48 hours.

Unless otherwise noted, all channelizing devices are spaced at the intervals recommended in Table 13 and all advance warning signs are spaced at the intervals recommended in Table 14.

Table 13. Typical Channelizing Device Spacing For Drop-Offs (West Virginia)

Speed	**Spacing**
25 to 45 mph	mph = device spacing in feet
50 to 70 mph	50 feet

Table 14. Typical Sign Spacing for Drop-Offs (West Virginia)

Speed	Spacing
20 mph	1,000 feet
30 mph	1,300 feet
40 mph	1,800 feet
50 mph	2,200 feet
60 mph	2,600 feet
70 mph	3,000 feet

4.1.18. Summary of State Practices

Table 15 lists a summary of state practices for treatment of edge drop-offs in work zones. The minimum depth at which special treatment is initiated as well as maximum depth of differential addressed and common use of temporary barrier rail (TBR) is shown.

Table 15. Summary of State Practices

State	Minimum Depth Treated	Maximum Depth Addressed
Iowa	2 inches	10 inches to 2 feet or greater, use TBR (informal)
Arizona	1 to 3 inches	5 feet or greater, use TRB
California	2 inches	6 inches to 2.5 feet, use TBR; >2.5 feet, special considerations
Florida	3 inches	Use TBR in certain situations; >5 feet, in clear zone, TBR required
Illinois	2 inches	>3 inches
Minnesota	Less than 2 inches	4 to 12 inches TBR use is optional; >12inches use is recommended
Missouri	2 inches	TBR use is optional for any height of drop-off
Montana	Any differentials	TBR use determined by formula
Nebraska	2 inches	>2 inches
New York	2 inches	2 feet or greater, use TBR in certain situations
North Dakota	1.5 inches	>12 inches, use TRB
Oregon	2 inches	4 inches
Pennsylvania	2 inches	>2 inches
South Dakota	3 inches	3 inches
Texas	1 inch	2 feet over 30 mph, use TBR in certain situations
West Virginia	2 inches	> 3 inches, use TBR for open lanes

4.2. Legal Exposure and Crash Analysis

4.2.1. Litigation Experience

For a six-year period from 1995 through 2000, eleven tort claims from five separate incidents were filed against the Iowa DOT alleging damages from edge drop-offs in work zones. Two of these claims totaling less than $1,000 each were denied.

Three claims totaling $3 million were filed for a single 1997 incident when a vehicle allegedly encountered an edge rut near a US 61 work area causing the driver to lose control resulting in a broadside collision and three fatalities. The contractor's insurance company paid a settlement of $300,000 with no direct cost to the state of Iowa.

Another 1997 incident on US 151 produced four separate claims totaling $4.52 million when a driver lost control after allegedly encountering an edge rut in a work zone resulting in a head-on collision with two fatalities and two injuries. These claims were in litigation at the time this report was prepared.

An incident involving a motorcycle operator and rider resulted in two claims totaling approximately $57,000 where loss of control was allegedly caused by a lane elevation differential. These claims were also not settled by the time this report was completed.

4.2.2. Work Zone Crash Reports

Iowa's crash analysis database lists 1,018 crashes occurring in work zones for the period 1998 through 2000. Of this total, 82 crashes were found to have occurred off the road surface resulting in 78 injuries. On-road surface crashes included 52 that resulted from head-on and sideswipe impacts. One fatality and 26 injuries were incurred in those crashes. While not possible to confidently define without further investigation, some of these crashes may have resulted from loss of control due to pavement or lane edge drop-offs.

Records for fatal work zone crashes in Iowa are much more complete. Using the Fatal Accident Reporting System (FARS) and individual crash narratives listed on the Iowa DOT web site, a more detailed analysis of data is possible. For the period from 1998 through 2000, a total of 32 fatalities occurred in Iowa work zones. Of that total, 11 fatalities resulted from crashes listed as head-on or crossed centerline as the contributing circumstance. However, the cause for that driver loss of control can only be surmised. It should further be noted that three fatal crashes resulted from impacts with temporary barrier rail in work zones during that same analysis period.

To provide pertinent information and documentation for potential tort claims, the Iowa DOT has adopted a procedure for reporting work zone crashes by field offices. Special forms are completed and submitted to the central office for review and reference. For the three-year period of 1999 through 2001, central office files contained a total of 189 crash reports. A review of these reports found that the majority involved rear end collisions. However many of the crashes also resulted when a vehicle lost control, crossed centerline, and collided with another vehicle. Only about five of the crash reports could be identified as definitely related to edge differentials and these did not result in serious damages. In addition, some of the crashes involved impacts with temporary barrier rail.

4.3. Evaluation of Active Projects in Iowa

A total of eight project sites featuring pavement drop-offs, located in or near Ames, Ankeny, and Des Moines, Iowa, were reviewed, four in rural locations and four in an urban environment. Three of the rural projects were located on four-lane divided (interstate) highways.

One rural two-lane improvement involved an approximate 20-inch drop-off adjacent to a traffic lane on one side of the roadway and a lesser differential located several feet laterally from the traffic lane on the opposite side. The drop-off conditions on both sides of the highway existed during both working and non-working hours. SHOULDER DROP OFF warning signs were installed at the beginning of the project and vertical panels were used to delineate the edge of the travel way. The speed limit through the work zone was reduced from 55 to 25 mph, however road users maintained travel speeds in the range of 35 to 50 mph. At some point after project initiation a changeable message sign was installed to urge drivers to watch their speed. Motorists did not appear to experience difficulties while driving through the work zone during the relatively short observation period.

The three rural interstate projects involved shallow drop-offs along the outside edge of the shoulder. Vertical panels, drums, and type III barricades were used separate road users from the work area. Traffic maintained travel speeds of approximately 65 mph.

Urban improvements were evaluated in four locations, including a two-lane road and three four-lane highways. The two-lane project included a drop-off of approximately eight inches. Vehicle travel speed through the work area approximated 35 mph with no observable driver difficulties. Urban four-lane work activities featured lane closures with merging of traffic required. The speed limit was reduced from 45 mph to 25 mph, resulting in drivers actually slowing to about 35 mph through the work area. Tubular markers were used to separate opposing traffic, arrow panels used to indicate a merge, vertical panels delineated the edge of the traffic lane, and type III barricades were used to close the lanes under construction. On one project a type III barricade and road closure sign were improperly positioned so as to appear as if the open lane was actually closed. Another project had flagger symbol signs in place but a flagger was not present. At another location, turning traffic was not advised in advance of an impending lane closure. Also on this project, two lanes of normal traffic were merged into one shortly after an intersection and only a short merge area was provided. Other observations noted that several tubular markers were knocked down or missing and that visibility of some channelizing devices was obscured by dirt, especially with the tubular markers. However, road users did not seem to experience difficulty negotiating through the work areas during the relatively short observation time.

Although road users did appear to negotiate these work zones safely and without difficulty, it should be noted that these were short-term observations in daylight conditions. Longer duration reviews, especially at night, may have resulted in different conclusions.

4.4. Development of Traffic Control Plan Selection Criteria

4.4.1. General Observations for Predicted Crash Costs in Work Zones

Consideration of potential crashes and resultant costs there from is necessary when evaluating alternatives for various drop-off treatment options. Several assumptions and conclusions for predicted crash costs can be made using studies referenced in this report, experience, and judgment.

In general predicted crash costs associated with a given drop-off magnitude increase with traffic volume, regardless of treatment mitigation. This observation also held for increasing traffic speed. Also as the lateral distance from an edge differential to the edge of a travel lane increases, the predicted costs of crashes decrease. In all cases, predicted crash costs increase proportionally with an increase in project length. That is, if the project length doubles, predicted crash costs increases by a factor of two. Project duration also affect crash costs, longer exposure increases predicated costs. Finally, it should be noted that for similar treatments, traffic volumes, speeds, drop-off magnitudes, lateral clearances, and project lengths, predicted crash costs were always higher for two-lane, two-way (TLTWO) highways compared to four-lane divided facilities. Further, it was found that four-lane undivided roadways have consistently higher predicted crash costs than four-lane divided, but not as high as TLTWO roads.

*4.4.2. Cost-Effectiveness Selection Procedure (*Roadside Design Guide*)*

For this analysis, the procedure described in Appendix A of the AASHTO *Roadside Design Guide* was used. The software program ROADSIDE 5.0, furnished with the 1996 edition, was employed to analyze two different highway types under several conditions of traffic speed, volume, depth of and distance to a drop-off, and length of exposure. The initial analysis determined predicted crash costs considering these factors for drop-offs without physical protection other than warning signs and channelizing devices, i.e., an unprotected edge. Severity indices were determined from the *Roadside Design Guide* for each circumstance. The results in predicted cost of crashes per week are illustrated in the report appendix in Table A.1 for TLTWO highways and Table A.4 for four-lane divided roads.

An analysis was conducted considering the same variables when a drop-off is treated with a 3:1 sloped earth wedge. This exercise indicated a period of exposure at which furnishing this feature would be cost effective, if only predicted crash costs and estimated cost of the wedge are considered. As can be seen in Table A.2 for a two lane roadway, furnishing a sloped wedge can be cost effective after only a few weeks exposure for volumes over 6,000 ADT and speeds of 90 km/hour. These data are illustrated graphically in the appendix in Figure A.1. As would be expected, four lane divided highways indicate a positive benefit cost ratio in even shorter time periods, one week of exposure or less for higher volumes and speeds. These results can be found in Table A.5 and illustrated in Figure A.2, both in the report appendix.

The use of a temporary barrier rail to shield drop-offs under several conditions was also reviewed, with interesting results. On TLTWO highways, temporary barrier rail was not found to be cost effective except with very high traffic volumes and unrealistic durations of exposure. As shown in Table A.3 in the appendix, a positive benefit cost could be achieved only after 46 weeks of exposure on a two-lane road with 10,000 ADT volume. Figure A.3 illustrates the date graphically for specific conditions. For four-lane divided highways, however, a positive benefit cost is attained in a much shorter time period. Table A.6 in the appendix illustrates beneficial results after 12 weeks of exposure for a 254 mm (10 inch) drop-off with 30,000 ADT. This time reduces to 7 weeks when volumes approach 50,000 ADT. Please refer to Figure A.4 for a graphical illustration.

To analyze possible influence additional lanes might contribute, similar criteria were applied to a six lane divided highway. For equal analysis factors, Roadside predicts only slightly higher crash costs for six-lane versus four-lane roads. Thus, as can be surmised from Tables A.7 through A.9, a positive benefit from either earth wedge or temporary barrier treatments will be obtained in approximately the same or slightly less time exposure as the number of lanes available for traffic increases.

An interesting result can be observed from the analysis when lateral distance to the drop-off is increased from 0 to 3.6 m (12 feet), an approximate lane width. For example, Table A.6 shows that the time to achieve a positive benefit cost approximately doubles when a closed lane can be allowed between the drop-off and an active traffic lane.

Using ROADSIDE 5.0 for short-term analysis can result in inaccurate results under certain conditions such as lower volumes and drop-off dimensions. For these situations, the crash costs for an unprotected edge will be computed as less than those with protective features in place, which may not be logical. For these situations, the positive benefit cost cells in the aforementioned tables are noted as “n/a.”

4.4.3. Analysis Using Other Methods

Studies identified in the literature search process provide other analysis options for determination and selection of appropriate ~~an~~d economically feasible temporary traffic control measures in work zones that feature edge drop-offs.

The report *Assuring Appropriate Levels of Safety in Construction Zones Where Pavement Edges and Drop-Offs Exist* by Ivey et al. (*33*) provides one such option. In this report that was discussed in Section 2.3.5, SIs for crash cost determination were developed considering such factors as height of drop-off, traffic speed, and resultant lane penetration after steering back onto the traveled way. Severity index formulae were devised for various drop-off heights from one inch to 40 inches and over.

These higher severity indices can be used in the ROADSIDE 5.0 program as described in the previous section. Since many SI values are approximately double those listed in the *Roadside*

Design Guide, a positive benefit/cost ratio will be achieve in a much shorter time of exposure for the examples calculated with ROADSIDE 5.0. Examples of SI computations using the Ivey et. al. formulae are included in the appendix.

Another analysis process is presented in *Guidelines for Positive Barrier Use in Construction Zones* by Sicking (*34*). In this report, a computer program is discussed that allows analysis of the benefit/cost comparison for temporary barrier use in several situations. A source of this program could not be identified, but the report does contain several graphs relating traffic volumes and speeds to assess cost-effective temporary barrier use in common work zone activities. For example, a graph for structural work with a potential for damage to false work if impacted by an errant vehicle, shows a positive economic benefit for barrier use when traffic operating speed is 40 mph and volume approximates 10,000 ADT. In contrast, even with a project duration of a year, barrier use to separate opposing traffic in a head-to head operation could not be economically justified with a traffic volume of 5,000 ADT and operating speed of 50 mph. All illustrations in this report assume long-term exposure.

Although varying results will be obtained depending on analysis methods used, severity index level selected, and crash costs employed, analytical procedures can be applied in the selection of effective, appropriate traffic control measures for a given situation or utilized to develop general guidelines for design of traffic control plans.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1. Summary of Findings

5.1.1. State Practices

A review of practices and policies followed in several states ascertained a considerable variation in procedures for addressing potential safety hazards of edge drop-offs in work zones. As illustrated in Table 16, only one common variable was found the depth of edge differential. Although a few states have established treatment for drop-offs of less than two inches, most do not address specific traffic control for edge drop-offs until a magnitude of two inches or more occurs, and then the most common treatment is installation of warning signs and other common traffic control devices.

Table 16. Factors Considered in Edge Treatment Practices

State	Depth	Location	AADT	Hwy Type	Speed	Project Duration	Time of Day
Iowa	•	•		•			
Arkansas	•	•					
California	•	•					
Florida	•	•					
Illinois	•	•			•		
Minnesota	•	•			•	•	
Missouri	•	•					•
Montana	•	•	•		•		
Nebraska	•						
New York	•	•	•		•	•	
North Dakota	•	•			•		
Ohio	•	•			•		•
Oregon	•			•			
Pennsylvania	•	•		•	•		
South Dakota	•						
Texas	•	•	•			•	
West Virginia	•	•		•	•		

Florida and South Dakota initiate special treatment for edge drop-offs after a depth of three inches is exceeded. Arkansas provided recommendations for addressing drop-offs exceeding five feet, however a formula developed by the State of Montana could be applied to any drop-off dimension. California requires special consideration for any drop-off exceeding 2.5 feet. Specific traffic control and protection measures vary widely among responding states, with special measures generally described beginning with a differential of 1–3 inches and, in many states, up to a depth of several feet.

Twelve of the 17 state practices reviewed describe the use of temporary traffic barriers as a mitigation measure. The criteria for use of temporary barrier rail considered in each of those twelve states are described in Table 17.

Table 17. Typical Criteria for Consideration of Temporary Traffic Barriers

State	Criteria
Iowa	Drop-off depth >10 inches, located within 10 feet of travel way (informal)
Arkansas	Drop-off depth >5 feet
California	Drop-off depth >6 inches, located within 8 feet of travel way; special engineering consideration for all drop-offs >2.5 feet
Florida	Drop-off depth >3 inches, located within 12 feet, project duration > 1 day
Minnesota	Optional for drop-off depth >4 inches, if no wedge, located adjacent to travel way, speed >30 mph, project duration >3 days, length <50 feet; if >12 inches, recommended
Missouri	Alternative for use with lane closures when drop-off depth >2 inches
Montana	Drop-off located within 30 feet of travel way, if no wedge provided, exposures exceeding 48 hours, spacing factor <20 feet (by formula)
New York	Drop-off depth >2 feet, speed limit > 45 mph, AADT ≥7500, project duration ≥ 60 days
North Dakota	Drop-off depth >4 inches if no wedge, all drop-offs depth >12 inches, located adjacent to travel way, speed limit >30 mph, project duration >7 days, project length >50 feet
Ohio	Drop-off depth >5 inches located between travel lanes, drop-off depth >2 feet located within 30 feet of travel way, overnight exposure
Texas	Drop-off depth >2 feet, speed limit >40 mph
West Virginia	Drop-off depth >3 inches, project duration >48 hours, speed limit >45 mph, located within 30 feet of travel way on multilane highways, located within 20 feet of travel way on undivided highways

The minimum depth of drop-off warranting consideration of temporary barrier rail use varies from two inches to five feet among the states; thus a common general criteria could not be identified.

In relation to other state practices, it was concluded that Iowa procedures, even though informal in some applications, are quite comparable in traffic control measures for warning of and protecting edge differentials in work zones. Criteria used in Iowa for consideration of temporary barrier rail use are more conservative than some states, but less so than others.

It should be noted that at the time of contact, none of the states indicated that a formal analysis of the effectiveness of their edge drop-off treatment practices had been undertaken.

5.1.2. Crash Analysis and Litigation Experience

Iowa experiences an average of approximately 360 work zone crashes annually, of which about 75 percent are rear-end collisions. Over one thousand crashes were noted for the period of 1998 through 2000. Only a small percentage of these crashes occur as a result of a vehicle leaving the roadway and some road surface crashes result head-on collisions or sideswipes. Although these loss-of-control incidents could have been affected by pavement of shoulder edge conditions, this fact is not evident from database records.

Likewise, 189 work zone crash reports furnished by Iowa DOT field offices over a three-year period, 1999 through 2001, indicated only a few that could be directly related to pavement edge differentials and these did not result in serious consequences. These reports did document several instances of loss-of control where cause was not established. Some collisions with temporary barrier rail were also noted.

For the six years from 1995 through 2000, 11 tort claims were filed against the state of Iowa alleging damages from edge drop-offs in work zones. Several of these claims were minor, less than $1,000 each, and some were denied. However, other claims totaled several million dollars were noted. One series of claims was settled by a contractor's insurance company for $300,000, with no direct cost to the state, and several others were still in litigation at the time this report was completed.

While it appeared that work zone crashes and resultant tort claims due to edge drop-offs are not common in Iowa, these incidents do occur and alleged negligence in providing proper warning and protection can have notable consequences. As was observed in Chapter 2 of this report, the state of Louisiana paid over $1,100,000 for one work zone drop-off related crash and several million dollars in claims were still being litigated in Iowa at the time this report was completed.

As was noted earlier, approximately 75 percent of Iowa work zone crashes result from rear-end collisions and steps to mitigate these occurrences should be considered. Extensive temporary traffic control measures, including possible use of barrier rail to protect edge drop-offs, can result in significant speed differentials and subsequent rear end collisions. Based on observations of the Pennsylvania Department of Transportation, one suggestion to decrease rear-end collisions would be to constantly update motorists on the traffic flow through the work zone with advance changeable message signs. Iowa has made use of advance warning systems in selected work zones with some success. The Pennsylvania implemented the Computerized Highway Information Processing System (CHIPS), which is an alternative that might merit further consideration. In addition, other early warning devices have been developed and implemented with varying degrees of success including portable rumble strips, flashing lights, and radar speed trailers. Designing of temporary traffic control to avoid severe speed differentials and alerting approaching drivers to work zone activities with possible slower traffic ahead is imperative in reducing rear-end collisions

5.1.3. Active Project Observations

No major deficiencies were noted in the temporary traffic control plans and procedures used by the Iowa DOT in work zones involving pavement edge differentials. Some unsatisfactory devices and practices were observed in local urban project traffic control, but most of these could have been corrected with a higher level of surveillance and maintenance. However, road users seemed to travel through both local and state work zones without much difficulty and nor significantly reducing travel speeds. It should be noted that these projects were observed for only a short period of time during daylight hours. Longer observation periods, particularly at night may have revealed other conclusions.

5.1.4. Traffic Control Selection Criteria

Use of extraordinary devices and measures to provide desirable safety for road users and workers is a responsible consideration for transportation agencies. Since many of these methods can dramatically increase costs of temporary traffic control in work zones, a reliable process to assist in analysis of suitable, but cost effective procedures is needed.

This study examined several similar past research efforts in this regard but used a software program, ROADSIDE 5.0, from AASHTO's *Roadside Design Guide,* to determine the feasibility of selecting the most appropriate temporary traffic control strategy for work zones that feature edge drop-offs. Of particular interest was the analysis of cost effective use of temporary barrier rail to protect edge drop-off locations.

Using ROADSIDE 5.0, it was concluded that the common use of a 3:1 or flatter sloped wedge can be cost effective at modest traffic volumes for both two lane, two way roads and four lane facilities. This conclusion is most evident when the drop-off is immediately adjacent to an open traffic lane. If a lane closure can be provided to separate traffic from the potential hazard, use of an earthen or granular wedge is much less compelling. A similar deduction cannot be drawn for length of a drop-off condition, however. Relatively short extents of drop-offs, 100 feet or less, indicate more benefit from wedge placement than longer reaches. Considering the comparative low cost of placement and the intrinsic value to safety, sloped wedge placement should be considered during non-working periods in all high-speed applications where a significant lateral buffer between traffic and drop-off cannot be provided. Another beneficial approach would be to limit the time of exposure that traffic would have to a drop-off situation. Contractors should be required to eliminate drop-offs within a limited working day period.

ROADSIDE 5.0 was also employed to predict cost effective use of temporary barrier rail to shield drop-offs in several work zone applications. In addition, other studies were reviewed for feasible recommendations. Although more conservative results would be obtained using higher severity indices and crash costs, several conclusions can be surmised from this analysis and comparison with other study results.

Due primarily to lower traffic volumes and speeds, TBR use on two-lane, two-way highways would not be cost effective in a reasonable exposure period. This observation is even more evident for longer lengths of a drop-off condition. Use of TBR in a TLTWO would be only economical in short work zones for long term exposure on very high volume and operating speed roadways. This finding is consistent with studies reviewed and other states' practices.

In four-lane divided highway application however, TBR usage can be economically feasible with relatively short exposure times. Both the Sicking report graphs (34) and ROADSIDE 5.0 analysis yield similar results for TBR use adjacent to long-term structure work. Furthermore, Ivey et al. (*4*) recommended selection criteria in approximate agreement with this conclusion. In contrast to the finding for sloped wedge treatment, TBR use is more easily justified in shorter length application, due to the much higher cost. As with the sloped wedge analysis, however, significant benefit is gained when a lane closure separates traffic from the drop-off and this is certainly an option to consider if resulting reduced capacity does not adversely affect road user safety. Similar conclusions can be drawn for other multilane divided roadways, with the number of lanes positively, but only slightly affecting benefits of edge drop-off treatments.

It should be noted that significantly different results are obtained in analysis of four-lane undivided roadway applications. As might be expected, ROADSIDE 5.0 predicts crash costs 20 to 30 percent higher for undivided versus divided highways with all other factors equal. Use of TBR for four lane undivided work zones would thus be cost effective at lower volumes and speeds than on divided roadways.

This analysis process demonstrates a method to quantify strategy options for temporary traffic control design in work zones. Although this evaluation considered edge drop-off situations, a similar methodology could also be employed to assess appropriate temporary measures to shield roadside obstructions in work areas, such as bridge piers, etc. More conservative results could be obtained using higher severity indices and predicted crash costs. In addition, several intuitive factors are not considered in the analysis, such as TBR contribution to worker safety and productivity. Improved driver performance in work zone with TBR protection is also a possible consideration in strategy decision making. Other potential impacts to public travel can also be analyzed using software programs such as QuickZone V 1.0, available from the Federal Highway Administration. Tools such as this permit more thorough consideration of a wide variety of issues involved in work zone traffic control. These factors, in addition to quantifiable costs, merit appropriate evaluation and probably justify the application of a factor of safety to analysis results.

5.2. Recommendations

A major goal of this study was to develop recommendations to supplement or strengthen current strategies used by the Iowa DOT in designing safe and cost-effective temporary traffic control for work zones that feature elevation differentials. Although present practices of the Iowa DOT as exemplified in standards and specifications were found to be overall quite satisfactory, the following recommendations are offered for consideration:

- Continue with current practice for temporary traffic control in work zones with elevation differentials less than 6 inches. Existing Standard Road Plans and Specifications seem satisfactory for these applications.

- Consider requiring placement of a temporary, compacted 3:1 or flatter wedge or fillet along the edge of any drop-off exceeding 2 inches during non-work periods. Current Standard Road Plans RS-2 and RS-62 as well as Specification 1107.09 allow options to this potentially beneficial practice.

- Reduce exposure of traffic to drop-off conditions as much as possible. Each project should be evaluated for a reasonable maximum drop-off exposure time for efficient operations. A specific working day requirement for elimination should be stipulated in each situation. In some applications, a single working day of exposure may be appropriate.

- Include design consideration for use of temporary barrier rails for all situations involving drop-offs over 6 inches on high-volume, high-speed, multilane highways such as freeways and expressways. Research data would indicate that minimum values of 5,000 AADT and 90 km/hour may be advisable threshold limits. ROADSIDE 5.0 and /or graphs described in this report can be used for that purpose.

- Review use of this methodology to analyze temporary barrier rail use to shield obstructions in work zones, such bridge piers, abutments, etc.

- Consider development and adoption of minimum standards for use of temporary barrier rails using a benefit-cost approach. Such a standard could mandate temporary barrier rails for a combination of specified drop-off, traffic volume, operating speed, exposure time, and allowable lateral clearance. A simplified relationship of volume to time of exposure could be developed to assist in selecting temporary barrier rails as a feasible temporary traffic control measure.

- AASHTO has published a 2002 edition of the *Roadside Design Guide* and an improved analysis tool; the Roadside Safety Analysis Program (RSAP) software will replace ROADSIDE 5.0. The RSAP program is described as much more sophisticated than ROADSIDE, considering many more factors and using “real world” data for such elements as impact speed and angle and vehicle orientation. When this program is available, a similar analysis to that described in this report should be undertaken to verify indicated criteria.

- While not directly related to edge drop-off exposure, in recognition of the most frequent crash cause in Iowa work zones, undertake a study to identify possible mitigation measures for rear-end collisions.

5.3. Future Research

This study identified possible methods for analyzing cost-effective measures for various temporary traffic control options in work zones that include edge differentials. But much more could be accomplished in this area, including more in-depth evaluation of temporary barrier use but also many other strategies could be reviewed. A flowchart or other guidance method for selecting appropriate temporary traffic control for edge drop-off exposure could be developed using the methodology described in this report.

As was mentioned in the recommendations (Section 5.2), research of the causes and identification of potential mitigation for rear end collisions in work zones would be valuable. Analysis of the effectiveness of advance warning devices and methods such as portable rumble strips, speed trailers, and changeable message signs could be included.

Significant concern exists for flagger safety. Comparative study of the possible improved safety contribution of portable traffic signals in substitution for flaggers would be valuable. These devices are in common use in Europe and have been considered in other states, but requirements of the MUTCD would need to be considered here.

Investigation of driver behavior and performance has been undertaken in many research efforts, but many apply to permanent traffic control devices and pavement markings. Since driver error contributes to a significant percentage of work zone crashes, more study in this field may be warranted. Driver perception and reaction to various levels of temporary traffic control would be an interesting and beneficial subject for research and may pay benefits in work zones with extensive levels of temporary traffic control, such as those featuring edge differentials.

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APPENDIX

SAMPLE CALCULATIONS

Severity Index Values (Using Ivey et al. Formulae)

When drop-off depth is 1 to 5 inches, SI = (3.5 + 0.5Y) x (V/60) (scrubbing conditions)

When drop-off depth is 5 to 20 inches; SI = (V/10) – 1 (dragging conditions)

where

Y = Lane violation in feet, assumed to be 3 feet
V = Vehicle speed in mph

SI for a two-inch drop-off, speed = 90 km/hour (56 mph):

SI = (3.5 + 0.5 x 3) x (56/60) = 4.66

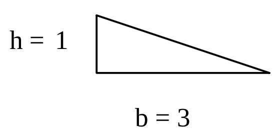
SI for a six-inch drop-off, speed = 90 km/hour (56 mph):

SI = (56/10) –1 = 4.59

Earth Wedge Construction Costs (from Summary of Awarded Bid Prices, Year 2001, Iowa DOT)

Average cost for embankment in place: $6.64/cy

Area of wedge with 3:1 (horizontal: vertical) slope: 0.5 x base x height



Six-inch drop-off:

0.5 x (6 in x 3) x 6 in = 54 in^2
54 in^2 x [(1 $ft)^2$/(12 $in)^2$] x [(1 $yd)^2$/(3 $ft)^2$] = 0.0412 yd^2

Ten-inch drop-off:

0.5 x (10 in x 3) x 10 in = 150 in^2
150 in^2 x {(1 $ft)^2$/(12 $in)^2$] x [(1 $yd)^2$/(3 $ft)^2$] = 0.1157 yd^2

Volume of wedge for various lengths, one side only: area x length

Six-inch drop-off:

For 30 m (32.8 yd) length: 0.0412 yd x 32.8 yd = 1.351 cy
For 400 m (437.45 yd) length: 0.0412 yd^2 x 437.45 yd = 18.23 cy
For1200 m (1312.34 yd) length: 0.0412 yd^2 x 1312.34 yd = 54.68 cy

Ten-inch drop-off:

For 30 m (32.8 yd) length: 0.1157 yd^2 x 32.8 yd = 3.795 cy
For 400 m (437.45 yd) length: 0.1157 yd^2 x 437.45 yd = 50.63 cy
For 1200 m (1312.34 yd) length: 0.1157 yd^2 x 1312.34 yd = 151.89 cy

Total cost of earth wedge construction, various lengths, one side only:

Six-inch drop-off:

For 30 m length: $6.64/cy x 1.351 cy = $8.97
For 400 m length: $6.64/cy x 18.23 cy = $121.05
For 1200 m length: $6.64/cy x 54.68 cy = $363.07

Ten-inch drop-off:

For 30 m length: $6.64/cy x 3.795 cy = $25.20
For 400 m length: $6.64/cy x 50.63 cy = $336.18
For 1200 m length: $6.64/cy x 151.89 cy = $1,008.55

Cost to remove earth wedge: assume one-half cost to place

Temporary Barrier Rail Costs (from Summary of Awarded Bid Prices, Year 2001, Iowa DOT)

Temporary barrier rail: $7.11/ft or $23.32/m
Cost for a length of 30 m: $23.32/m x 3 m = $700
Cost for a length of 400 m: $23.32/m x 400 m = $ 9,328
Cost for a length of 1200 m: $23.32/m x 1200 m = $2,7984

Total Cost Associated with Leaving Drop-off Unprotected

Total cost = crash costs from AASHTO ROADSIDE 5.0

Mitigating a Drop-Off with a 3:1 Sloped Earth Wedge

Positive benefit/cost = wedge costs/crash costs unprotected – crash costs w/ wedge

Example of 152 mm (6 in) drop-off, 400 m length, 10,000 ADT, 0 offset, 90 km/hour speed, four-lane divided highway, one side only:

Crash costs w/o wedge, from ROADSIDE 5.0: $39/week
Crash costs w/ wedge, from ROADSIDE 5.0: $29/week
Cost of earth wedge, place and remove: $182
Positive benefit/cost: $182/$39/week – $29/week = approximately 18 weeks

Providing a Temporary Barrier Rail to Shield Drop-Off

Positive benefit/cost = barrier cost/crash costs w/o protection – crash costs w/ barrier

Example: 254 mm (10 in) drop-off, 30 m length, 0 offset, 30,000 ADT, 110 km/hour (68 mph) speed limit, four-lane divided highway:

Crash costs w/o protection, from ROADSIDE 5.0: $115/week
Crash costs w/ barrier, from ROADSIDE 5.0: $57/week
Cost of temporary barrier rail: $700
Positive benefit/cost: $700/$115/week – $57/week = approximately 12 weeks

DATA TABLES AND FIGURES

Notes

ADT	average daily traffic
Speed	traffic velocity in kilometers per hour
Depth	pavement drop-off depth in millimeters
SI	severity index obtained from the Roadside Design Guide
X	offset distance from the drop-off to open traffic lane in meters
Cost of Crashes/yr	computer program ROADSIDE 5.0 output in years
Cost of Crashes/wk	(cost of crashes per year) / (52 weeks)
Cost of Wedge	one-time cost to place and remove 3:1 sloped earth wedge
Cost of Barrier	one-time cost to place and remove temporary concrete barrier
Positive Benefit Cost	number of weeks for cost of protecting a drop-off is more cost effective than no protection

Table A.1. Unprotected Drop-Off on TLTWO Highway (Using Roadside Design Guide SI Values)

ADT	Speed (km/hr)	Depth (mm)	SI	X (m)	Length (m)	Cost of Crashes/yr	Cost of Crashes/wk
2000	70	152	1.67	0	30	$ 38	$ 1
6000	70	152	1.67	0	30	$ 113	$ 2
10000	70	152	1.67	0	30	$ 189	$ 4
2000	90	152	2.03	0	30	$ 59	$ 1
6000	90	152	2.03	0	30	$ 177	$ 3
10000	90	152	2.03	0	30	$ 295	$ 6
2000	70	152	1.67	0	400	$ 386	$ 7
6000	70	152	1.67	0	400	$ 1,159	$ 22
10000	70	152	1.67	0	400	$ 1,931	$ 37
2000	90	152	2.03	0	400	$ 595	$ 11
6000	90	152	2.03	0	400	$ 1,715	$ 33
10000	90	152	2.03	0	400	$ 2,859	$ 55
2000	70	254	2.66	0	30	$ 171	$ 3
6000	70	254	2.66	0	30	$ 514	$ 10
10000	70	254	2.66	0	30	$ 856	$ 16
2000	90	254	3.11	0	30	$ 320	$ 6
6000	90	254	3.11	0	30	$ 960	$ 18
10000	90	254	3.11	0	30	$ 1,600	$ 31
2000	70	254	2.66	0	400	$ 1,749	$ 34
6000	70	254	2.66	0	400	$ 5,246	$ 101
10000	70	254	2.66	0	400	$ 8,744	$ 168
2000	90	254	3.11	0	400	$ 3,104	$ 60
6000	90	254	3.11	0	400	$ 9,313	$ 179
10000	90	254	3.11	0	400	$ 15,521	$ 298
2000	70	152	1.67	3.6	30	$ 19	$ 0
6000	70	152	1.67	3.6	30	$ 58	$ 1
10000	70	152	1.67	3.6	30	$ 96	$ 2
2000	90	152	2.03	3.6	30	$ 27	$ 1
6000	90	152	2.03	3.6	30	$ 80	$ 2
10000	90	152	2.03	3.6	30	$ 133	$ 3
2000	70	152	1.67	3.6	400	$ 190	$ 4
6000	70	152	1.67	3.6	400	$ 570	$ 11
10000	70	152	1.67	3.6	400	$ 950	$ 18
2000	90	152	2.03	3.6	400	$ 252	$ 5
6000	90	152	2.03	3.6	400	$ 756	$ 15
10000	90	152	2.03	3.6	400	$ 1,261	$ 24
2000	70	254	2.66	3.6	30	$ 59	$ 1
6000	70	254	2.66	3.6	30	$ 176	$ 3
10000	70	254	2.66	3.6	30	$ 294	$ 6
2000	90	254	3.11	3.6	30	$ 145	$ 3
6000	90	254	3.11	3.6	30	$ 434	$ 8
10000	90	254	3.11	3.6	30	$ 724	$ 14
2000	70	254	2.66	3.6	400	$ 582	$ 11
6000	70	254	2.66	3.6	400	$ 1,746	$ 34
10000	70	254	2.66	3.6	400	$ 2,911	$ 56
2000	90	254	3.11	3.6	400	$ 1,369	$ 26
6000	90	254	3.11	3.6	400	$ 4,107	$ 79
10000	90	254	3.11	3.6	400	$ 6,845	$ 132

Table A.2. Drop-Off Mitigated with 3:1 Sloped Earth Wedge, TLTWO Highway

ADT	Speed (km/hr)	Depth (mm)	SI	X (m)	Length (m)	Cost of Crashes/yr	Cost of Crashes/wk	Cost of Wedge	Unprotected Cost of Crashes/wk	Positive Benefit Cost (weeks)
2000	70	152	1.3	0	30	$ 29	$ 1	$ 14	$ 1	n/a
6000	70	152	1.3	0	30	$ 86	$ 2	$ 14	$ 2	n/a
10000	70	152	1.3	0	30	$ 144	$ 3	$ 14	$ 4	14
2000	90	152	1.7	0	30	$ 44	$ 1	$ 14	$ 1	n/a
6000	90	152	1.7	0	30	$ 137	$ 3	$ 14	$ 3	n/a
10000	90	152	1.7	0	30	$ 220	$ 4	$ 14	$ 6	7
2000	70	152	1.3	0	400	$ 293	$ 6	$ 182	$ 7	182
6000	70	152	1.3	0	400	$ 880	$ 17	$ 182	$ 22	34
10000	70	152	1.3	0	400	$ 1,467	$ 28	$ 182	$ 37	20
2000	90	152	1.7	0	400	$ 427	$ 8	$ 182	$ 11	56
6000	90	152	1.7	0	400	$ 1,281	$ 25	$ 182	$ 33	22
10000	90	152	1.7	0	400	$ 2,135	$ 41	$ 182	$ 55	13
2000	70	254	1.92	0	30	$ 44	$ 1	$ 38	$ 3	15
6000	70	254	1.92	0	30	$ 132	$ 3	$ 38	$ 10	5
10000	70	254	1.92	0	30	$ 220	$ 4	$ 38	$ 16	3
2000	90	254	2.32	0	30	$ 122	$ 2	$ 38	$ 6	10
6000	90	254	2.32	0	30	$ 365	$ 7	$ 38	$ 18	3
10000	90	254	2.32	0	30	$ 609	$ 12	$ 38	$ 31	2
2000	70	254	1.92	0	400	$ 449	$ 9	$ 504	$ 34	20
6000	70	254	1.92	0	400	$ 1,347	$ 26	$ 504	$ 101	7
10000	70	254	1.92	0	400	$ 2,245	$ 43	$ 504	$ 168	4
2000	90	254	2.32	0	400	$ 1,181	$ 23	$ 504	$ 60	14
6000	90	254	2.32	0	400	$ 3,544	$ 68	$ 504	$ 179	5
10000	90	254	2.32	0	400	$ 5,907	$ 114	$ 504	$ 298	3
2000	70	152	1.3	3.6	30	$ 10	$ 0	$ 14	$ 0	79
6000	70	152	1.3	3.6	30	$ 30	$ 1	$ 14	$ 1	26
10000	70	152	1.3	3.6	30	$ 49	$ 1	$ 14	$ 2	15
2000	90	152	1.7	3.6	30	$ 20	$ 0	$ 14	$ 1	104
6000	90	152	1.7	3.6	30	$ 60	$ 1	$ 14	$ 2	36
10000	90	152	1.7	3.6	30	$ 100	$ 2	$ 14	$ 3	22
2000	70	152	1.3	3.6	400	$ 98	$ 2	$ 182	$ 4	103
6000	70	152	1.3	3.6	400	$ 293	$ 6	$ 182	$ 11	34
10000	70	152	1.3	3.6	400	$ 488	$ 9	$ 182	$ 18	20
2000	90	152	1.7	3.6	400	$ 188	$ 4	$ 182	$ 5	148
6000	90	152	1.7	3.6	400	$ 565	$ 11	$ 182	$ 15	50
10000	90	152	1.7	3.6	400	$ 942	$ 18	$ 182	$ 24	30
2000	70	254	1.92	3.6	30	$ 15	$ 0	$ 38	$ 1	45
6000	70	254	1.92	3.6	30	$ 45	$ 1	$ 38	$ 3	15
10000	70	254	1.92	3.6	30	$ 75	$ 1	$ 38	$ 6	9
2000	90	254	2.32	3.6	30	$ 55	$ 1	$ 38	$ 3	22
6000	90	254	2.32	3.6	30	$ 165	$ 3	$ 38	$ 8	7
10000	90	254	2.32	3.6	30	$ 275	$ 5	$ 38	$ 14	4
2000	70	254	1.92	3.6	400	$ 149	$ 9	$ 504	$ 11	197
6000	70	254	1.92	3.6	400	$ 448	$ 26	$ 504	$ 34	66
10000	70	254	1.92	3.6	400	$ 747	$ 43	$ 504	$ 56	39
2000	90	254	2.32	3.6	400	$ 521	$ 23	$ 504	$ 26	139
6000	90	254	2.32	3.6	400	$ 1,563	$ 68	$ 504	$ 79	47
10000	90	254	2.32	3.6	400	$ 2,605	$ 114	$ 504	$ 132	28

Table A.3. Drop-Off Shielded by Temporary Barrier Rail, TLTWO Highway

ADT	Speed (km/hr)	Depth (mm)	SI	X (m)	Length (m)	Cost of Crashes/yr	Cost of Crashes/wk	Cost of Barrier Rail	Unprotected Cost of Crashes/wk	Positive Benefit Cost (weeks)
2000	70	152	2.2	0	30	$ 84	$ 2	$ 700	$ 1	n/a
6000	70	152	2.2	0	30	$ 252	$ 5	$ 700	$ 2	n/a
10000	70	152	2.2	0	30	$ 420	$ 8	$ 700	$ 4	n/a
2000	90	152	2.5	0	30	$ 161	$ 3	$ 700	$ 1	n/a
6000	90	152	2.5	0	30	$ 482	$ 9	$ 700	$ 3	n/a
10000	90	152	2.5	0	30	$ 804	$ 15	$ 700	$ 6	n/a
2000	70	152	2.2	0	400	$ 857	$ 16	$ 9,328	$ 7	n/a
6000	70	152	2.2	0	400	$ 2,571	$ 49	$ 9,328	$ 22	n/a
10000	70	152	2.2	0	400	$ 4,285	$ 82	$ 9,328	$ 37	n/a
2000	90	152	2.5	0	400	$ 1,560	$ 30	$ 9,328	$ 11	n/a
6000	90	152	2.5	0	400	$ 4,679	$ 90	$ 9,328	$ 33	n/a
10000	90	152	2.5	0	400	$ 7,799	$ 150	$ 9,328	$ 55	n/a
2000	70	254	2.2	0	30	$ 84	$ 2	$ 700	$ 3	418
6000	70	254	2.2	0	30	$ 252	$ 5	$ 700	$ 10	139
10000	70	254	2.2	0	30	$ 420	$ 8	$ 700	$ 16	83
2000	90	254	2.5	0	30	$ 161	$ 3	$ 700	$ 6	229
6000	90	254	2.5	0	30	$ 482	$ 9	$ 700	$ 18	76
10000	90	254	2.5	0	30	$ 804	$ 15	$ 700	$ 31	46
2000	70	254	2.2	0	400	$ 857	$ 16	$ 9,328	$ 34	544
6000	70	254	2.2	0	400	$ 2,571	$ 49	$ 9,328	$ 101	181
10000	70	254	2.2	0	400	$ 4,285	$ 82	$ 9,328	$ 168	109
2000	90	254	2.5	0	400	$ 1,560	$ 30	$ 9,328	$ 60	314
6000	90	254	2.5	0	400	$ 4,679	$ 90	$ 9,328	$ 179	105
10000	90	254	2.5	0	400	$ 7,799	$ 150	$ 9,328	$ 298	63
2000	70	152	2.2	3.6	30	$ 29	$ 1	$ 700	$ 0	n/a
6000	70	152	2.2	3.6	30	$ 86	$ 2	$ 700	$ 1	n/a
10000	70	152	2.2	3.6	30	$ 144	$ 3	$ 700	$ 2	n/a
2000	90	152	2.5	3.6	30	$ 73	$ 1	$ 700	$ 1	n/a
6000	90	152	2.5	3.6	30	$ 218	$ 4	$ 700	$ 2	n/a
10000	90	152	2.5	3.6	30	$ 364	$ 7	$ 700	$ 3	n/a
2000	70	152	2.2	3.6	400	$ 285	$ 5	$ 9,328	$ 4	n/a
6000	70	152	2.2	3.6	400	$ 856	$ 16	$ 9,328	$ 11	n/a
10000	70	152	2.2	3.6	400	$ 1,426	$ 27	$ 9,328	$ 18	n/a
2000	90	152	2.5	3.6	400	$ 688	$ 13	$ 9,328	$ 5	n/a
6000	90	152	2.5	3.6	400	$ 2,064	$ 40	$ 9,328	$ 15	n/a
10000	90	152	2.5	3.6	400	$ 3,439	$ 66	$ 9,328	$ 24	n/a
2000	70	254	2.2	3.6	30	$ 29	$ 1	$ 700	$ 1	1213
6000	70	254	2.2	3.6	30	$ 86	$ 2	$ 700	$ 3	404
10000	70	254	2.2	3.6	30	$ 144	$ 3	$ 700	$ 6	243
2000	90	254	2.5	3.6	30	$ 73	$ 1	$ 700	$ 3	506
6000	90	254	2.5	3.6	30	$ 218	$ 4	$ 700	$ 8	169
10000	90	254	2.5	3.6	30	$ 364	$ 7	$ 700	$ 14	101
2000	70	254	2.2	3.6	400	$ 285	$ 5	$ 9,328	$ 11	1633
6000	70	254	2.2	3.6	400	$ 856	$ 16	$ 9,328	$ 34	545
10000	70	254	2.2	3.6	400	$ 1,426	$ 27	$ 9,328	$ 56	327
2000	90	254	2.5	3.6	400	$ 688	$ 13	$ 9,328	$ 26	712
6000	90	254	2.5	3.6	400	$ 2,064	$ 40	$ 9,328	$ 79	237
10000	90	254	2.5	3.6	400	$ 3,439	$ 66	$ 9,328	$ 132	142

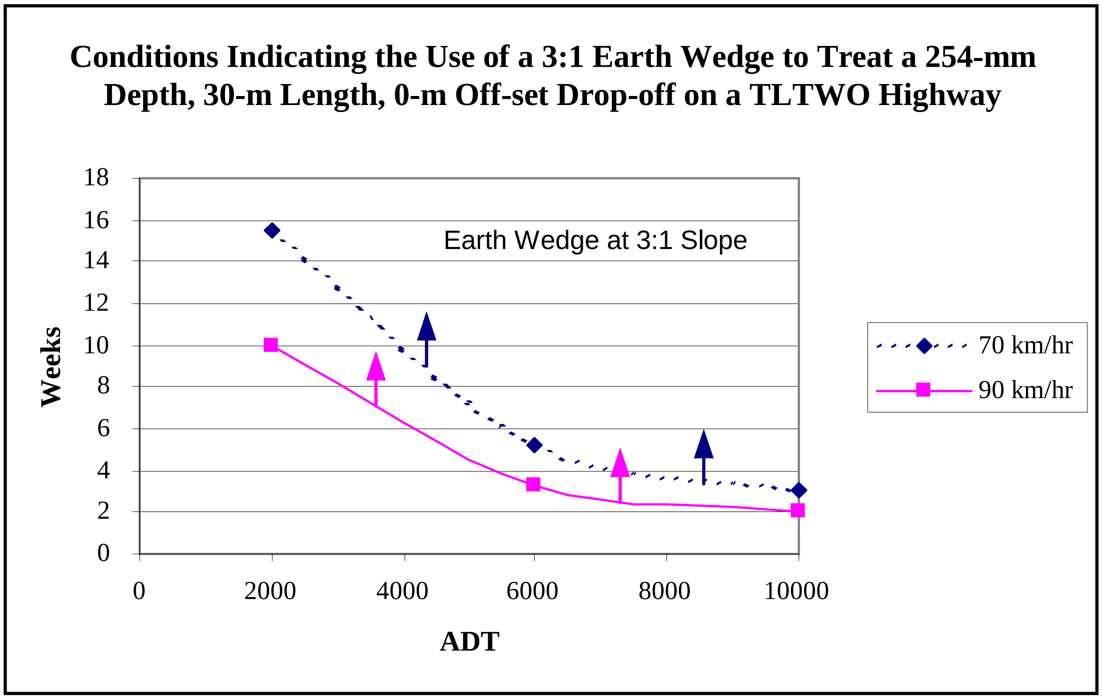


Figure A.1. Area Above Curves Indicates Time of Exposure for Cost-Effective Use of Sloped Earth Wedge for Treatment of the Edge Drop-Off

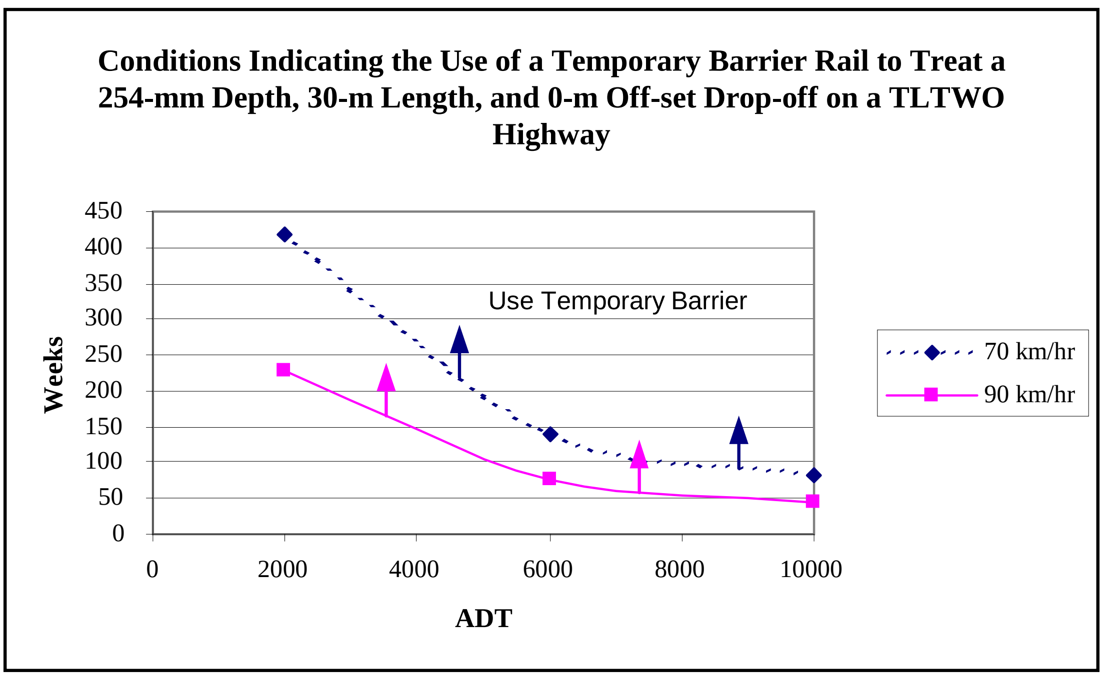


Figure A.2. Area Above Curves Indicates Time of Exposure for Cost-Effective Use of Temporary Barrier Rail to Treat the Edge Drop-Off

Table A.4. Unprotected Drop-Off on Four-Lane Divided Highway (Using Roadside Design Guide SI Values)

ADT	Speed (km/hr)	Depth (mm)	SI	X (m)	Length (m)	Cost of Crashes/yr	Cost of Crashes/wk
10000	90	152	2.03	0	30	$ 206	$ 4
30000	90	152	2.03	0	30	$ 618	$ 12
50000	90	152	2.03	0	30	$ 1,030	$ 20
10000	110	152	2.43	0	30	$ 538	$ 10
30000	110	152	2.43	0	30	$ 1,614	$ 31
50000	110	152	2.43	0	30	$ 2,690	$ 52
10000	90	152	2.03	0	400	$ 2,020	$ 39
30000	90	152	2.03	0	400	$ 6,061	$ 117
50000	90	152	2.03	0	400	$ 10,102	$ 194
10000	110	152	2.43	0	400	$ 5,021	$ 97
30000	110	152	2.43	0	400	$ 15,062	$ 290
50000	110	152	2.43	0	400	$ 25,104	$ 483
10000	90	254	3.11	0	30	$ 1,119	$ 22
30000	90	254	3.11	0	30	$ 3,356	$ 65
50000	90	254	3.11	0	30	$ 5,594	$ 108
10000	110	254	3.58	0	30	$ 1,986	$ 38
30000	110	254	3.58	0	30	$ 5,975	$ 115
50000	110	254	3.58	0	30	$ 9,928	$ 191
10000	90	254	3.11	0	400	$ 10,970	$ 211
30000	90	254	3.11	0	400	$ 32,909	$ 633
50000	90	254	3.11	0	400	$ 54,848	$ 1,055
10000	110	254	3.58	0	400	$ 18,527	$ 356
30000	110	254	3.58	0	400	$ 55,581	$ 1,069
50000	110	254	3.58	0	400	$ 92,635	$ 1,781
10000	90	152	2.03	3.6	30	$ 89	$ 2
30000	90	152	2.03	3.6	30	$ 226	$ 4
50000	90	152	2.03	3.6	30	$ 444	$ 9
10000	110	152	2.43	3.6	30	$ 267	$ 5
30000	110	152	2.43	3.6	30	$ 800	$ 15
50000	110	152	2.43	3.6	30	$ 1,334	$ 26
10000	90	152	2.03	3.6	400	$ 838	$ 16
30000	90	152	2.03	3.6	400	$ 2,515	$ 48
50000	90	152	2.03	3.6	400	$ 4,192	$ 81
10000	110	152	2.43	3.6	400	$ 2,430	$ 47
30000	110	152	2.43	3.6	400	$ 7,290	$ 140
50000	110	152	2.43	3.6	400	$ 12,151	$ 234
10000	90	254	3.11	3.6	30	$ 482	$ 9
30000	90	254	3.11	3.6	30	$ 1,445	$ 28
50000	90	254	3.11	3.6	30	$ 2,408	$ 46
10000	110	254	3.58	3.6	30	$ 985	$ 19
30000	110	254	3.58	3.6	30	$ 2,954	$ 57
50000	110	254	3.58	3.6	30	$ 4,923	$ 95
10000	90	254	3.11	3.6	400	$ 4,552	$ 88
30000	90	254	3.11	3.6	400	$ 13,655	$ 263
50000	90	254	3.11	3.6	400	$ 22,759	$ 438
10000	110	254	3.58	3.6	400	$ 8,976	$ 173
30000	110	254	3.58	3.6	400	$ 26,902	$ 517
50000	110	254	3.58	3.6	400	$ 44,837	$ 862

Table A.5. Drop-Off Mitigated With 3:1 Sloped Earth Wedge, Four-Lane Divided Highway

ADT	Speed (km/hr)	Depth (mm)	SI	X (m)	Length (m)	Cost of Crashes/yr	Cost of Crashes/wk	Cost of Wedge	Unprotected Cost of Crashes/wk	Positive Benefit Cost (weeks)
10000	90	152	1.7	0	30	$ 154	$ 3	$ 14	4	14
30000	90	152	1.7	0	30	$ 462	$ 9	$ 14	12	5
50000	90	152	1.7	0	30	$ 769	$ 15	$ 14	20	3
10000	110	152	2.3	0	30	$ 434	$ 8	$ 14	10	7
30000	110	152	2.3	0	30	$ 1,302	$ 25	$ 14	31	2
50000	110	152	2.3	0	30	$ 2,170	$ 42	$ 14	52	1
10000	90	152	1.7	0	400	$ 1,509	$ 29	$ 182	39	19
30000	90	152	1.7	0	400	$ 4,527	$ 87	$ 182	117	6
50000	90	152	1.7	0	400	$ 7,544	$ 145	$ 182	194	4
10000	110	152	2.3	0	400	$ 4,049	$ 78	$ 182	97	10
30000	110	152	2.3	0	400	$ 12,148	$ 234	$ 182	290	3
50000	110	152	2.3	0	400	$ 20,247	$ 389	$ 182	483	2
10000	90	254	2.32	0	30	$ 426	$ 8	$ 38	22	3
30000	90	254	2.32	0	30	$ 1,277	$ 25	$ 38	65	1
50000	90	254	2.32	0	30	$ 2,129	$ 41	$ 38	108	1
10000	110	254	2.79	0	30	$ 826	$ 16	$ 38	38	2
30000	110	254	2.79	0	30	$ 2,479	$ 48	$ 38	115	1
50000	110	254	2.79	0	30	$ 4,132	$ 79	$ 38	191	0
10000	90	254	2.32	0	400	$ 4,175	$ 80	$ 504	211	4
30000	90	254	2.32	0	400	$ 12,524	$ 241	$ 504	633	1
50000	90	254	2.32	0	400	$ 20,873	$ 401	$ 504	1,055	1
10000	110	254	2.79	0	400	$ 7,710	$ 148	$ 504	356	2
30000	110	254	2.79	0	400	$ 23,131	$ 445	$ 504	1,069	1
50000	110	254	2.79	0	400	$ 38,552	$ 741	$ 504	1,781	0
10000	90	152	1.7	3.6	30	$ 66	$ 1	$ 14	2	31
30000	90	152	1.7	3.6	30	$ 199	$ 4	$ 14	4	27
50000	90	152	1.7	3.6	30	$ 331	$ 6	$ 14	9	6
10000	110	152	2.3	3.6	30	$ 215	$ 4	$ 14	5	14
30000	110	152	2.3	3.6	30	$ 646	$ 12	$ 14	15	5
50000	110	152	2.3	3.6	30	$ 1,076	$ 21	$ 14	26	3
10000	90	152	1.7	3.6	400	$ 626	$ 12	$ 182	16	45
30000	90	152	1.7	3.6	400	$ 1,878	$ 36	$ 182	48	15
50000	90	152	1.7	3.6	400	$ 3,130	$ 60	$ 182	81	9
10000	110	152	2.3	3.6	400	$ 2,032	$ 39	$ 182	47	24
30000	110	152	2.3	3.6	400	$ 6,097	$ 117	$ 182	140	8
50000	110	152	2.3	3.6	400	$ 10,162	$ 195	$ 182	234	5
10000	90	254	2.32	3.6	30	$ 183	$ 4	$ 38	9	7
30000	90	254	2.32	3.6	30	$ 550	$ 11	$ 38	28	2
50000	90	254	2.32	3.6	30	$ 916	$ 18	$ 38	46	1
10000	110	254	2.79	3.6	30	$ 410	$ 8	$ 38	19	3
30000	110	254	2.79	3.6	30	$ 1,229	$ 24	$ 38	57	1
50000	110	254	2.79	3.6	30	$ 2,049	$ 39	$ 38	95	1
10000	90	254	2.32	3.6	400	$ 1,732	$ 33	$ 504	88	9
30000	90	254	2.32	3.6	400	$ 5,197	$ 100	$ 504	263	3
50000	90	254	2.32	3.6	400	$ 8,661	$ 167	$ 504	438	2
10000	110	254	2.79	3.6	400	$ 3,732	$ 72	$ 504	173	5
30000	110	254	2.79	3.6	400	$ 11,196	$ 215	$ 504	517	2
50000	110	254	2.79	3.6	400	$ 18,660	$ 359	$ 504	862	1

Table A.6. Drop-Off Shielded by Temporary Barrier Rail, Four-Lane Divided Highway

ADT	Speed (km/hr)	Depth (mm)	SI	X (m)	Length (m)	Cost of Crashes/yr	Cost of Crashes/wk	Cost of Barrier Rail	Unprotected Cost of Crashes/wk	Positive Benefit Cost (weeks)
10000	90	152	2.5	0	30	$ 562	$ 11	$ 700	$ 4	n/a
30000	90	152	2.5	0	30	$ 1,686	$ 32	$ 700	$ 12	n/a
50000	90	152	2.5	0	30	$ 2,811	$ 54	$ 700	$ 20	n/a
10000	110	152	3	0	30	$ 994	$ 19	$ 700	$ 10	n/a
30000	110	152	3	0	30	$ 2,983	$ 57	$ 700	$ 31	n/a
50000	110	152	3	0	30	$ 4,972	$ 96	$ 700	$ 52	n/a
10000	90	152	2.5	0	400	$ 5,512	$ 106	$ 9,328	$ 39	n/a
30000	90	152	2.5	0	400	$ 16,535	$ 318	$ 9,328	$ 117	n/a
50000	90	152	2.5	0	400	$ 27,559	$ 530	$ 9,328	$ 194	n/a
10000	110	152	3	0	400	$ 9,279	$ 178	$ 9,328	$ 97	n/a
30000	110	152	3	0	400	$ 27,838	$ 535	$ 9,328	$ 290	n/a
50000	110	152	3	0	400	$ 46,397	$ 892	$ 9,328	$ 483	n/a
10000	90	254	2.5	0	30	$ 562	$ 11	$ 700	$ 22	65
30000	90	254	2.5	0	30	$ 1,686	$ 32	$ 700	$ 65	22
50000	90	254	2.5	0	30	$ 2,811	$ 54	$ 700	$ 108	13
10000	110	254	3	0	30	$ 994	$ 19	$ 700	$ 38	37
30000	110	254	3	0	30	$ 2,983	$ 57	$ 700	$ 115	12
50000	110	254	3	0	30	$ 4,972	$ 96	$ 700	$ 191	7
10000	90	254	2.5	0	400	$ 5,512	$ 106	$ 9,328	$ 211	89
30000	90	254	2.5	0	400	$ 16,535	$ 318	$ 9,328	$ 633	30
50000	90	254	2.5	0	400	$ 27,559	$ 530	$ 9,328	$ 1,055	18
10000	110	254	3	0	400	$ 9,279	$ 178	$ 9,328	$ 356	52
30000	110	254	3	0	400	$ 27,838	$ 535	$ 9,328	$ 1,069	17
50000	110	254	3	0	400	$ 46,397	$ 892	$ 9,328	$ 1,781	10
10000	90	152	2.5	3.6	30	$ 242	$ 5	$ 700	$ 2	n/a
30000	90	152	2.5	3.6	30	$ 726	$ 14	$ 700	$ 4	n/a
50000	90	152	2.5	3.6	30	$ 1,210	$ 23	$ 700	$ 9	n/a
10000	110	152	3	3.6	30	$ 493	$ 9	$ 700	$ 5	n/a
30000	110	152	3	3.6	30	$ 1,479	$ 28	$ 700	$ 15	n/a
50000	110	152	3	3.6	30	$ 2,466	$ 47	$ 700	$ 26	n/a
10000	90	152	2.5	3.6	400	$ 2,287	$ 44	$ 9,328	$ 16	n/a
30000	90	152	2.5	3.6	400	$ 6,861	$ 132	$ 9,328	$ 48	n/a
50000	90	152	2.5	3.6	400	$ 11,435	$ 220	$ 9,328	$ 81	n/a
10000	110	152	3	3.6	400	$ 4,491	$ 86	$ 9,328	$ 47	n/a
30000	110	152	3	3.6	400	$ 13,474	$ 259	$ 9,328	$ 140	n/a
50000	110	152	3	3.6	400	$ 22,457	$ 432	$ 9,328	$ 234	n/a
10000	90	254	2.5	3.6	30	$ 242	$ 5	$ 700	$ 9	152
30000	90	254	2.5	3.6	30	$ 726	$ 14	$ 700	$ 28	51
50000	90	254	2.5	3.6	30	$ 1,210	$ 23	$ 700	$ 46	30
10000	110	254	3	3.6	30	$ 493	$ 9	$ 700	$ 19	74
30000	110	254	3	3.6	30	$ 1,479	$ 28	$ 700	$ 57	25
50000	110	254	3	3.6	30	$ 2,466	$ 47	$ 700	$ 95	15
10000	90	254	2.5	3.6	400	$ 2,287	$ 44	$ 9,328	$ 88	214
30000	90	254	2.5	3.6	400	$ 6,861	$ 132	$ 9,328	$ 263	71
50000	90	254	2.5	3.6	400	$ 11,435	$ 220	$ 9,328	$ 438	43
10000	110	254	3	3.6	400	$ 4,491	$ 86	$ 9,328	$ 173	108
30000	110	254	3	3.6	400	$ 13,474	$ 259	$ 9,328	$ 517	36
50000	110	254	3	3.6	400	$ 22,457	$ 432	$ 9,328	$ 862	22

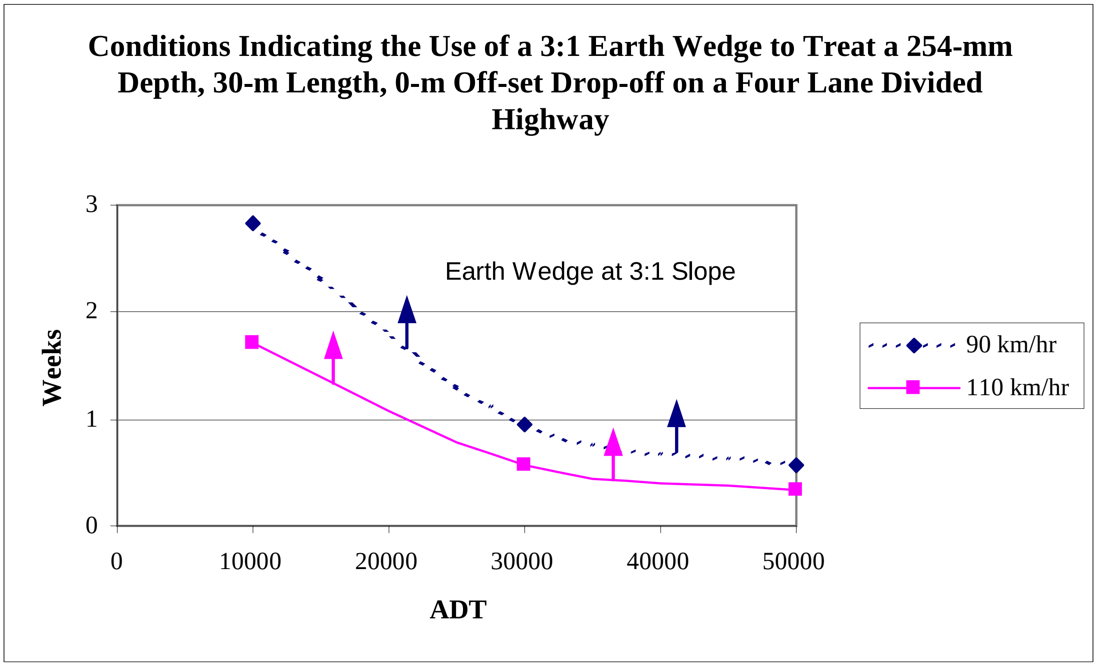


Figure A.3. Area Above Curves Indicates Time of Exposure for Cost-Effective Use of Sloped Earth Wedge to Treat the Edge Drop-Off

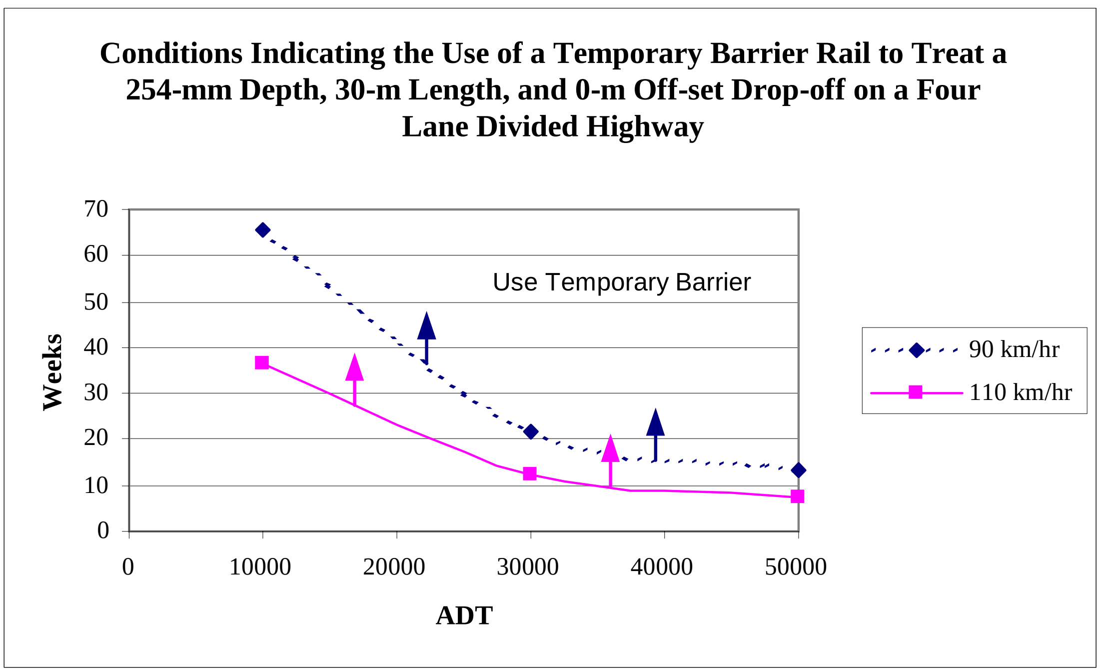


Figure A.4. Area Above Curves Indicates Time of Exposure for Cost-Effective Use of Temporary Barrier Rail to Treat Edge Drop-Off

Table A.7. Unprotected Drop-Off on Six-Lane Divided Highway (Using Roadside Design Guide SI Values)

ADT	Speed (km/hr)	Depth (mm)	SI	X (m)	Length (m)	Cost of Crashes/yr	Cost of Crashes/wk
10000	90	152	2.03	0	30	$ 214	$ 4
30000	90	152	2.03	0	30	$ 643	$ 12
50000	90	152	2.03	0	30	$ 1,071	$ 21
10000	110	152	2.43	0	30	$ 560	$ 11
30000	110	152	2.43	0	30	$ 1,679	$ 32
50000	110	152	2.43	0	30	$ 2,798	$ 54
10000	90	152	2.03	0	400	$ 2,101	$ 40
30000	90	152	2.03	0	400	$ 6,304	$ 121
50000	90	152	2.03	0	400	$ 10,506	$ 202
10000	110	152	2.43	0	400	$ 5,222	$ 100
30000	110	152	2.43	0	400	$ 15,665	$ 301
50000	110	152	2.43	0	400	$ 26,108	$ 502
10000	90	254	3.11	0	30	$ 1,163	$ 22
30000	90	254	3.11	0	30	$ 3,490	$ 67
50000	90	254	3.11	0	30	$ 5,817	$ 112
10000	110	254	3.58	0	30	$ 2,065	$ 40
30000	110	254	3.58	0	30	$ 6,195	$ 119
50000	110	254	3.58	0	30	$ 10,325	$ 199
10000	90	254	3.11	0	400	$ 11,408	$ 219
30000	90	254	3.11	0	400	$ 34,225	$ 658
50000	90	254	3.11	0	400	$ 57,042	$ 1,097
10000	110	254	3.58	0	400	$ 19,268	$ 371
30000	110	254	3.58	0	400	$ 57,804	$ 1,112
50000	110	254	3.58	0	400	$ 96,340	$ 1,853
10000	90	152	2.03	3.6	30	$ 92	$ 2
30000	90	152	2.03	3.6	30	$ 277	$ 5
50000	90	152	2.03	3.6	30	$ 461	$ 9
10000	110	152	2.43	3.6	30	$ 277	$ 5
30000	110	152	2.43	3.6	30	$ 832	$ 16
50000	110	152	2.43	3.6	30	$ 1,387	$ 27
10000	90	152	2.03	3.6	400	$ 872	$ 17
30000	90	152	2.03	3.6	400	$ 2,616	$ 50
50000	90	152	2.03	3.6	400	$ 4,360	$ 84
10000	110	152	2.43	3.6	400	$ 2,527	$ 49
30000	110	152	2.43	3.6	400	$ 7,582	$ 146
50000	110	152	2.43	3.6	400	$ 12,637	$ 243
10000	90	254	3.11	3.6	30	$ 501	$ 10
30000	90	254	3.11	3.6	30	$ 1,503	$ 29
50000	90	254	3.11	3.6	30	$ 2,504	$ 48
10000	110	254	3.58	3.6	30	$ 1,024	$ 20
30000	110	254	3.58	3.6	30	$ 3,072	$ 59
50000	110	254	3.58	3.6	30	$ 5,119	$ 98
10000	90	254	3.11	3.6	400	$ 4,874	$ 94
30000	90	254	3.11	3.6	400	$ 14,201	$ 273
50000	90	254	3.11	3.6	400	$ 23,669	$ 455
10000	110	254	3.58	3.6	400	$ 9,326	$ 179
30000	110	254	3.58	3.6	400	$ 27,978	$ 538
50000	110	254	3.58	3.6	400	$ 46,630	$ 897

Table A.8. Drop-Off Mitigated with 3:1 Sloped Earth Wedge, Six-Lane Divided Highway

ADT	Speed (km/hr)	Depth (mm)	SI	X (m)	Length (m)	Cost of Crashes/yr	Cost of Crashes/wk	Cost of Wedge	Unprotected Cost of Crashes/wk	Positive Benefit Cost (weeks)
10000	90	152	1.7	0	30	$ 160	$ 3	$ 14	$ 4	13
30000	90	152	1.7	0	30	$ 480	$ 9	$ 14	$ 12	4
50000	90	152	1.7	0	30	$ 800	$ 15	$ 14	$ 21	3
10000	110	152	2.3	0	30	$ 451	$ 9	$ 14	$ 11	7
30000	110	152	2.3	0	30	$ 1,354	$ 26	$ 14	$ 32	2
50000	110	152	2.3	0	30	$ 2,257	$ 43	$ 14	$ 54	1
10000	90	152	1.7	0	400	$ 1,569	$ 30	$ 182	$ 40	18
30000	90	152	1.7	0	400	$ 4,708	$ 91	$ 182	$ 121	6
50000	90	152	1.7	0	400	$ 7,846	$ 151	$ 182	$ 202	4
10000	110	152	2.3	0	400	$ 4,211	$ 81	$ 182	$ 100	9
30000	110	152	2.3	0	400	$ 12,634	$ 243	$ 182	$ 301	3
50000	110	152	2.3	0	400	$ 21,057	$ 405	$ 182	$ 502	2
10000	90	254	2.32	0	30	$ 443	$ 9	$ 38	$ 22	3
30000	90	254	2.32	0	30	$ 1,328	$ 26	$ 38	$ 67	1
50000	90	254	2.32	0	30	$ 2,214	$ 43	$ 38	$ 112	1
10000	110	254	2.79	0	30	$ 859	$ 17	$ 38	$ 40	2
30000	110	254	2.79	0	30	$ 2,479	$ 48	$ 38	$ 119	1
50000	110	254	2.79	0	30	$ 4,297	$ 83	$ 38	$ 199	0
10000	90	254	2.32	0	400	$ 4,342	$ 84	$ 504	$ 219	4
30000	90	254	2.32	0	400	$ 13,025	$ 250	$ 504	$ 658	1
50000	90	254	2.32	0	400	$ 21,708	$ 417	$ 504	$ 1,097	1
10000	110	254	2.79	0	400	$ 8,019	$ 154	$ 504	$ 371	2
30000	110	254	2.79	0	400	$ 24,057	$ 463	$ 504	$ 1,112	1
50000	110	254	2.79	0	400	$ 40,094	$ 771	$ 504	$ 1,853	0
10000	90	152	1.7	3.6	30	$ 69	$ 1	$ 14	$ 2	31
30000	90	152	1.7	3.6	30	$ 207	$ 4	$ 14	$ 5	10
50000	90	152	1.7	3.6	30	$ 344	$ 7	$ 14	$ 9	6
10000	110	152	2.3	3.6	30	$ 224	$ 4	$ 14	$ 5	14
30000	110	152	2.3	3.6	30	$ 671	$ 13	$ 14	$ 16	5
50000	110	152	2.3	3.6	30	$ 1,119	$ 22	$ 14	$ 27	3
10000	90	152	1.7	3.6	400	$ 651	$ 13	$ 182	$ 17	43
30000	90	152	1.7	3.6	400	$ 1,953	$ 38	$ 182	$ 50	14
50000	90	152	1.7	3.6	400	$ 3,256	$ 63	$ 182	$ 84	9
10000	110	152	2.3	3.6	400	$ 2,038	$ 39	$ 182	$ 49	19
30000	110	152	2.3	3.6	400	$ 6,115	$ 118	$ 182	$ 146	6
50000	110	152	2.3	3.6	400	$ 10,192	$ 196	$ 182	$ 243	4
10000	90	254	2.32	3.6	30	$ 191	$ 4	$ 38	$ 10	6
30000	90	254	2.32	3.6	30	$ 572	$ 11	$ 38	$ 29	2
50000	90	254	2.32	3.6	30	$ 953	$ 18	$ 38	$ 48	1
10000	110	254	2.79	3.6	30	$ 426	$ 8	$ 38	$ 20	3
30000	110	254	2.79	3.6	30	$ 1,278	$ 25	$ 38	$ 59	1
50000	110	254	2.79	3.6	30	$ 2,131	$ 41	$ 38	$ 98	1
10000	90	254	2.32	3.6	400	$ 1,802	$ 35	$ 504	$ 94	9
30000	90	254	2.32	3.6	400	$ 5,405	$ 104	$ 504	$ 273	3
50000	90	254	2.32	3.6	400	$ 9,008	$ 173	$ 504	$ 455	2
10000	110	254	2.79	3.6	400	$ 3,881	$ 75	$ 504	$ 179	5
30000	110	254	2.79	3.6	400	$ 11,644	$ 224	$ 504	$ 538	2
50000	110	254	2.79	3.6	400	$ 19,406	$ 373	$ 504	$ 897	1

Table A.9. Drop-Off Shielded by Temporary Barrier Rail, Six-Lane Divided Highway

ADT	Speed (km/hr)	Depth (mm)	SI	X (m)	Length (m)	Cost of Crashes/yr	Cost of Crashes/wk	Cost of Barrier Rail	Unprotected Cost of Crashes/wk	Positive Benefit Cost (weeks)
10000	90	152	2.5	0	30	$ 585	$ 11	$ 700	$ 4	n/a
30000	90	152	2.5	0	30	$ 1,754	$ 34	$ 700	$ 12	n/a
50000	90	152	2.5	0	30	$ 2,923	$ 56	$ 700	$ 21	n/a
10000	110	152	3	0	30	$ 1,034	$ 20	$ 700	$ 11	n/a
30000	110	152	3	0	30	$ 3,103	$ 60	$ 700	$ 32	n/a
50000	110	152	3	0	30	$ 5,171	$ 99	$ 700	$ 54	n/a
10000	90	152	2.5	0	400	$ 5,732	$ 110	$ 9,328	$ 40	n/a
30000	90	152	2.5	0	400	$ 17,197	$ 331	$ 9,328	$ 121	n/a
50000	90	152	2.5	0	400	$ 28,661	$ 551	$ 9,328	$ 202	n/a
10000	110	152	3	0	400	$ 9,651	$ 186	$ 9,328	$ 100	n/a
30000	110	152	3	0	400	$ 28,952	$ 557	$ 9,328	$ 301	n/a
50000	110	152	3	0	400	$ 48,253	$ 928	$ 9,328	$ 502	n/a
10000	90	254	2.5	0	30	$ 585	$ 11	$ 700	$ 22	63
30000	90	254	2.5	0	30	$ 1,754	$ 34	$ 700	$ 67	21
50000	90	254	2.5	0	30	$ 2,923	$ 56	$ 700	$ 112	13
10000	110	254	3	0	30	$ 1,034	$ 20	$ 700	$ 40	35
30000	110	254	3	0	30	$ 3,103	$ 60	$ 700	$ 119	12
50000	110	254	3	0	30	$ 5,171	$ 99	$ 700	$ 199	7
10000	90	254	2.5	0	400	$ 5,732	$ 110	$ 9,328	$ 219	85
30000	90	254	2.5	0	400	$ 17,197	$ 331	$ 9,328	$ 658	28
50000	90	254	2.5	0	400	$ 28,661	$ 551	$ 9,328	$ 1,097	17
10000	110	254	3	0	400	$ 9,651	$ 186	$ 9,328	$ 371	50
30000	110	254	3	0	400	$ 28,952	$ 557	$ 9,328	$ 1,112	17
50000	110	254	3	0	400	$ 48,253	$ 928	$ 9,328	$ 1,853	10
10000	90	152	2.5	3.6	30	$ 252	$ 5	$ 700	$ 2	n/a
30000	90	152	2.5	3.6	30	$ 726	$ 14	$ 700	$ 5	n/a
50000	90	152	2.5	3.6	30	$ 1,258	$ 24	$ 700	$ 9	n/a
10000	110	152	3	3.6	30	$ 513	$ 10	$ 700	$ 5	n/a
30000	110	152	3	3.6	30	$ 1,538	$ 30	$ 700	$ 16	n/a
50000	110	152	3	3.6	30	$ 2,564	$ 49	$ 700	$ 27	n/a
10000	90	152	2.5	3.6	400	$ 2,379	$ 46	$ 9,328	$ 17	n/a
30000	90	152	2.5	3.6	400	$ 7,136	$ 137	$ 9,328	$ 50	n/a
50000	90	152	2.5	3.6	400	$ 11,893	$ 229	$ 9,328	$ 84	n/a
10000	110	152	3	3.6	400	$ 4,671	$ 90	$ 9,328	$ 49	n/a
30000	110	152	3	3.6	400	$ 14,013	$ 269	$ 9,328	$ 146	n/a
50000	110	152	3	3.6	400	$ 23,355	$ 449	$ 9,328	$ 243	n/a
10000	90	254	2.5	3.6	30	$ 252	$ 5	$ 700	$ 10	146
30000	90	254	2.5	3.6	30	$ 755	$ 15	$ 700	$ 29	49
50000	90	254	2.5	3.6	30	$ 1,258	$ 24	$ 700	$ 48	29
10000	110	254	3	3.6	30	$ 513	$ 10	$ 700	$ 20	71
30000	110	254	3	3.6	30	$ 1,538	$ 30	$ 700	$ 59	24
50000	110	254	3	3.6	30	$ 2,564	$ 49	$ 700	$ 98	14
10000	90	254	2.5	3.6	400	$ 2,379	$ 46	$ 9,328	$ 94	194
30000	90	254	2.5	3.6	400	$ 7,136	$ 137	$ 9,328	$ 273	69
50000	90	254	2.5	3.6	400	$ 11,893	$ 229	$ 9,328	$ 455	41
10000	110	254	3	3.6	400	$ 4,671	$ 90	$ 9,328	$ 179	104
30000	110	254	3	3.6	400	$ 14,013	$ 269	$ 9,328	$ 538	35
50000	110	254	3	3.6	400	$ 23,355	$ 449	$ 9,328	$ 897	21