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Studies to Develop Guidelines for Work Zone Barrier Use on Freeways

Technical Report 0-7020-R1

Cooperative Research Program

TEXAS A&M TRANSPORTATION INSTITUTE
COLLEGE STATION, TEXAS

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Texas Department of Transportation
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16. Abstract

This report describes research efforts to:

- Investigate the issues affecting temporary barrier deployment in work zones with constrained cross sections.
- Identify and evaluate available options to potentially address those issues.
- Develop improved guidelines regarding barrier deployment on Texas freeways.

Efforts included:

- A review of literature relevant to the deployment and use of barriers in work zones and Texas work zone crashes to better understand any direct or indirect influence of barrier presence.
- Surveys of key stakeholders to identify the state of the practice in barrier use and road user perceived difficulties in traveling through various types of work zones with barriers.
- Field evaluations of multiple barrier deployments on freeway work zones in constrained cross sections to identify deployment issues.
- Development of analytical approaches to help guide work zone designers and other project staff when making work zone barrier deployment decisions.

A stand-alone set of recommended guidelines was prepared and is included as the appendix to the report.

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DISCLAIMER

This research was performed in cooperation with the Texas Department of Transportation (TxDOT) and the Federal Highway Administration (FHWA). The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of FHWA or TxDOT. This report does not constitute a standard, specification, or regulation.

This report is not intended for construction, bidding, or permit purposes. The engineer in charge of the project was Gerald Ullman, P.E. #66876.

The United States Government and the State of Texas do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

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CHAPTER 1: INTRODUCTION

STATEMENT OF THE PROBLEM

Longitudinal continuous barriers are often used in long-term work zones on Texas freeways to separate opposing traffic flows, protect workers from traffic, and protect traffic from hazards within the work space (e.g., pavement edge drop-offs, construction equipment, and materials/debris). Often, the barrier must be placed very near or at the edge of the travel lanes, eliminating emergency shoulders on one or both sides of the travel lanes. This condition may exist for long stretches of the freeway. Lane shifts may also be installed and moved periodically as the project moves through the various phases of construction.

The constrained cross section through these freeway work zones can create challenges for various users of the facility. For example, drivers of large trucks often mention increased difficulties in maintaining lane positioning when operating immediately adjacent to barriers through a work zone. The lack of emergency shoulders means that drivers of vehicles who become disabled must try to continue until reaching an exit ramp where they can pull off the freeway. If they are not able to reach the exit, they become disabled in a travel lane, creating a bottleneck with potentially significant operational and safety risks. Law enforcement efforts are likewise hampered by a lack of shoulders since there are no longer places available to pull drivers over to issue citations.

Barrier deployment close to the travel lanes can also create other issues. Instances of rainwater ponding in travel lanes where a barrier has hampered drainage have been noted. Instances of impacts with an unanchored barrier deflecting into opposing travel lanes and causing operational issues have also been reported. Improved guidance is needed on how to best deploy barriers in freeway work zones when the cross section is constrained. This report documents the efforts and results of research performed to develop this guidance.

PROJECT OBJECTIVES

The objectives of the project were as follows:

- Develop an improved understanding of the issues affecting barrier deployment in work zones with constrained cross sections.
- Identify and evaluate available options to potentially address those issues.
- Develop improved guidelines regarding barrier deployment on Texas freeways.

The following tasks were performed to meet these objectives:

- Performed a review of literature relevant to the deployment and use of barriers in work zones.
- Analyzed a sample of Texas work zone crashes to better understand any direct or indirect influence of barrier presence, focusing on crashes associated with large trucks or emergency responders.

- Surveyed key construction personnel to identify the state of the practice in barrier use and other design criteria for freeway work zones.
- Surveyed trucking industry and law enforcement representatives to identify road users' perceived difficulties in traveling through various types of work zones with barriers.
- Conducted field evaluations of multiple barrier deployments on freeway work zones in constrained cross sections to identify deployment issues that exist.
- Identified and demonstrated analytical approaches to developing guidance pertaining to key work zone barrier deployment decisions.
- Developed a set of guidelines for work zone barrier use.

REPORT ORGANIZATION

Chapter 1 contains the introduction to this report. Chapter 2 summarizes the results of the literature review and work zone crash analysis. Chapter 3 documents the results of surveys of key stakeholders, whereas chapter 4 describes the findings of the field evaluations. The guidelines developed from these research activities are described in chapter 5. Finally, chapter 6 presents a summary of the critical findings from the project. The appendix presents a set of recommended guidelines.

CHAPTER 2:
REVIEW OF THE LITERATURE AND ANALYSIS OF TEXAS WORK ZONE CRASHES

LITERATURE REVIEW

The use of barriers to provide positive protection in work zones is based on the concept that barriers be used where the costs of providing the barrier plus the costs of crashes that occur with the barrier are less than the costs of crashes that would occur if the barrier was not used. Drop-offs, work equipment and materials, the proximity of workers and work areas to traffic traveling through the work zone, the volume and speed of that traffic, and its composition all influence this trade-off analysis. These safety-related factors interact with how the construction activities themselves will be accomplished because those activities will define where and how much space is required and thus how close barriers, if used, will have to be placed to the actual travel lanes.

Evaluation Techniques

Essentially, all research-based efforts to examine work zone positive protection needs over the years have been based on an encroachment-based hazard analysis methodology developed to evaluate roadside safety hardware needs. The basic premise of this type of analysis is a series of conditional probabilities of a vehicle leaving the travel way and striking an object. In a work zone context, the object can be a pavement edge drop-off, structural components under construction (e.g., culvert, abutment, and bridge pillar), or workers and work vehicles/equipment/materials. The goal is to reduce the severity of work zone crashes by shielding those objects with barriers. The assumption is that impacts with the barrier will be less severe than impacts with the other objects (including workers). Therefore, the encroachment-based hazard analysis requires a number of predictions, including but not limited to:

- The expected frequency of or probability that vehicles unintentionally leave the roadway (i.e., a roadside encroachment).
- The probability that, given a vehicle has left the roadway, it will travel out laterally to the distance at which an object (e.g., drop-off, equipment or vehicles, workers, or barrier) is located and that its path intersects those objects.
- The expected severity of the crash, given that a vehicle has left the roadway and struck the object or objects.

Guidance regarding the use of positive protection in work zones for pavement drop-off conditions can be traced to research performed at the Texas A&M Transportation Institute and elsewhere in the mid-1980s (*1*, *2*). The analysis used a hazard encroachment methodology for estimating the frequency of vehicles reaching the pavement drop-off some distance away from the travel lanes and then considered the expected crash severities of vehicles running into drop-offs of various heights and edge designs. Vehicle overturning and snagging on the edge of the drop-off were the primary drivers of the crash severity estimation; loss-of-control outcomes that ultimately could lead to head-on or sideswipe collisions with other vehicles remaining on the traveled way were not considered. The current Texas Department of Transportation (TxDOT) policy on the use of positive barriers to protect work zone drop-offs is documented in the agency's *Roadway Design Manual* (*3*) and includes the decision-making plot (shown in Figure 1) resulting from that analysis, which is also found in the *Roadside Design Guide* (*4*). Traffic exposure is the multiplication of:

- The portion of roadway annual average daily traffic (AADT) traveling within 20 feet of an edge drop-off greater than 2 feet.
- The duration in years that the drop-off condition will exist.

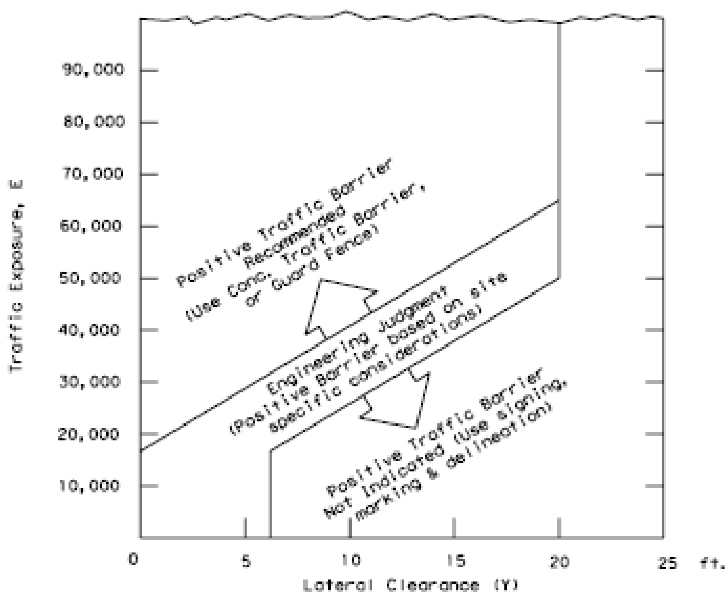


Figure 1. TxDOT Guidance for Selection of Positive Protection in Work Zones (*3*).

Beyond pavement edge drop-off concerns, one of the earliest efforts to characterize the risks and costs of worker and equipment impacts in work zones used a linear relationship between crash severity and encroaching vehicle speed (see Figure 2) (*5*). Past efforts to include worker and equipment considerations have involved placing both in various assumed locations within a work zone of a given design and performing an encroachment-based analysis to assess the expected crash costs associated with them. The expected crash costs of an intruding vehicle at a given speed were then compared to the costs of providing positive protection. Depending on how the work zone was laid out, different results were achieved. Although the documentation of these efforts is somewhat unclear, it appears that the worker and equipment were assumed to be fixed and remain present for the entire duration of the analysis. Obviously, such assumptions are highly conservative because workers are present only when work activity is occurring. Likewise, although work equipment may be present during periods of work inactivity at the site, such equipment is often moved and parked as far away from the traveled way as possible, if not protected by a barrier. Similarly, the number of workers and work areas as well as the number of vehicles or equipment present will differ dramatically from work zone to work zone.

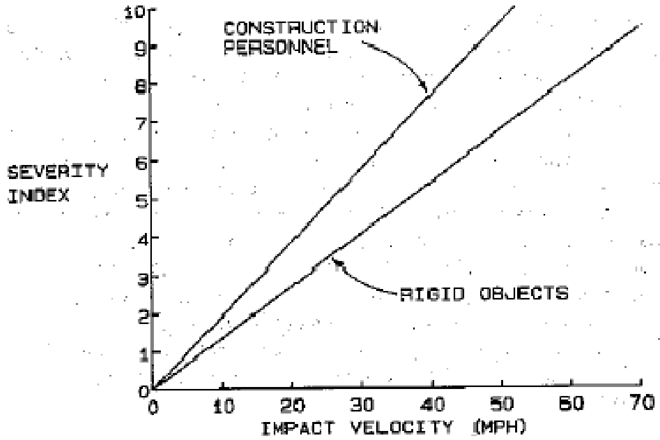


Figure 2. Relationship between Speed and Crash Severity Index Assumed for Workers and Construction Equipment (*5*).

There have been efforts over the years to computerize the roadside hazard analysis methodology, such as the BARRIER VII computer program first developed in the 1970s (*6*). As computer technology evolved, efforts to develop a microcomputer analysis tool eventually resulted in the development of the Roadside Safety Analysis Program (RSAP) (*7*). RSAP uses both probabilistic and deterministic methods to estimate the expected frequency and severity of roadside crashes involving hazards versus removing, relocating, redesigning, or shielding the hazards with barriers.

To date, there have been three attempts to used RSAP to analyze positive protection benefits and costs for work zone scenarios. In the first effort, researchers used RSAP to evaluate a series of typical work zone situations where positive protection would commonly be considered (*8*, *9*):

- Outside lane and shoulder closure for part-width construction on a four-lane divided highway.
- Outside shoulder closure on a four-lane divided highway with minor encroachment.
- Median shoulder closure on a four-lane divided highway with minor encroachment.
- Bridge reconstruction with a temporary diversion/runaround on a two-lane, two-way highway.

Researchers created drop-offs, vehicle/equipment, and worker area hazards for each scenario, and evaluated the differences in crash costs of using channelizing devices versus barriers to protect those hazards (see Figure 3). Crashes involving workers were modeled as always resulting in fatalities (i.e., severity index of 10), and impacts with equipment and vehicles were modeled using severity indices for rigid objects that resulted in fatal, incapacitating, and possible incapacitating crashes. Plots of benefit-cost (B/C) ratios were then created for various operating speed and traffic exposure conditions (traffic volumes multiplied by the duration of the work zone). For the four conditions listed previously, the plots were fairly consistent. Assuming a six-month work zone on a 60-mph divided facility, the researchers estimated positive protection could be justified once traffic demands reached 10,000 to 15,000 vehicles per day (vpd). Lower speeds and volumes would require longer-duration work zones to achieve similar positive B/C ratios, whereas shorter-duration work zones could justify barrier use if operating speeds and traffic volumes were higher.

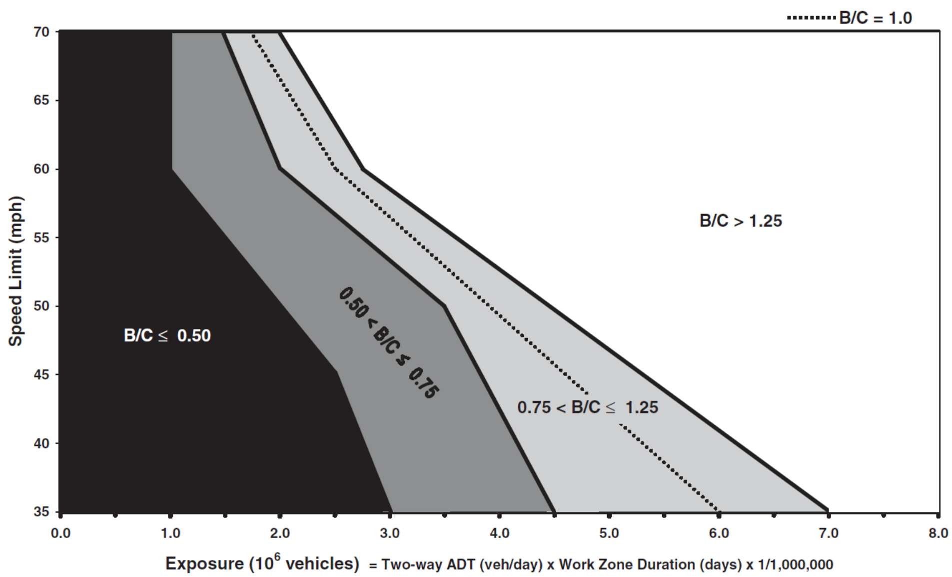


Figure 3. Analysis Results of a Typical Freeway Part-Width Construction Lane Closure Scenario (*8*).

In another attempt to use RSAP for work zone positive protection analysis, researchers modeled the entire area behind the barrier as a single hazard and calibrated the severity index of an impact with that hazard area based on intrusion crash data. This effort focused on non-pavement drop-off hazards (i.e., risks of impact with workers, equipment, or materials within the work space) (*10*). The researchers used F-type portable concrete barrier (PCB) installation and removal costs from recent TxDOT projects in the analysis. In addition, comprehensive crash costs were updated with the values published by the Federal Highway Administration (FHWA) at the time. The encroachment rate was increased by 40 percent based on the researchers' judgment considering that overall crash rates tend to increase in work zones compared to non-work zone conditions at the same location.

Table 1 summarizes the results of that research project. For multilane freeway facilities with 70-mph operating speeds and work zones adjacent to travel lanes, intrusion crash costs savings alone appeared to justify PCB protection once the roadway AADT approaches 40,000 vpd over a year-long work zone, so long as there are constant hazards in the work space being protected by barriers. Similarly, if travel speeds were lower (i.e., 50 mph), PCB use for reducing intrusion crash cost potential alone did not appear to be justifiable at any AADT levels. Any lateral buffer space that is provided between the work area and traffic moving through the work zone dramatically reduced the cost-effectiveness of PCB use strictly for intrusion crash protection.

Table 1. Minimum AADT Required to Justify Use of PCB for Intrusion Crash Protection (*10*).

Facility	Operating Speed (mph)	Work Zone Offset (ft)	Minimum AADT (vpd)[1]
Multilane	70	0	40,000
		12	60,000
		20	75,000
Multilane	50	Any	None
Two lane	70 or 50	Any	None

[1] Assumes a one-year work zone.

As part of a third effort to use RSAP to evaluate positive protection benefits and costs, researchers developed a spreadsheet tool for the Idaho Transportation Department that allowed consideration of these temporal adjustments to risks, both alone and in conjunction with other typical roadside hazards in the work zone (e.g., pavement edge drop-offs) (*11*). At the time that this effort was initiated, the third version of RSAP had been released (RSAPv3). Researchers used more recent FHWA values for crash costs, based on the value of statistical life (VSL) model published in 2014 (*12*). In this effort, sensitivity analyses with low and medium VSL ($5.2 million and $9.1 million, respectively) were also conducted to assess VSL assumptions on the B/C. The results showed positive benefits in protecting drop-offs and work areas at higher volumes and when they are present closer to the travel lanes at lower volumes. In all cases, the analysis represents a work zone condition where work activity is occurring at all times through the entire work area. In the guidelines that were subsequently developed based on this analysis, researchers used a series of exposure adjustment factors to account for periods in which work is not occurring and/or only a portion of the area being considered for positive protection has work activity occurring.

Researchers next fitted non-linear regression curves to the data to adjust the shapes of the crash cost reductions versus AADT curves and develop the spreadsheet tool and implementation guidance. Equivalent AADT and exposure times in weeks that would result in a positive benefit from barrier use were calculated using these regression curves. The B/C ratio obtained from the regression curves for an equivalent AADT was divided by 52 to obtain the equivalent exposure in weeks that would result in a positive benefit from barrier use for when only work activities are of concern (shown in Figure 4). The regression curves for the no-drop-off condition (i.e., work space intrusion costs) and the drop-off condition were similar enough and justified using the same curves for both (for an equivalent AADT and exposure time). Thus, the guidance is based around estimating equivalent exposures for the work space intrusion costs and for any drop-off exposure costs.

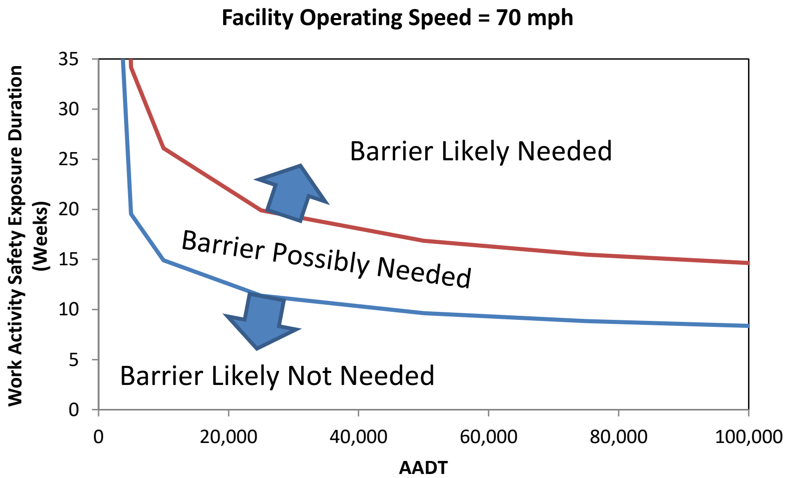


Figure 4. Barrier Use Guidance Based on Equivalent AADT and Exposure Time When Only Work Activity Hazards Are of Concern (*11*).

Issues Pertaining to Large Trucks

An analysis brief by the Federal Motor Carrier Safety Administration documents several important points regarding large trucks in work zones (*13*):

- Large-truck fatal crashes in work zones are more likely to involve three or more vehicles as opposed to large-truck crashes outside work zones.
- Large-truck involvement in work zone fatal crashes is more likely than in fatal crashes in general.
- The majority of large-truck fatal crashes in work zones involve large trucks that are in transport, and most involve rear-end collisions.

Several characteristics of large trucks can pose challenges to accommodating work zones. Table 2 summarizes the characteristics and corresponding implications on work zone designs (*14*). Consequently, several work zone design strategies to accommodate large trucks have been suggested for work zones on high-speed multilane roadways:

- When narrower lane widths are needed during construction, consider maintaining one 12-foot lane that trucks can use, and take the lane width reduction from the other lanes that automobiles would still be able to use.
- Minimize capacity reductions (even for short durations) that will create unexpected queues.
- If queues are unavoidable, position lane closures so that the upstream end of queues that are expected are not located in areas of limited sight distance, or use queue warning systems to provide advance notification of stopped or slow traffic to drivers upstream, or use enforcement or maintenance/courtesy patrol vehicles (with lights activated) that try to maintain a position 1/4 mile upstream of the queue.
- Avoid starting lane closures over hill crests, on or just past horizontal curves, or where bridges or other features limit sight distance to the closure.

- Consider closing entrance ramps if sufficient acceleration lane lengths cannot be maintained during construction or if work-zone-induced congestion prevents smooth merging at a design speed.
- Specify work zone access points be designed to minimize speed differentials between delivery trucks and main line traffic.
- Develop work-zone-specific response plans if a work zone is located on the current hazmat route.
- Use speed display trailers to gain motorists' attention when approaching and traveling through a work zone.

Table 2. Large-Truck Characteristics Relative to Other Vehicles.

Characteristics		Implications to Work Zone Designs
Physical	Longer and wider	Less lateral clearance and recovery area
	Heavier	More kinetic energy to dissipate, increasing crash severity
	Higher center of gravity	Pavement cross-slope changes, crossovers, and significant lane shifts increase chance for losing vehicle control (especially for liquid loads)
Operational	Larger blind spots	More difficult to merge out of a closed lane or see an automobile attempting to merge into the open lane
	Lower acceleration and deceleration rates	Increased frustration of drivers of personal vehicles following large trucks; more challenging for drivers of large trucks to stop in time
	Greater distance between driver eye and vehicle headlights	Reduced brightness of retroreflective signs or visibility of vehicles ahead at night

The efficacy of these suggested strategies in reducing large-truck-involved work zone crashes has not been verified through independent research.

Research in Virginia found that the proportion of injury and fatal crashes was substantially larger among heavy-vehicle-involved crashes than among crashes involving passenger vehicles only (*15*). Similarly, research using Highway Safety Information System data from Minnesota examined large-truck crash severity in work zones and found that crashes occurring when workers were present tended to have higher likelihoods of severe injuries although that did not necessarily mean that workers were directly involved in the crash (*16*). Furthermore, lane closures were less likely to result in injury and serious injury crashes than other types of work zones (e.g., shoulder closures, lane shifts, and intermittent/moving closures), and crashes occurring in the work zone transition area were less likely to result in injury or serious injury. Meanwhile, researchers in Kansas examined several years of work zone crashes and found that a large percent of fatal work zone crashes involved heavy trucks, and complicated work zone geometry was also found to be associated with greater fatality likelihood (*17*, *18*). Although there is a consistently demonstrated correlation between heavy trucks and increased crash severity, research from New Mexico has shown that the during-work-zone frequency of large-truck crashes is not different at a statistically significant level from pre-work-zone conditions (*19*).

One shortcoming of much of the extant research regarding heavy-truck crashes in work zones is the lack of available information regarding work zone configuration (*20*). Murray was able to determine that the area immediately adjacent to construction activity is where most truck-involved work zone crashes occur, which is consistent with the trend for all vehicle crashes in work zones. Also, sign spacing requirements are based on the ability of passenger vehicles to stop and do not consider the greater stopping distance requirements for heavy trucks.

Finally, researchers in North Carolina were able to develop a data set of truck-involved multivehicle crashes indicating whether a barrier was present in the median of a work zone (*21*). The researchers examined truck-involved work zone crashes through the lenses of injury severity and total harm (i.e., crash cost) and developed statistical models demonstrating that crashes on two-way, divided roads with median barriers were typically lower in severity than crashes on one-way and two-way roads without barriers. However, the study did not specify whether the barrier was permanent or present as part of the work zone traffic control plan. Additionally, the researchers found that crashes were more severe when they occurred in the area adjacent to the construction activity.

Issues Pertaining to Law Enforcement

The presence of law enforcement in and around work zones is common, specifically to help control speed (*22*). Studies consistently demonstrate the effectiveness of law enforcement as a speed control measure at work zones in comparison to other techniques (*23*). A common work zone location for law enforcement deployment is at or before the beginning of a lane closure, and a circulating patrol is generally thought of as not any more effective than a stationary patrol (*22*). When barriers are present and emergency shoulders are removed, enforcement within the work zone is difficult since there is no place to pull traffic violators over to safely issue a citation. For this and other reasons, a fairly large amount of research has been devoted to assessing the feasibility and effectiveness of automated/camera enforcement in work zones (*24*, *25*, *26*).

One alternative to restricting enforcement to stationary positions or to using automated enforcement is to provide law enforcement refuge areas throughout the work zone. Past research has been performed to determine the appropriate design recommendations for enforcement pullout/refuge areas (*27*, *28*). Through a review of the American Association of State Highway and Transportation Officials *Green Book* geometric design standards and examination of the driving behavior of passenger vehicle drivers who accelerate and merge into traffic after a traffic stop in a non-work zone location, the researchers determined that a 0.25-mile-long enforcement refuge area would be sufficient for a highway work zone with a speed limit of 60 mph. The spacing for the enforcement refuge areas, evaluated through surveying both law enforcement and construction contractors, was recommended to be between 2 and 3 miles. Figure 5 illustrates the difficulty ratings from contractors and the usefulness ratings from law enforcement personnel based on the spacing between refuge areas. These results were eventually incorporated into work zone design guidance on high-speed roadways (see Figure 6) (*9*). Such an area could also serve as an emergency refuge area for disabled vehicles and can be coordinated with access points that include acceleration lanes for construction vehicles leaving the work space.

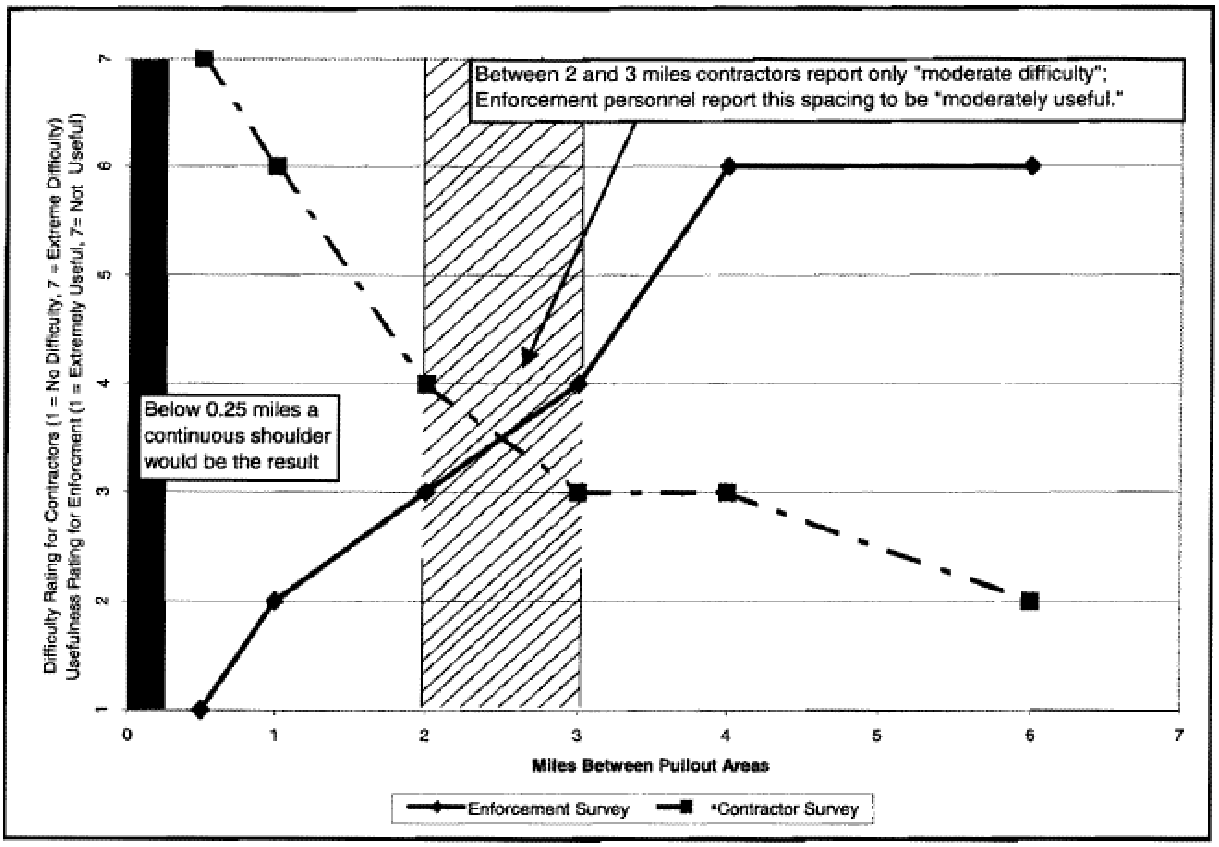


Figure 5. Comparison of Responses from Contractor and Law Enforcement on the Difficulty and Usefulness of Refuge Areas Based on Their Spacing (*27, 28*).

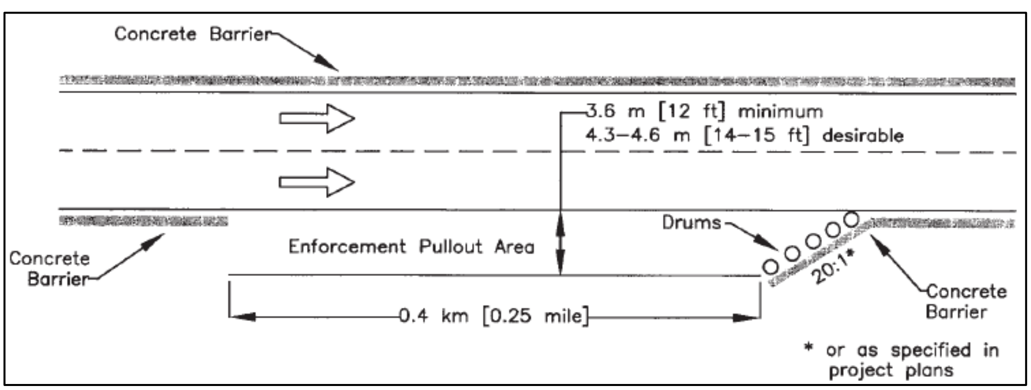


Figure 6. Example of a Work Zone Enforcement Area Design (*9*).

Emergency Turnout Areas

The use of barriers in work zones is often synonymous with lack of available shoulder space. Consequently, there is little room available for motorists to pull over in a work zone to address vehicular issues, such as changing a flat tire. On high-speed facilities, this blockage can result in severe crashes. A case study review of a sample of fatal work zone crashes included one that was attributed to such a scenario (*29*). A vehicle stalled in a traffic lane, resulting in a queue behind the stalled vehicle. A large truck did not perceive the queue in time and struck a vehicle at the rear of the queue, resulting in fatalities. It was hypothesized that the availability of an enforcement pullout area at the spacing described by Ullman and Schrock (*27*) might have prevented such a crash from happening.

Emergency Vehicle Mobility

The timing of construction activity and the weather have been found to affect emergency vehicle response time in work zones, in terms of both total time and variability. Researchers in China used the Fatality Analysis Report System (FARS) database provided by the National Highway Traffic Safety Administration to investigate the relationship between recorded crash time and emergency medical services (EMS) arrival time (*30*). The researchers found that crashes occurring on weekdays, holidays, under poor light conditions, at night, and in adverse weather typically had longer response times, while holiday crashes also experienced more variability in response time. However, the influence of barrier presence and temporary removal of shoulders could not be examined due to a lack of exposure data about those conditions within FARS.

Pooling Water

In addition to mobility concerns regarding law enforcement and emergency personnel, the presence of barriers has the potential to trap water in pools on the roadway surface (*31*). In extreme cases, such as those observed during recent hurricanes in Texas and Louisiana, permanent median barriers have the potential to act as a dam and encourage flooding, while portable median barriers can be damaged or destroyed and require repair before roads can be re-opened. Recently published guidance recommends that barriers with greater hydraulic capacity be used in work zones, that any available shoulder be used to create a temporary water storage area, or that supplemental drainage systems be implemented (*31*). The document further suggests that *Manual on Uniform Traffic Control Devices* (MUTCD)-compliant signage be considered in areas prone to flooding.

Other Factors Agencies Use to Make Barrier Use Decisions

Federal regulations encourage agencies to consider the use of positive protection in work zones (*32*). Most agencies mimic the language in the regulations, listing factors they consider in the decision-making process:

- Project scope and duration.
- Anticipated traffic speeds through the work zone.
- Anticipated traffic volume.
- Vehicle mix.

- Type of work (as related to worker exposure and crash risks).
- Distance between traffic and workers and extent of worker exposure.
- Escape paths available for workers to avoid a vehicle that has intruded into the work space.
- Time of day (e.g., night work).
- Work area restrictions (including impact on worker exposure).
- Consequences of roadway departures on road users and workers.
- Potential hazards to workers and road users presented by the positive protection device itself, including during device placement and removal.
- Geometrics that may increase crash risks (e.g., limited sight distance and large degrees of horizontal curvature).
- Access to/from the work space.
- Roadway classification.
- Impacts of positive protection on project cost and duration.

Even though these factors aid in the decision of whether to use positive protection, they do not provide guidance about the minimum lateral offsets to travel lanes or other design features that influence the overall operational and safety efficiency of the work zone.

TEXAS FREEWAY WORK ZONE CRASH CHARACTERISTICS

As part of this task, the researchers obtained crash data from several recent and ongoing freeway work zones in Texas. Furthermore, the researchers singled out large-truck and emergency responder crashes to examine the crash characteristics and contribution factors. To select work zone projects, the researchers focused on the functional class (freeway), type of work, duration, and presence of longitudinal concrete barrier. The work zones selected included a series of reconstruction projects along Interstate 35, which widened the roadway from four to six lanes. The projects occurred near the cities of Salado, Troy, Bruceville-Eddy, Lorena, Waco, and West. The researchers selected a project on Interstate 635, near Dallas, pertaining to the improvement of guardrail to design standards and installation of crash cushions; and a project on Interstate 10 near San Antonio, which consisted of grading, structures, surfacing, and signing. Table 3 summarizes these projects and the crashes that occurred during these projects and on these interstate project limits.

Table 3. List of Selected Construction Projects and Associated Crashes.

City	Interstate	Start Date	End Date	Duration (Months)	Length (Miles)	Crashes
Salado	I-35	1/5/2012	7/16/2015	42.9	2.36	165
Troy	I-35	3/12/2012	11/28/2014	33.0	6.35	235
Bruceville-Eddy	I-35	6/25/2012	2/11/2016	44.2	11.09	837
Lorena	I-35	3/5/2012	5/8/2015	38.6	5.97	496
Waco	I-35	10/22/2010	12/8/2013	38.1	13.01	904
West	I-35	10/17/2011	10/19/2014	36.6	6.75	470
San Antonio	I-10	5/1/2018	5/1/2019	12.2	9.50	759
Dallas	I-635	11/27/2017	12/20/2018	12.9	8.00	695

As Table 3 shows, the projects that were selected for the crash data investigation varied in length and duration. However, the majority were over 5 miles long and were in place for over one year. Altogether, 4561 crashes occurred within the boundaries of the construction projects during the work zones' duration.

The researchers examined the crash severity for each construction project crash, and the results show that each work zone was associated with a few fatal crashes on average (see Table 4), despite differences in duration and length. The researchers compared the percentage of crashes by severity for each of the work zones. As Figure 7 shows, the fatal crash percentage was similar across the various projects. However, differences were observed for injury and property damage only (PDO) crashes. The typical range of injury crash percentage was between 14 and 25 percent for the projects on Interstate 35. However, more injuries were associated with the construction project on Interstate 10 (32 percent) and the construction project on Interstate 635 (43 percent).

Table 4. Severity of Work Zone Crashes for Each Construction Project.

City	Interstate	Crashes	Fatal Crashes	Injury Crashes	PDO Crashes	Fatalities	Injuries
Salado	I-35	165	2	24	138	2	38
Troy	I-35	235	2	63	169	2	120
Bruceville-Eddy	I-35	837	4	204	623	4	378
Lorena	I-35	496	3	133	356	3	232
Waco	I-35	904	4	242	653	4	411
West	I-35	470	4	105	361	4	169
San Antonio	I-10	759	2	244	499	2	356
Dallas	I-635	695	3	299	380	3	472
Total		**4,561**	**24**	**1,314**	**3,179**	**24**	**2,176**

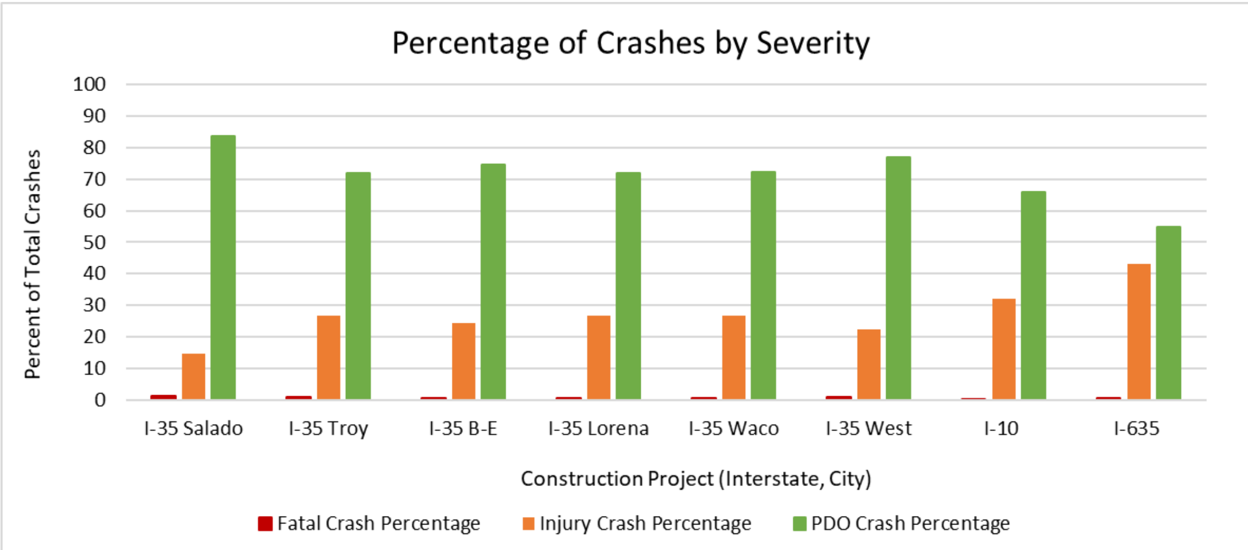


Figure 7. Percentage of Crashes by Severity for Selected Construction Projects.

Emergency Responder-Involved Crashes

The researchers examined crashes that involved emergency responder vehicles, such as ambulances, firefighter trucks, and police cars/trucks. The data set had only two crashes that involved ambulances, zero crashes that involved firefighter trucks, and 12 crashes that involved police cars/trucks associated with the projects selected.

Ambulance Crashes

The researchers found only two crashes that involved ambulances in the work zones examined:

- The first crash involving an ambulance occurred in March 2012 on the construction project near Waco on Interstate 35 Southbound:
    - The crash involved two other vehicles, a sport utility vehicle and a pickup truck.
    - The crash occurred during daylight (2:47 p.m.) during clear weather and on a dry roadway surface.
    - The manner of collision indicated by the officer was a sideswipe.
    - The crash was a PDO and did not include any injuries (actual or possible).
    - Based on the listed contributing factors for the vehicles involved in the crash, the pickup truck changed lanes when unsafe (faulty evasive action), resulting in a sideswipe crash. No contributing factors were listed for the ambulance and the sport utility vehicle involved in the crash.
- The second crash involving an ambulance occurred in July 2018 on the construction project near San Antonio on Interstate 10:
    - The crash involved a two-door passenger vehicle.
    - The crash occurred during daylight (11:53 a.m.) during cloudy and dry conditions.

- The manner of collision indicated by the officer was a sideswipe.
- The crash severity was listed as a possible injury.
- Based on the listed contributing factors, the vehicles involved in the crash changed lanes when unsafe, resulting in a sideswipe crash.

Law Enforcement Crashes

The researchers found 12 crashes that involved police cars/trucks associated with the projects selected. The majority of these crashes, as Table 5 shows, occurred during clear weather and on a dry road surface, except for two crashes (one on Interstate 35 near West and one on Interstate 635 near Dallas).

Table 5. Work Zone Crashes Involving Law Enforcement.

ID	City	Interstate	Date	Weather	Lighting Condition	Road Surface	Crash Type
1	Lorena	I-35	10/30/2012	Clear	Dark-lighted	Dry	Single vehicle
2	Waco	I-35	11/21/2011	Clear	Dark-lighted	Dry	Sideswipe
3	West	I-35	05/06/2012	Clear	Daylight	Dry	Single vehicle
4	West	I-35	05/15/2013	Cloudy	Daylight	Wet	Single vehicle
5	Dallas	I-635	03/11/2018	Clear	Dark-lighted	Dry	Single vehicle
6	Dallas	I-635	03/09/2018	Clear	Dark-lighted	Dry	Single vehicle
7	Dallas	I-635	07/09/2018	Clear	Daylight	Dry	Rear end
8	Dallas	I-635	12/08/2018	Rain	Dark-lighted	Wet	Single vehicle
9	San Antonio	I-10	06/02/2018	Clear	Dark-lighted	Dry	Angle
10	San Antonio	I-10	06/20/2018	Clear	Dark-lighted	Dry	Sideswipe
11	San Antonio	I-10	04/18/2019	Clear	Daylight	Dry	Rear end
12	San Antonio	I-10	05/14/2019	Cloudy	Daylight	Dry	Rear end

Proportionally, there were more law-enforcement-involved crashes in the work zones on Interstate 10 and Interstate 635 (four crashes each) than on the rest of the work zones on Interstate 35, despite these two work zones being the shortest in duration, at 12.2 and 12.9 months, respectively. Half of the crashes were recorded as sideswipe, rear-end, and angle crash types, whereas the other half were recorded as single-vehicle crashes. The researchers examined the single-vehicle crashes to examine if the vehicle involved in the crash hit any object (see Table 6). Two of these crashes that occurred on Interstate 35 near West involved law enforcement vehicles hitting the concrete median barrier, whereas the rest were recorded as hitting other fixed objects.

Table 6. Single-Vehicle Work Zone Crashes Involving Law Enforcement.

ID	City	Interstate	Weather	Lighting Condition	Road Surface	Crash Type	Object Struck
1	Lorena	I-35	Clear	Dark-lighted	Dry	Single vehicle	Other fixed object
3	West	I-35	Clear	Daylight	Dry	Single vehicle	Concrete barrier
4	West	I-35	Cloudy	Daylight	Wet	Single vehicle	Median barrier
5	Dallas	I-635	Clear	Dark-lighted	Dry	Single vehicle	Other fixed object
6	Dallas	I-635	Clear	Dark-lighted	Dry	Single vehicle	Other fixed object
8	Dallas	I-635	Rain	Dark-lighted	Wet	Single vehicle	Other fixed object

Lastly, the researchers examined the crash contributing factors associated with each vehicle involved in these crashes. In doing so, the researchers found that only one of the crashes coded as a single-vehicle crash involved a contributing factor. This crash (ID 4 in Table 6) occurred on Interstate 35 near West, during daylight, cloudy, and wet conditions, contributed unsafe speed from a law enforcement vehicle to the crash. The researchers examined the crash contributing factors, shown in Table 7, of the multi-vehicle crashes in Table 5 and found these to be attributed to inattention, unsafe speed, and unsafe change of lanes. The non-law enforcement vehicle driver contributed to four of the five crashes examined.

Table 7. Contributing Factors for Work Zone Crashes Involving Law Enforcement.

ID	Unit 1	Unit 1 Contributing Factor	Unit 2	Unit 2 Contributing Factor
2	Passenger car	Driver inattention	Police car/truck	Not applicable
7	Pickup	Not applicable	Police car/truck	Changed lanes when unsafe
8	Passenger car	Driver inattention	Police car/truck	Not applicable
9	Passenger car	Failed to control speed	Police car/truck	Not applicable
10	Passenger car	Other	Police car/truck	Not applicable

Large-Truck Crashes

The researchers queried 880 crashes involving large trucks (i.e., trailer, semi-trailer, tractor truck, and pole trailer). The crash characteristics that were examined included severity, manner of collision, weather, lighting, and object struck. Lastly, the researchers summarized unit (vehicle) contributing factors for large trucks to ascertain whether large-truck crash contributing factors are any different from those of all vehicle crashes. Table 8 summarizes the severity of large-truck crashes in the eight work zones examined. Occasionally, the severity of a crash is not identified within the crash database. Consequently, the sum of the large-truck crashes across the severity levels does not always equal the total number of large-truck crashes that were identified.

Table 8. Severity of Large-Truck Work Zone Crashes for Each Construction Project.

City	Interstate	Large-Truck (LT) Crashes	LT Fatal Crashes	LT Injury Crashes	LT PDO Crashes
Salado	I-35	42	0	6	35
Troy	I-35	53	0	12	38
Bruceville-Eddy	I-35	194	3	37	150
Lorena	I-35	134	0	33	101
Waco	I-35	240	3	42	189
West	I-35	124	1	24	94
San Antonio	I-10	28	1	7	19
Dallas	I-635	65	1	23	37
Total		**880**	**9**	**184**	**663**

Table 9 summarizes the manner of collision of the large-truck work zone crashes. Overall, sideswipes and rear-end collisions made up the majority of large-truck-involved crashes in each of the work zones. The researchers examined weather conditions for the crashes that included large trucks, and the results (see Table 10) show that most crashes occurred during clear weather. Fewer large-truck crashes occurred during rain or cloudy weather, and very few occurred during other weather conditions such as fog, sleet/hail, and severe winds. Similarly, when researchers reviewed the road surface condition for the large trucks, shown in Table 11, most of the large-truck crashes occurred on a dry road surface. The second most common pavement condition during a crash was a wet road surface, which aligns with the weather information breakdown in Table 10.

A review of the lighting conditions (see Table 12) for the large-truck crashes revealed that the majority occurred during daylight. The second most common lighting condition for Interstate 35 large-truck-involved work zone crashes was the dark-not-lighted condition, whereas it was the dark-lighted condition for work zones on Interstates 10 and 635.

Table 9. Manner of Collision for Large-Truck Work Zone Crashes.

City	Interstate	Single Vehicle	Rear End	Angle	Sideswipe	Head On	Total
Salado	I-35	8	9	3	20	2	42
Troy	I-35	8	19	1	24	1	53
Bruceville-Eddy	I-35	60	64	3	61	6	194
Lorena	I-35	39	38	2	51	4	134
Waco	I-35	54	83	5	95	3	240
West	I-35	34	42	1	44	3	124
San Antonio	I-10	5	11	2	10	0	28
Dallas	I-635	6	23	2	34	0	65

Table 10. Weather Conditions for Large-Truck Work Zone Crashes.

Weather Condition	I-35 Salado	I-35 Troy	I-35 Bruceville-Eddy	I-35 Lorena	I-35 Waco	I-35 West	I-10 San Antonio	I-635 Dallas
Rain	8	1	40	24	22	14	4	17
Clear	28	44	127	86	185	88	17	30
Cloudy	6	8	20	19	26	16	6	18
Sleet/hail	0	0	3	2	4	1	0	0
Snow	0	0	1	1	0	0	0	0
Severe crosswinds	0	0	1	0	1	0	0	0
Blowing sand/snow	0	0	0	1	0	0	0	0
Fog	0	0	0	1	2	5	0	0
Other	0	0	2	0	0	0	0	0
Unknown	0	0	0	0	0	0	1	0

Table 11. Road Surface Conditions for Large-Truck Work Zone Crashes.

Road Surface Condition	I-35 Salado	I-35 Troy	I-35 Bruceville-Eddy	I-35 Lorena	I-35 Waco	I-35 West	I-10 San Antonio	I-635 Dallas
Wet	7	3	39	24	21	18	4	20
Dry	34	50	142	100	210	103	23	45
Standing water	1	0	6	6	4	2	0	0
Ice	0	0	7	4	5	1	0	0
Unknown	0	0	0	0	0	0	1	0

Table 12. Lighting Conditions for Large-Truck Work Zone Crashes

Lighting Condition	I-35 Salado	I-35 Troy	I-35 Bruceville-Eddy	I-35 Lorena	I-35 Waco	I-35 West	I-10 San Antonio	I-635 Dallas
Daylight	25	34	120	92	173	81	22	47
Dark-not lighted	15	15	65	38	52	40	1	0
Dark-lighted	1	3	5	3	10	3	4	17
Dusk	1	0	3	1	3	0	0	0
Dawn	0	0	0	0	2	0	0	1
Dark-unknown	0	1	0	0	0	0	0	0
Other	0	0	1	0	0	0	0	0

The researchers compared the object struck field for the large truck and all other vehicles (except emergency responder vehicle crashes, which were previously discussed) to ascertain if large-truck crashes were more likely to result in hitting the median barrier or any other work zone equipment (see Table 13). The following results were observed:

- The percentage of median-barrier crashes were similar for large trucks and other vehicles. However, the percentage of crashes resulting in hitting the concrete median barrier was slightly higher for large trucks than for other vehicles: 7.4 percent for large trucks versus 6.5 percent for other vehicles.
- The percentages of crashes resulting in hitting work zone machinery, stockpiled material, and other work zone barricades, cones, and signs were very small and similar between large trucks and other vehicles.
- Even though the percentage of crashes resulting in jack-knifed vehicles was low, large trucks were involved in 18 such crashes, whereas other vehicles were only involved in four.
- Another interesting observation made involved 15 large-truck crashes resulting in a hit to the top of the underpass or tunnel. This could be due to the overhead clearance information missing from the overpasses or due to large-truck drivers misjudging the clearance.

Lastly, researchers examined the contributing factors recorded for each large-truck unit involved in a work zone crash and compared these to the contributing factors for other vehicles (except emergency responders) involved in work zone crashes. The results, tabulated in Table 14, included the following:

- Speeding was less of a factor for large trucks than for other vehicles.
- Fewer instances of inattention, following too closely, and faulty evasive actions were recorded for drivers of large trucks involved in crashes relative to drivers of other vehicles involved in crashes.
- Despite concerns to the contrary, fatigue was not significantly overrepresented in large-truck crashes relative to non-large-truck crashes.
- Large trucks were cited more frequently as performing unsafe lane changes and failing to drive in a single lane than for non-large-truck crashes.
- Vehicle or load size and weight were a factor in large-truck crashes, despite the fact that the percentage of these crashes was small.

Table 13. Object Struck during Large-Truck Work Zone Crashes.

Object Struck	Large Trucks		Other Vehicles	
	Count	**Percent**	**Count**	**Percent**
Not applicable	589	66.9	2,475	67.5
Hit median barrier	88	10.0	380	10.4
Overturned	21	2.4	122	3.3
Hit concrete traffic barrier	65	7.4	238	6.5
Hit fence	2	0.2	8	0.2
Hit guardrail	9	1.0	76	2.1
Hit previously wrecked vehicle	3	0.3	7	0.2
Other	16	1.8	64	1.7
Ditch	2	0.2	13	0.4
Hit by fallen/blowing rocks from a truck	2	0.2	2	0.1
Embankment	2	0.2	8	0.2
Hit delineator or marker post	0	0.0	3	0.1
Hit utility pole	2	0.2	7	0.2
Hit tree, shrub, or landscaping	1	0.1	8	0.2
Hit luminaire pole	0	0.0	9	0.2
Hit highway sign	6	0.7	55	1.5
Hit work zone machinery or stockpiled materials	2	0.2	3	0.1
Hit object from another vehicle in road	9	1.0	4	0.1
Hit work zone barricade, cones, signs, or material	7	0.8	31	0.8
Hit culvert headwall	0	0.0	5	0.1
Hit retaining wall	6	0.7	51	1.4
Hit other fixed object	2	0.2	36	1.0
Hit top of underpass or tunnel	15	1.7	1	0.0
Hit curb	2	0.2	16	0.4
Jack-knifed	18	2.0	4	0.1
Hit house, building, or building fixture	1	0.1	0	0.0
Hit fallen trees or debris on road	0	0.0	3	0.1
Hit hole in road	0	0.0	4	0.1
Hit side of bridge (bridge rail)	4	0.5	22	0.6
Hit end of bridge (abutment or rail end)	1	0.1	0	0.0
Hit attenuation device	1	0.1	5	0.1
Hit pier or support at underpass, tunnel, or overhead sign bridge	2	0.2	1	0.0
Hit overhead signal light, wires, signs, etc.	1	0.1	0	0.0
Hit railroad crossing gates	1	0.1	0	0.0
Hit commercial sign	0	0.0	2	0.1
Hit traffic signal pole or post	0	0.0	3	0.1
Hit other machinery	0	0.0	1	0.0
Total	**880**	**100.0**	**3,667**	**100.0**

Note: Blue highlighting denotes objects described in the previous text.

Table 14. Contributing Factors for Units Involved in Work Zone Crashes.

Contributing Factor	Large Trucks		Other Vehicles	
	Count	Percent	Count	Percent
Not applicable	2,028	68.1	3,610	47.4
Unsafe speed	51	1.7	300	3.9
Failed to control speed	243	8.2	1,358	17.8
Speeding (over limit)	0	0.0	6	0.1
Driver inattention	34	1.1	365	4.8
Changed lane when unsafe	213	7.2	340	4.5
Failed to yield right of way (ROW)—yield sign	2	0.1	26	0.3
Followed too closely	33	1.1	363	4.8
Road rage	0	0.0	6	0.1
Faulty evasive action	34	1.1	159	2.1
Cell/mobile phone use	1	0.0	4	0.1
Distraction in vehicle	4	0.1	39	0.5
Failed to drive in single lane	55	1.8	104	1.4
Under influence of drugs	4	0.1	9	0.1
Had been drinking	0	0.0	14	0.2
Under influence of alcohol	10	0.3	67	0.9
Fleeing or evading police	0	0.0	5	0.1
Fatigued or asleep	12	0.4	43	0.6
Taking medication	0	0.0	1	0.0
Ill	1	0.0	12	0.2
Handicapped driver	1	0.0	1	0.0
Load not secured	15	0.5	11	0.1
Oversized vehicle or load	16	0.5	1	0.0
Fire in vehicle	4	0.1	2	0.0
Parked in traffic lane	3	0.1	11	0.1
Disabled in traffic lane	11	0.4	15	0.2
Parked without lights	0	0.0	1	0.0
Parked and failed to set brakes	1	0.0	0	0.0
Disregarded stop and go signal	1	0.0	25	0.3
Disregarded stop sign or light	2	0.1	20	0.3
Disregarded turn marks at intersection	2	0.1	12	0.2
Disregarded warning sign at construction	7	0.2	4	0.1
Failed to heed warning sign	2	0.1	0	0.0
Failed to yield ROW—private drive	1	0.0	12	0.2
Failed to yield ROW—turning left	0	0.0	50	0.7
Failed to yield ROW—stop sign	3	0.1	34	0.4
Failed to yield ROW—open intersection	2	0.1	7	0.1
Failed to yield ROW—turn on red	0	0.0	4	0.1
Failed to pass to left safely	2	0.1	10	0.1
Failed to signal or gave wrong signal	1	0.0	1	0.0
Failed to pass to right safely	0	0.0	3	0.0
Failed to yield ROW—emergency vehicle	0	0.0	0	0.0
Failed to stop at proper place	0	0.0	5	0.1
Impaired visibility	4	0.1	17	0.2
Wrong side—not passing	1	0.0	2	0.0

Contributing Factor	Large Trucks		Other Vehicles	
	Count	**Percent**	**Count**	**Percent**
Wrong way—one-way road	1	0.0	3	0.0
Turned improperly—wrong lane	3	0.1	12	0.2
Turned when unsafe	3	0.1	16	0.2
Turned improperly—cut corner on left	2	0.1	0	0.0
Turned improperly—wide right	4	0.1	9	0.1
Passed on right shoulder	1	0.0	1	0.0
Overtake and pass insufficient clearance	0	0.0	3	0.0
Backed without safety	9	0.3	8	0.1
Improper start from parked position	0	0.0	1	0.0
Pedestrian failed to yield ROW to vehicle	4	0.1	9	0.1
Animal on road—wild	1	0.0	13	0.2
Animal on road—domestic	2	0.1	7	0.1
Other	69	2.3	262	3.4
No contributing factor provided	74	2.5	195	2.6
Total	**2,977**	**100.0**	**7,618**	**100.0**

Note: Highlighting denotes results described in the previous text: green for factors affecting other vehicles more and red for factors affecting large trucks more.

In summary, the crash investigation results showed a small number of emergency responder crashes (involving two ambulances and 12 police vehicles) occurring during the work zone projects on Interstate 35, Interstate 635, and Interstate 10. The main contributing factors to these crashes were driver inattention, change of lanes when unsafe, and failure to control speed.

The review of the 880 large-truck crashes showed no effects from weather, road surface, or lighting conditions. Large trucks were slightly more likely to be involved in crashes that resulted in hitting the concrete barrier. The factors contributing to large trucks being involved in crashes more often than other vehicles were failure to drive in a single lane and change of lanes when unsafe.

CHAPTER 3:
STAKEHOLDER SURVEYS

The research team performed a series of electronic surveys with multiple stakeholder groups to capture the current state of the practice regarding barrier use in freeway work zones as well as perceived difficulties in accommodating work zones where barriers are used, particularly those with highly constrained cross sections. Because of conditions existing at the time, electronic surveys were administered via email. Stakeholders surveyed included TxDOT and contractor personnel, enforcement personnel, emergency responders, and commercial motor vehicle drivers.

PERCEPTIONS OF TXDOT AND CONTRACTOR PERSONNEL

Researchers sought input from both the Construction Division and from area offices in the Waco, Dallas, and Fort Worth Districts. The Construction Division survey sought out what design guidance (if any) is used in making barrier use decisions. The area office surveys focused on implementation and maintenance challenges encountered regarding barrier use in work zones.

Overall, only limited guidance was identified for making barrier use decisions in work zones. Primarily, decisions are made in accordance with the "Treatment of Pavement Drop-Offs in Work Zones" appendix of the *Roadway Design Manual* (*3*). Characteristics such as traffic composition (i.e., the proportion of trucks) do not play a role in the decision about barrier use. The speed of the roadway dictates the type of barrier used but not whether it is used, and the main determinant for the use of barriers is the proximity of workers to traffic. Efforts are made to maintain lane widths of at least 11 feet through freeway work zones. With respect to access points, typically, at least every other ramp is kept open, or else a detour is provided. Division staff noted that emergency response within the work zone is taken into account by coordinating the availability of access points. Lane shift designs are based on criteria for shift tapers in the MUTCD, which takes traffic speeds and the extent of lateral shift into consideration but not vehicle mix (*33*).

Researchers reached out to TxDOT area office contacts at various projects in the Dallas, Fort Worth, and Waco Districts to identify what issues pertaining to barrier installation, repositioning, and maintenance have occurred. Staff were also queried about whether complaints specific to the deployment of the barriers had been received from the public. Although most of the contacts indicated that they had not seen or experienced any issues of this type or did not respond to the query, a few contacts did provide some comments. These are summarized as follows.

Requirements for When Temporary Barrier Must Be Anchored Are Difficult to Find

TxDOT staff responding to the queries noted that space is often extremely limited in urban freeway widening and reconstruction projects. Ensuring that 2 feet of working width is behind the barrier to allow for deflection is often a challenge, and it is sometimes necessary to anchor or pin the barrier to reduce working width requirements. The respondent noted that guidance on the need for anchoring/pinning of the barrier was difficult to find within TxDOT. For example, barrier use to separate opposing traffic where adequate inside shoulders cannot be provided should be clear on the need to pin the barrier to minimize deflection into the opposing lane if the barrier is hit from the other direction. As discussed in the next chapter, a question was raised about whether a 2-foot buffer space is sufficient for temporary median barriers on very high-volume urban freeways because instances of barrier deflection exceeding that distance do occur fairly regularly.

Connecting Temporary Concrete Barrier to Existing Bridge Rails Can Be a Challenge

In one instance, the respondent noted that the contractor had to widen the pavement to accomplish the connection properly.

Roadway Vibrations Caused by Heavy Vehicles Can Be Challenging

One respondent indicated that "barrier creep" can be a problem at some work zones if pavement vibrations due to heavy loads passing by are a possibility. Over time, the vibrations can cause barriers to serpentine, which can increase snagging potential by vehicles that impact the barrier. It is not clear how much lateral deviations in offset should be allowed before the barrier should be realigned.

Complaints from the Driving Public Have Occurred When "Cattle Chute" Work Zones Have Been Used

A respondent noted that they generally do not receive many complaints from the driving public regarding the use of concrete barriers in work zones. The main exception to this statement is when the project requires barriers on both sides of the freeway immediately adjacent to the travel lanes. To combat this complaint, one respondent indicated that they had changed from two 12-foot lanes with 1-foot barrier offsets to two 11-foot lanes with 2-foot offsets to the barrier on both sides. According to the respondent, this seemed to work well. Of course, narrower lanes are less desirable from the perspective of drivers of large commercial motor vehicles. Other states have suggested maintaining one 12-foot lane and reducing other lanes to 11 feet when necessary, combined with advance signing notifying the operators of those large vehicles of the wider lane that is available.

Use of Barriers Can Create Challenges for Deploying and Maintaining Temporary Traffic Control Signing

Although not an issue specific to the application of barriers in work zones, barrier use in very tight work zones does create a challenge for deploying signing because there is no good place to place the sign supports in certain sections, such as where new pavement is being built above the existing travel lanes and temporary wire walls are being used immediately adjacent to the concrete barrier. It was noted that perhaps a sign mount that attached to a wire wall or soil nail could be developed for these situations.

PERCEPTIONS OF LAW ENFORCEMENT PERSONNEL

The researchers developed questions to gain feedback from law enforcement about the obstacles faced when conducting speed enforcement as well as responding to crashes near or within a work zone where barriers are used. The following topics were incorporated into the survey questions:

- The extent to which barriers in work zones hinder the ability to perform job duties (e.g., speed enforcement and emergency response).
- How the presence of barriers close to the travel lanes within work zones influences the amount of travel made through those work zone versus an alternative route as part of their normal travels in a corridor.
- The preferred spacing of access points into and out of work zones that have constrained cross sections with barriers close to the travel lanes.
- Experiences with enforcement efforts in work zones with barriers.
- Experiences with emergency response within, immediately upstream of, or immediately downstream of work zones with barriers.

Researchers received 70 responses from law enforcement officers working in various TxDOT districts, with work experience varying from one year to 40 years. The average work experience stated was 15 years. Of the 70 officers who responded, 64 (92 percent) had driven through a freeway work zone while working, and 61 (87 percent) officers stated that while driving through freeway work zones, they had noticed the use of concrete barriers.

When asked whether the presence of continuous barriers presents difficulty in conducting their work while driving through the work zone, as shown in Table 15, the majority of the officers stated significant or some difficulties in driving through work zones with concrete barriers (57.1 percent), and 22.9 percent stated slight difficulties. The remaining 20 percent of the officers reported no difficulties or did not recall any difficulties while driving through a freeway work zone with concrete barriers.

Officers were asked if they would consider taking an alternative route if access points were restricted through a freeway work zone with concrete barriers. Two-thirds of the officers, as shown in Table 16, stated that if their access point would be inaccessible, they would take an alternative route. Additionally, just under 25 percent of the officers stated that they would stay on the route and use the next available exit point.

Table 15. Difficulty Level Presented to Law Enforcement Officers While Driving through Freeway Work Zones with Concrete Barriers.

Category	Count	Percentage
Significantly	15	21.4
Somewhat	25	35.7
Slightly	16	22.9
Not noticeably	11	15.7
Do not recall	3	4.3

Table 16. Use of Alternative Route If Access Points of a Work Zone with Concrete Barriers Are Closed.

Category	Count	Percentage
Yes, if exit I need to take is closed	47	67.1
No, I use the next available exit	17	24.3
Other	6	8.6

When asked about other work zone characteristics associated with the presence of a concrete barrier that would prompt a change of route (see Table 17), almost half of the officers selected the closing of access points for several miles as one of the main reasons. Similarly, the lack of shoulder, or in other words, when the concrete barrier would be placed less than 1 foot from the edge line, was the second most cited reason (at almost 42 percent) for changing routes. The third and fourth most cited reasons for changing routes were a reduced number of lanes or narrower lanes (both cited by almost 39 percent of the officers as shown in Table 17). Narrow shoulders were less of a concern or reason for changing routes because only 14 percent of the officers cited that as a reason for changing routes. One officer stated that congestion caused by the reduction of lanes would be cause for changing routes.

Table 17. Freeway Work Zone Characteristics that Would Prompt the Use of Alternative Routes by Law Enforcement.

Category	Count	Percentage
Reduced number of lanes	27	38.6
Narrower lanes (less than 12 feet)	27	38.6
Narrower shoulders (barrier placed < 6 feet from edge line)	10	14.3
No shoulders (barrier placed < 1 foot from edge line)	29	41.4
No access points for several miles	34	48.6

Note: The percentages add up to more than 100 percent since responders were asked to select all that apply.

Officers were asked about their acceptable access point density while driving through freeway work zones with concrete barriers. As shown in Table 18, only about 11 percent of the officers were comfortable with an access point frequency of less than or equal to one for every 3 miles. Twenty percent of the officers stated that it was not acceptable to have any access point closures, whereas most officers stated that one access point per mile (38.6 percent) or one access point for every 2 miles (31.4 percent) was acceptable. This response was consistent with past research on this topic (*27*).

Table 18. Law Enforcement Acceptable Access Point Density in Freeway Work Zones with Concrete Barrier.

Category	Count	Percentage
All existing access points be opened	13	18.6
1 per mile	27	38.6
1 for every 2 miles	22	31.4
1 for every 3 miles	3	4.3
1 for every 4 miles	2	2.9
1 for 5 or more miles	3	4.3

Of the 70 officers interviewed, only 30 percent indicated having had experience conducting speed enforcement in freeway work zones (see Table 19). Officers were asked about what accommodations were made for them to be able to conduct speed enforcement in freeway work zones with concrete barriers. The accommodations stated by the officers were grouped into 9 criteria (see Table 20). While almost half of the officers did not provide any comments on the question, 27 percent of the officers stated the need for a safe space, either through a paved area or shoulder, typically associated with a break in the continuous barriers, in order to conduct speed enforcement. Safety was one of the most cited criteria, and a few officers mentioned the need for barrier protection from oncoming traffic. Other accommodations mentioned included the space to maneuver while pulling over speed violators, an acceleration lane to be able to get back into the lanes of traffic, or a crossover (U-turn). Several officers also mentioned proper work zone signing as being important.

With regards to law enforcement perceptions of emergency response to incidents within, immediately upstream of, or immediately downstream of work zones with barriers, about half of the officers (34, as shown in Table 21) who responded to the survey indicated that they had responded to a crash occurring near or within a work zone with concrete barriers.

Table 19. Law Enforcement Officers with Speed Enforcement in Freeway Work Zone Experience.

Category	Count	Percentage
Yes	21	30.0
No	44	62.9
I do not recall	5	7.1

Table 20. Accommodations Needed by Law Enforcement Officers to Conduct Speed Enforcement in Freeway Work Zone Experience.

Category	Count	Percentage
Shoulder (6+ feet), parking space, break in the barrier	19	27.1
Barrier to protect the officer	3	4.3
Acceleration lane	2	2.9
Open lanes for U-turn	2	2.9
Access points open	5	7.1
Sight distance (of traffic)	3	4.3
Proper work zone signs	4	5.7
Communication	1	1.4
No input, unsure, not applicable, or empty	34	48.6

Table 21. Law Enforcement Responding to Crashes near or within a Freeway Work Zone with Concrete Barriers.

Category	Count	Percentage
Never	23	32.9
Once or twice	2	2.9
A few times	18	25.7
More than a few times	14	20.0
I do not recall	13	18.6

Of the officers with experience in responding to crashes near or within a work zone (see Table 22), 15 (44 percent) stated that the crash response time was significantly affected, and 11 (32 percent) stated that response times were only slightly affected. Additionally, as shown in Table 23, over 90 percent of the officers that responded stated that time to process crashes was affected significantly (15 officers [44 percent]) or slightly (16 officers [47 percent]).

Table 22. Law Enforcement Officers' Crash Response Time in the Presence of Freeway Work Zone Concrete Barriers.

Category	Count	Percentage
Yes, significantly	15	44.1
Yes, slightly	11	32.4
No, not noticeably	8	23.5
I cannot recall	0	0.0

Table 23. Law Enforcement Officers Processing Crashes near or within a Freeway Work Zone with Concrete Barriers.

Category	Count	Percentage
Yes, significantly	15	44.1
Yes, slightly	16	47.1
No, not noticeably	2	5.9
I cannot recall	1	2.9

PERCEPTIONS OF EMERGENCY SERVICES PERSONNEL

Researchers surveyed EMS responders to gain feedback on how the use of concrete barriers in freeway work zones impacts the time it takes for them to respond to crashes. The questions on the survey addressed two areas:

- How the EMS staff's driving through a freeway work zone is impacted by the presence of concrete barriers.
- How the EMS staff's crash response and processing times are impacted when concrete barriers are present in freeway work zones.

Altogether, researchers obtained 46 responses from EMS staff. All the responders stated that they had driven through a freeway work zone, and all of them had seen concrete barriers used in freeway work zones. Over 65 percent of the responders (see Table 24) stated that continuous concrete barriers in freeway work zones present difficulties in their EMS abilities to drive through the work zone.

Table 24. Difficulty Level Presented to EMS Staff While Driving through Freeway Work Zones with Concrete Barriers.

Category	Count	Percentage
Significantly	11	23.9
Somewhat	19	41.3
Slightly	6	13.0
Not noticeably	8	17.4
Do not recall	2	4.3

EMS staff were asked about their willingness to use an alternative route, if available, or continue driving through freeway work zone (see Table 25). The majority stated that they would use an alternative route if the needed exit was closed. One responder mentioned that the decision to forgo using an alternative route would depend on the distance to the next available/open access point.

Table 25. Use of Alternative Route If Access Points of a Work Zone with Concrete Barriers Are Closed.

Category	Count	Percentage
Yes, if exit I need to take is closed	33	71.7
No, I use the next available exit	12	26.1
Other	1	2.2

Over 70 percent of the EMS responders (see Table 26) stated that narrow lanes were the main reason that would prompt the use of alternative routes. Around half of the responders cited issues such as reduced number of lanes, no shoulders, and no access points for several miles as other reasons for the use of alternative routes. Narrower shoulders were only cited by 40 percent of EMS responders as an issue when driving through freeway work zones with concrete barriers.

One responder stated in the comments field that traffic congestion and backup in work zones had increased the transportation-to-hospital time by 5–15 minutes.

Table 26. Freeway Work Zone Characteristics that Would Prompt the Use of Alternative Routes by EMS.

Category	Count	Percentage
Reduced number of lanes	26	56.5
Narrower lanes (less than 12 feet)	33	71.7
Narrower shoulders (barrier placed < 6 feet from edge line)	18	39.1
No shoulders (barrier placed < 1 foot from edge line)	24	52.2
No access points for several miles	22	47.8

Note: The percentages add up to more than 100 percent since responders were asked to select all that apply.

EMS staff were asked about their preferences for acceptable access point density when driving through freeway work zones (see Table 27), and over 21 percent of the responders stated their preference for all access points to remain open during work zone activities. The majority of the responders stated they would find one access point per mile or one access point for every 2 miles as acceptable. Only 13 percent of the responders were willing to accept one access point for every 3 miles, and fewer (less than 5 percent) were willing to accept fewer access points per mile when driving through work zones.

Table 27. EMS Acceptable Access Point Density in Freeway Work Zones with Concrete Barriers.

Category	Count	Percentage
All existing access points be opened	10	21.7
1 per mile	15	32.6
1 for every 2 miles	12	26.1
1 for every 3 miles	6	13.0
1 for every 4 miles	1	2.2
1 for 5 or more miles	1	2.2

PERCEPTIONS OF THE TRUCKING INDUSTRY

Originally, this survey was going to be given to truck drivers in rest areas and weigh stations where the researchers believed they could have obtained a large number of survey participants. However, due to the COVID-19 situation, this methodology for data collection was not possible. Therefore, the research team attempted to reach out to freight companies to assist in the distribution of the survey to truck drivers. The research team attempted to contact the following trucking companies via their respective corporate websites:

- Old Dominion Freight Line.
- JB Hunt.
- Mongoose Freight Solutions.
- Swift Transportation.

- Schneider International.
- Landstar System.
- Werner Enterprises.
- Prime.
- US Xpress Enterprises.

The research team attempted to navigate through electronic and human operators to identify a method to distribute the survey to truck drivers. However, the process generally resulted in dead ends in the form of redirection loops and hang-ups. Unfortunately, only one response was obtained and recorded.

The first part of the survey consisted of the same questions asked of law enforcement officers and EMS staff, and the second part aimed to gain information on truck drivers' experience with lane shifting in freeway work zones. The one truck driver who responded to the survey had 45 years of experience and on average drove over 60,000 miles per year. The truck driver stated that he had experience driving through freeway work zones and had noticed the use of barriers in some of these work zones, and such presence did present a challenge in driving a large truck on the freeway. However, the driver stated that the presence of the continuous concrete barriers did not prompt him to use an alternative route, and typically he used the planned route, despite the work zone conditions. One of the work zone characteristics that would prompt the use of an alternative route, as the truck driver stated, was narrower lanes. Lastly, the truck driver stated an acceptable access point density of one access point for every 2 miles, consistent with responses by enforcement personnel.

Finally, the truck driver stated that he had experience driving through work zones in which a lane shift and continuous concrete barriers were present. The driver stated that he had had experience maneuvering the truck and staying in the same lane, and once or twice he had come close to hitting a concrete barrier due to a sudden lane shift or narrower lanes in the work zone.

SUMMARY OF FINDINGS

The survey of the various stakeholders on this subject verified many of the concerns already expressed regarding the use of barriers in freeway work zones, particularly those where cross sections are constrained. A summary of the major thoughts extracted from the surveys is as follows:

- Although decisions about when to use barriers in work zones should consider a wide range of risks and site-specific factors, the pavement edge drop-off criteria in the TxDOT *Roadway Design Manual* drive many of those decisions.
- Most work zone designers strive to maintain at least 11-foot lanes through the work zone.
- Efforts are made to keep at least every other exit or entrance ramp open within a freeway work zone. If that is not possible, efforts are made to define a specific detour route. Decisions to temporarily close ramps are typically coordinated with local emergency response personnel.

- Lane shifts are designed as shifting tapers using criteria set forth in the *MUTCD*.
- Requirements for when temporary barriers are to be anchored are not easy to find within the TxDOT standards. In addition, some project staff wonder whether the criteria are sufficient when traffic speeds are high, when a significant portion of the traffic stream includes large trucks, and where geometrics create potential impact angles that exceed the testing criteria upon which the current standards were based. On some roadways, vibrations caused by large trucks also lead to barrier creep over time, which can diminish the available deflection distance or working width of the barrier.
- Work zone project staff do regularly get complaints when the work zone is so constrained that little or no buffer space is available from the travel lanes to the barrier on the sides of the roadway (i.e., the "cattle chute" work zone design). Some designers have opted to reduce the lane widths from 12 feet to 11 feet to provide an additional 1-foot (or more) buffer space on each side, which has reduced the complaints.
- Most law enforcement personnel perceive the presence of barriers in work zones to adversely affect their enforcement and incident response activities. In work zones where barriers must be used, enforcement personnel indicate that access points (ramps) every mile or two are highly preferable to longer distances between access points. This finding is consistent with past research findings on the topic.
- Emergency response personnel also perceive travel through work zones with barriers near the travel lanes as more difficult than without barriers. Most emergency response personnel indicate that a lack of emergency shoulders does not normally influence their decisions to use a freeway through a work zone. However, narrowed lanes or lane closures as well as traffic congestion resulting from those conditions are often considered when deciding whether to use a freeway route through a work zone or an alternative route around the work zone.
- Similar to law enforcement personnel, emergency response personnel also perceive the availability of ramps every mile or two as sufficient for negotiating freeway work zones with barriers on both sides near the travel lanes.

CHAPTER 4: FIELD ANALYSIS OF BARRIER ISSUES IN FREEWAY WORK ZONES

INTRODUCTION

Researchers used the TxDOT Project Tracker (https://www.txdot.gov/inside-txdot/projects/project-tracker.html) to identify 14 work zones in locations where concrete barriers were likely to be used. Projects in the Fort Worth, Dallas, and Waco Districts were selected to facilitate data collection by research staff and to provide a range of roadway traffic volumes, cross sections, and types of work. Table 28 summarizes the projects examined. Overall, research staff collected video data on over 82 centerline miles of work zones.

Table 28. Projects Analyzed.

District	Roadway	Limits Examined	Approximate Length (Miles)
WAC	I-35	Meyers Lane to 15th Street	5.8
WAC	I-35E	I-35W to Ellis County Line	7.9
FTW	I-35W	US 287 to Denton County Line	7.2
FTW	I-820	I-35W to Marine Creek Parkway	4.5
FTW	I-820/SH 121 Interchange	Randol Mill Road to SH 121	3.7
FTW	SH 360	North of Abrams Street to I-20	5.4
FTW	I-30/SH 360 Interchange	Cooper Street to Dallas County Line	4.5
DAL	PGBT (SH 161)	I-30 to I-20	6.0
DAL	PGBT (SH 161)	Beltline Road to I-35E	9.1
DAL	I-635/SH 121 Interchange	SH 114 to FM 2499	2.1
DAL	I-635	US 75 to I-30	11.0
DAL	I-35E	US 67 to I-30	4.8
DAL	US 67	I-35E to I-20	4.7
DAL	US 67	I-20 to FM 1382	5.5

PGBT = President George Bush Turnpike

VIDEO DRIVE-THROUGH RESULTS

Once video drive-through data were gathered at each project, the video files were reviewed manually to identify locations where excessive tire scrub marks, vehicle impact scars, or other indications of vehicle-barrier interactions had occurred. General roadway, traffic, and work zone characteristics upstream and within the vicinity of the marks were then reviewed to hypothesize why the abundance of marks might have occurred.

Not all projects had barriers deployed along their entire length. Some projects used barriers primarily on the right side of the travel lanes, other projects used barriers primarily on the left side of the travel lanes, and still other projects used barriers on both sides of the travel lanes, creating a “cattle chute” or tunnel-like situation. In most cases, barriers were deployed within 1–2 feet of the outside of the edge line. In a few instances, the barriers were positioned immediately adjacent to the edge line.

Overall, there was a mix of temporary single-slope barriers and F-shape barriers in use across the projects. In a few projects, combinations of both types of barriers were in use. It was not clear whether such mixing was by design to address specific needs and conditions within the project or was simply what the contractor had in stock to deploy.

Once the video drive-throughs were reviewed and analyzed, the research team consolidated the various notes and trends identified through the reviews. The following insights were gleaned from the data.

Short Lane Shifts Do Surprise Some Drivers

Most of the projects reviewed used lane shift lengths that met or exceeded the one-half length of a merging taper shown in TxDOT Traffic Control Plan Standard Sheet TCP 2-18, where merging taper length is the product of the lateral merge distance required and the posted speed limit. Such shifts did not exhibit an extraordinary amount of tire scuffing or impacts. However, one lane shift was observed where significant indications of tire scrubbing and barrier impact were evident (see Figure 8). Based on the video data, it was estimated that the lane shift offset was nearly a full travel lane (12 feet). The posted speed limit was 55 mph, which would suggest a lane shift length of 330 feet be used. In addition, operating speeds higher than 55 mph often exist during off-peak hours. However, it appeared that the shift length may have been less than that.

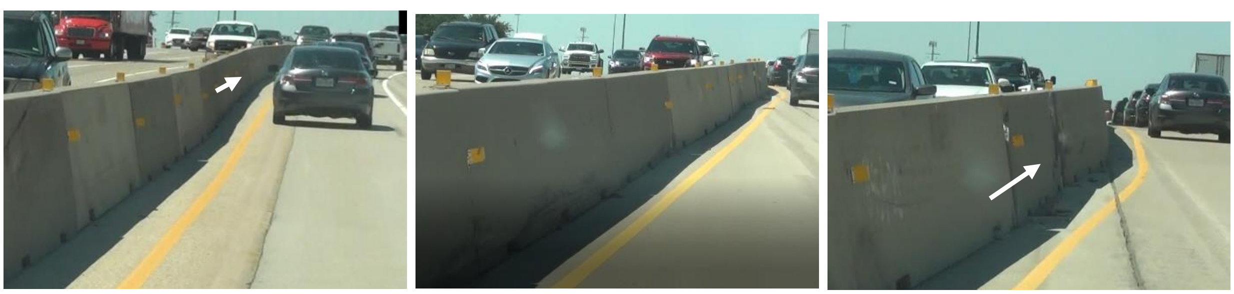


Figure 8. Illustration of Short Lane Shift Length Effects on Barrier Scuffing/Impacts.

Barrier Segments Can Deflect Significantly When Impacted

Temporary concrete barriers are considered rigid relative to other barrier types. Although such barriers will generally not deflect as much as other barrier types, they do deflect some. The amount of deflection depends on the size of the impacting vehicle, vehicle speed, and angle of impact. Most barrier segments in work zones are not pinned to the pavement. Although the barrier will perform satisfactorily from a crashworthy standpoint, the implications of potential deflection distances should be considered in barrier offset placement. In addition to deflection considerations from traffic impacts, consideration of possible displacement toward the traffic lanes by construction equipment hitting the barrier from the work space side should also be considered, as shown in Figure 9.

Figure 9. Examples of Barriers Deflected by Traffic Impacts (Left) or Construction Equipment (Right).

Barrier Scuffs and Impact Scars Appear Less Frequent When the Barrier Maintains Consistent Offset with Edge Lines

One of the concerns with use of temporary barriers in work zones is their proximity to travel lanes. Most state departments of transportation (including TxDOT) strive to provide 1–2 feet of offset between the edge of the barrier and the edge line. Unfortunately, instances arise where work space requirements are such that it is not possible to provide that offset. In some instances, the barrier must be positioned immediately adjacent to the edge line or, in even more constrained locations, placed on the existing edge line, effectively encroaching into the travel lane and reducing its width slightly. Interestingly, a review of barrier scuffs and impacts suggests that motorists overall accommodate barrier proximity adjacent to the travel lanes relatively well. The frequency of scuff marks and impact scars in sections where the barrier was 1 foot or closer to the edge line did not appear to be substantially greater than in sections where the barrier appeared to be about 2 feet or more away from the travel lanes. Barriers closer to the edge of the travel lanes do cause most drivers to shy away from the barrier slightly, including large trucks (see Figure 10). However, the research team found that large trucks continued to use the lanes immediately adjacent to barriers and appeared to be traveling at normal speeds. All of the work zones examined appeared to have maintained normal 12-foot travel lanes. It is not known how narrow (i.e., 11-foot) lanes would have influenced large-truck lane position within the work zones examined in this effort.

Figure 10. Example of a Large Truck Shying Away from the Work Zone Barrier.

Although the difference between a 2-foot barrier offset and a 1-foot or even 0-foot offset did not appear to significantly influence the frequency of scuff marks or impact scars on the barrier, researchers did note that locations where the barrier offset changed significantly along the length of the work zone did appear to be associated more frequently with scuffs and scars (see Figure 11). Short sections of barriers, rather than long continuous sections at a consistent offset from the travel lanes, experienced similar scuffing. Researchers hypothesized that when barriers are positioned close to the travel lanes, drivers begin to subconsciously key on their proximity to the barrier as part of their guidance function of the driving task. When the barrier offset changes over a relatively short distance, drivers may inadvertently begin to follow the barrier alignment rather than the edge line and lane lines on the pavement and result in lane departures. If the barrier offset increases quickly, it may "pull" drivers away from the travel lane into the shoulder. If the barrier offset decreases quickly, it may "push" drivers across the adjacent lane line. In either case, an over-response by drivers when they realize they have departed their intended lane could lead to the observed barrier scuffs and impacts in those areas. Such violations of driver expectancy can also lead to the edge line itself being worn out by vehicles that cross the edge line as they are "pulled" toward the barrier.

Contractors Should Consult Barrier Crashworthiness Experts for Unusual Situations

The researchers identified several instances in the video data where the application or repair of barriers (presumably from previous impacts) seemed unusual enough to raise a question about whether the barrier would perform as designed and crash tested. In one instance, a barrier connection was applied to two barrier ends that appeared to have significant damage. Presumably, the connection itself was done because the original connection hardware was damaged (see Figure 12).

Figure 11. Examples Where Inconsistent Barrier Presence and Offset Distance Are Associated with Increased Tire Scuffs and Impact Scars.

Figure 12. Example of a Barrier Connection between Damaged Barrier Segment Ends.

In another situation, an F-shape barrier was used to close an exit ramp. To create the required length needed, barrier segments were installed on top of barrier curb sections upstream of the exit ramp, effectively raising the height of the lower safety slope. At the exit point itself, another barrier segment was placed on the pavement but could not be connected to the upstream barrier segment because of the height differential due to the barrier curb, and so a temporary connector was applied (see Figure 13).

Figure 13. Barrier Segments with Nonstandard Deployment Heights and Connections.

In one additional situation, single unconnected barrier segments were deployed on the outside curve where an entrance ramp merged with the main lanes (see Figure 14). The primary question here would be whether the individual barrier segment itself would perform satisfactorily if impacted by an out-of-control vehicle from the main lanes. Although it appears that the segment is angled away from the entrance ramp edge line at perhaps something close to the desired 20:1 ratio, an errant main lane vehicle coming across the ramp could potentially impact the barrier at an angle that exceeds the conditions for which the barrier was designed and tested. The contractors in these examples may have indeed obtained input from experts regarding the crashworthiness of these deployments and repairs. Still, it bears mentioning that such expertise should be consulted when dealing with these site-specific situations when they arise.

Figure 14. Example of an Unconnected Barrier Segment on a Horizontal Curve at an Entrance Ramp Merge Point.

Single-Slope Barriers Can Create Sight Distance Challenges for Low-Profile Vehicles at Merge Points

Although the researchers did not observe an instance where single-slope barriers used in a work zone created sight distance issues for drivers of low-profile vehicles where driver eye height is reduced, it is important to note the need for such considerations when specifying the use of barriers in work zones. On freeways, potential sight distance issues might occur primarily around entrance ramp merge points, especially if the entering traffic is coming from surface street level up to main lanes that are elevated. Another potential issue location that may not be as immediately apparent is around access points to and from the work space. Researchers found one instance around an access point where the barrier transitioned from a single-slope barrier to an F-shape barrier near the access point, which enhanced the abilities of main lane drivers to better see work vehicles that may be leaving the work space (see Figure 15).

Figure 15. Example of Switching from a Single-Slope Barrier to an F-Shape Barrier near a Work Space Access Point.

Barrier Use at Entrance Ramps and Work Space Access Points with Short or No Acceleration Lanes Can Create Challenges for Vehicles Attempting to Merge onto the Freeway

It is common practice to apply barrier to the outer edge of entrance ramps as they merge onto the main lanes when work is occurring adjacent to the main lanes. It is also common to reduce the length of acceleration lanes to maximize the available work space. However, combining reduced acceleration lane lengths with barriers adjacent to the travel lane creates challenges for entering motorists when traffic volumes are high but traffic is still flowing at normal speeds. During these times, very little room for error exists for entering motorists to accelerate to main lane speeds, find an acceptable gap, and merge into that gap before striking the barrier. If a gap is not found, the entering vehicle may need to decelerate rapidly and eventually stop. This creates a large speed differential as the vehicle then attempts to find a gap and accelerate from a stop condition to highway speeds. A similar problem can also exist at work space access points as construction vehicles attempt to quickly find a gap before running into the barrier (see Figure 16).

Figure 16. Example of a Short Acceleration Lane Adjacent to a Barrier at a Work Space Access Point.

CHAPTER 5:
DEVELOPMENT OF TEMPORARY BARRIER GUIDELINES

Temporary barriers serve an important safety and mobility role in work zones, separating opposing traffic flows and separating work spaces from traffic spaces. In many cases, right-of-way and cross-section constraints limit what can and cannot be done from a temporary traffic control plan perspective. However, in other cases there are options in how the available roadway cross section is allocated between work activities and accommodating traffic while that work occurs. These decisions, in turn, influence how barriers are deployed. Ultimately, these trade-off decisions affect traffic safety and mobility, worker safety, and work task durations and quality. In this chapter, information is provided to aid work zone designers and contractors about how to deploy barriers in work zones. Information is provided on the following topics:

- Trade-offs between lane widths and lateral buffer distances to barriers.
- Whether to provide refuge areas for stranded motorists and the design of those areas (widths and lengths).
- Maximum acceptable distances between exit ramps within a work zone without emergency shoulders available.
- Recommended design elements for lane shifts.
- Recommendations on barrier anchoring requirements in work zones.

For each topic, the underlying research findings used to develop a recommended guideline are presented. These findings were then used to generate guidelines that could be incorporated into existing standard drawings or other TxDOT manuals. These guidelines are provided as an appendix to this report.

TRADE-OFFS BETWEEN LANE WIDTHS AND LATERAL BUFFER DISTANCES TO BARRIERS

Work zone barrier placement decisions are most often dictated by space availability and constructability requirements. However, in situations where some flexibility exists, analyses to assess the relative trade-offs between two or more alternatives can be useful. For example, two possible trade-off scenarios that work zone designers often face include:

- Deciding when it is preferable to place barriers adjacent to the travel lanes on both sides of the freeway through the work zone (i.e., creating a “cattle chute” scenario for drivers) to reduce overall project time versus maintaining an emergency shoulder on one or both sides of the freeway but increasing the duration of the project.
- Deciding whether to maintain 12-foot lanes through the work zone but providing little or no buffer space to the barrier versus narrowing the lanes to 11 feet but providing an additional foot of buffer space to the barriers.

Mathematically, a trade-off analysis of barrier deployment options is based on computing the differences in the number of crashes expected under each alternative. If the alternatives also involve a difference in construction costs, the difference in crashes would be converted to a societal crash cost value to compare against the difference in construction costs.

Research shows that work zones typically result in increased crashes relative to pre-work zone conditions. For freeway facilities, the increase in crashes depends most directly on the pre-work zone average daily traffic, the number of travel lanes available, and the expected duration of the work zone. Thus, reducing the duration of a work zone reduces the expected number of additional crash costs that would occur. Baseline work zone crash modification factors (CMFs) have been developed for both four-lane and six-lane freeway/interstate work zones using data from Texas, Virginia, Ohio, and Utah (*34*):

$$CMF_{4-lanes\,WZ} = \frac{e^{-10.036+1.164\,ln\,(AADT)}}{e^{-11.231+1.248\,ln\,(AADT)}}$$

$$CMF_{\;6-lanes\,WZ} = \frac{e^{-9.987+1.164\,ln(AADT)}}{e^{-12.420+1.356\,ln(AADT)}}$$

Data were not sufficient to develop similar models for larger freeways. Therefore, it is recommended to use the CMF for six-lane work zones for freeway work zones involving more than eight lanes as well.

The appropriate CMF is applied to an estimate of what would be the normal (non-work zone) number of crashes expected on the roadway segment over the duration of an alternative to yield how many crashes would be expected to occur during the project. Thus, this approach also requires a model to predict what the normal frequency of crashes would be expected to be on the roadway segment over the duration of the project. A safety performance function generated from the *Highway Safety Manual* (*35*) could be used, but a model that has been calibrated to regional conditions would be preferable. Fortunately, a 2015 study of the effects of different lane and shoulder width combinations on Texas freeways provides a useful model for this purpose (*36*):

$$N_{Total} = 1.0027\;x\;L\;x\;AADT^{0.539}\;x\;e^{(-1.0243RUD-1.0877RDD-0.0241[Nlane\;x\;ALW]-0.0735RSW-0.0646LSW)}$$

Where:

N_{Total}	=	Total crashes expected per year.
L	=	Length of segment (miles).
AADT	=	Average annual daily traffic (veh/day).
RUD	=	Distance to closest upstream ramp (miles).
RDD	=	Distance to closest downstream ramp (miles).
Nlane	=	Number of lanes in the section.
ALW	=	Average lane width (feet).
RSW	=	Average width of right shoulder (feet).
LSW	=	Average width of left shoulder (feet).

An advantage of this model is that it already incorporates estimates of the effects of altering lane and shoulder widths upon crash expectancies, albeit for non-work zone conditions. Ideally, CMFs would be used for those changes that are calibrated to work zone conditions for a trade-off analysis. Unfortunately, such CMFs do not currently exist.

The incorporation of both lane width and shoulder width differences into the model makes intuitive sense, and the fact that the model focuses explicitly on Texas freeways and interstates makes it preferable for this project. Combining this model of lane and shoulder effects with the estimated overall work zone CMF described previously provides a reasonable way of assessing the trade-off effects of alternative work zone design decisions involving placement of barriers. An additional term is simply needed to normalize the analysis to the duration of the work zone alternative being considered:

$$N_{Alt} = CMF_{4-or\ 6-lanes\ WZ}\ x\ n_{Alt}\ x\ N_{Total_{Alt}}$$

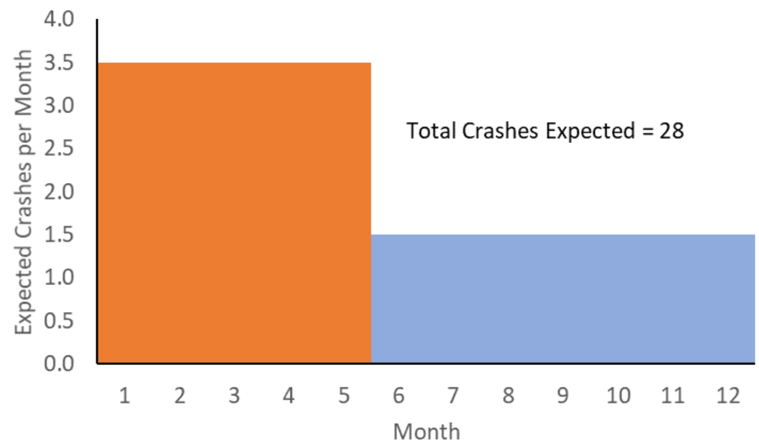
Where:

N_{Alt}	=	Total number of crashes expected during the time when the alternative is in the work zone condition.
n_{Alt}	=	Duration of the alternative (years).
$N_{Total_{Alt}}$	=	N_{Total} based on conditions for the alternative.

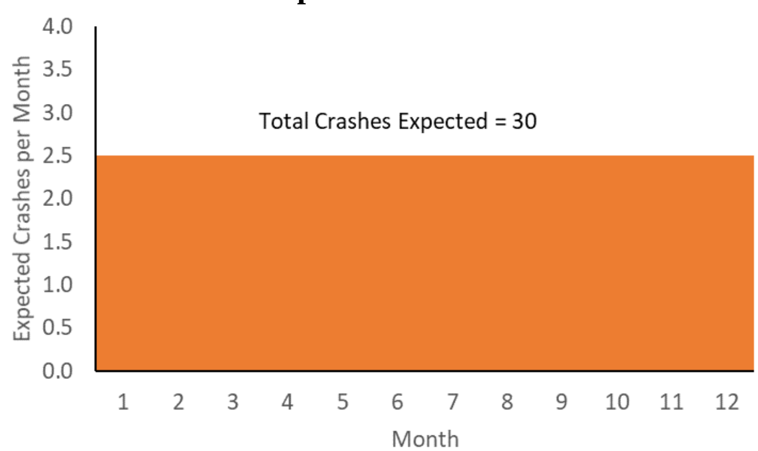
Other variables are previously defined.

The model represents both directions of travel. If different design elements will exist in each direction, two versions of the model would need to be used, each assuming the design elements of one direction exist in both directions. The results of the analysis can then be halved to represent what would be expected to occur in the direction that those design elements represent. Also, for a trade-off analysis using these models to be comparable, the service life for each alternative needs to be the same in order to account for the effect of different project durations on the cumulative crash experience on the facility. The simplest way to accommodate this requirement is to evaluate the work zone conditions of each alternative for their expected durations, and then use the N_{Total} equation for conditions after the project is completed for the shorter-duration alternative to normalize both alternatives to the same overall duration.

For example, assume a hypothetical situation in which two alternatives for performing a project are being considered. The first alternative involves more restrictive conditions and would be expected to result in 3.5 crashes per month during the project. However, the project itself could be completed in five months. The second alternative would be less restrictive, expected to result in only 2.5 crashes per month during the project. However, it would take 12 months to complete. Once the project was completed, the newly repaired road segment would be expected to create only 1.5 crashes per month. Figure 17 shows a graph of expected crashes for both alternatives. Because the first alternative would be completed faster, it would reach its reduced non-work zone crash rate starting in month 6. Conversely, the second alternative would last through month 12 before it would reach its reduced non-work zone crash rate, after which both alternatives would experience the same crash rate per month. While the first alternative experiences a 40 percent higher crash rate during the project relative to alternative 2 (3.5 crashes/month versus 2.5 crashes/month), the total number of crashes expected to occur during a one-year period is actually greater for alternative 2 due to its longer duration as a work zone before returning the roadway to its normal state with a lower crash rate.



Crashes expected for Alternative 1



Crashes expected for Alternative 2

Figure 17. Comparison of Alternative Crash Expectancies during a Project.

Next, analyzing the difference in expected crashes alone between alternatives may be sufficient when the question only pertains to the effect of differing project durations. However, in some cases, the differences may also involve differences in construction costs. In those cases, it is useful to consider the societal costs of the difference in expected crashes against the difference in expected construction costs. To do this, the difference in expected crashes can be multiplied by the average societal costs of a work zone crash on freeways and interstates. Recommended comprehensive crash cost values published by FHWA are useful for this purpose (*37*). Based on the work zone crash data described in Chapter 2 of this report pertaining to the relative distribution of freeway/interstate work zone crash severities and updating the crash cost numbers in Harmon et al. (*37*) to 2019 dollars using the consumer price index (*38*), an average Texas interstate/freeway work zone crash cost of $142,890 is computed as shown in Table 29.

Table 29. Computation of an Average Freeway/Interstate Work Zone Crash Cost in Texas.

Crash Severity	Comprehensive Crash Cost (2019 Dollars)	Proportion of Freeway/Interstate Work Zone Crashes	Proportion × Crash Cost
Fatal (K)	$12,031,933	0.0065	$77,821
Incapacitating injury (A)	$697,710	0.0197	$13,728
Non-incapacitating injury (B)	$211,443	0.0961	$20,326
Possible injury (C)	$133,790	0.1642	$20,970
PDO	$12,676	0.7135	$9,045
Total		**1.000**	**$142,890**

Referring back to the alternatives comparison illustrated in Figure 17, if it is assumed that the severity distribution of crashes once the project was completed was the same as it was during the project, the reduction of two crashes under alternative 1 relative to alternative 2 would be equivalent to $285,780 in societal crash cost savings. If alternative 2 involved lower project costs (perhaps due to easier delivery of materials, for instance), the amount of the reduced cost could be compared to this reduction in crash costs when deciding which alternative to implement. Of course, comprehensive crash costs are borne by the public, whereas TxDOT bears the actual project costs. For this reason, the work zone designer may not be able to consider the two types of costs equal in the decision-making process. Nevertheless, considerations of both costs can help guide decision making regarding work zone design.

PROVISION OF EMERGENCY TURNOUTS FOR STRANDED MOTORISTS

In locations where an emergency shoulder wide enough for a stranded motorist to park on is temporarily removed due to space constraints in a work zone, a question that arises is whether providing spots where a section of the shoulder is retained as an emergency stopping location should be provided, and if so, how that spot should be designed (e.g., overall length and barrier flare rates). Theoretically, such a refuge area might reduce the likelihood of a disabled vehicle having to come to a stop in a travel lane and creating a significant safety hazard.

A review of national practice shows that a few but not all states provide emergency refuge areas or turnouts for disabled vehicles (*9*). Agencies that do use them typically provide them at 0.5- to 1.0-mile intervals. Figure 18 shows an example of an emergency turnout from Mahoney et al. (*9*). The length shown does not allow a vehicle that has pulled over to stop in the area to re-enter the traffic stream at speed. Thus, this design may not be sufficient on higher-volume roadways where there are very few gaps of sufficient lengths between vehicles in the right lane to allow a vehicle in the turnout to safely re-enter the traffic stream. The literature does not contain useful information on how frequently such turnouts are provided, or how many crashes they may prevent from occurring.

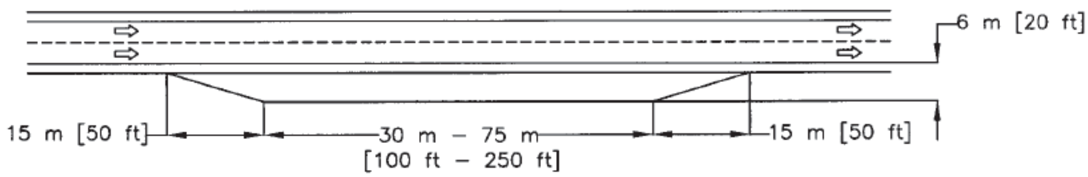


Figure 18. Example of an Emergency Turnout (*9*).

Even though data on the effectiveness of turnouts for crash reduction are not available, the crash prediction model described previously can also be used to assess the relative trade-offs of providing emergency turnouts in work zones where full-length emergency shoulders cannot be provided. Specifically, it is possible to estimate the expected number of crashes that would occur in the no-turnout scenario and then compute what reduction in crashes would have to occur to offset the increased cost (and likely longer project duration) if turnouts were incorporated into the work zone design.

For example, consider a 3-mile widening project on a suburban four-lane interstate serving 45,000 vpd. The work zone designer is contemplating the need to design the project to provide an emergency turnout during a six-month phase when only 2-foot buffer spaces can be provided on the left and right of the travel lanes. It is expected that the contractor could sequence work in a way that could accommodate the turnout for the same six-month period but would increase the cost of the project by $750,000. An entrance ramp and an exit ramp are both located 1 mile from the midpoint of the work zone where the turnout is being considered.

Based on the output of the crash prediction model, this phase of the project without the turnout would be computed to experience 18.79 crashes during the six-month phase:

$$CMF_{4-lanes\,WZ} = \frac{e^{-10.036+1.164\,ln\,(45000)}}{e^{-11.231+1.248\,ln\,(45000)}} = 1.343$$

$$N_{Alt\ no\ turnout}$$
$$= 1.343\ x\ 0.5\ x\ 1.0027\ x\ 3\ x\ 45000^{0.539}\ x\ e^{(-1.0243\ x\ 1-1.0877\ x\ 1-0.0241[4\ x\ 12]-0.0735\ x\ 2-0.0646\ x\ 2)}$$
$$N_{Alt\ no\ turnout} = 18.79\ crashes$$

Based on the average work zone crash cost of $142,890 from Table 29, these 18.79 crashes would be expected to impose a comprehensive societal cost upon the public of $2,684,922. Thus, in order to offset the increased cost of construction, the emergency turnouts would need to be expected to reduce these crashes by $750,000/$2,684,922 × 100, or 27.9 percent. However, studies of the effect of all incidents suggest that less than 10 percent of all crashes on a freeway are the result of a previous incident such as a stalled vehicle or a prior crash (*39*). It is reasonable to assume that only a small portion of even those secondary crashes are due to a stalled vehicle in a travel lane (the assumption being that a turnout would potentially allow the stalled vehicle to pull out of the lane). Consequently, it is very unlikely that the crash cost savings of providing emergency turnouts in this instance could offset the increased costs of providing the turnouts. If the provision of turnouts had increased the overall duration of the project, the effect of the longer project on crashes (and the amount by which turnouts would have had to reduce those crashes to be cost-effective) would also need to have been considered as previously described.

Emergency turnouts could also result in significant mobility benefits by reducing the amount of delay that might occur if a stalled vehicle remained in a travel lane rather than move to a turnout. However, incorporation of mobility considerations into a trade-off analysis requires more detailed data about stalled vehicle behaviors. For example, the frequency of stalled vehicles that occur, how far they typically travel with drivers knowing they are having trouble before they stop moving completely, and the distribution of these events by time of day would all be important variables in a trade-off analysis. Unfortunately, as stated previously, stalled vehicle data such as these are not readily available at this time.

MAXIMUM EXIT RAMP SPACINGS

When a work zone requires the temporary loss of emergency shoulders, the spacing between exit ramps influences the likelihood of vehicle stalls occurring in travel lanes and the effectiveness of law enforcement efforts. The closer the spacing between exit ramps, the less likely that a vehicle in distress will not be able to reach the exit and will become stalled in a freeway travel lane. Similarly, the greater the distance between exit ramps, the longer it takes enforcement to make a traffic stop since the violating vehicle will need to travel to an exit to find a place to pull over. In addition, the potential exists for the violating vehicle to make an incorrect decision and stop in the travel lane when the enforcement vehicle activates its flashing lights.

Unfortunately, data are not available regarding the probability of vehicles in distress not making it to an exit as a function of the distance to the exit ramp. Likewise, the reduction in effectiveness of law enforcement efforts (as well as the probability of incorrect driver response to enforcement efforts) has not been quantified. However, previous research of the appropriate distance between enforcement pullout areas in work zones determined that a 2- to 3-mile distance was the best trade-off between enforcement effectiveness and construction efficiency (*27*). If used, enforcement pullout areas need to be long enough to allow both the enforcement vehicle and the vehicle being pulled over to enter the area and decelerate to a stop. The pullout area also needs to be long enough to allow the vehicles to accelerate prior to re-entering the traffic stream once the enforcement activity is completed.

LANE SHIFT DESIGN

Lane shift designs vary widely in terms of the distance laterally that a lane must be moved. Intuitively, a lane shift of only 1 foot or so laterally is much easier for drivers to accommodate than a lateral shift across one or more travel lanes. In addition, performing the lateral movement over a shorter distance is more difficult than accomplishing it over a longer distance.

The *Texas Manual on Uniform Traffic Control Devices* provides guidance on the length of shift tapers (*40*). Specifically, the length of a lane shift taper is computed as one-half the length of a merging taper, which itself is a function of the posted speed limit and the width of the lateral distance being closed:

$$Shift\ Taper\ Length\ (ft) = \frac{WS}{2}$$

Where:

W = Width of the lateral shift (feet).

S = Posted speed limit (mph).

The equation itself was developed through trial and error as a practical means of determining acceptable taper lengths. In most situations, agencies and contractors find that the tapers deployed using these criteria work well. However, in situations where the barrier is located close to the edge of the travel lanes, field personnel perceive an increase in barrier hits and crashes with the barrier around these lane shifts. Furthermore, it is perceived that large trucks may be overrepresented in these hits and crashes. Although the analysis of work zone crash data in Chapter 2 could not verify that most of the crashes involving barriers were associated with lane shift locations, other research has suggested that lane shifts are associated with an approximate 21 percent increase of crash risk in work zones (*41*). Unfortunately, that research was not able to determine how differences in lane shift design criteria affected this increase in crash risk. As a result, it is not possible to perform a trade-off analysis of the effect of lengthening the shift taper that is believed to be able to reduce the challenges of negotiating lane shifts by large trucks when barriers are positioned close to the travel lanes.

ANCHORING BARRIERS IN WORK ZONES

TxDOT standard sheets specify the need to anchor concrete barriers in work zones where site conditions will not allow up to 2 feet of deflection to occur if impacted by a vehicle (*42*, *43*). Meanwhile, steel barriers always require anchoring at each end and will deflect significantly when impacted if not also anchored intermittently along their lengths (*44*, *45*). Given that concrete barriers are what is typically used in work zone situations where space is tight, the remainder of this section addresses concrete barrier anchoring considerations only.

The 2-foot allowable deflection requirement for unpinned temporary barriers is based on crash test results and some degree of engineering judgment about what constitutes a practical worst-case impact condition of the barrier. However, a field review of barriers in use in several work zones (described in Chapter 4) identified multiple locations where the barrier had been impacted and had deflected more than 2 feet. The specific impact conditions (vehicle size and weight, speed, and impact angle) causing those deflections were not available. Fortunately, none of the deflected locations were constrained on the back side of the barrier and so did not appear to have created an unsafe situation. Nevertheless, it is readily apparent that the potential for deflections to exceed the 2-foot criteria does occur in Texas freeway work zones. The challenge is in determining the likelihood of such an impact where the consequence of that impact is deemed unacceptable (e.g., locations where a deflection beyond 2 feet could push the barrier into the opposing travel lane).

Although specific data on impact frequencies and impact conditions in work zones are not available, the crash prediction model previously discussed could once again be used to provide an estimate of the likelihood of a crash-reportable barrier impact in those sections where barrier anchoring is being considered. Although such an analysis would not guarantee that the impact itself would be sufficient to cause a barrier deflection of greater than 2 feet, it would provide an order-of-magnitude estimate of the likelihood of such a barrier impact. If the additional costs of providing anchoring to the barrier appear excessive relative to the likelihood of a barrier impact, then the cost relative to an even smaller likelihood of a barrier impact that would create more significant deflection would be even more excessive.

To perform such an analysis, the same crash prediction model and work zone CMF equation described previously can be used. Meanwhile, a review of work zone crash data documented in Chapter 2 suggested that 17 percent of work zone crashes where barriers are used involve impacts with the barrier. This percentage was essentially the same for automobiles and for large trucks. Although it is likely that most of the large deflections observed in the field evaluations were the result of large trucks hitting the barrier at large impact angles, that could not be verified through this research. Therefore, estimating the likelihood of any barrier-impact crash rather than only large-truck-involved crashes seems to be a conservative approach to performing this type of cost-effectiveness assessment. The process would involve:

- Computing the expected number of crashes in a work zone of a given length using the previous equations.
- Multiplying that value by the 17 percent of expected crashes that may involve collisions with the barrier.
- Comparing that value by the additional cost of anchoring the barrier where deflection risks are of concern.

As an example of this process, the previous example involving a 3-mile widening project on a suburban four-lane interstate serving 45,000 vpd is again used. An entrance ramp and an exit ramp are both located 1 mile from the midpoint of the work. In this scenario, 2-foot buffer spaces can be provided on the left and right of the travel lanes in both directions, implying that the median barrier would not need to be anchored. However, the work zone designer recognizes that a large horizontal curve in the middle of the section (approximately 1 mile in length) together with a high (25 percent) large-truck percentage presents a risk of a high-angle barrier impact by a large truck that could deflect the median barrier, if unanchored, across the 2-foot buffer and into the travel lane in the opposing direction. Anchoring would add $250,000 to the cost of the project. The project is expected to last one year. The computation of possible barrier crashes in that 1-mile section would be as follows:

$N_{Barrier} =$
$1.343 \; x \; 1 \; x \; 1.0027 \; x \; 1 \; x \; 45000^{0.539} \; x \; e^{(-1.0243 \; x \; 1 - 1.0877 \; x \; 1 - 0.0241[4 \; x \; 12] - 0.0735 \; x \; 2 - 0.0646 \; x \; 2)} \; x \; 0.17$
$N_{Barrier} = 2.1 \; crashes$

Thus, the model would predict that there will be slightly more than two barrier crashes within the 1-mile section of roadway over the duration of the project. Protecting against excessive barrier deflection would therefore cost $250,000/2.1 = $119,048 per potential barrier crash. The designer could then consider other aspects of the project (e.g., schedule and budget constraints) to assess whether it would be cost-effective to require the anchoring.

CHAPTER 6: SUMMARY OF FINDINGS

This report documents the efforts of the research team to:

- Investigate the issues affecting temporary barrier deployment in work zones with constrained cross sections.
- Identify and evaluate available options to potentially address those issues.
- Develop improved guidelines regarding barrier deployment on Texas freeways.

To accomplish these objectives, the team:

- Performed a review of literature relevant to the deployment and use of barriers in work zones.
- Analyzed a sample of Texas work zone crashes to better understand any direct or indirect influence of barrier presence, focusing on crashes associated with large trucks or emergency responders.
- Surveyed key construction personnel to identify the state of the practice in barrier use and other design criteria for freeway work zones.
- Surveyed trucking industry and law enforcement representatives to identify road users' perceived difficulties in traveling through various types of work zones with barriers.
- Conducted field evaluations of multiple barrier deployments on freeway work zones in constrained cross sections to identify deployment issues that exist.
- Identified and demonstrated analytical approaches to developing guidance pertaining to key work zone barrier deployment decisions.
- Developed a set of guidelines on work zone barrier use.

The literature review summarized numerous research efforts to evaluate the effects of temporary barrier use in work zones upon motorist and worker safety. Guidance on when to use temporary barriers if pavement edge drop-off conditions exist within the work zone has been incorporated into current TxDOT work zone design procedures, and several research efforts have been undertaken to include considerations of vehicle intrusions into the work space for worker and motorist safety in decisions about when to use temporary barriers. The challenges that temporary barriers close to the travel lanes within work zones present to drivers of large trucks as well as law enforcement and emergency response personnel have also been documented in past research, as have recommendations on ways to limit some of those challenges. However, data and analysis of the effectiveness of those recommendations in terms of reduced safety and mobility impacts are not currently known.

Analyses of crashes occurring at a sample of Texas freeway work zones suggested both similarities and differences in trends from project to project. Unfortunately, it was not possible to positively correlate any of these differences specifically to differences in work zone barrier deployments at those projects. Large-truck collisions with barriers in work zones occurred slightly more often (as a percentage of all truck crashes in work zones) than automobile crashes in work zones. Even so, a rear-end collision was still the most common type of work zone crash for both types of vehicles. The analysis also did not reveal significant insights about work zone barrier effects upon law enforcement or emergency response vehicle crashes in work zones, primarily because of very low sample sizes.

Surveys of TxDOT construction personnel, law enforcement personnel, emergency response personnel, and drivers of large trucks were adversely affected by the pandemic in calendar year 2020. Responses that were obtained yielded the following insights:

- Although decisions about when to use barriers in work zones should consider a wide range of risks and site-specific factors, the pavement edge drop-off criteria in the TxDOT *Roadway Design Manual* drive many of those decisions.
- Most work zone designers strive to maintain at least 11-foot lanes through the work zone.
- Efforts are made to keep at least every other exit or entrance ramp open within a freeway work zone. If that is not possible, efforts are made to define a specific detour route.
- Decisions to temporarily close ramps are typically coordinated with local emergency response personnel.
- Lane shifts are designed as shifting tapers using criteria set forth in the MUTCD.
- Requirements for when temporary barriers are to be anchored are not easy to find within the TxDOT standards.
- On some roadways, vibrations caused by large trucks also lead to barrier creep over time, which can also diminish the available deflection distance or working width of the barrier.
- Work zone project staff regularly get complaints when the work zone is so constrained that little or no buffer space is available from the travel lanes to the barrier on the sides of the roadway (i.e., the "cattle chute" work zone design). Some designers have opted to reduce the lane widths from 12 feet to 11 feet to provide an additional 1-foot (or more) buffer space on each side, which has reduced the complaints.
- Most law enforcement personnel perceive the presence of barriers in work zones to adversely affect their enforcement and incident response activities. In work zones where barriers must be used, enforcement personnel indicate that access points (ramps) every mile or two are highly preferable to longer distances between access points. Emergency response personnel also perceive the availability of ramps every mile or two as sufficient for negotiating freeway work zones with barriers on both sides near the travel lanes.

Field evaluations of temporary barrier use at a sample of Texas freeway work zones also yielded several useful insights:

- Barrier scuffs and scrapes in advance of lane shifts do suggest that short lane shifts surprise some drivers.
- Barrier segments often deflect more than 2 feet when impacted, which can adversely affect operations and safety in constrained work zone cross sections.
- Barrier scuffs and impact scars appear less frequent when the barrier maintains consistent offset with edge lines. Conversely, locations where the barrier is moving away or shifting back toward the travel lanes show increased barrier scuffs and impacts.

- Field conditions often create unique, unexpected deployment conditions for temporary barriers in work zones. Contractors should consult barrier crashworthiness experts when encountering such unusual situations.
- Single-slope barriers can create sight distance challenges for low-profile vehicles at merge points in work zones.
- Barrier use at entrance ramps and work space access points with short or no acceleration lanes can create challenges for vehicles attempting to merge onto the freeway.

Finally, researchers developed some crash-analysis-based guidance to aid work zone designers when making trade-off decisions between lane widths and lateral buffer distances to barriers, determining whether to provide refuge areas for stranded motorists, and determining whether to require temporary barriers to be anchored in the work zone even if a 2-foot deflection distance is available. The appendix presents a final set of recommended guidelines.

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APPENDIX:
WORK ZONE BARRIER USE GUIDELINE RECOMMENDATIONS

The use of temporary barriers in work zones is an important safety tool in the work zone designer's toolbox. Barriers are used to separate the traffic space through a work zone from the work space, and to keep opposing traffic on divided roadways separated. Ideally, barriers are used where the costs of providing the barrier plus the costs of crashes that occur with the barrier present are less than the costs of crashes that would occur if the barrier were not used. Pavement edge drop-offs, work equipment and materials, the proximity of workers and work areas to traffic traveling through the work zone, the volume and speed of that traffic, and its composition all influence whether the benefits of barrier use outweigh its costs. These safety-related factors interact with how the construction activities themselves will be accomplished because those activities will define where and how much space is required for work to occur and thus how close barriers (if used) will have to be placed to the actual travel lanes. Different allocations of available right of way to the traffic space versus the work space can also influence how long work activities themselves take before a project is completed.

GENERAL WORK ZONE BARRIER USE RECOMMENDATIONS

Currently, Appendix B of the TxDOT *Roadway Design Manual* provides guidelines on when barriers are to be used in work zones to protect motorists from pavement edge drop-offs. The guidelines consider:

- The amount of traffic passing through the work zone.
- The duration of the work zone.
- The depth of the pavement edge drop-off.
- The lateral distance of the pavement edge drop-off from the travel lanes.

Conditions other than pavement edge drop-offs should also be considered when determining whether barriers are to be used within the work zone. Federal regulations (23 CFR 630 Subpart K) require that an engineering study be performed to determine if positive protection to separate the work space from the traffic space is needed for a work zone project. The study shall consider the following factors and characteristics:

- Project scope and duration.
- Anticipated traffic speeds through the work zone.
- Anticipated traffic volume.
- Vehicle mix.
- Type of work (as related to worker exposure and crash risks).
- Distance between traffic and workers, and extent of worker exposure.
- Escape paths available for workers to avoid a vehicle intrusion into the work space.
- Time of day when workers will be present (e.g., night work).
- Work area restrictions (including the impact on worker exposure).
- Consequences from/to road users resulting from roadway departure.

- Potential hazard to workers and road users presented by the positive protection device itself and during device placement and removal.
- Geometrics that may increase crash risks (e.g., poor sight distance and sharp curves).
- Access to/from the work space.
- Roadway classification.
- Impacts of positive protection use on project cost and duration.

At a minimum, positive protection devices shall be considered in work zone situations that place workers at increased risk from motorized traffic, and where positive protection devices offer the highest potential for increased safety for workers and road users, such as:

- Work zones that provide workers no means of escape from motorized traffic (e.g., tunnels and bridges)
- Long-duration work zones (e.g., two weeks or more) resulting in substantial worker exposure to motorized traffic.
- Projects with high anticipated operating speeds (e.g., 45 mph or greater), especially when combined with high traffic volumes.
- Work operations that place workers close to travel lanes open to traffic.
- Roadside hazards, such as drop-offs or unfinished bridge decks, that will remain in place overnight or longer.

Part of the engineering study might include decisions about how best to allocate available traffic space between travel lanes (number and width) and shoulder or lateral offset to the barrier. Maintaining normal lane widths and existing shoulder widths may be possible but at increased cost and duration of the project. Conversely, constraining lane widths and temporary barrier offset from the lanes may increase crash risks but at a decreased cost and duration of the project. The following section provides a recommended approach to performing trade-off analyses to aid with these decisions.

COMPARING TEMPORARY BARRIER OFFSET ALTERNATIVES

In general terms, comparing alternatives about how space is allocated between traffic and the work space, and how the traffic space is allocated between travel lanes and barrier offsets from the travel lanes, can be accomplished through a relatively simple four-step procedure:

- Step 1: Identify the characteristics of each alternative being considered.
- Step 2: Set the comparison duration to the longest-duration alternative being considered.
- Step 3: Determine the expected number of crashes for each alternative over the common comparison duration of the alternatives.
- Step 4: Convert the difference in expected crashes between alternatives to the difference in societal crash costs (if needed).

Step 1: Identify the Characteristics of Each Alternative Being Considered

The first step in the comparison is to identify the key characteristics of each alternative being considered:

- Number of travel lanes in each direction of travel.
- Average lane widths.
- Offset of the barrier from the edge of the travel lanes.
- Length of the work zone being analyzed.
- AADT.
- Distance to upstream or downstream ramps.
- Expected duration of the work zone.

Step 2: Set the Comparison Duration to the Longest-Duration Alternative Being Considered

In most cases, the alternatives being analyzed will have different expected durations associated with them (e.g., a more constrained alternative may result in a much quicker completion). The benefits of earlier completion of such an alternative must be accounted for in the analysis. Therefore, the basis of comparison is the longest duration of the alternatives being considered.

Step 3: Determine the Expected Number of Crashes for Each Alternative over the Common Comparison Duration of the Alternatives

Two relatively simple predictive models are used to generate the expected number of crashes for each alternative of interest. The first is a model of total expected crashes for a Texas freeway with conditions for the alternative being analyzed:

$$N_{Total} = 1.0027\ x\ L\ x\ AADT^{0.539}\ x\ e^{(-1.0243RUD-1.0877RDD-0.0241[Nlane\ x\ ALW]-0.0735RSW-0.0646LSW)}$$

Where:

N_{Total}	=	Total crashes expected per year.
L	=	Length of segment (miles).
$AADT$	=	Average annual daily traffic (veh/day) .
RUD	=	Distance to the closest upstream ramp (miles).
RDD	=	Distance to the closest downstream ramp (miles).
$Nlane$	=	Number of lanes in the section.
ALW	=	Average lane width (feet).
RSW	=	Average width of the right shoulder (feet).
LSW	=	Average width of the left shoulder (feet).

The model itself was developed using non-work zone data, so the results from this model must be adjusted upward to account for the overall increase expected because it will be in a work zone:

$$CMF_{4-lanes\,WZ} = \frac{e^{-10.036+1.164\,ln\,(AADT)}}{e^{-11.231+1.248\,ln\,(AADT)}}$$

$$CMF_{\;6-lanes\,WZ} = \frac{e^{-9.987+1.164\,ln(AADT)}}{e^{-12.420+1.356\,ln(AADT)}}$$

Data were not sufficient to develop similar models for larger freeways. Therefore, it is recommended to use the CMF for six-lane work zones for freeway work zones involving more than six lanes as well.

In addition:

$$N_{Alt} = CMF_{4-or\;6-lanes\,WZ}\;x\;n_{Alt}\;x\;N_{Total_{Alt}}$$

Where:

N_{Alt}	=	Total number of crashes expected during the time when the alternative is in the work zone condition.
n_{Alt}	=	Duration of the alternative work zone condition (years).
$N_{Total_{Alt}}$	=	N_{Total} based on the work zone conditions of the alternative.

If one of the alternatives being considered will result in a shorter duration than the other alternative, the analyst will need to compute the number of crashes expected to occur (using the roadway characteristics that will exist after the project is completed) during the time between when the first (shorter-duration) alternative would be completed and when the longer-duration alternative would be completed, and add that to the expected crash number for the first alternative. In this way, the comparison of expected crashes between alternatives will be based on the same overall analysis duration:

$$N_{Alt\;1} = CMF_{4-or\;6-lanes\,WZ}\;x\;n_{Alt\;1}\;x\;N_{Total_{Alt\;1}} + \;N_{Total_{After\;WZ\;Alt\;2-\;Alt\;1}}$$

Where:

$N_{Alt\;1}$	=	Number of crashes expected during the time when alternative 1 is in the work zone condition.
$n_{Alt\;1}$	=	Duration of the alternative 1 work zone condition (years).
$N_{Total_{Alt\;1}}$	=	N_{Total} based on the work zone conditions of alternative 1.
$N_{Total_{After\;WZ\;Alt\;2-\;Alt\;1}}$	=	N_{Total} based on the after-work zone conditions for the difference in durations between alternative 2 and alternative 1.

Step 4: Convert the Difference in Expected Crashes between Alternatives to the Difference in Societal Crash Costs (If Needed)

If the two alternatives being compared will also result in different construction costs, the difference in the expected number of crashes between the alternatives should be multiplied by an average Texas freeway work zone crash cost of $142,890 (in 2019 dollars). This difference in societal comprehensive crash costs can then be compared to the difference in project costs to assess which alternative is preferred from an economic standpoint.

LANE WIDTHS VERSUS BARRIER OFFSET WIDTHS

Based on the predictive crash model described in the previous section, reducing lane widths through the work zone in order to increase the barrier offset from the travel lanes will result in fewer crashes than retaining wider lanes and placing the barrier closer to the travel lanes. A work zone with two 11-foot lanes and 1-foot offset to barriers on both sides of the travel lanes is expected to result in 8.6 percent fewer crashes than a work zone with two 12-foot lanes and no offset to the barrier on either side. The same reduction in expected crashes would be computed if reducing lane widths to increase barrier offsets from 2 to 3 feet, from 3 to 4 feet, etc. Lane widths less than 11 feet should not be used within freeway work zones because they create significant challenges to drivers of large commercial motor vehicles.

EMERGENCY TURNOUT LOCATIONS

It is recommended that emergency turnouts be used cautiously in freeway work zones, especially on high-volume facilities. Using the methodology described previously, a trade-off analysis of the effects of providing turnouts on construction costs and duration should be compared to the comprehensive societal crash costs expected during the project without turnouts provided. If the turnouts would have to result in more than a very small percentage reduction of the crashes otherwise expected on the facility, it would not be expected to be a cost-effective countermeasure to implement.

If used, emergency turnouts should be at least 100 feet long (and preferably much longer), 20 feet wide, and follow current TxDOT guidance regarding barrier flare rates into and out of the turnout area.

ENFORCEMENT PULLOUT AREAS

In situations where emergency shoulders are not available within the work zone, it is recommended that exit ramp spacing be limited to 2 miles or less so that both enforcement and emergency response activities are not unduly hampered. If exit ramp spacing exceeds this distance and no emergency shoulders are available anywhere within the work zone, consideration should be given to providing an intermittent enforcement pullout area. Such an area could also serve as an emergency refuge area for disabled vehicles and can be coordinated with access points that include acceleration lanes for construction vehicles leaving the work space. A cost-effectiveness assessment as described previously on emergency turnouts could be performed to aid in the decision. If enforcement/refuge areas are included, advance signing notifying drivers of the upcoming area should also be included. Figure A-1 illustrates the recommended design characteristics of an enforcement pullout area.

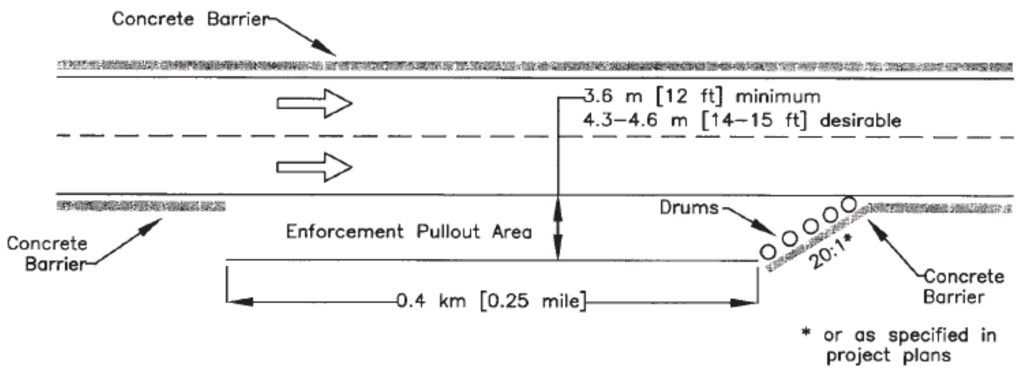

Figure A-1. Recommended Work Zone Enforcement Pullout Area Design Criteria.

BARRIER USE AT LANE SHIFTS

Currently, there is a lack of definitive data about the effects of differences in lane shift design criteria upon crashes, particularly those involving large trucks when barriers are positioned close to the travel lanes. Therefore, it is not possible to recommend specific changes to the Texas MUTCD guidance for shifting tapers as follows:

$$Shift\ Taper\ Length\ (ft) = \frac{WS}{2}$$

Where:
W = Width of the lateral shift (feet).
S = Posted speed limit (mph).

Work zone designers should continue to use the Texas MUTCD equation as an absolute minimum for work zone lane shifts. However, designers should strive to provide a shift taper length longer than the minimum (up to the length of a merging taper) whenever it is feasible to do so. It is also recommended that designers use prevailing 85th percentile speeds on a facility, rather than a reduced work zone speed limit or design speed, when computing appropriate taper lengths. For example, use of an 85th percentile speed of 70 mph in a freeway work zone rather than a 55-mph work zone speed limit would increase the length of a lane shift by 27 percent. For a full 12-foot lateral shift in travel lanes, this is equivalent to a 90-foot increase in the length of the lane shift.

DECISIONS ON WHEN TO ANCHOR TEMPORARY BARRIERS

Field assessments of unanchored temporary barrier deployments suggest that such barriers are often impacted under conditions that regularly result in deployments greater than the required 2-foot deflection criteria listed in TxDOT standards CSB (7)-10 and SSCB (5)-10. Work zone designers should critique locations where greater than a 2-foot deflection is likely to result in adverse operational and safety consequences (e.g., where work will be occurring right next to the barrier or where a temporary barrier is separating opposing traffic flows with only a 2-foot offset from the travel lanes) to determine if the temporary barrier should be anchored.

To assist in the critique, it is recommended that work zone designers consider performing a cost-effectiveness assessment of potential barrier crashes against the added costs and time of anchoring barriers in locations where potential deflections exceeding 2 feet may cause significant operational or other safety issues within the work zone. The predictive model of work zone crashes previously described can be used to estimate the expected number of crashes in the work zone over the duration of the project. This estimate should then be multiplied by a factor of 0.17, representing the percentage of Texas freeway work zone crashes that involve impacts with a barrier. Although many of those crashes will not involve impact conditions that would result in more than the 2-foot deflection allowance in the standard, engineering judgment can be used to judge the likelihood of such an impact in relation to any increase in costs and project duration that may result from requiring the temporary barrier to be anchored.