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16. Abstract

The goal of this project was to develop implementation guidance that the Texas Department of Transportation (TxDOT) can use to make better decisions regarding when and where to use positive protection in work zones and when to consider exposure control and other traffic control measures that could improve work zone safety. The specific objectives of the project were as follows:

- Analyze the benefits and costs of using portable concrete barrier (PCB) for positive protection in work zones.
- Analyze the benefits and costs associated with the use of moveable and portable barrier technologies that can be more quickly deployed and removed at work sites than traditional PCB.
- Analyze the benefits and costs of non-positive protection devices that can be used to improve safety and reduce work zone intrusion events in work zones.
- Develop implementation guidelines for these various technologies.

Researchers also developed guidelines for portable concrete barrier use in work zones. Guidelines regarding the use of portable steel barrier, mobile barrier, and truck-mounted attenuators were also developed. General guidance and information regarding the use of exposure control measures and other traffic control measures to reduce work space intrusion risks were also included in this report.

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WORK ZONE POSITIVE PROTECTION GUIDELINES

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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 the 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 L. Ullman, Ph.D., 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.

ACKNOWLEDGMENTS

This project was conducted in cooperation with TxDOT and FHWA. The research documented here was overseen by a TxDOT Project Monitoring Committee. Ismael Soto served as the project director. Tom Beeman, Bobby Dye, and Gary Tarter served as project advisors. Wade Odell served as the TxDOT Research Engineer. The assistance and direction provided by these individuals over the course of the project is gratefully acknowledged.

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INTRODUCTION

STATEMENT OF THE PROBLEM

On December 5, 2007, the Federal Highway Administration (FHWA) published 23 CFR Part 630 Subpart K – Temporary Traffic Control (630.1102 – 630.1110)] with an effective date of December 4, 2008 (*1*). The objective of the rule is to "decrease the likelihood of highway work zone fatalities and injuries to workers and road users." The new rule establishes requirements related to five items for Federal-aid projects:

- General agency guidance or project-specific measures identified through engineering studies to determine the need for positive protection in work zones,
- Exposure control measures to avoid or minimize worker exposure to motorized traffic and motorist exposure to work activities,
- Other traffic control strategies (including uniformed law enforcement officers) to minimize work zone crashes,
- Safe entry/exit of work vehicles onto/from the travel lanes,
- Contract pay items to ensure availability of funds for these provisions.

The rule includes a list of 15 factors for state transportation agencies to consider when developing guidance for the use of positive protection, exposure control measures, and other traffic control strategies (or combinations thereof):

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

11. Potential hazard to workers and road users presented by device itself and during device placement and removal.
12. Geometrics that may increase crash risks (e.g., poor sight distance, sharp curves).
13. Access to/from work space.
14. Roadway classification.
15. Impacts on project cost and duration.

At a minimum, the rule states that positive protection shall be considered where work zone conditions place workers at increased risk from motorized traffic (e.g., tunnels and bridges that limit worker escape routes, long duration projects on high-speed facilities that place workers in close proximity to motorized traffic, etc.) and where positive protection devices can significantly improve safety (such as to protect a pavement edge drop-off that will be in place overnight or longer). However, the rule does not provide specific requirements or thresholds on positive protection usage. Rather, states are responsible for developing general policies or project-specific decision frameworks for determining situations, locations and types of positive protection to use (e.g., traditional portable concrete barrier [PCB] or some of the newer barrier technologies). FHWA also encourages states to consider techniques intended to reduce the likelihood that a vehicle intrusion into the work zone will occur at all.

PROJECT OBJECTIVES

The goal of this project was to develop implementation guidance that the Texas Department of Transportation (TxDOT) can use to make better decisions regarding when and where to use positive protection in work zones, and when to consider exposure control and other traffic control measures that could improve work zone safety. The specific objectives of the project were:

- Analyze the benefits and costs of using portable concrete barrier for positive protection in work zones.
- Analyze the benefits and costs associated with the use of moveable and portable barrier technologies that can be more quickly deployed and removed at work sites than traditional PCB.

- Analyze the benefits and costs of non-positive protection devices that can be used to improve safety and reduce work zone intrusion events in work zones.
- Develop implementation guidelines for these various technologies.

CONTENTS OF THIS REPORT

The next chapter provides background on current guidelines and practices nationally and within Texas regarding the use of positive protection in work zones. The methodology and results of analyses performed to investigate each of the first three objectives listed above are then incorporated into the next three chapters of this report. The final chapter provides a summary of the results and key conclusions. A set of recommended implementation guidelines, suitable as a stand-alone document for inclusion into TxDOT manuals, is provided as an appendix.

BACKGROUND

REVIEW OF STATE DOT POSITIVE PROTECTION PRACTICES IN WORK ZONES

A review of state DOT policies and guidelines pertaining to positive protection use in work zones finds that many are formulated very similarly to the requirements stated in the federal regulations. The policy often indicates that positive barrier will be "considered" for a variety of situations and then lists the same factors found in the subpart K requirements almost verbatim. It should be noted that several states, including Texas, include some guidance pertaining to the protection of large (greater than 2 ft) drop-offs near the travel lanes. However, positive protection guidelines beyond that particular condition are fairly limited.

One of the few exceptions found is in Maryland, where specific criteria are defined for when positive barrier protection will be required (*2*):

"It is the policy of the Maryland State Highway Administration (SHA) that temporary traffic barrier protection is required for all work on high-speed facilities where

(1) The operation occurs on the roadway or shoulder, or is within 10 ft of the edge of a travel lane open to traffic, and the duration of work is expected to be at least two weeks and the limits of the work area remain unchanged for that duration.

OR

(2) There is no means of escape for workers from motorized traffic (e.g., tunnels, bridges, etc.), and the duration of work is expected to be at least two weeks and the limits of the work area remain unchanged for that duration."

The Maryland SHA policy does include provisions to deviate from these criteria, but such deviation requires an engineering study to determine why temporary traffic barrier protection is not feasible. The preparation and submission of an official waiver must be approved by the senior manager of the lead office.

The Virginia DOT (VDOT) is another agency that has established a fairly rigorous analysis approach for determining when positive barrier shall be used in work zones (*3*).

However, the VDOT procedure is based on analysis of any fixed objects that will be placed in close proximity of the travel lanes during the work zone. The potential of a run-off-the-road crash occurring and hitting the fixed object (if it cannot be removed) is first estimated. If the potential for a crash to occur is 0.5 or higher (i.e., the potential is at least 50 percent), a positive barrier is to be used. VDOT does distinguish between the use of PCB and the use of barrier guardrail fence, which is indicated in the VDOT guidance as being "less positive."

The Michigan DOT has specified that positive barriers *should* be used under the following conditions:

- on all bridge work where a precipitous drop-off is within 4 ft of the toe of the barrier closest to the active travel lanes,
- where there is scaffolding or other structures or equipment with workers overhead in place for three days or more,
- where motorized and non-motorized travel lanes are adjacent to each other with no difference in elevations or mountable curbs with vehicle operating speeds of 45 mph or higher, and
- on all long-duration (three days or more) projects where workers are continuously within 6 ft of an open high speed traffic lane or lanes in one specific direction (*4*).

It is not clear from the guidance whether "continuous" refers to time, to the length of work activity relative to the length of the barrier, or both.

In each of the above examples, concerns over work zone crashes (those in addition to drop-off crashes) drive the development of the guidance. However, further review and investigation by the research team failed to uncover any background analyses that may have been used to arrive at the threshold criteria used in each case. It appears that the minimum duration thresholds for Maryland and Michigan reflect the practicalities of moving PCB into and out of a work zone, rather than any type of benefit-cost analysis. The fact that neither discusses traffic demand nor expected crash frequency provides further evidence supporting this hypothesis. In contrast, the guidelines followed by VDOT explicitly consider crash risk, using run-off-road crash rates and the roadway annual average daily traffic (AADT) to estimate risk. However, as noted previously, the guidelines are designed only to consider fixed objects that exist within the work area. Consequently, none of the examples listed attempts to consider the worker intrusion crash risk potential formally in the analysis process.

TXDOT WORK ZONE POSITIVE PROTECTION PRACTICES

Given the lack of formal guidance on the topic, researchers chose to survey district personnel around the state to determine any informal processes or rules-of-thumb that were being followed with respect to positive protection use in work zones. Researchers designed the survey to determine the following:

- Factors and criteria that are considered in deciding whether to use positive protection for a given work zone segment.
- Work zone situations (i.e., roadway types, traffic volumes, speeds, project types, roadside hazards, etc.) where positive protection is almost always used.
- Work zone situations where deciding whether to use positive protection is the most difficult.
- Factors other than worker or traffic safety (e.g., contractor productivity, simplicity of installation or removal, etc.) that are considered (as well as how they are considered) in work zone positive protection decisions.
- Decision criteria used to specify other vehicle intrusion countermeasures (e.g., reduced speed limits, enforcement, etc.) in construction plans.

The primary inventory tool was an emailed survey of TxDOT districts as well as follow-up phone interviews of a selected number of survey respondents. Information gathered from the emailed survey and phone interviews was supplemented with additional insights gathered from published TxDOT guidance documents as well as temporary traffic control plans for recently bid construction projects in Texas. Appendix A contains a copy of the survey instrument. Twelve districts completed the survey, providing information on 53 projects in which positive protection was used. Overall, the researchers received a fairly wide range of responses regarding the applications where barrier is typically used. Bridge replacement, roadway widening and reconstruction, interchange reconstruction, and ramp reversal projects were all identified. In most cases, the projects were scheduled to last from 6 months to 5 years (although one district did report using positive protection for a one-month job). In all but one case, portable concrete barrier (either safety-shaped, F-shaped, single-slope, or low-profile) was the positive protection technology of choice (the remaining project had used water-filled barrier). A summary of findings for each of the above topics is provided below.

Positive Protection Decision Factors and Criteria

District personnel reported considering a number of factors and criteria when deciding whether or not to use positive protection:

- Pavement edge drop-off presence and height (40 percent).
- Worker and motorist safety (19 percent).
- Close horizontal offsets to hazards (e.g., work area or edge drop-off) (17 percent).
- High traffic speed (17 percent of projects).
- Exposed structures (e.g., bridge abutments) (15 percent).
- Small separation between traffic in opposing directions (6 percent).
- Project duration (4 percent).

For some projects, respondents identified multiple factors or criteria such that the total of the percentages listed exceeds 100. As shown in the list, the most common reasons or factors cited for using positive protection was the presence of a pavement or edge drop off that met or exceeded the current drop-off depth and lateral proximity criteria specified in the TxDOT *Roadway Design Manual* (*5*) (which came from previous pavement edge drop-off research [*6*]). Exposed structures such as bridge abutments within the clear zone, which require positive protection in all cases, were also cited as a reason quite frequently.

In several instances, respondents cited worker and motorist safety as a consideration that led to the use of positive protection. However, when those districts were contacted to determine what specific thresholds were used (type of work, AADT level, roadway speed, percent trucks, etc.), none could be identified. Rather, survey respondents indicated that they typically consider the body of evidence in a more qualitative manner and try to make a judgment call as to whether the safety risks outweigh the additional costs of requiring barriers. One district indicated that they noted that an average daily traffic (ADT) of about 30,000 vehicles per day (vpd) was about the volume level at which they started thinking more about possible barrier use on a project.

Survey respondents did note that positive protection use generally required that the project be fairly lengthy in duration. Of the projects provided to the research team for examination, only 11 percent were less than one year in duration and 36 percent were 3 years duration or longer.

Work Zone Situations where Positive Protection Is Used

The majority of projects identified by the districts tended to fall under one of four main project categories. As would be expected, these types of projects tend to be longer-duration activities and the types of projects that can involve the creation of temporary drop-offs and fixed objects within the clear zone:

- Bridge replacement/repair/widening – 36 percent.
- Roadway reconstruction – 21 percent.
- Roadway widening – 15 percent.
- Interchange construction/reconstruction – 13 percent.

As might also be expected, positive protection is used most often on freeway facilities and least often on farm-to-market road projects. The combination of high speeds and high traffic volumes make it easier for work zone designers to justify in their minds the use of positive protection. The distribution of projects using barriers by roadway type is provided below:

- Freeway projects – 36 percent.
- US highway projects – 34 percent.
- State highway projects – 15 percent.
- Farm-to-Market road projects – 13 percent.

The remaining project was located on a loop roadway.

Projects where It Is Difficult to Decide on Positive Protection Use

Although the survey respondents indicated that they did not have specific criteria or thresholds of one or more factors that they used to decide when to use positive protection in work zones for situations other than drop-offs or fixed object protection, none of the surveys or subsequent interviews revealed any insights or experiences about instances in which the decision to provide or not provide positive protection was difficult. As stated previously, those interviewed decided primarily based on drop-off or fixed-object concerns, and the occasional project in which positive protection was specified for other safety concerns did not seem to cause the survey participants much concern.

Factors Other than Worker or Traffic Safety Considered in Positive Protection Decisions

None of the survey respondents identified any other reasons (such as productivity, simplicity of installation and removal, etc.) that they consider when making decisions about work zone positive protection. Discussions during interviews suggested that those types of reasons would (or should) come from the contractor's perspective as part of their bid. If the contractor felt that it was in their best interest to use positive protection for those or other reasons, the respondents assumed that they would indicate so in their bid and assume the costs of providing the barrier. None of those interviewed could recall a case in which they had agreed to pay for barrier that was suggested by the contractor to be included that was not with regards to a safety issue (such as a drop-off or fixed-object) that had been missed during work zone design.

Types of Barrier End Treatments Used

Another facet of the surveys targeted district use of various types of barrier end treatments used in work zone projects. Respondents identified a variety of end treatments among the 53 projects for which information were provided:

- Taper barrier so blunt end is outside of clear zone.
- ABSORB 350 Crash Cushion.
- Narrow React 350.
- Metal Beam Guardrail Fence.

- QuadGuard (of different widths).
- Trinity Attenuating Crash Cushion.
- Sloped End Terminal for Low-Profile Barrier.
- TAU II Crash Cushion.
- Sand-filled Plastic Barrels.
- REACT Crash Cushion.
- Single Guardrail Terminal.

For the most part, tapering the barrier was preferred where possible because it was the cheapest alternative available. When that was not possible, survey respondents indicated that it was usually the contractor's choice as to what to use, as long as it could fit within the space available and could function properly. In a few cases, the work zone designer would specify a particular crash cushion be used in a location, presumably based on an analysis of how the crash cushion would perform if hit and how the impacting vehicle would react and interact with other aspects of the work zone.

Technologies Other than Positive Protection to Reduce Intrusion Risk

The second part of the survey inventoried the use of other technologies, techniques and strategies meant to reduce the risk and consequences of vehicle intrusions into the work area. Respondents identified a total of 13 projects in response to this question. The strategies noted as being used for this purpose included:

- Reduced speed limits.
- Portable changeable message signs (PCMS).
- Speed display trailers.
- Enhanced law enforcement presence.
- Lane rental provisions in the contract to limit the number of lane closures used by the contractor.

Most of the respondents who provided information about these applications did not have any data indicating whether or not they were effective (most did believe they were, though).

Use of Truck-Mounted Attenuators

The final questions of the survey examined respondent practices and perceptions toward the use of truck-mounted attenuators (TMAs). A number of typical low-speed mobile operation maintenance activities were identified where TMA usage would typically be considered:

- Striping.
- Patching.
- Paving (overlays or seal-coats).
- Guardrail repair.
- RPM installation.
- Crack sealing.
- Sweeping.

Several respondents simply responded to this question by stating that they follow the TxDOT TCP standard sheet requirements, and always use TMAs during mobile operations.

ANALYSIS OF EXPECTED CRASH REDUCTION BENEFITS AND COSTS OF PORTABLE CONCRETE BARRIER USE IN WORK ZONES

The encroachment-based hazard protection benefit-cost analysis approach outlined in the AASHTO Roadside Design Guide was viewed as the most logical methodology for calculations of crash cost benefits associated with portable concrete barrier use for positive protection in work zones (*7*). Researchers used the Roadside Safety Analysis Program (RSAP) to perform the analysis. RSAP was developed with the intent of evaluating permanent roadside hazard situations and so suffers from a number of limitations relative to its use for work zone analyses (*8*). However, earlier attempts at evaluating barrier need in construction zones essentially relied on the same general approach (discussed in greater detail below) and so suffered from the same types of limitations. In other words, RSAP was still the most relevant tool available for this assessment. It should be noted that RSAP is currently undergoing significant revisions to improve ease of input and use (*9*). However, it does not appear that any of these enhancements will make it any more applicable to work zone analysis situations.

BACKGROUND

Basic Theory of Encroachment Hazard Analysis and Its Implementation in RSAP

The basic premise of the encroachment hazard 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 (culvert, abutment, bridge pillar, etc.), or workers and work vehicles/equipment/materials. The goal is to reduce the severity of crashes with those objects by protecting them with barrier. The assumption is that impacts with the barrier will be less severe and so less costly than impacts with the other objects. Therefore, the analysis requires a number of predictions regarding:

- The expected frequency that vehicles lose control and leave the travel way (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 is located.
- The probability that a crash is of a given severity, given that a vehicle has left the roadway and traveled out laterally and struck the object.

In RSAP, the probability of an encroachment off of the travel way by a vehicle depends on the amount of traffic using a facility and the facility type. Figure 1 illustrates the encroachment models used in RSAP (*8*). The actual frequency is then adjusted if the roadway section is located on a curve or hill (since encroachments increase somewhat as the degree of curvature and percent grade increases).

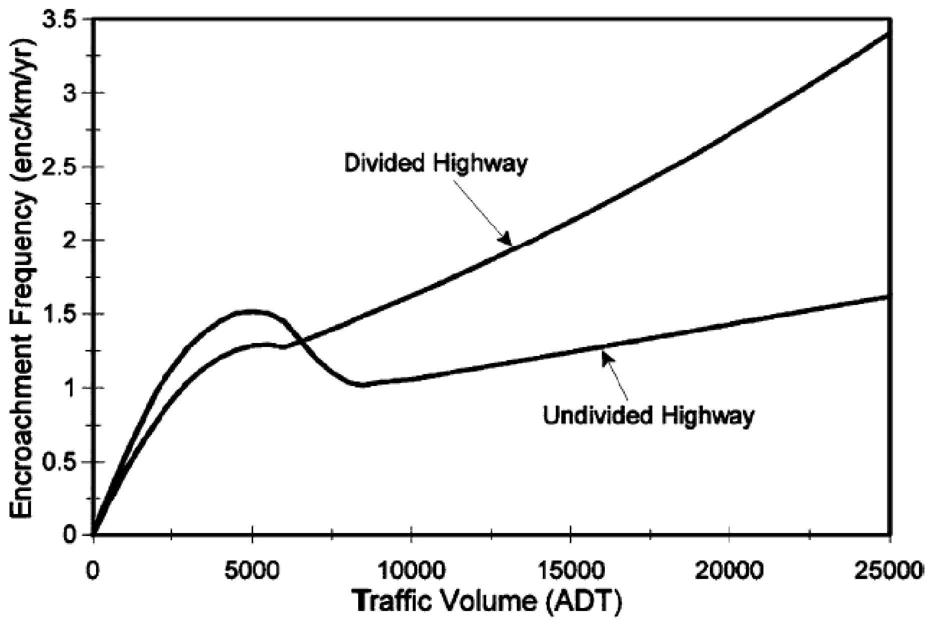


Figure 1. Encroachment Module Used in RSAP (*8*).

The “bumps” in encroachment at lower ADT levels are somewhat counterintuitive and can cause some analytical difficulties in that it implies that encroachment rates decrease slightly at ADTs between 5000 and 7000 vehicles per day. However, it is hypothesized that roadway geometrics as well as vehicle-to-vehicle interactions (or lack thereof) at very low volumes may be partially responsible for these trends.

Figure 2 presents the probabilities of lateral distance traversal assumed in RSAP. These probabilities are also adjusted based on side slopes and other roadside conditions if present and provided by the user. The probability that an encroaching vehicle will reach a given lateral distance decreases by 50 percent or more in the first four meters (about 12 ft).

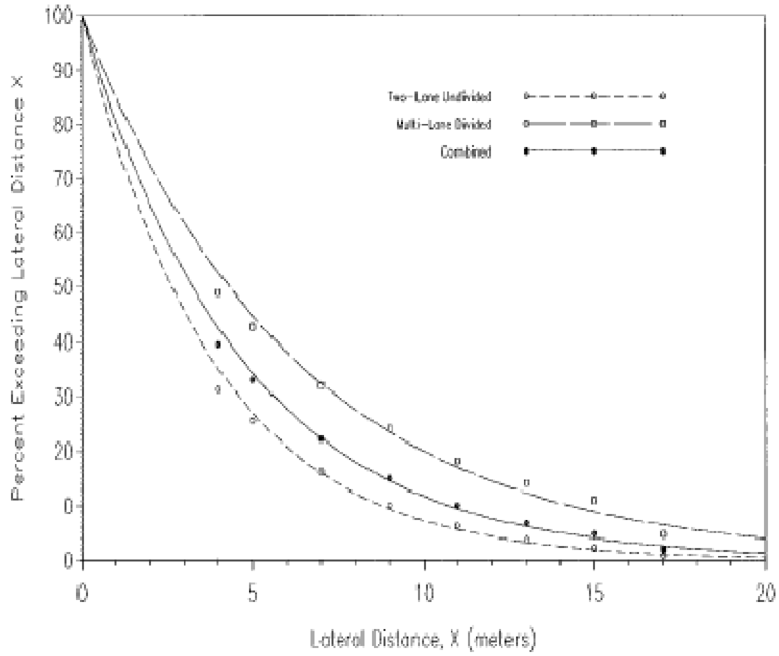


Figure 2. Lateral Extent of Encroachment Probability Model in RSAP.

To estimate the severity of crashes that occur given an encroaching vehicle has traveled out laterally and impacted with an object, RSAP utilizes a series of detailed vehicle kinematic models to predict how vehicles (and occupants within the vehicle) will respond to the impact. Given that the resulting crash severities can vary dramatically depending on how the vehicle impacts the object (in terms of location of the object, vehicle speed and heading, etc.), RSAP uses Monte Carlo simulation techniques to arrive at an average crash severity for the condition. The severity index describes the likelihood of an injury or fatality for the given condition evaluated (see Table 1), and can be multiplied by standard crash cost values to estimate the average expected crash cost for that condition.

Table 1. Relationship between Crash Severity Index and Injury Severity Level (*8*).

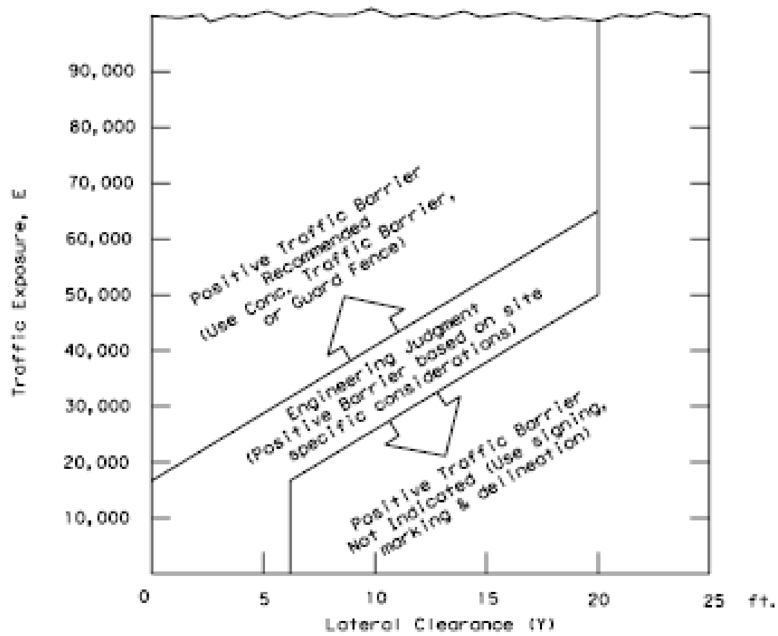
	Injury Level (%)						
SI	**None**	**PDO1**	**PDO2**	**C**	**B**	**A**	**K**
0	100.0	--	--	--	--	--	--
0.5	--	100.0	--	--	--	--	--
1	--	66.7	23.7	7.3	2.3	--	--
2	--	--	71.0	22.0	7.0	--	--
3	--	--	43.0	34.0	21.0	1.0	1.0
4	--	--	30.0	30.0	32.0	5.0	3.0
5	--	--	15.0	22.0	45.0	10.0	8.0
6	--	--	7.0	16.0	39.0	20.0	18.0
7	--	--	2.0	10.0	28.0	30.0	30.0
8	--	--	--	4.0	19.0	27.0	50.0
9	--	--	--	--	7.0	18.0	75.0
10	--	--	--	--	--	--	100.0

C = minor or possible injury.
B = moderate or non-incapacitating injury.
A = severe or incapacitating injury.
K = fatal injury.

Previous Efforts to Evaluate Barrier Needs in Work Zones

Current TxDOT guidance regarding the use of positive protection in work zones for pavement drop-off conditions (see Figure 3) can be traced to research performed at TTI and elsewhere in the mid 1980s (*6*, *10*). The analysis made use of the hazard encroachment methodology for estimating the frequency of vehicles reaching the hazard (pavement drop-off) some distance away from the travel lanes and then considered the expected crash severities of vehicles running into drop-off areas of various heights and edge designs. Vehicle overturning and snagging on the edge of the drop-off were the primary results 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 travel way were not considered. The limitations of the recommendations are acknowledged in the TxDOT guidance (*10*):

Figure 3… "*provides a practical approach to the use of positive barriers for the protection of vehicles from pavement drop-offs. Other factors, such as the presence of heavy machinery, construction workers, or the mix and volume of traffic, may make positive barriers appropriate, even when the edge condition alone may not justify the barrier.*"



1 E = ADT x T

Figure 3. Barrier Use Recommendations for Pavement Drop-Off Protection in Work Zones (*10*).

However, it is the consideration of worker and work equipment hazards and consequences of impacts that is the major area of emphasis in the effort described in this chapter. One of the earliest efforts to characterize the risks and costs of worker and equipment impacts in work zones utilized a linear relationship between crash severity and encroaching vehicle speed, as shown in Figure 4 (*11*). Others have argued that workers have a very low probability of survival if involved in vehicle collisions as low as 30 miles per hour (mph) and so have assumed a 100 percent probability (or nearly so) of a worker fatality if struck, regardless of vehicle speed (*12, 13, 14*).

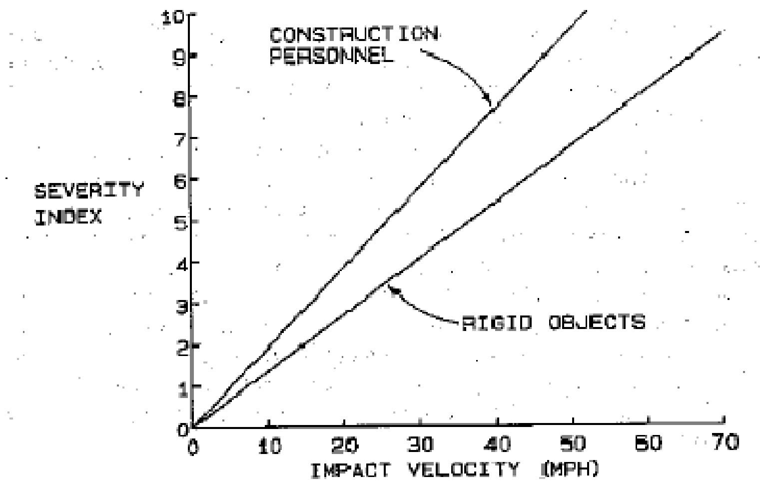


Figure 4. Relationship between Speed and Crash Severity Index Assumed for Workers and Construction Equipment (*11*).

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 (see Figures 5 through 7 as examples). For Figure 5 and Figure 6, the ADT thresholds for barrier warrants reflect a one-year analysis period (*11*). For shorter duration work zones, the ADT values would simply be adjusted appropriately (i.e., the break-even point for a 6-month project would be twice the AADTs shown in the figures). Figure 7 presents vehicle exposure in terms of ADT times the number of days of the project.

Although the documentation of these efforts is somewhat sketchy as to how exactly this was done, 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, as 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 travel way as possible, if not protected by a barrier. On the other hand, one could argue that worker protection decisions should not be based on "average" crash costs that might be expected as is used by the existing analysis tool, and so an overestimate of worker presence (e.g., assuming they are at the site 24 hours a day) is one way to manipulate the analysis output to provide a greater than 50 percent chance that barrier presence is justified (i.e., the probability of not providing a barrier at a location where a worker would be struck is significantly less than 50 percent).

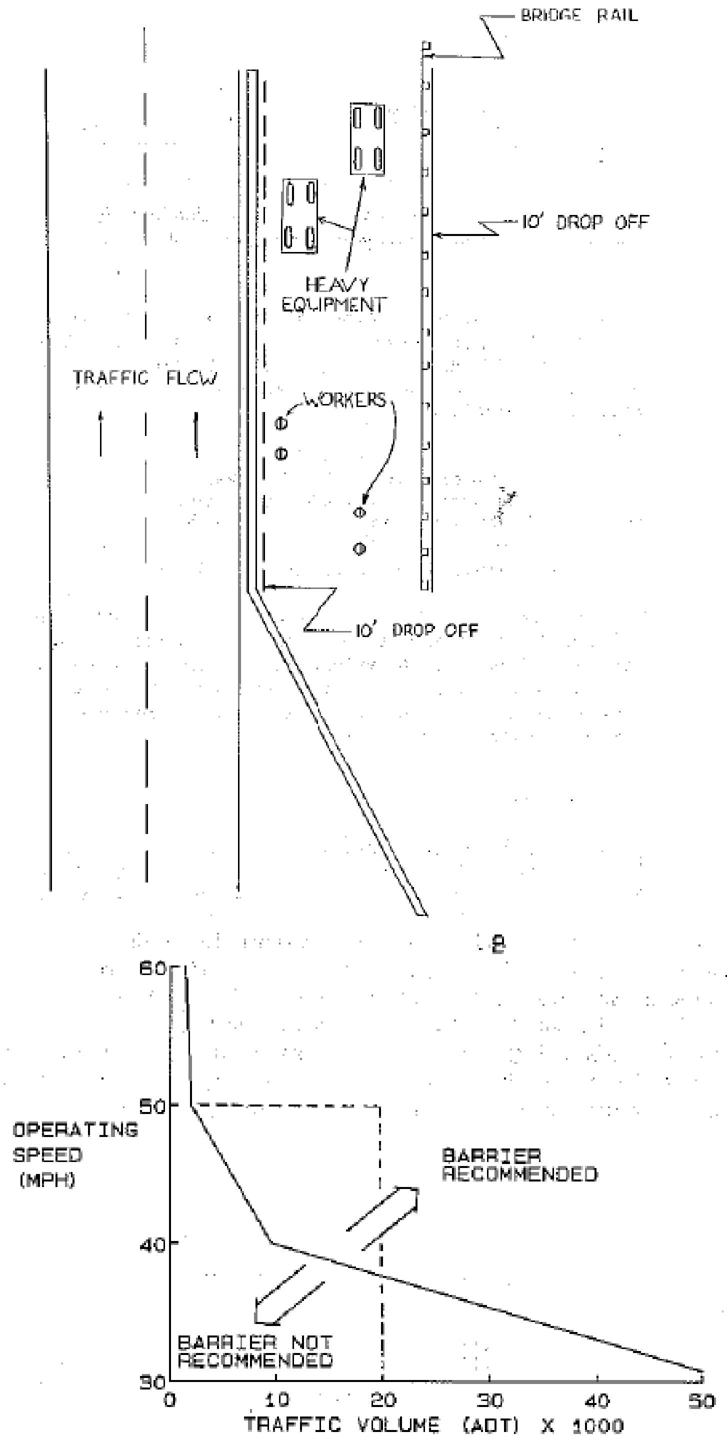


Figure 5. A Typical Freeway Bridge Widening Work Zone Scenario (*11*).

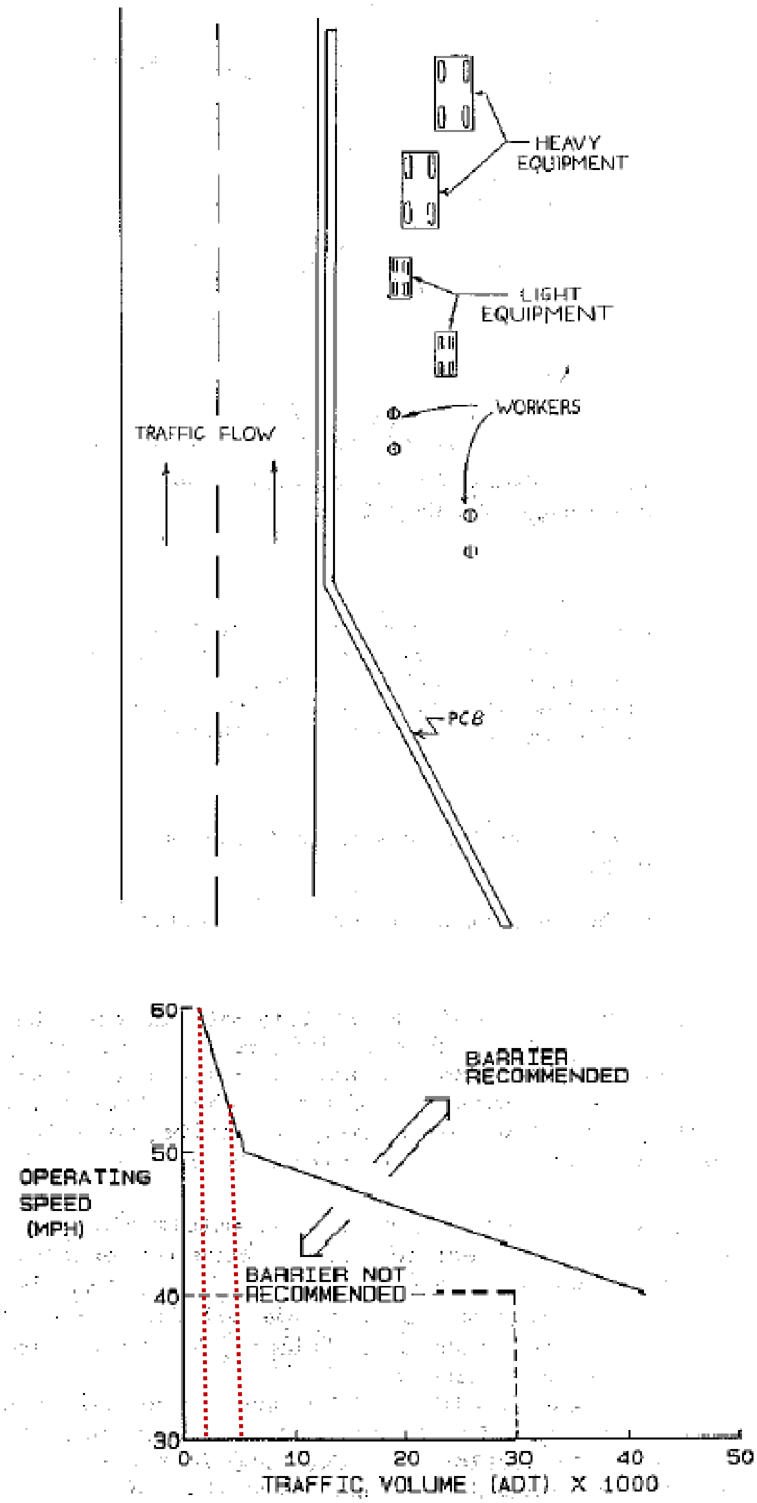
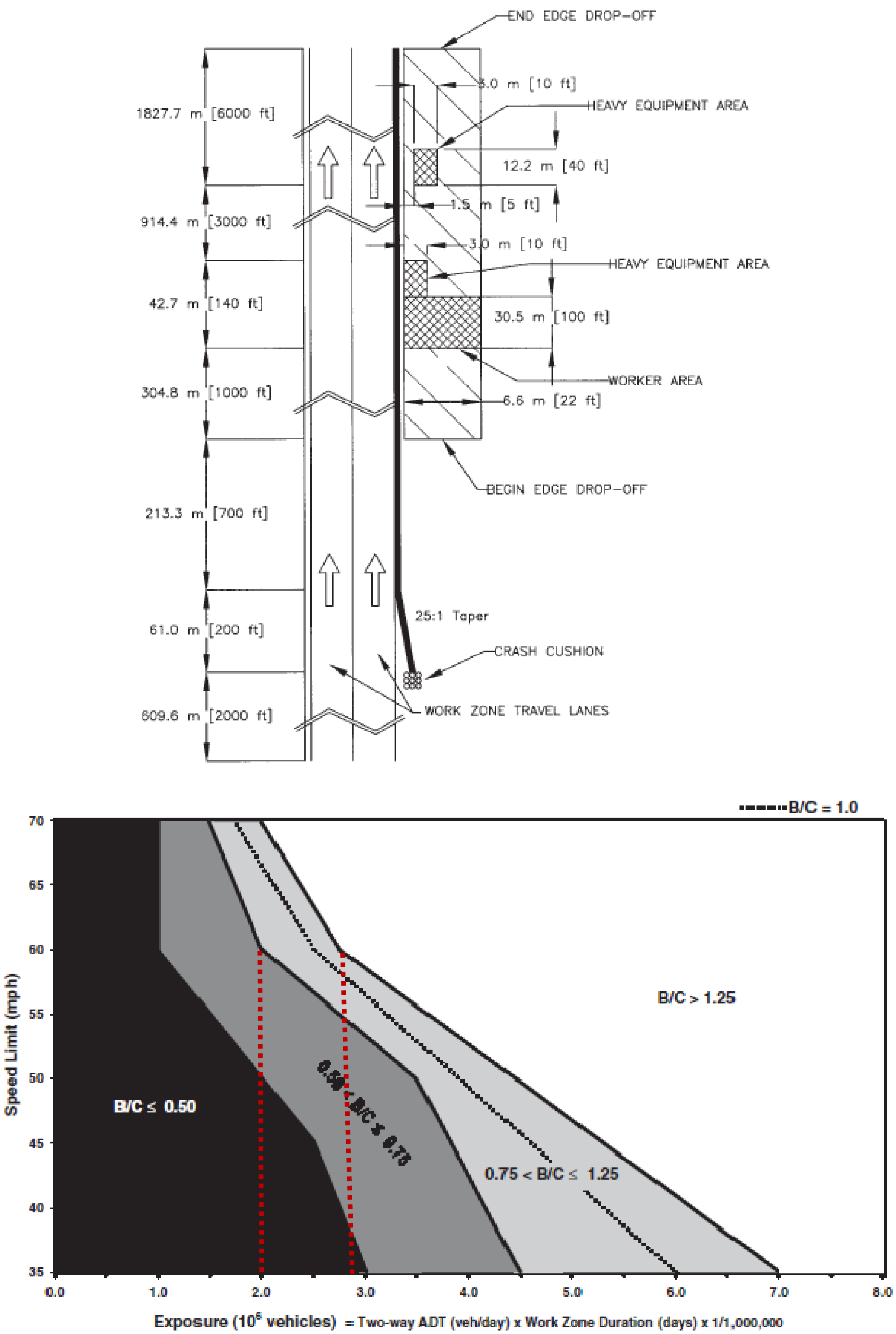


Figure 6. A Typical Roadway Widening Scenario (*11*).



(U.S. customary)

Figure 7. A Typical Freeway Part-Width Construction Lane Closure Scenario (*14*).

The other aspect of these assessments is that they combine the various hazards in arbitrary and fixed ways so as to limit their usefulness in evaluating the potential need for positive protection in future projects that are not exactly of the type that was modeled in these assessments. For example, consider the point at which barrier is recommended for work zones depicted in Figure 6 and Figure 7. The results in Figure 6 and Figure 7 both assume that a 1 ft pavement drop-off exists next to the travel lanes. Although both configurations appear similar, evaluation of the benefit-cost graphs would suggest highly different results. Assuming both represent one-year work zones, Figure 6 suggests that barrier should be considered if the roadway served as little as 2000 to 5000 vehicles per day. In contrast, Figure 7 suggests that barrier should be considered once ADTs reach 6000 to 8000 vpd (calculated by taking the exposure number on the x-axis in Figure 7, multiplying by one million, and dividing by 365 days in a year). This occurs despite the fact that Figure 7 assumes a very large working area due to the presence of both workers and construction equipment, and any intrusion into this area by any encroaching vehicle is assumed to result in a fatality. Differences also exist in terms of societal costs of crashes of a given severity, as well as barrier costs. Certainly, a change in the size and shape of the worker area or changes to those cost values just mentioned would yield different benefit-cost results and thus limit the usefulness of the graphs provided.

These examples illustrate the need to consider worker and construction equipment safety risk and protection needs separate from other features that could necessitate barrier use (e.g., pavement drop-offs), and to establish a mechanism for tailoring the amount, location, and duration of these hazards within work zones to an overall assessment of the appropriateness of PCB protection. The rest of this chapter describes efforts undertaken on this project to formulate this type of analysis for PCB use.

OBJECTIVE

The objective of the effort described in this chapter was to develop a better method of accounting for worker and construction equipment risk within the framework of an encroachment-based analysis of work zone crash costs. In this way, the benefit-cost assessment of the use of PCB to reduce worker and motorist risk could be quantified.

METHODOLOGY

A two-step analysis process was utilized for this part of the project:

1. Assessment of RSAP's ability to match current TxDOT decisions and criteria regarding PCB use in work zones.
2. Computation of crash cost reductions achievable through the use of PCB in work zones of various configurations.

The first step was accomplished through two efforts:

- Comparison of the benefit-cost ratios of PCB use by RSAP at two recent TxDOT construction projects.
- Assessment of the output of RSAP relative to the current pavement drop-off guidance in use by TxDOT.

Texas A&M University-Kingsville (TAMUK) researchers conducted the analysis of the two construction projects, whereas the assessment of the relationship between RSAP output and current TxDOT pavement drop-off guidance was performed by TTI.

For the second step of the analysis, researchers used RSAP to examine the expected intrusion crash costs as a function of volume and proximity of the work areas to traffic. This required a somewhat different approach to assessing worker and work equipment risk in work zones than what has been performed previously. Those efforts incorporated an arbitrary assignment of workers (both number and location) and work equipment within a protected area, along with an assumed severity risk profile for possible impacts with either item, into the overall estimate of crash costs due to pavement drop-offs and other fixed hazards. Of course, neither workers nor equipment stay in one place or even maintains the same relative lateral distance to the travel way during the course of a project. In addition, there are periods of time in which workers are not present, something that previous analysis efforts typically ignored. Even the number of workers and pieces of equipment themselves are highly variable from project to project, even for those projects that are similar in nature.

As the final part of this analysis, researchers examined the use of PCB to reduce intrusion risk in two different ways:

1. If the intrusion costs were the sole justification for PCB use in the work zone.
2. If those costs would contribute incrementally to a decision whether or not to use PCB to protect a pavement drop off or other work zone hazard.

The costs associated with the provision of PCB protection of workers and work equipment should be treated differently, depending on the overall needs of the work zone project being analyzed. In the first category described above, the costs of providing PCB and removing/storing it after the project is completed would need to be offset by the estimated savings in intrusion crash costs. In the second category, the same PCB costs would be compared to the combined crash cost savings potential achievable by protecting a drop-off condition and the protection of other intrusion crashes that occur.

RESULTS

Appropriateness of RSAP

TAMUK researchers investigated the functionality and reasonableness of the RSAP model for Texas work zone analysis by applying it to two different work zones that were actually implemented with PCB. The researchers initially reviewed a variety of projects via online project plans available through the TxDOT website. Two projects were selected:

- A 1.8-mile pavement rehabilitation project on US 281 between CR 449 and FM 2508 south of Alice, TX.
- A 1.6-mile pavement rehabilitation project on I-37 between Carbon Plant Road and McKinzie Road in Corpus Christi, TX.

The US 281 project was a 2-year effort. In this area, US 281 carried an average of 16,000 vehicles per day. A 60-mph speed limit was established within the work zone. PCB was used through much of the work zone to separate the travel lanes from work activity (including a pavement drop-off). Other characteristics of the project are shown in Table 2. Similarly, the I-37 project was a 19-month effort. This facility carries a significantly higher amount of traffic (70,300 vpd). A 60-mph speed limit was also established in the work zone. A short section of roadway within the work zone was protected by PCB. Other parameters of the project are shown in Table 3.

Table 2. RSAP Parameters for the US 281 Project.

US 281 RSAP Programming Parameters									
Cost Data	Work Zone Duration			Discount Rate			Annual Maintenance Cost		
	2 years			4%			$10,000		
Highway Data	Area Type	Functional Class	Highway Type	No. of Lanes	Lane Width	Right Shoulder Width	Speed Limit	ADT	Percent Truck
	Rural	Freeway	2-Lane divided	4	12 ft	10 ft	60 mph	16,000	0.32
Segment Data	Segment 1			Segment 2			Segment 3		
	Segment Length	Vertical Grade	Median Width	Segment Length	Vertical Grade	Median Width	Segment Length	Vertical Grade	Median Width
	3000 ft	0	77 ft	3600 ft	0	77 ft	3000 ft	0	77 ft
Feature Data	Category	Type		Width	Length	Offset From Road	Distance from beginning		Flare
	Longitudinal	TL-3 PCB		2 ft	10 ft	8 ft	500 ft		N/A

Table 3. RSAP Parameters for the I-37 Project.

I-37 RSAP Programming Parameters									
Cost Data	Work Zone Duration			Discount Rate			Annual Maintenance Cost		
	19 months			4%			$25,000		
Highway Data	Area Type	Functional Class	Highway Type	No. of Lanes	Lane Width	Right Shoulder Width	Speed Limit	ADT	Percent Truck
	Rural	Interstate	2-Lane divided	4	12 ft	10 ft	60 mph	70,300	6.6%
Segment Data	Segment 1			Segment 2			Segment 3		
	Segment Length	Vertical Grade	Median Width	Segment Length	Vertical Grade	Median Width	Segment Length	Vertical Grade	Median Width
	1600 ft	0	77 ft	3200 ft	0	77 ft	3200 ft	0	77 ft
Feature Data	Category	Type		Width	Length	Offset From Road	Distance from beginning		Flare
	Longitudinal	TL-3 PCB		2 ft	10 ft	1.6 ft	650 ft		N/A

Researchers utilized national inputs for various data required in RSAP in terms of PCB installation and maintenance costs, crash costs, etc. Even so, the results of the analyses supported the use of PCB in both cases. As shown in Table 4, the benefit-cost ratios exceeded 1.0. In the case of the US 281 project, the longer duration and other factors resulted in a B/C ratio in excess of 1.5.

Table 4. Results of RSAP Analysis of TxDOT Projects.

Project	Exposure (Vehicle-Days x 10^6)	Benefit-Cost Ratio of PCB Use
US 281	11.6	> 1.5:1
I-37	40.6	> 1.3:1

For the second part of the assessment of RSAP appropriateness for Texas, TTI researchers used recent TxDOT bid PCB prices for installation, movement, and removal/storage. In addition, crash cost values were updated to those recommended by FHWA (*15*). Then, a series of RSAP runs were made to evaluate the effect of lateral distance and vehicle exposure upon the benefit-cost values of providing PCB to protect a pavement drop-off.

With regard to the costs of providing PCB in work zones, one finds considerable variability in unit bid prices (per foot) as a function of district, barrier type, and amount to be used. Smaller amounts of barrier tended to have wider variation in prices than did projects with long sections of barrier specified. The values finally entered into RSAP are shown in Table 5.

Table 5. PCB Unit Costs for Texas.

PCB Type	Costs per foot		
	Furnish and Install	Install Designated Source	Remove
Safety Shape	$37.50	$7.98	$4.92
F-Shape	$47.00	$14.96	$7.40
Low-Profile (45 mph or less)	$24.66	$4.78	$13.08

With regard to the crash cost values, the data from the FHWA report (*15*) were initially in 2001 dollars. Consequently, the human capital cost components to the overall value were multiplied by the ratio of the Consumer Price Index (CPI) for 2008 and that for 2001. Then, the difference between the comprehensive cost and the human capital cost for 2001 was multiplied with the ratio of Employment Cost Index (ECI) for 2008 and that for 2001. Adding the two components yields the comprehensive cost per crash in 2008 dollar value. The updated unit crash cost values by crash severity and roadway speed were entered into RSAP and are reported in Table 6.

Table 6. Comprehensive Cost Values Updated to 2008 Dollars.

Speed Limit/Severity	≤ 45 mph	≥ 50 mph
K	$4,541,640	$4,978,305
A	$262,789	$310,540
B+C	$80,932	$76,208
O	$6,996	$6,808

With these modified values entered into RSAP, a series of typical work zones were analyzed to evaluate how well RSAP coincides with current TxDOT pavement drop-off guidance. A multilane roadway segment was created, and a vertical drop-off was modeled as existing parallel to the roadway at various distances from the travel way. The encroachment rate was increased by 40 percent to account for the generally higher crash rates that exist in work zones, similar to the approach taken in earlier uses of RSAP for work zone analysis (*13, 14*). For each drop-off lateral offset configuration, roadway ADT was manipulated, and the benefit-cost ratio of providing PCB versus a no-PCB condition were compared to the costs of providing that barrier. RSAP is somewhat limited in the drop-off conditions it can model, currently allowing either 1-ft or 7-ft drop-offs to be evaluated. Consequently, the 7-ft drop-off condition was used in the analysis, which may have resulted in somewhat higher crash severities than would occur with a 2-ft drop-off, which is the threshold TxDOT uses. On the other hand, researchers used the most expensive average PCB cost value scenario (furnish and install plus removal costs) for all of the analysis, which is probably higher than what would exist for many projects. Researchers estimated the ADT and lateral distance values at which the B/C ratio reaches 0.75, 1.0, and 1.5 as a way to reflect conditions that generally does not require protection (B/C < 0.75), is in the range of possible barrier need and should be examined through an engineering analysis (0.75 < B/C < 1.25), and those conditions where barrier use is generally going to be easily justifiable (B/C > 1.25). Current TxDOT guidance compared to RSAP output is shown in Figure 8.

As the figure indicates, RSAP results align very well with current TxDOT guidelines at close lateral distances (i.e., 5 ft from the travel lanes). However, RSAP and existing guidance diverge as the lateral offset of the drop-off increases. Specifically, RSAP results are less sensitive to traffic exposure than existing guidance, meaning that it does not take as much additional traffic exposure to justify PCB use at greater lateral offsets than what currently exists as guidance. However, the RSAP analysis condition is for a much deeper drop-off condition than was used to generate the existing TxDOT guidance. In addition, the updated crash costs are substantially higher (even accounting for inflation) than what was used to develop the current guidance. Consequently, researchers were comfortable that the RSAP output was a reasonable tool for work zone PCB analyses.

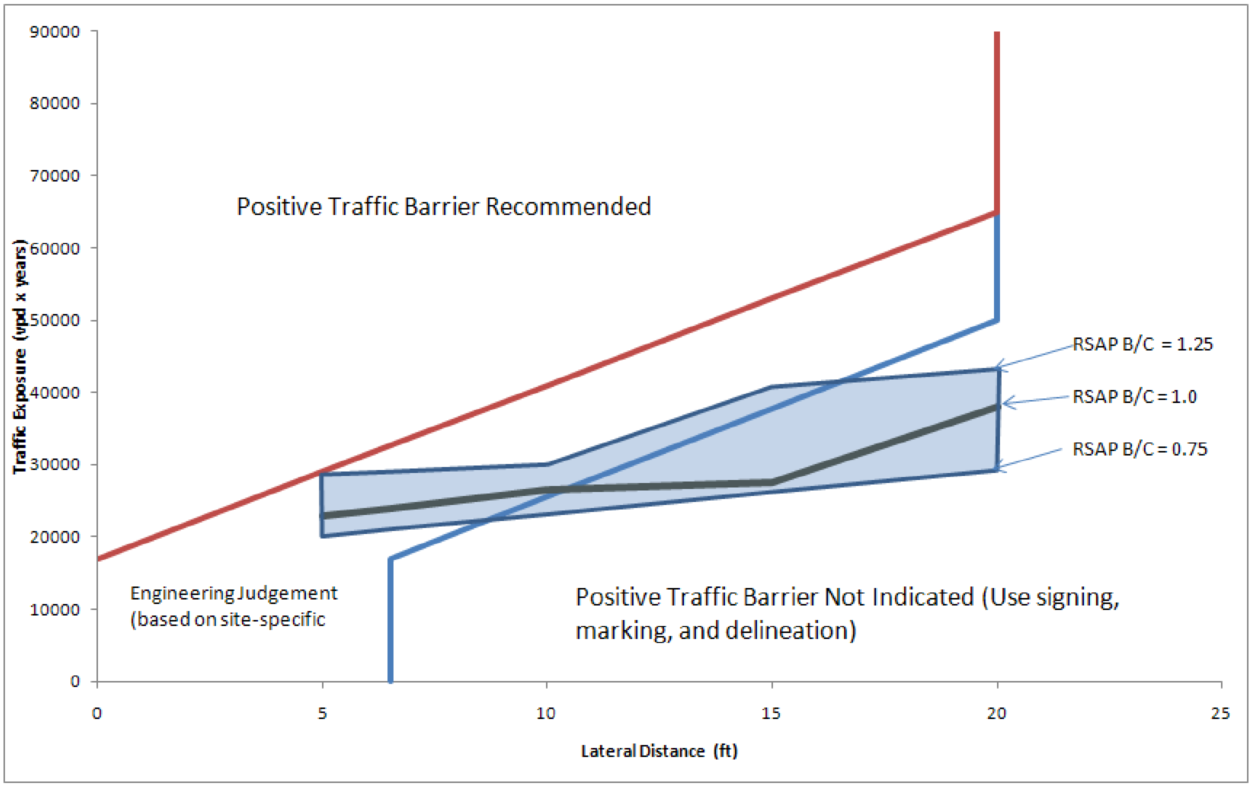


Figure 8. Comparison of TxDOT and RSAP Assessment of Work Zone Drop-Off Conditions.

Assessment of Intrusion Crash Costs Considerations

PCB Justification Based Solely on Intrusion Costs

Once the researchers were comfortable with the output that RSAP was providing and its general agreement with TxDOT drop-off guidance, researchers evaluated a generic work zone without a pavement drop-off condition. Specifically, researchers examined a continuous intrusion area hazard as depicted in Figure 9. Analysis of the entire work zone as an intrusion area was a major departure from the efforts to model individual workers or specific work areas with higher severity indices as was done previously.

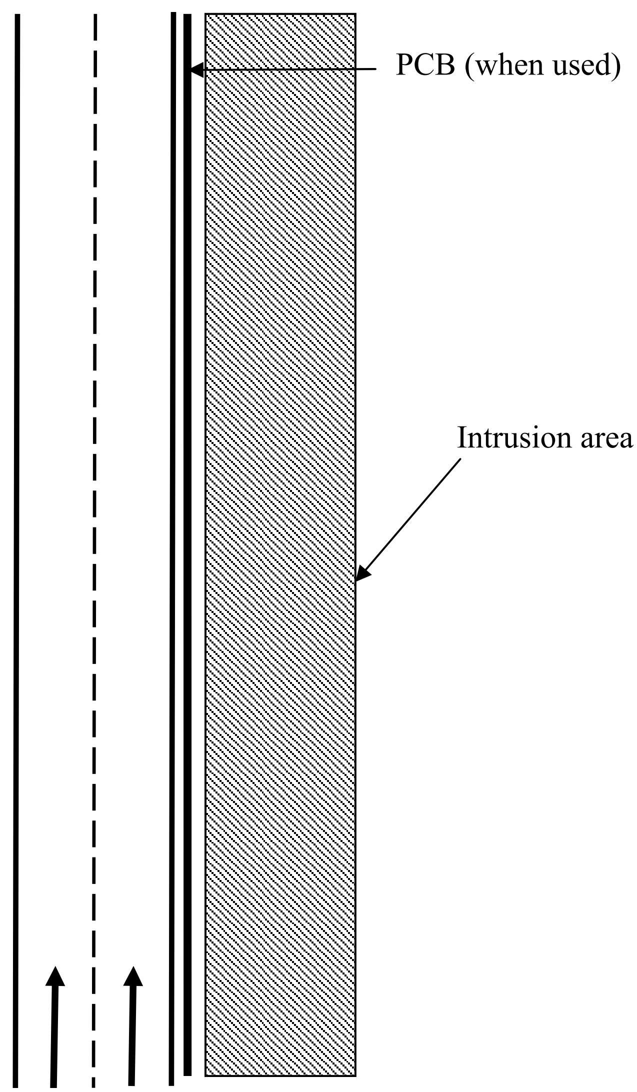


Figure 9. Illustration of Representation of Intrusion Area Hazard in RSAP.

Typically in work zones, workers do not stay in one place or even maintain the same relative lateral distance to the travel way during the course of a project. In addition, there are workers are not present, something that previous analysis efforts typically ignored. Also, the number of workers varies greatly from project to project, even for those projects that are similar in nature. The solution to this challenge adopted by the researchers was to not attempt to portray individual workers and equipment but rather simply represent the entire work area in terms of the severities of intrusion events that occur. Previous analyses assumed a higher severity risk profile for possible impacts with workers when portraying individual workers in the work zone. To better represent intrusion area as a whole, previously-published data regarding the severity of intrusion crashes and near misses at highway work zones in New York (*16*) was utilized. The distribution of property-damage-only, injury, and fatal crashes observed from intrusion crashes in that database provided an indication of the overall severity of intrusion events into work zones. Table 7 presents that data.

Table 7. Severity of Intrusion Crashes in New York (*16*).

Crash Severity	Daytime Work Zones (n=133)	Nighttime Work Zones (n=39)	Both Types Combined (n=172)
Fatal	2.3%	7.7%	3.5%
Injury	36.8%	53.8%	40.7%
PDO	60.9%	38.5%	55.8%

The researchers then mapped this distribution to the Severity Index matrix presented in Table 1. Due to the relatively high percentage of fatal crashes occurring in that dataset, it was concluded that intrusion events equated to a severity index of 5. The researchers further assumed that these intrusion events represented an intrusion speed of approximately 55 miles per hour (since most of these events were on freeway or other high-speed roadways). Assuming that the SI value would be zero when speeds are zero, and would be 5 when operating speeds were 50 mph, the SI versus impact speed relationship shown in Figure 10 was incorporated into RSAP analysis of the entire work zone as an intrusion area.

A series of analyses at different ADT levels were then computed with and without the work zone area protected by PCB. Researchers used RSAP to analyze two operating speeds through the work zone: 50 and 70 mph. The researchers acknowledge that it is very difficult to get motorists to reduce their speeds significantly when traversing work zones on high-speed facilities, and so the 70 mph condition is probably the more realistic condition in most rural areas, unless heavy enforcement or other speed control measures are being used.

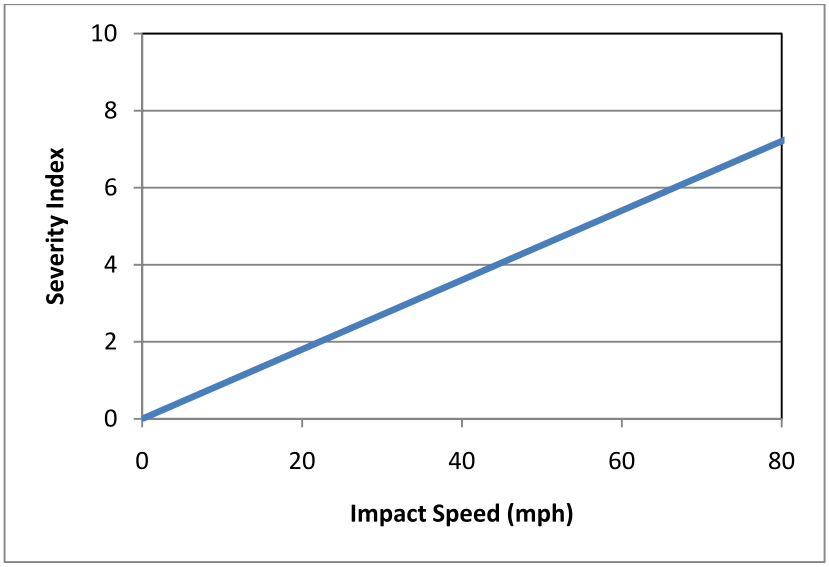
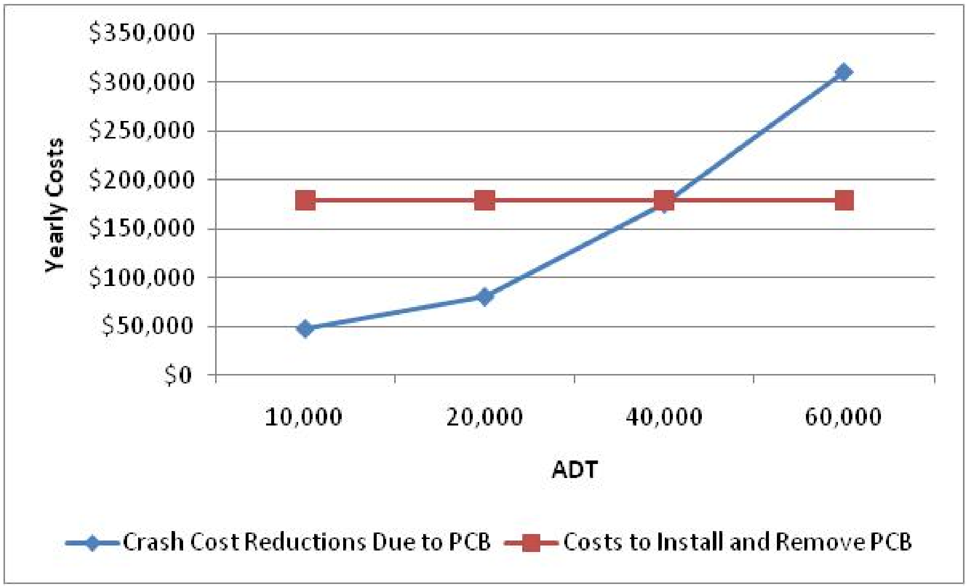


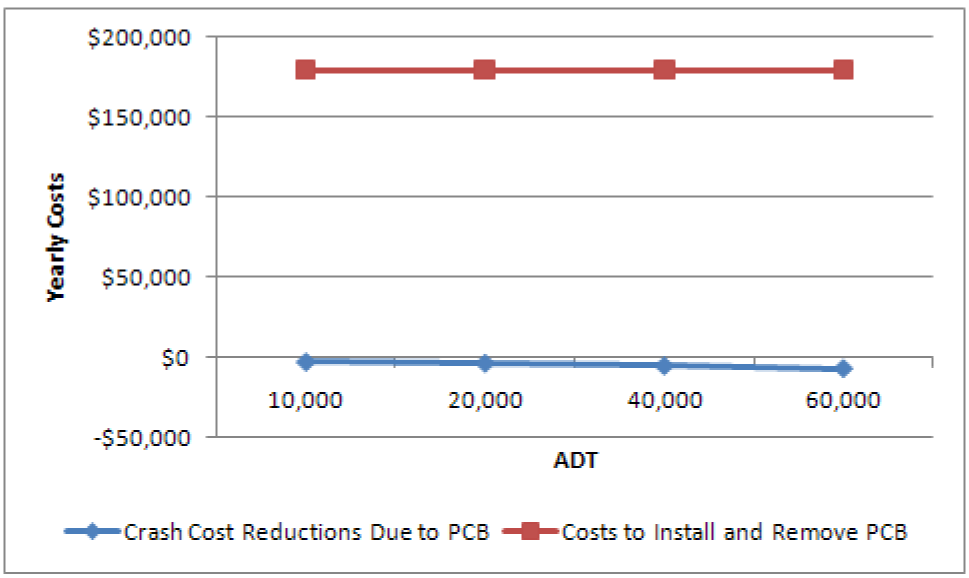
Figure 10. Intrusion Severity Index Relationship Developed for Use in RSAP.

For analysis purposes, Figure 11 illustrates a one-year, one-half mile work zone on a 70-mph divided highway with the actual work area located two feet beyond the edge of the travel lane (the buffer distance corresponding to either PCB or channelizing devices placed next to the travel lane). Under this scenario, intrusion crash costs savings alone can justify PCB protection once the roadway ADT approaches 40,000 vpd, as long as there are constant hazards in the work area. Furthermore, this value can simply be extrapolated to look at other work zone durations (i.e., this is equivalent to a 6-month work zone with an ADT of 80,000 vpd, a 2-year work zone on a 20,000 vpd facility, etc.).

Interestingly, if the operating speed on the facility is 50 mph, Figure 11 indicates that intrusion crash costs alone would not justify PCB use under any ADT levels. The presence of PCB actually increases crash costs slightly at that speed over a no-PCB condition, according to RSAP. This is due primarily to a reduced frequency of intrusions that extend beyond the assumed 2-ft buffer zone between the travel lane and intrusion area under the 50-mph condition (relative to those occurring if speeds are 70 mph).



(a) 70 mph Operating Speed

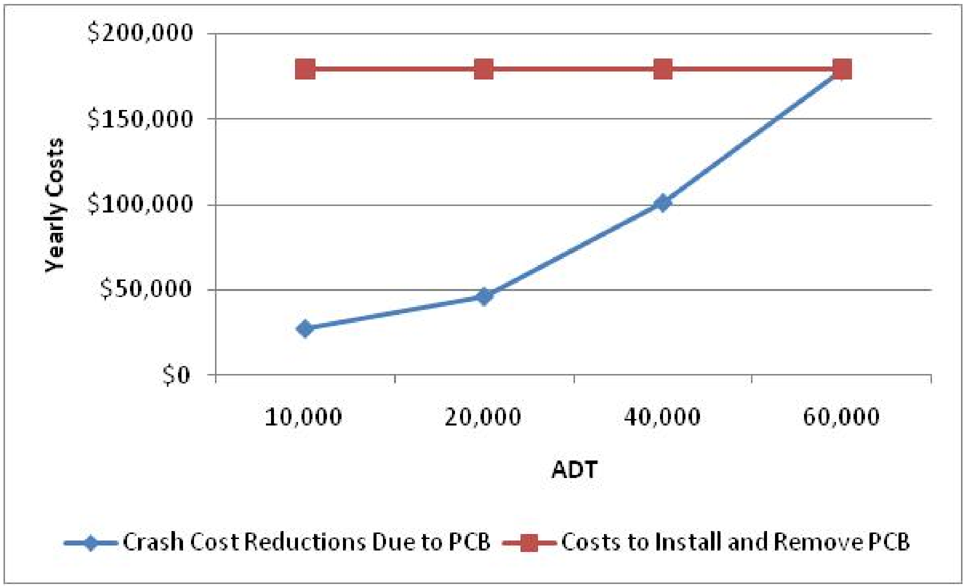


(b) 50 mph Operating Speed

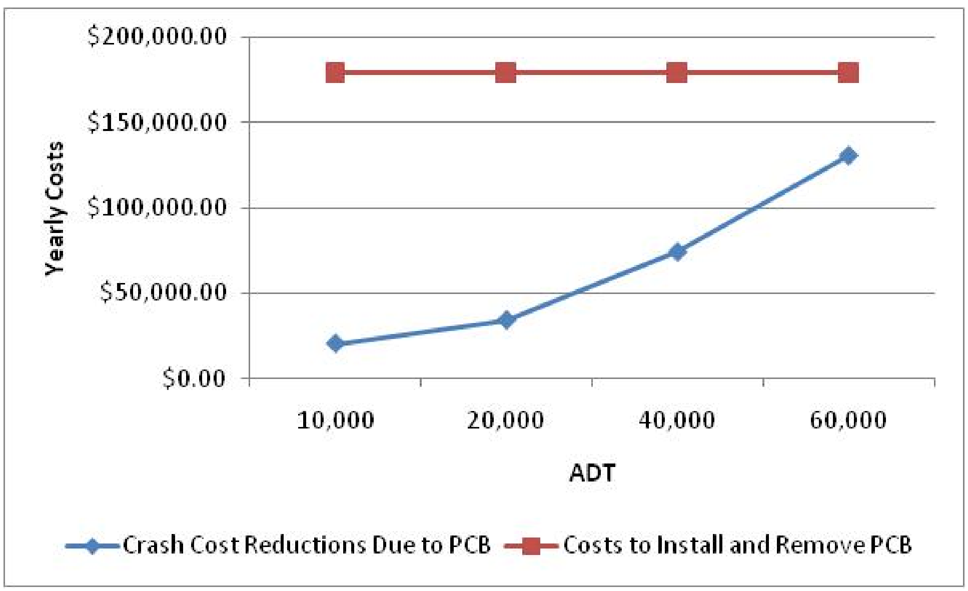
Figure 11. Comparison of Yearly Intrusion Crash Cost Savings and PCB Costs for a 0.5-mi Work Zone on a Multilane Highway.

Further analyses using RSAP also suggests that any lateral buffer space that is provided between the work area and traffic moving through the work zone will also dramatically reduce the cost-effectiveness of PCB use strictly for intrusion crash protection. As an example, Figure 12 presents the identical analysis of the 0.5-mile work zone on a 70-mph facility but with the work area located one lane removed from traffic (i.e., there exists a 12-ft buffer space) and also at 20 ft from the travel lane. At these lateral distances, the PCB can generate modest reductions in intrusion crash costs, but these do not completely offset the costs of providing and removing the PCB until the ADT values reach approximately 60,000 to 75,000 vpd (for a one-year work zone). This would suggest that, under these situations, the intrusion crash cost reduction benefit would generally have to be combined with drop-off or other protection considerations in order to fully justify PCB use. Of course, proportionally lower ADTs could justify PCB use if the work zone is longer than one year in duration.

These graphs were considered reasonable assessments of multilane facilities (both divided and undivided). Researchers believed the different characteristics of a two-lane, two-way highway warranted separate examination of this roadway configuration. Figure 13 shows this analysis. The same types of effects are evident. For the 70-mph scenario, some crash cost reductions are seen by providing PCB but not enough to surpass the installation costs over the range of ADTs possible on two-lane highways unless the project is several years long. The 50-mph scenario results in slightly greater crash costs when the PCB is in place relative to the costs of crashes occurring without PCB present. The analysis indicates that it takes considerable exposure (the product of ADT and work zone duration) to justify the use of PCB at a project on a two-lane highway strictly on the basis of reducing work zone intrusion crash costs other than those attributable to pavement drop-offs. Whereas consideration of other types of intrusion crashes can be added to pavement drop-off criteria and potentially justify PCB use at lower ADTs and project durations, it alone cannot justify PCB use in most cases, even if the hazards in the work area are continually present.

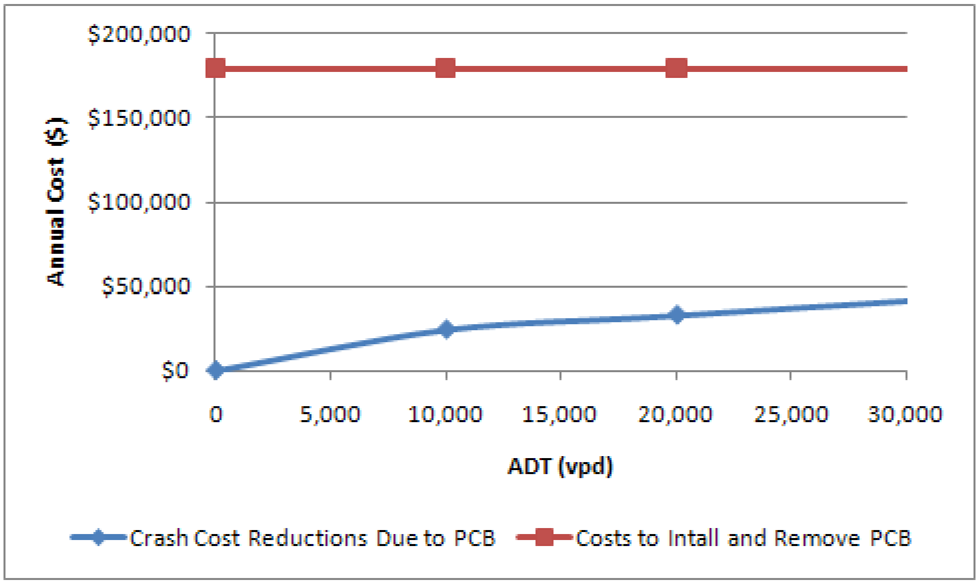


(a) 12-ft work area offset from traffic

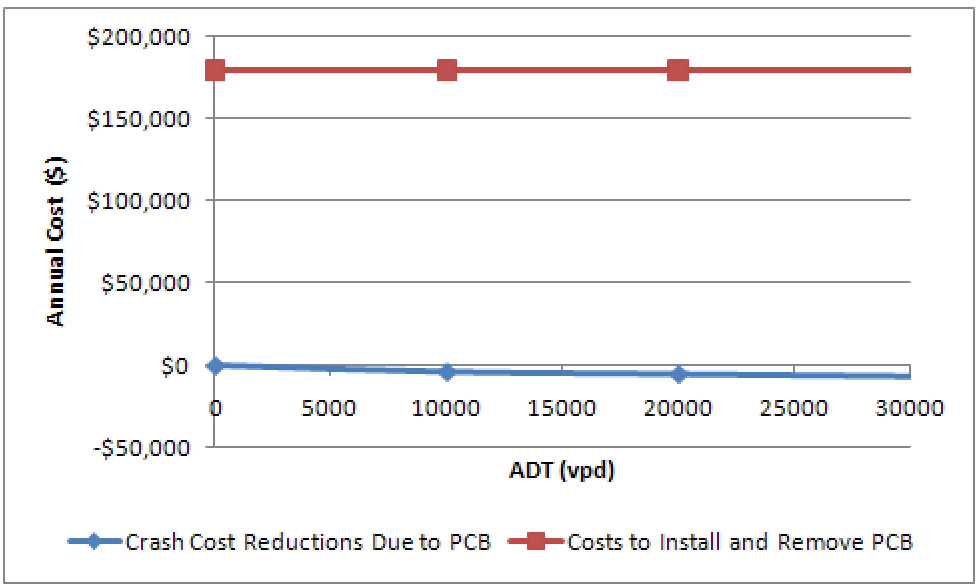


(b) 20-ft work area offset from traffic

Figure 12. Comparison of Yearly Intrusion Crash Cost Savings and PCB Costs for a 0.5-mi Work Zone Located 12 ft and 20 ft from Travel Lanes on a Multilane Highway, 70 mph Operating Speed.



(a) 70 mph Operating Speed



(b) 50 mph Operating Speed

Figure 13. Comparison of Yearly Intrusion Crash Cost Savings and PCB Costs for a 0.5-mi Work Zone on a 2-Lane Undivided Roadway.

Researchers found that the analyses are extremely sensitive to the assumptions regarding the continuous presence of workers, equipment, and materials in the work area that would constitute an intrusion area hazard. To illustrate this point, Figure 14 illustrates the annual crash costs estimated by RSAP due to impacts with the barrier and due to intrusions into the work/equipment/materials space. As can be seen, the actual differences in those types of costs are fairly small for the same analysis period (one year). Consequently, if there exists significant periods of time during a project in which there are no hazards within the work/equipment/materials space, no crash reduction benefits can be generated, and the additional crash costs that occur with the barrier that has been installed could quickly overwhelm any benefit that may be gained by protecting the work/equipment/materials space during some portion of time when such hazards are present. Comparing the two lines in Figure 14, if the work/equipment/materials space were vacant as little as five percent of the time, the increased crash costs due to having the barrier in place would exceed the crash costs that would be expected to occur when work/equipment/materials were present, and so it would not be possible to justify PCB use solely on the basis of reducing those types of intrusions.

Intrusion Cost Effect on PCB Drop-Off Criteria

The effect of estimated intrusion crash costs on the decision criteria currently used by TxDOT for drop-off protection was also examined using RSAP. The approach used was to add the potential intrusion crash cost increases (i.e., those involving workers, equipment, and materials as estimated in the previous section) to those already represented in the existing TxDOT pavement drop-off guidance, which represents the intrusion crash costs expected to be incurred by motorists if a pavement drop-off is present. Initially, the researchers believed that this approach would double-count intrusion effects if the drop-off condition was located immediately adjacent to the travel lanes (i.e., the drop-off itself would always be the first hazard encountered if a motorist left the travel lane. However, depending on the height of the drop-off, it is possible that the vehicle itself would remain stable and continue to move through the work area until striking some other object. Consequently, the additive approach of intrusion effects was ultimately adopted in this analysis.

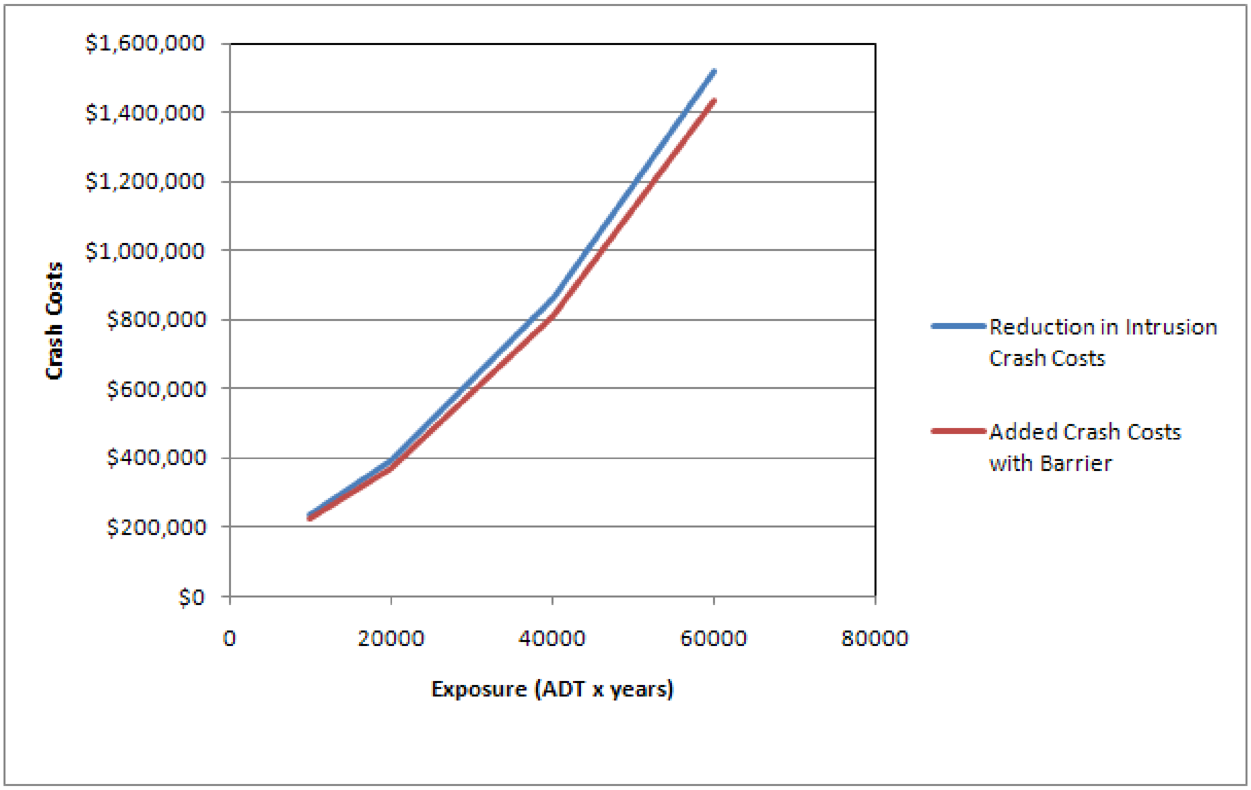


Figure 14. Intrusion Crash Costs Reduced versus Barrier Crash Costs Added, 70-mph Operating Speed.

The TxDOT guidance on use of PCB for drop-off scenarios (depicted in Figures 3 and 8) was interpreted such that the upper limit separating the "barrier recommended" and "engineering judgment" sections of the graph was assumed to be equivalent to a benefit/cost (B/C) ratio of 1.25 and the lower limit separating the "engineering judgment" and "barrier not needed" sections was assumed to be equivalent to a B/C ratio of 0.75.

One can envision two distinct scenarios in which the combination of drop-off crash costs and other intrusion crash costs should be considered together. The first of these, depicted in Figure 15, is a scenario where a pavement drop-off condition is located some distance away from the travel lanes, and workers/equipment/materials are positioned between the drop-off and the travel lanes. In this case, the barrier would always be positioned adjacent to the travel lanes (when used). The costs of impacts with the barrier would thus be the same regardless of the lateral distance of the drop-off, as would the costs of vehicle intrusions into the work/ equipment/materials space since it also remains at the same distance from the travel lane, but the crash costs due to the drop-off when the barrier is not used would decrease as the lateral offset of the drop-off increases. This is because the frequency of errant vehicles reaching the drop-off would decrease.

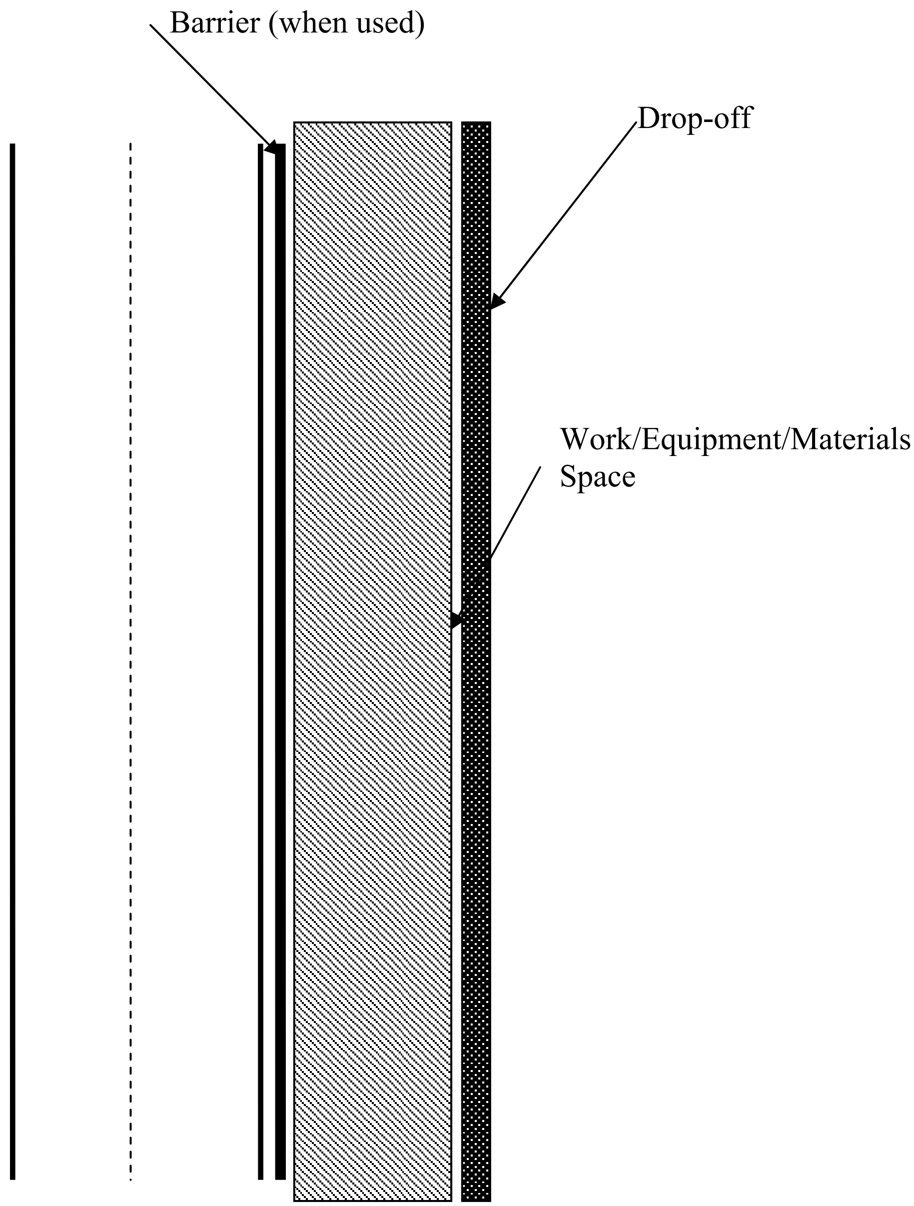


Figure 15. Scenario where Work Space Is between Drop-Off and Traffic.

Figure 16 depicts the second scenario where the drop-off is always being the first hazard encountered by an encroaching vehicle, and the work/equipment/materials space is located beyond the drop-off.

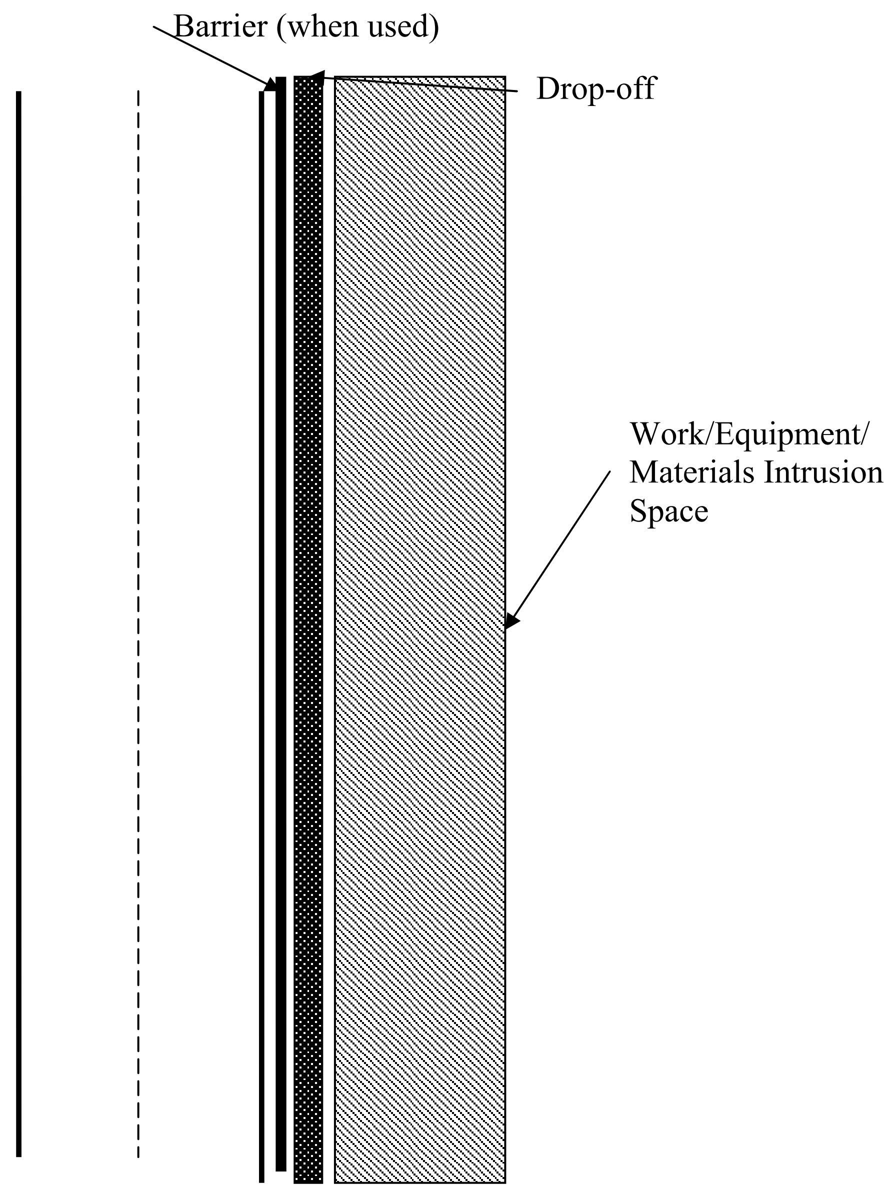


Figure 16. Scenario where the Drop-Off Is between the Work Space and Traffic.

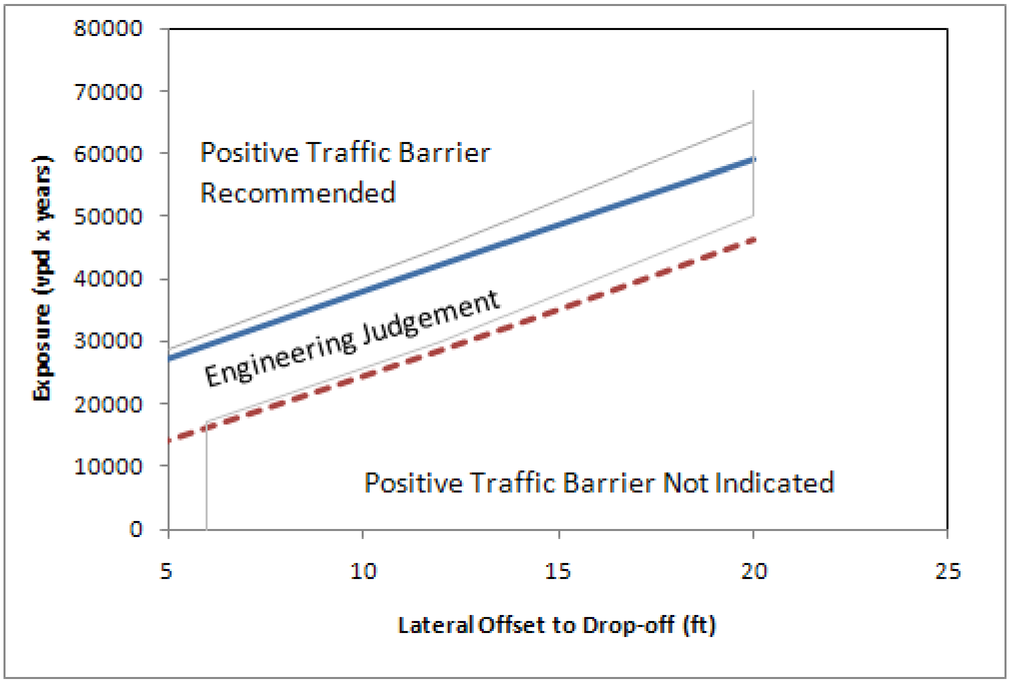
Researchers used the crash cost reductions (including the costs of crashes with the barrier) calculated from the RSAP work/equipment/materials space intrusion crash analyses and added the estimated drop-off crash costs that would be averted by having a barrier in place. This latter value was calculated by using the RSAP barrier crash cost estimates at various offset values to determine the remaining crash cost reduction benefit that correlates with the exposure and lateral offset value shown in the drop-off guidance. The combined crash cost benefits were then compared to the PCB installation and maintenance costs to develop an overall B/C ratio.

Figures 17 and 18 present the results of incorporating the current pavement edge drop-off positive protection guidance with the results of intrusion crash cost analyses described in this chapter (the combination of drop-off crash costs and work/equipment/materials space intrusions). Figure 17 represents the condition where the work/equipment/materials space is located immediately adjacent to the travel lanes and the drop-off is located beyond the work area, whereas Figure 18 is the condition where the work area is beyond the lateral offset of the drop-off condition. The grey lines represent the original pavement drop off guidelines, and the colored lines reflect the combined analyses results. The assumptions in these situations are that work activity is occurring every other day (3–4 days per week) for 8 hours per day for which intrusion crashes are of concern (obviously, the drop-off concern exists 24/7). The graphs are appropriate for any duration work zone. All that needs to be done is to estimate the work zone duration as a fraction of a year and multiply by the ADT to determine the actual exposure number to be used in the graphs.

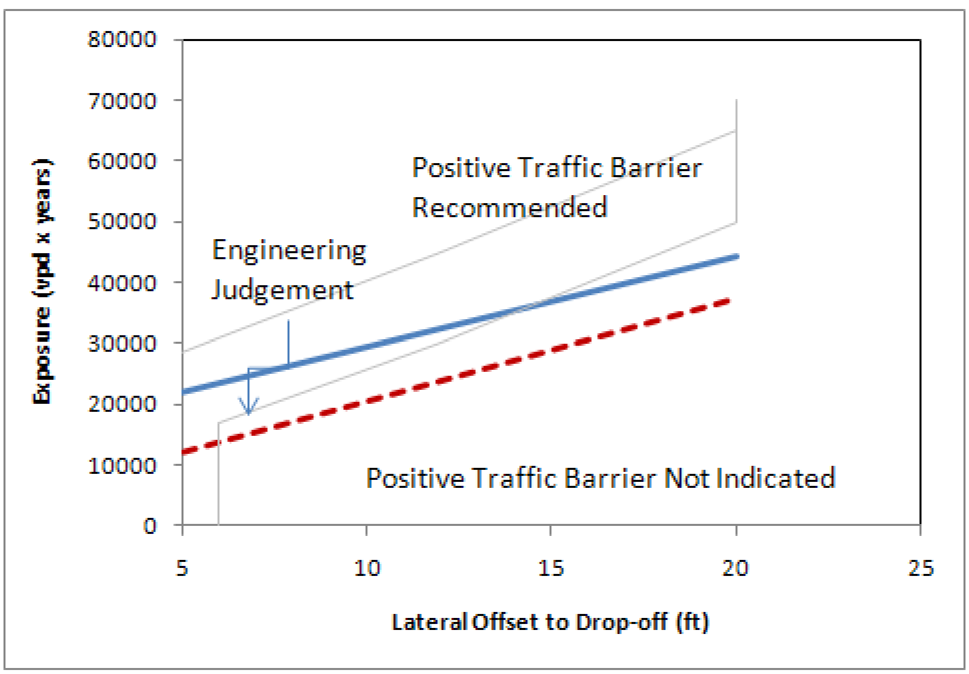
In Figure 17, the lateral axis begins at 5 ft, as it is unlikely that work activity could occur in an area any narrower between travel lanes and the drop-off itself. In addition, two conditions are presented—one representing the situation in which intrusion hazards are present continuously during the work zone and one in which it is assumed that there are work zone intrusion hazards only for 3–4 days per week for 8 hours per day (i.e., a typical project work schedule, for example). For comparison purposes, the lightly-shaded lines represent the existing positive protection drop-off criteria in the graphs. The condition where intrusion crash risks are present only during normal work hours (costs other than those associated with running to the drop-off) has a fairly minor effect upon the positive protection thresholds already established for drop-off conditions. In contrast, the condition where intrusion hazards are expected to be present continuously during the work zone has positive protection threshold values that are much less than those which consider pavement drop-off conditions only. The graphs are also less sensitive to lateral offset of the drop-off to the travel lanes (i.e., the slope of the line is flatter), since it is assumed that work activity is occurring right up to the buffer area next to the travel lane (or positive protection if provided). Consequently, the influence of the drop-off upon crash costs diminishes as its lateral offset increases (for a given exposure level) and more of the crash costs of concern become associated with intrusion into the work/equipment/materials space.

In Figure 18, positive protection thresholds are provided when the work space is located beyond the drop-off location. The graphs look similar in shape to those shown in Figure 17, although the influence of the work space intrusion hazard analysis upon the recommendations is less dramatic. Such a result should be expected. In situations where the work space is located beyond the lateral offset of the drop-off condition, the risk of an errant vehicle traversing out to the drop-off and then to the other intrusion risks in the work space is dramatically less than when the drop-off and other intrusion hazards are located much closer to the travel lanes.

In both Figures 17 and 18, the effect of considering work/equipment/materials space intrusion crash costs is fairly limited when these types of hazards are expected to exist only occasionally (i.e., 3–4 days per week, 8 hours per day). It is only when the hazards are expected to be present almost continuously do the graphs differ dramatically from that of existing drop-off guidance. Consequently, justification of PCB use based on consideration of both drop-off costs and work space intrusion costs is highly dependent upon assumptions about how the work space will be managed. In most cases, occasional work space hazard presence is likely to be the more realistic assumption. However, situations where work activity is anticipated to occur around the clock, and limited work space locations such as bridges or tunnels where equipment and materials must be stored close to the travel lanes even when activity is not occurring, may justify utilizing the guidance based on a continuous presence of work space hazards.

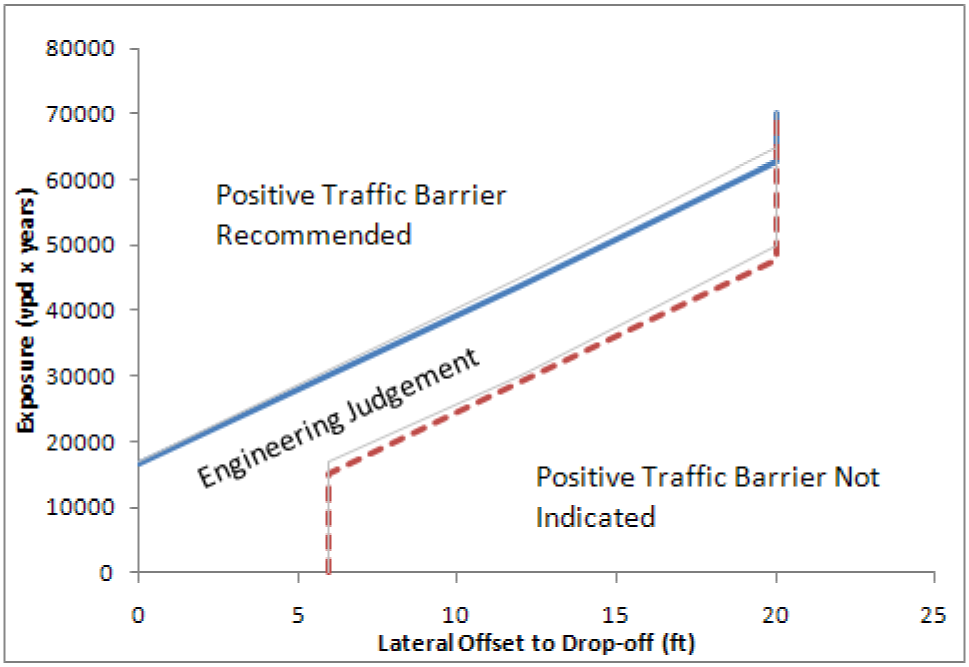


(a) Work/Equipment/Materials Space Intrusion Crash Risks Exist 8 hours per day, 3–4 days per week

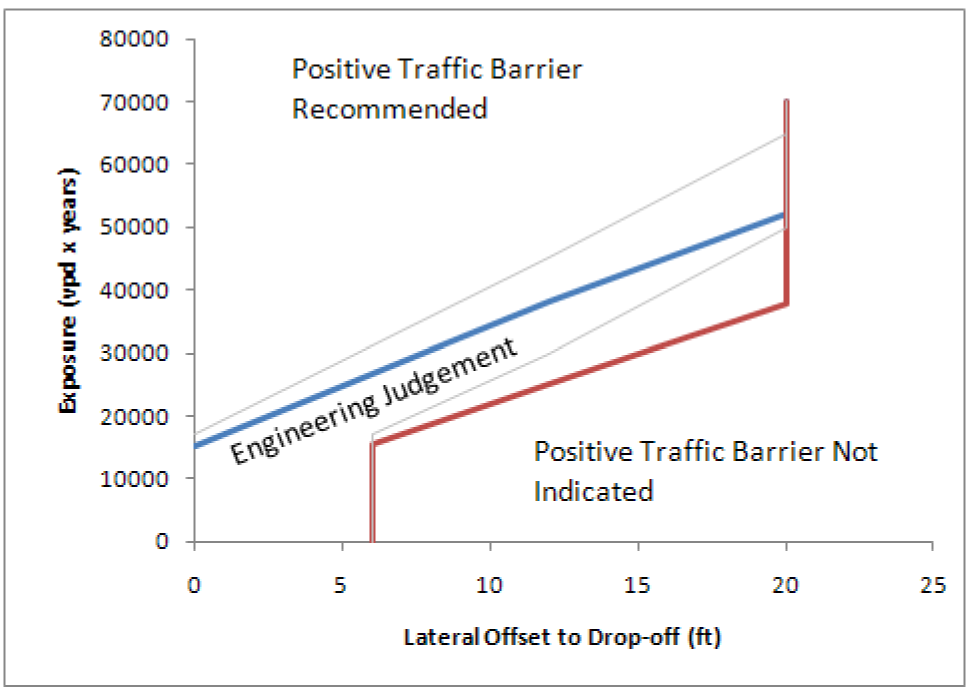


(b) Work/Equipment/Materials Space Intrusion Crash Risks Exist Continuously (24/7)

Figure 17. Recommended PCB Usage Guidance when Work Space Is in Front of the Drop-Off and Immediately Adjacent to the Travel Lanes.



(a) Work/Equipment/Materials Space Intrusion Crash Risks Exist 8 hours per day, 3–4 days per week



(b) Work/Equipment/Materials Space Intrusion Crash Risks Exist Continuously (24/7)

Figure 18. Recommended PCB Usage Guidance when Work Space Is beyond the Drop-Off.

ANALYSIS OF EXPECTED CRASH REDUCTION BENEFITS AND COSTS OF PORTABLE AND MOBILE BARRIERS IN WORK ZONES

INTRODUCTION

Although PCB is by far the most common positive barrier in use statewide, its size and weight make installation/removal and transport costs fairly significant. As a result, it is generally not feasible for use in more temporary applications. Recently, barrier technologies that are more portable than PCB have become available. These include moveable concrete barriers, steel barriers, water-filled barriers, and vehicle-mounted mobile barriers (*17*-*19*) are some samples. These technologies can be transported, installed in or next to a travel lane, and removed more quickly than traditional PCB. These characteristics make such protection viable options for even short-term and short-duration work operations. However, such systems also cost more initially than PCB (although prices are likely to begin coming down as their penetration into the marketplace increases) and have somewhat different crash test characteristics, such as greater lateral deflections if not fully anchored when hit, than PCB. Another type of portable protection system is the truck-mounted attenuator. TMAs are attached to the rear of shadow vehicles or work vehicles moving at slow speeds on a roadway in a mobile work operation. Crash tests have verified the ability of this type of technology to reduce rear-end crash severity.

Although these technologies do offer the potential for reducing work zone crash costs, the cost-effectiveness of these technologies under various roadway and work zone situations has not been fully assessed. This chapter documents the methodology and results of analyses performed to examine the crash cost reduction benefits and implementation costs of these types of technologies.

DESCRIPTIONS OF PORTABLE BARRIER SYSTEMS

Moveable Barrier

Moveable barrier technology has existed for several years. This technology consists of short (1-meter) segments of concrete barrier linked together, each with a special T-shaped top. A specially designed transfer machine moves along, lifting the barrier by its top and transferring it laterally to the other side of the machine (see Figure 19). The design of the system is such that is protected from approaching traffic by the barrier itself at all times. The system requires a rather lengthy time to set up and is generally used where a fairly long section of barrier must be moved one or more times per day. However, once in place, the barrier can be moved laterally to close or open a lane at a fairly quick pace (about 3 mph).

Figure 19. Example of Moveable Barrier and a Barrier Transfer Machine.

Several TxDOT districts (Austin, Dallas, and El Paso) have utilized the technology on one or more projects. Costs of the technology vary, but appear to fall in the $70 to $150 per linear ft category. This cost includes the movement of the barrier as many times as needed during the project. Functionally, researchers considered moveable barriers to be equitable to PCB in terms of protection from lateral vehicle intrusions into the work space, the primary benefit being in terms of its ability to avoid reducing capacity during peak travel periods and thus reduce creating queues and delays. Consequently, the work/equipment/materials space intrusion crash cost analyses performed in the previous chapter are considered to be relevant for moveable barrier. The breakeven ADT where the costs of the barrier would be offset solely by the reduced intrusion crash costs would be much higher, though, because moveable barrier is two to three times the cost of PCB.

Steel Barrier

Recently, steel barrier segments that can be quickly unloaded at a worksite and linked together to provide longitudinal crash protection have been developed to protect workers from work space intrusions during work activities that last only a short time at any one location (see Figure 20). Some steel barrier designs include retractable wheels that can be lowered so that the steel sections can be moved by hand laterally across travel lanes as needed to create protected work spaces. Other designs include wheels and vehicle attachments that allow the barrier to be moved along with the work activity as it progress down the roadway. Minimum lengths of steel barrier are required to achieve various crash test performance levels. The extent of lateral deflection depends on the specific barrier design and whether the barrier is anchored at its ends or not. TxDOT has not had a lot of experience with this type of barrier yet. Based on very limited data, it appears that steel barrier is currently priced at approximately $180 per linear ft. However, this value is likely to change as the product becomes more commonly used.

Figure 20. Example of the Deployment and Use of Steel Barrier.

Mobile Barrier

Many work activities move slowly or intermittently along the roadway and so cannot be protected by temporary concrete barrier. Shadow vehicles with truck-mounted attenuators are typically used to protect workers on foot in mobile operations. However, these devices do not provide lateral impact protection. Recently, a few truck-mounted technologies have been developed to protect workers from lateral work space intrusions. Specifically, a steel beam “cage” is attached to a semi-tractor trailer cab that can then be towed to a location and deployed around a small area to protect a work crew on foot near moving traffic (see

Figure 21). Similar to steel barriers, mobile barriers have not been utilized significantly by TxDOT, although a few districts are contemplating the purchase of one or more units in the future. Such technology is fairly expensive to purchase, costing between $200,000 and $250,000 per unit. Once again, the price of the technology may change over time as more and more agencies adopt its use. Unfortunately, data on the longevity or effective service life of this technology are not readily available either.

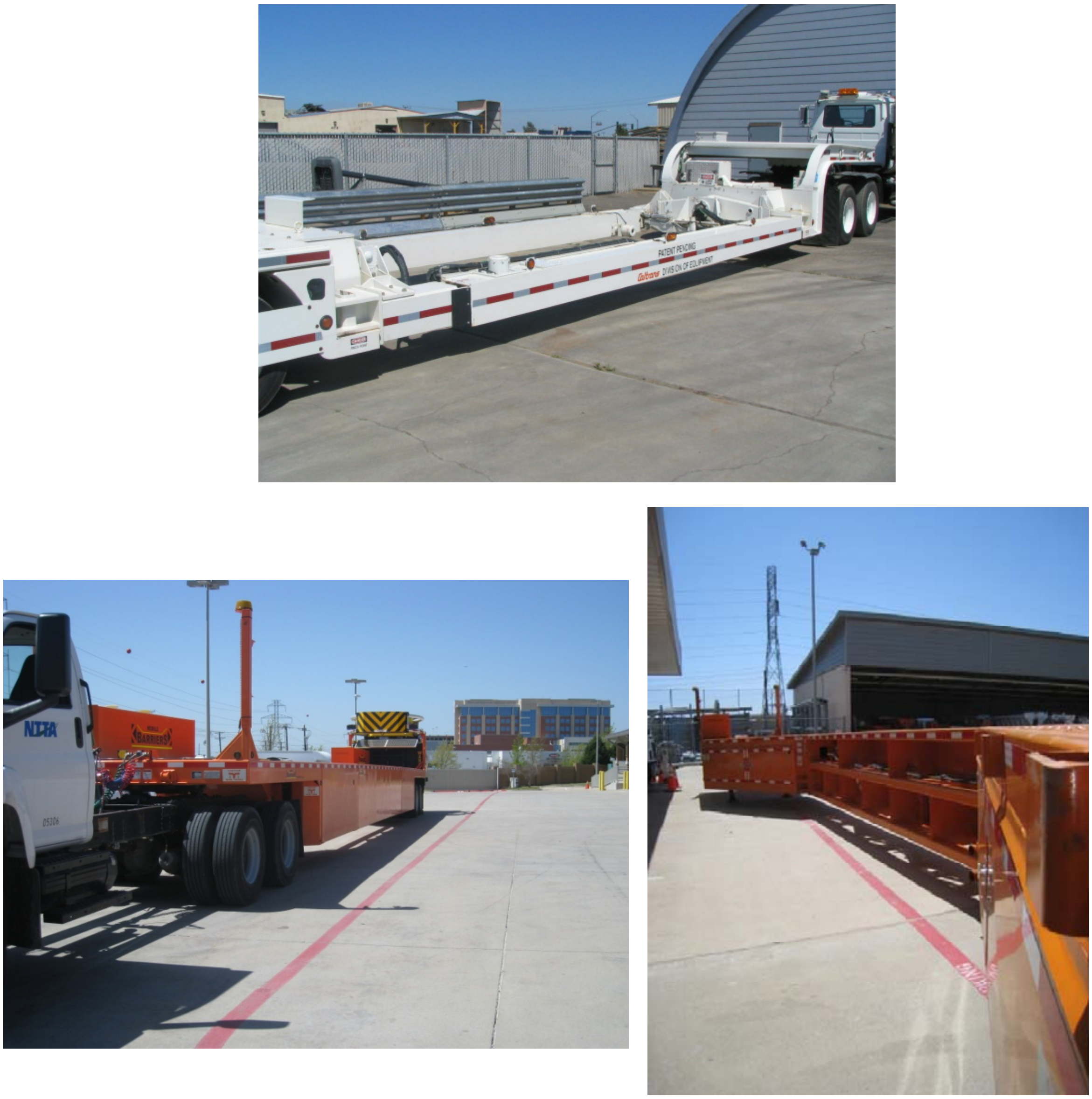


Figure 21. Examples of Mobile Barrier Technology.

Truck-Mounted Attenuators

Truck-mounted attenuators have been in existence for many years and are well-accepted as a crash protection device for mobile and short duration operations (see Figure 22). Several vendors and models of TMAs exist in the marketplace. The attenuator absorbs the impact energy of a rear-end crash into the work vehicle, reducing the severity of the crash for both the motorist and workers in the work vehicle. Care must be taken to match the correct type of TMA to the work vehicle and operating conditions on which the vehicle will be used. Work operations that involve workers on foot must be carefully planned with respect to how shadow vehicles and TMAs will be used to allow sufficient roll-ahead distance for the shadow vehicle to avoid hitting the workers in the event the TMA is impacted by an approaching motorist. The cost of a TMA varies by type, manufacturer, and quantity ordered; prices ranging between $15,000 and $20,000 each can be found on various company websites.

Figure 22. Example of a TMA in Use during a Mobile Operation.

ANALYSIS METHODOLOGIES

Researchers used two different types of analyses to evaluate these types of technologies. First, researchers analyzed portable steel barrier and mobile barrier with RSAP in an extension of the roadside hazard analysis used to evaluate PCB use. However, rather than consider the protection of an entire work zone as was done in the previous chapter for PCB, researchers evaluated a much smaller work space (45-ft length) in RSAP (see Figure 23). Any intrusions into this limited work space were modeled as always resulting in a worker fatality. This distance approximately equals the length of work area needed for many maintenance work activities based on a review of various work tasks performed by workers on foot (*18*). Obviously, an assumption of a worker fatality for each intrusion is very liberal and places a high degree of value on reducing intrusion risk. Still, given the fact that speed limits are generally not reduced for these types of work operations, and the high degree of importance that highway agencies and contractors are placing on improving worker safety, researchers view this assumption as reasonable.

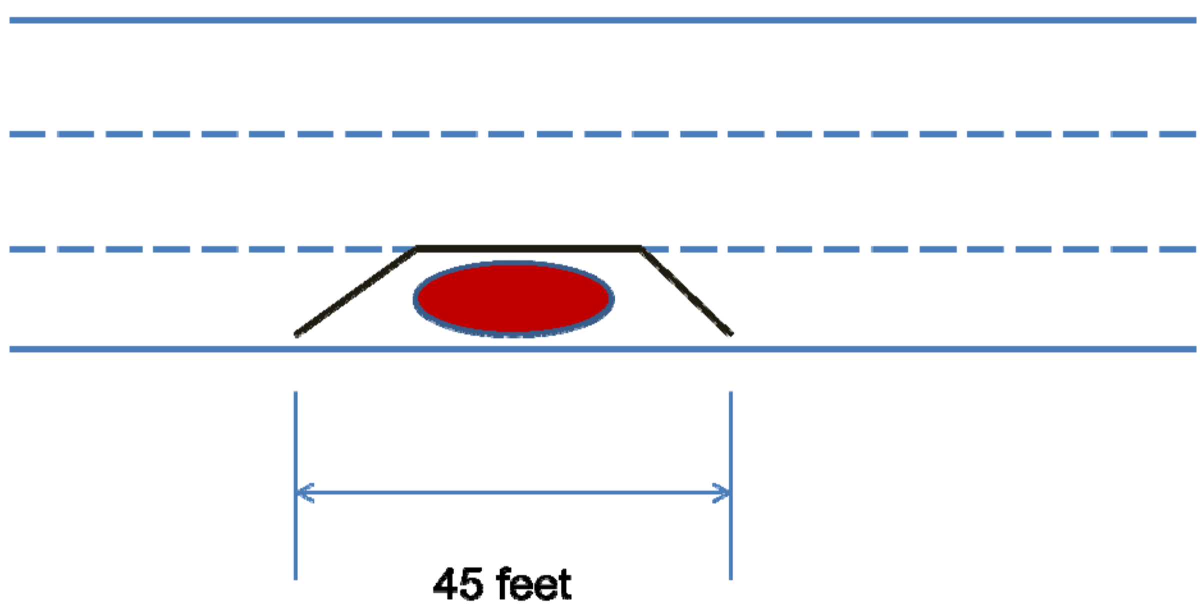


Figure 23. Short-Term Work Space Modeled in RSAP.

The values computed by RSAP for this analysis were subsequently converted to hourly crash cost reduction values, as these types of highly-portable barriers can be rolled in and out of travel lanes or shoulders as needed during hours of work activity only. The overall intent was not to develop simple benefit-cost comparisons of the various technologies, since the costs of these newer devices are likely to change significantly as demand for them increase and production costs decrease. In addition, the total service lives of these devices are not known with any degree of precision either. By estimating potential crash cost reductions of these devices on an hourly basis, it is possible to consider different device cost/service life assumptions to determine if the device can be cost effective under various roadway and traffic volume levels.

The second type of analysis focused specifically on truck-mounted attenuator use during mobile and short duration work activities. The purpose of a TMA is to reduce the severity of a rear-end collision by an approaching vehicle impacting a work vehicle that is temporarily stopped or moving at very slow speeds. For this analysis, researchers used rear-end crash rates at work zone operations measured in previous research (*16*) to estimate the frequency of rear-end collisions with a work vehicle. Analysis of crash outcome data involving work vehicles with and without TMAs provided data on the savings in crash costs that result from having a TMA in use.

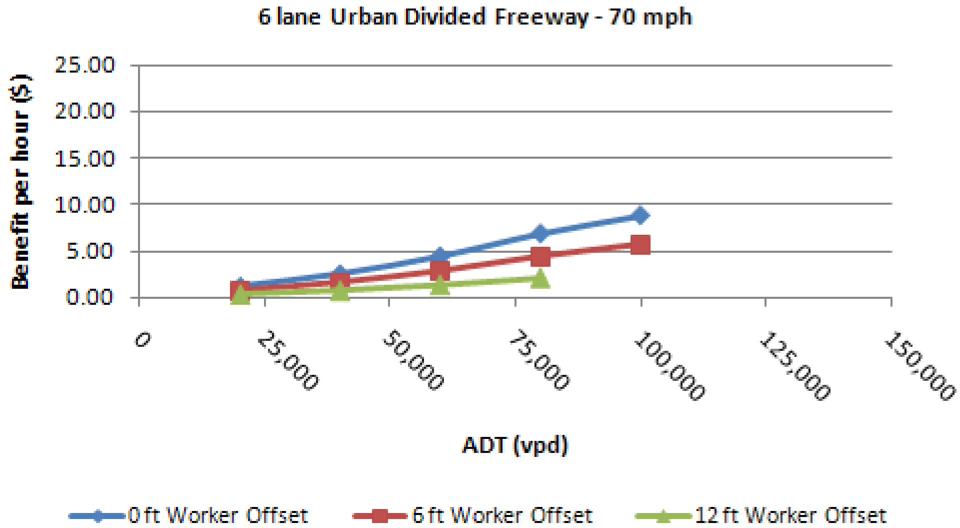
RESULTS

Portable Steel and Mobile Barrier Systems

Initially, researchers performed a number of RSAP analyses for various assumed approach speeds on various roadways. Researchers also examined the relative lateral distance between a travel lane and the location of the work space. However, researchers found that these variables did not have a significant effect on the output results over the range of parameters evaluated. The resulting outputs represented an annual exposure and so were divided by the number of hours in a year to achieve an hourly crash cost reduction estimate. The research team recognized that traffic volumes differ dramatically between daytime and nighttime conditions. However, single-vehicle run-off-road crashes typically comprise a greater proportion of crashes at night than during the day (*16*). Furthermore, data on work zone intrusion crashes also suggest that they represent a greater proportion of work zone crashes at night than during the day. In fact, analyses by the research team suggested that hourly work zone intrusion crash cost reductions would be approximately the same regardless of whether daytime or nighttime work operations were being considered.

Figure 24 illustrates the types of data obtained from the RSAP analyses once the output was converted to average hourly benefit of providing positive protection of these small work spaces. The hourly benefit is the difference in estimated crash costs without any protection present (in which case, any intrusion within the work space area would cause a fatality) and those when positive protection is present (in which case, the crash costs could be those sustained by the encroaching vehicle that impacts the protection technology). The assumption is that the portable and mobile barrier crash costs would be similar to those for portable concrete barrier. However, researchers did not have actual crash or test data involving those devices that could be used to verify or refute this assumption. As would be expected, the benefits are most significant for situations in which the work space is located immediately adjacent to moving traffic (i.e., it is in a closed traffic lane or in a closed shoulder). Additional graphs for rural freeway conditions, and undivided roadway conditions, are provided in Appendix B.

Based on the analysis results, researchers dropped the consideration of operating speed, and considered only work spaces located adjacent to the travel lane (with the typical 2-ft buffer defined where channelizing devices or the barriers would be located). The result of the analysis was the simplified graph shown in Figure 25. This graph can then be used to determine how many hours it would take to offset the cost of a particular positive protection device or technology when used on a facility serving a given ADT. For example, the cost of providing 200 ft of steel barrier to protect a work space that is priced at $180 per ft for various ADT levels is shown in Figure 26. Also shown in that figure is the breakeven hours needed if the price of steel barrier would drop to $100 per ft. Taking this computation one step farther, Figure 27 provides an estimate of the number of 6-hour work shifts that would be required to offset the cost of steel barrier at $180 and $100 per ft purchase prices. One sees that the cost of steel barrier protection of work activities can be recouped fairly quickly (within one to two years of daily use) once ADTs exceed 50,000 to 75,000 vpd, especially if steel barrier costs decrease in the near future.



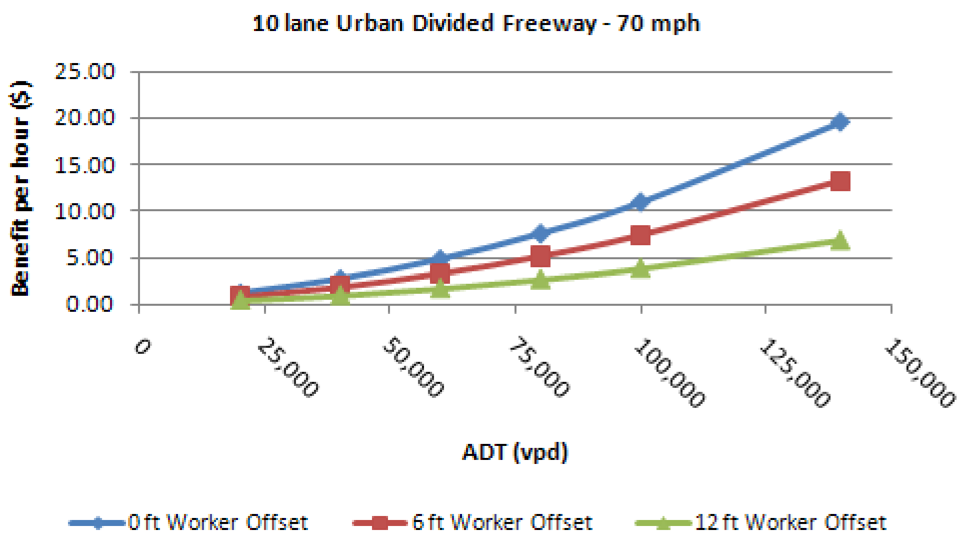


Figure 24. Examples of Estimated Positive Protection Benefits for a 45-ft Work Space with a Single Worker: 70 mph Urban Freeway Conditions.

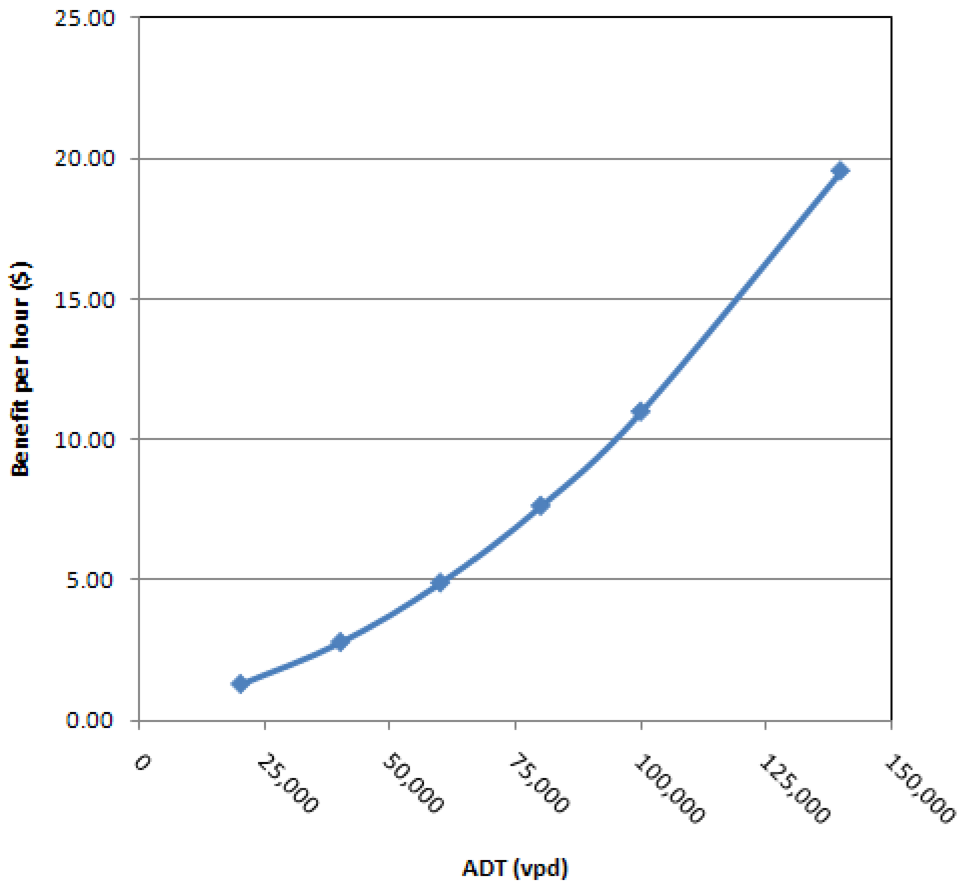


Figure 25. Simplified Relationship between ADT and Hourly Crash Cost Reduction Benefits of Portable or Mobile Positive Protection.

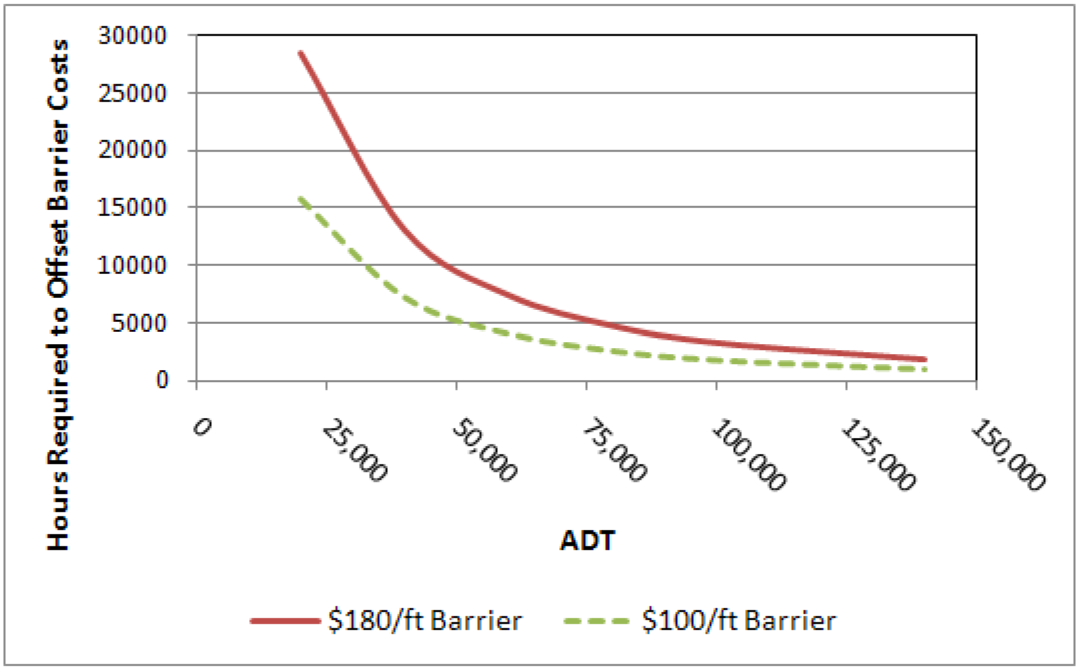


Figure 26. Hours to Offset Costs of Steel Barrier Use.

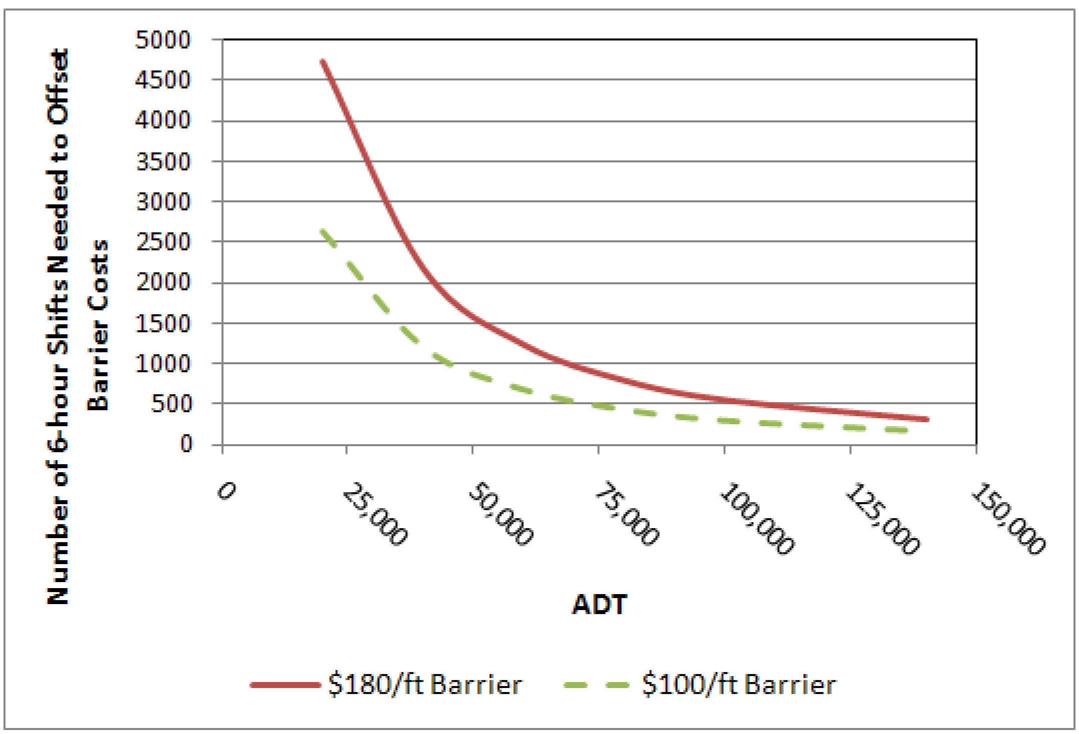


Figure 27. Six-Hour Work Shifts to Offset Costs of Steel Barrier Use.

A similar analysis can be performed for the use of mobile barriers. As discussed previously, these devices are currently priced at between $200,000 and $250,000. Figures 28 and 29 illustrate the number of hours and number of 6-hour work shifts that would be required to offset those costs via reduced work zone intrusion crash costs. As the figures indicate, it takes considerably longer (as much as ten times longer) to offset the costs of these types of devices with reduced work zone intrusion crash costs. However, these devices do still appear to be justifiable at higher ADT levels (i.e., ADTs greater than approximately 100,000 vpd). At these volume levels, the current costs of mobile barriers could be offset within 5 to 10 years of use. Obviously, if these devices decrease in cost over time, the costs could be reduced in a corresponding shorter duration.

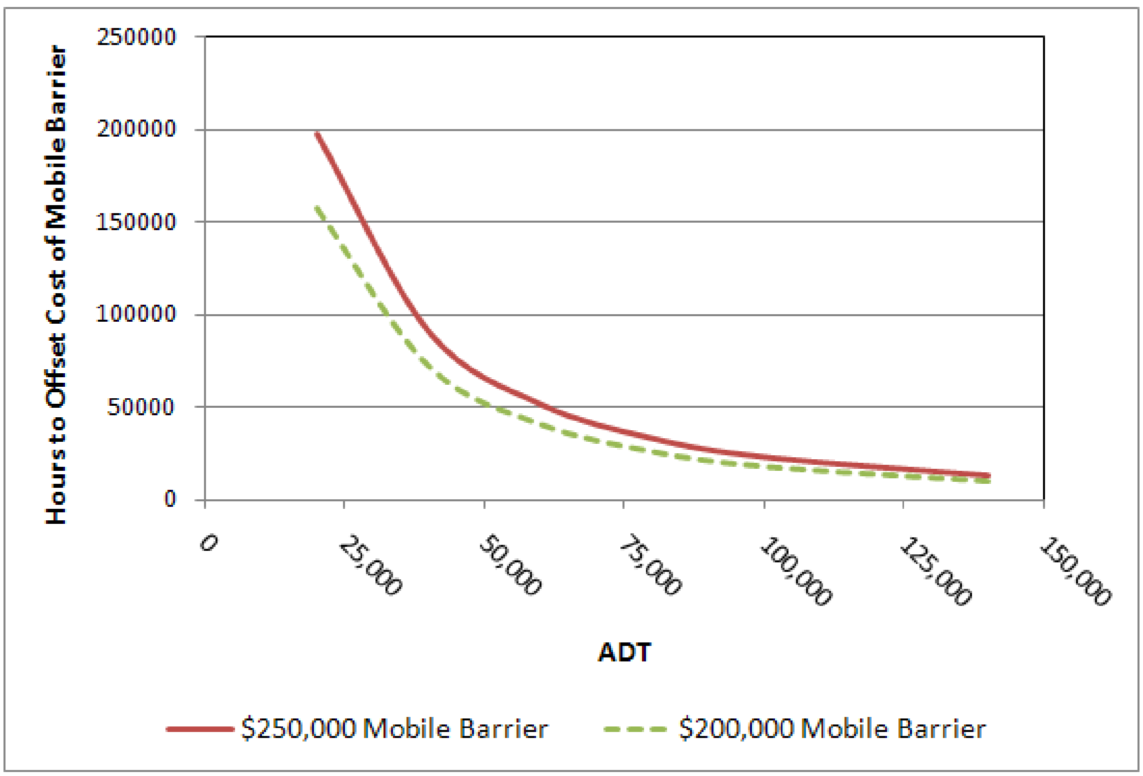


Figure 28. Hours to Offset Cost of Mobile Barrier.

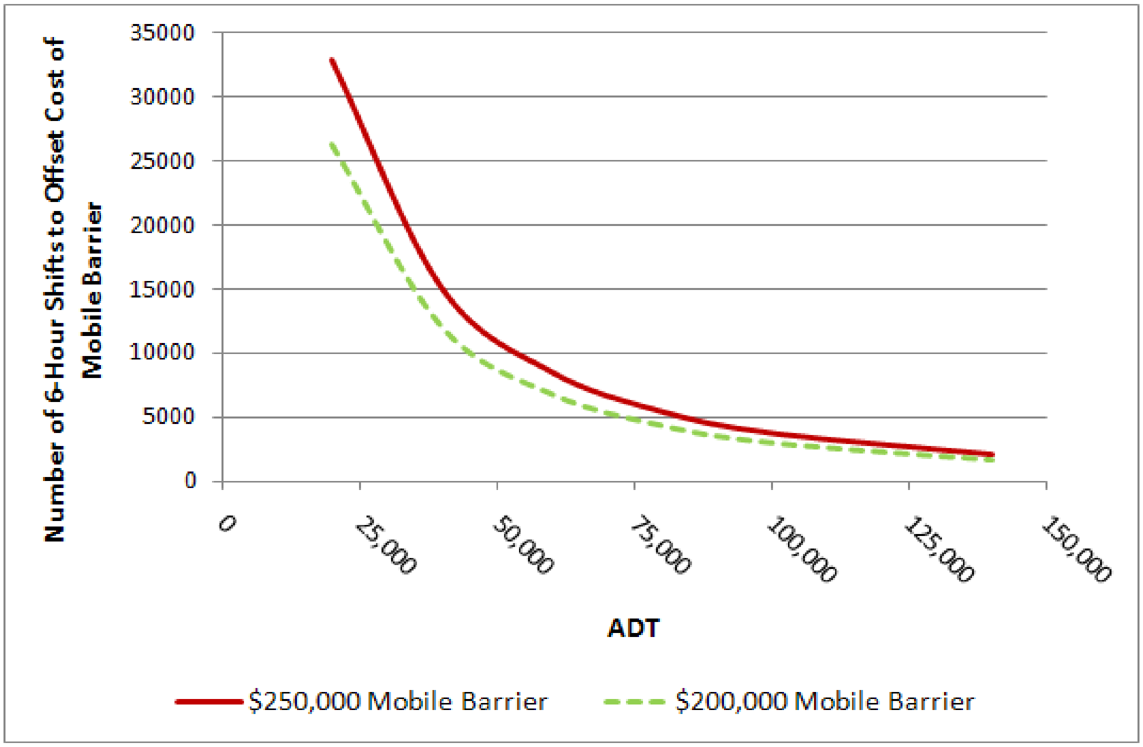


Figure 29. Six-Hour Work Shifts to Offset Costs of Mobile Barrier Use.

Truck-Mounted Attenuators

As described previously, an encroachment-based analysis model (i.e., RSAP) would not be appropriate for assessing the benefits and trade-offs associated with the use of TMAs during mobile and short-duration operations, as TMAs primarily protect work crews and the traveling public from rear-end crashes between motorists and slow-moving or stopped work vehicles. Rather, an analysis should be based on the expected reduction in those rear-end crash costs associated with the use of TMAs. The devices themselves are assumed to reduce the severity of such crashes, but not necessarily their frequency. Therefore, researchers hypothesized again that it should be possible to determine the number of hours of work activity needed to offset TMA costs at various roadway ADT levels as a way of assessing TMA cost-effectiveness. The key data items needed are an estimate of the reduction in crash costs that are achieved by the use of TMAs and the frequency of rear-end crashes that are likely to occur between a motorist and a work vehicle with or without a TMA present.

To assess crash cost reductions of TMA use, researchers utilized the New York State Department of Transportation (NYSDOT) work zone crash database from years 2000 through

2005. Researchers reviewed the narrative of the crashes to identify those that involved a collision between a motorist and a work vehicle. The NYSDOT database also identified whether or not the work vehicle impacted had a TMA in place at the time of the collision. By comparing the severity of the crashes where a TMA was not present to those when a TMA was in place, it was possible to determine the average reduction in crash severity that could be attributable to the presence of the TMA. Assigning the standard cost values for various levels of crash severity as previously documented in Table 6, it was then possible to estimate the average crash cost reduction that was achieved when a TMA was present.

The NYSDOT work zone crash database yielded a total of 186 crashes between motorists and work vehicles. As shown in Table 8, 63 percent of those collisions did involve a work vehicle that had a TMA attached, whereas 37 percent involved a collision with a work vehicle that did not have a TMA. The table also shows yearly counts of three crash severity levels (property-damage-only, injury, fatality). Summed over the five years, one sees the distribution of the crashes by severity for each condition of interest (with or without a TMA present). The numbers and percentages are very telling. For crashes where a TMA was present, approximately 65 percent of the crashes involved property damage only, and 35 percent involved an injury to the public or to a worker. No fatalities occurred in these types of crashes either. In contrast, 60 percent of the crashes where a TMA was not present involved an injury to the public or a worker. In addition, 3 percent of these types of crashes resulted in a fatality. Only 37 percent of the crashes resulted in just property damage. The differences between the with-TMA and without-TMA conditions were statistically significant at a 95 percent level of confidence. Comparing the percentages between the two conditions, one sees that TMAs reduce the chance of injury or death when rear-end collisions occur between motorists and work vehicles by 55 percent. Stated another way, the chance of injury or death is 1.8 times higher when a TMA is not present compared to when a TMA is present.

Table 8. Collisions between Motorists and Work Vehicles with and without a TMA.

Year	Crashes with TMAs			Crashes without TMAs		
	PDO	Injury	Fatal	PDO	Injury	Fatal
2000	10	6	0	4	11	1
2001	9	5	0	0	8	1
2002	20	9	0	9	6	0
2003	14	10	0	6	10	0
2004	12	3	0	5	6	0
2005	12	8	0	1	0	0
Totals	77 (65%)	41 (35%)	0 (0%)	25 (37%)	41 (60%)	2 (3%)

χ^2=16.243 > $\chi^2_{(0.05, 2)}$ = 5.991

PDO = property damage only

To estimate the average cost of a crash for both with- and without-TMA conditions, researchers multiplied the proportion of each severity level in Table 8 by the corresponding estimated cost of a crash of that severity level, based on crash cost research updated from 2001 to 2008 dollars using the Consumer Price Index (CPI) (*15*):

- PDO = $9,516.
- Injury = $120,477.
- Fatal = $4,978,305.

The result was an estimated average cost of a rear-end crash between a motorist and work vehicle of $48,070 if a TMA is present and $222,561 if no TMA is present, which is a difference of $174,490 per crash. Thus, rear-end crashes between motorists and work vehicles are almost four times more expensive if a TMA is not present to reduce the severity of the crash.

With the benefit of TMA use (in terms of crash cost savings) established, researchers then turned their attention to estimating the frequency with which such collisions occur. Unfortunately, the NYSDOT database does not include work zone exposure information upon which to develop estimates of motorist-work vehicle collision crash frequencies. Therefore, researchers assumed that the frequency of such collisions was comparable to the rate at which rear-end work zone collisions occur between motorists. While it can be argued that work vehicles have much greater conspicuity (warning lights, retroreflective high visibility markings, etc.) than typical vehicles driven by the public, work vehicles often travel at much lower speeds relative to the speed of traffic and so create larger and more frequent speed differentials than occur between motorists in two vehicles. To account for the fact that only rear-end collisions involving a work (shadow) vehicle were of interest, only a fairly small region around a work convoy (200 ft) was examined in the analysis. Overall, researchers believe that the analysis that follows represents a fairly reasonable (and likely conservative) assessment of rear-end crash potential between motorists and work vehicles.

Expected crash frequencies were based on the results of the recent national research of both daytime and nighttime work zones (*16*). In that study, crashes in work zones were modeled as a function of normal roadway crash risk, multiplied by a crash modification factor that accounted for increased crash risk due to work zone activities. For this analysis, the crash increases associated with work operations involving temporary lane closures were used, as illustrated in Table 9. Interestingly, the changes in work zone crash frequency were not found to be correlated to ADT, but were fairly constant over the entire range of ADTs included in the dataset.

Table 9. Crash Increases during Daytime and Nighttime Work Activities Involving Temporary Lane Closures.

Crash Severity	Daytime Work Activities	Nighttime Work Activities
PDO Crashes	+80.8%	+74.8%
Injury and Fatal Crashes	+45.5%	+42.3%

Although the increase in crash frequency due to the presence of work zone activity involving a temporary lane closure was found to be ADT independent, the proportion of the crashes that involved rear-end collisions was not. Rather, the proportion of crashes that involved rear-end collisions increased as the ADT of the roadway increased. Figure 30 illustrates this increase. The estimated work zone crashes expected to occur each hour of the mobile or short-duration work operation were then multiplied by the percentage of those crashes that are expected to involve rear-end collisions with the work vehicle and by the average reduction in crash costs attributable to the use of TMAs. Figure 31 shows the results of those computations.

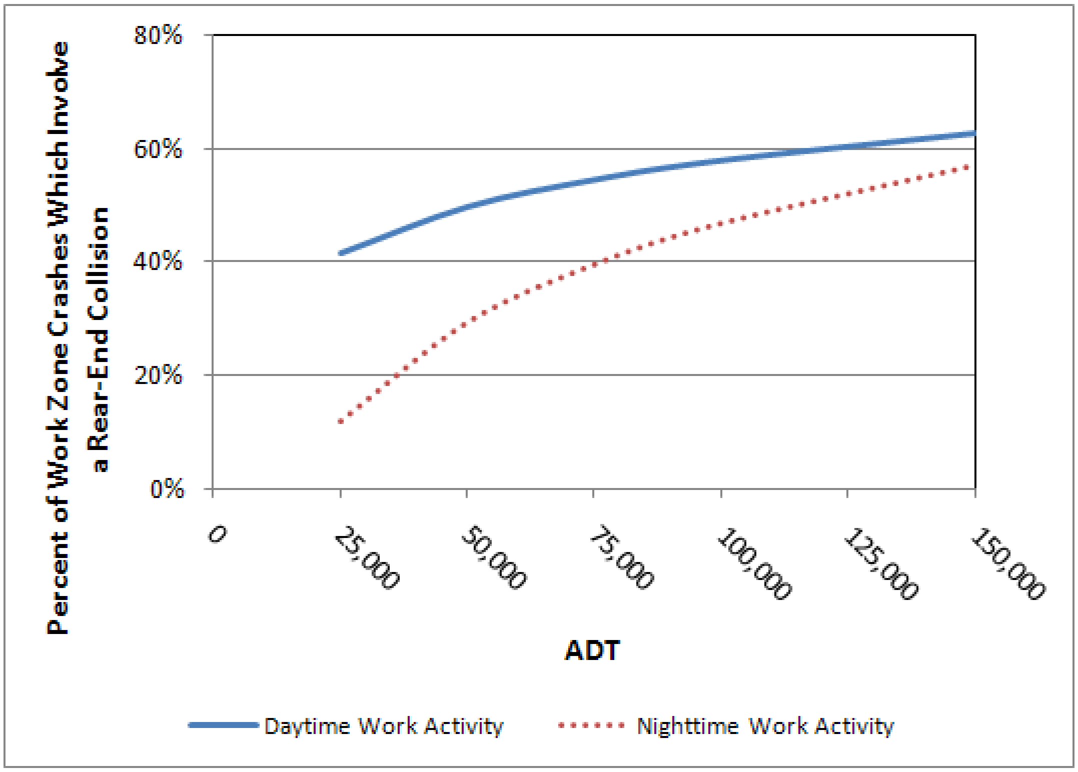


Figure 30. Work Zone Crashes Involving Rear-End Collisions (adapted from *16*).

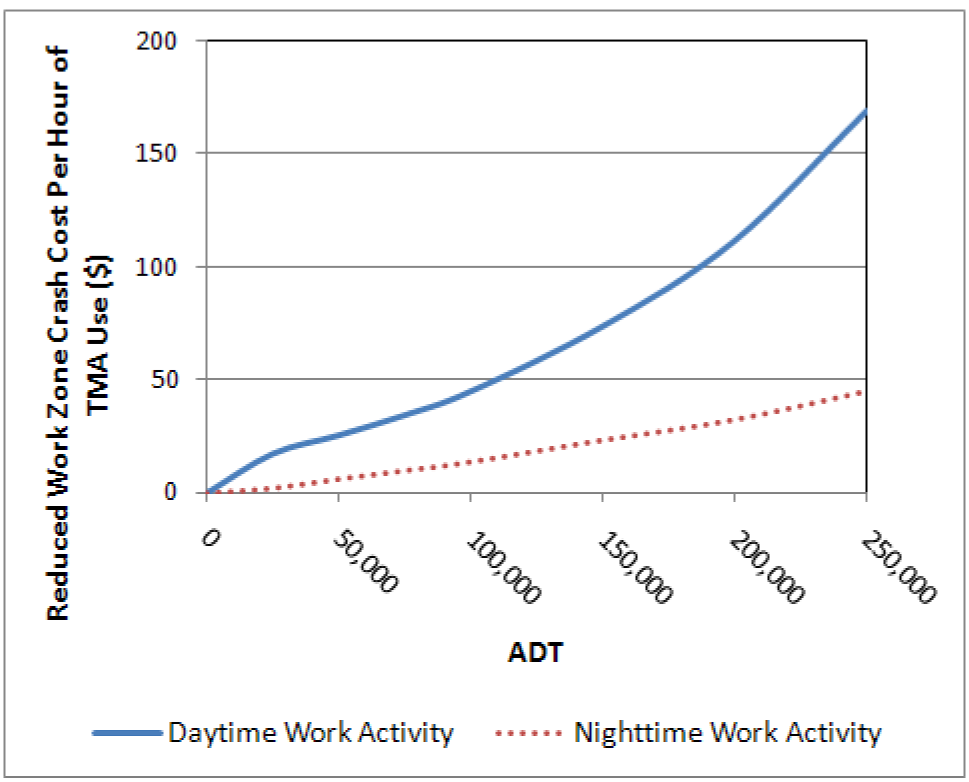


Figure 31. Hourly Crash Cost Reductions due to TMA Use.

As was done in the previous section for portable and mobile barriers, it is useful to examine TMA values in terms of the number of hours it takes to offset the costs of the device through reduced crash costs. A review of typical prices for TMAs suggests an approximate cost of about $15,000. Using this value, Figure 32 illustrates the number of hours needed to recoup the costs of TMA use as a function of ADT on a facility. One sees that it is fairly easy to offset the costs of TMAs at about any ADT level during daytime operations. At night, it becomes fairly easy to justify TMA use once ADTs exceed 50,000 vpd. Interestingly, that is the ADT level at which agencies typically begin conducting work operations that occur in travel lanes, including mobile and short-duration work activities, during nighttime hours to avoid creating excessive delays and queues (*16*). If the analysis is again extended to consider the number of 6-hour work shifts needed to offset TMA costs, one finds that the devices do not require extremely long service lives to justify their use. In fact, as Figure 33 suggests, a TMA will offset its costs in expected reduced work zone crash costs in about one year or less of use during the day at any volume level and at night when ADTs are above 50,000 vpd.

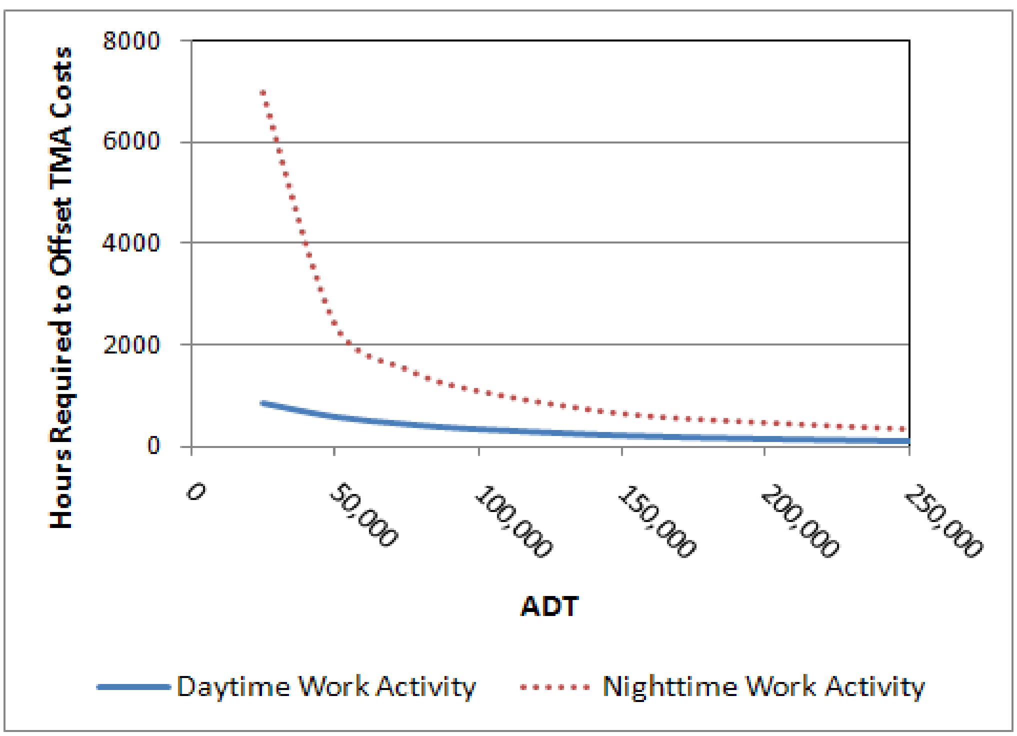


Figure 32. Hours to Offset Costs of TMA Use.

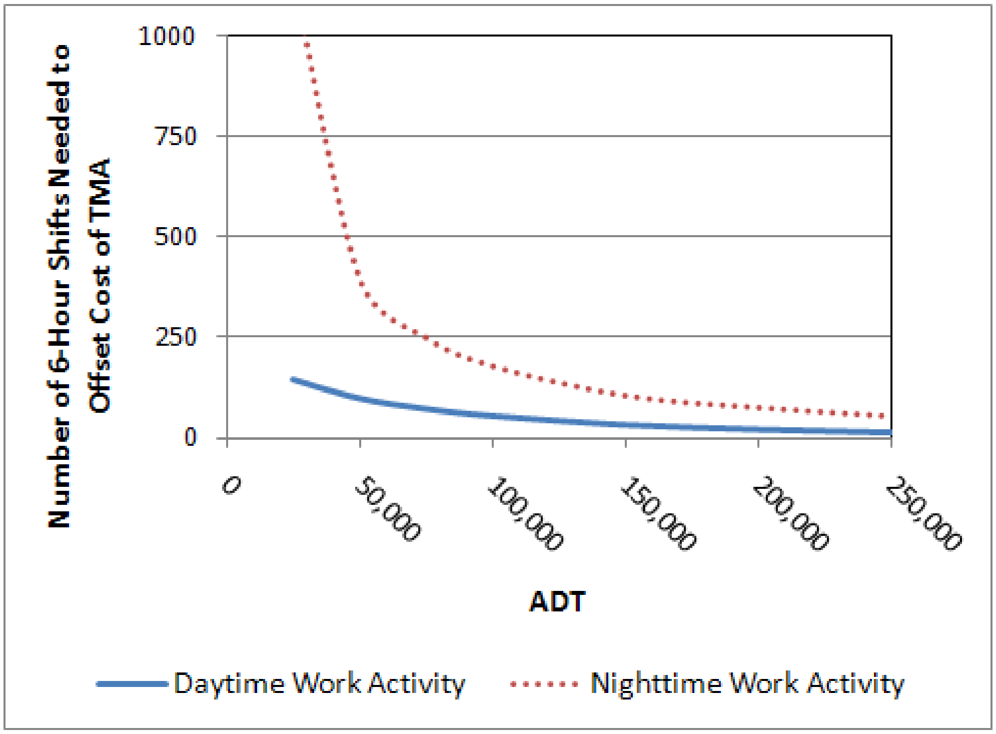


Figure 33. Number of Work Shifts Needed to Offset TMA Use.

ASSESSMENT OF OTHER TRAFFIC CONTROL MEASURES TO REDUCE WORK ZONE INTRUSIONS

INTRODUCTION

Even if an engineering analysis of a work zone indicates that PCB or other barrier protection is not justified, the FHWA regulations direct state agencies to consider other techniques believed to have the potential to reduce vehicle crashes and intrusion potential into the work area or to reduce the consequences of such intrusions should they occur (*20*). These techniques tend to fall into one or more of the following categories:

- Exposure control techniques.
- Other traffic control improvements (improved worker and vehicle visibility, methods to improve driver or worker alertness, speed reduction techniques).

The reduction of worker and motorist exposure to work zones is a significant emphasis area for FHWA as well as for TxDOT and other state highway agencies. Efforts in this category include:

- Full road closures.
- Moving work activities to nights and/or weekends when traffic volumes are lower.
- Efforts to increase traffic diversion to other routes or modes in the corridor.
- Contracting techniques to increase the pace of work and thus reduce total work zone durations.

Past research has shown that these techniques do have the potential to reduce crashes in the work zone (*16*). However, the implications of these strategies on crashes elsewhere in the corridor have not yet been assessed.

An argument that is often made is that drivers sometimes do not adequately detect and recognize the presence of workers and the need to be more careful when negotiating the work zone. Therefore, enhancements to the visibility of the work zone or to the workers and vehicles themselves could help reduce work zone crash (including intrusion crash) potential. These techniques include specifying warning lights on advance warning signs, use of PCMSs, high-visibility apparel requirements for workers, enhanced vehicle warning light systems, and enhanced lighting systems for night work operations (especially if flaggers are used). Once again, while the effect of some of these countermeasures has been assessed in terms of speed reductions or other operational influences, none have been correlated to a measurable reduction in crash likelihood.

Techniques used to enhance driver alertness and awareness of the work zone is assumed to correspond to reduced crash likelihood (including intrusion crashes into the work area); once again this has not been established for certain through objective research. Many of the techniques listed above for speed reduction and improved visibility (rumble strips, drone radar, enforcement presence, PCMS usage, vehicle warning light systems, enhanced work zone lighting systems, etc.) are believed to raise driver awareness levels as well. The display of dynamic information to the driver (delays, presence of queues, etc.) on PCMS through the application of work zone ITS systems also falls into this category. Also included in this category are those techniques that aid the worker in identifying when an errant vehicle has entered into the work area (spotters, intrusion alarms, etc.).

Excessive speeds through work zones are often cited as a major concern by work zone traffic control designers and field personnel alike. It is typically argued that slower speeds allow more time for drivers to react to an unexpected situation or to correct their vehicle path if they begin to leave the travel way for some reason. It is also recognized that crash severity is reduced when speeds are slower. Speed display trailers or portable changeable message signs (PCMS) that provide feedback to the driver about their speed, drone radar, portable rumble strips, the CB Wizard, and flagging have all been tried as work zone speed management techniques (*20*). The amount of speed reductions achieved with these techniques varies. On the other hand, the provision of law enforcement personnel in work zones has typically achieved more substantial speed reductions when such personnel are present, as has the use of pilot cars to lead vehicles through the work zone. However, these techniques are manpower intensive and significantly more expensive to employ.

In this chapter, researchers summarize the key considerations relative to the application of these non-positive-protection strategies for improving safety in work zones.

EXPOSURE CONTROL TECHNIQUES

The fewer times motorists encounter work zones, the fewer chances there are for work zone-related crashes to occur. Reducing the number of work zones, the length of time during which work zones are set up and the adverse impact that work zones have on traffic will reduce the exposure of road users and workers to crashes (*16*).

Several strategies are available to accomplish this particular objective (*20*):

- Strategies to reduce work zone duration and to reduce the number of work zones that are required.
- Full-time roadway closure for construction operations.
- Nighttime road work.
- Demand management programs to reduce volumes through work zones.

Techniques that accelerate construction progress can be viewed as a type of safety benefit, even though such techniques are not typically implemented as a way to improve safety. These can consist of changes to project design, scheduling, and sequencing to accelerate the work of construction. Typically, these changes and innovations occur because of contract acceleration incentives included in the project bid documents. If the duration of a work zone on a facility is reduced over time, then vehicle exposure to the work zone (and resulting additional crash costs due to the work zone) will undoubtedly be lower, assuming that comparable levels of safety are provided in the work zones that are actually used.

As an example, Figure 34 presents the estimated additional crash costs that occur per 100 hours of daytime work zone per work-zone-mile, based on a recent study of daytime and nighttime work zones (*16*). The values illustrate the reduction in crash costs that can be achieved for each 100-hour reduction in work zone duration. Efforts that reduce the amount of inactive work zone time are typically the simplest to achieve. However, the use of innovative construction practices can also lead to reduced work activity times as well. A similar graph for nighttime conditions is shown in Figure 35.

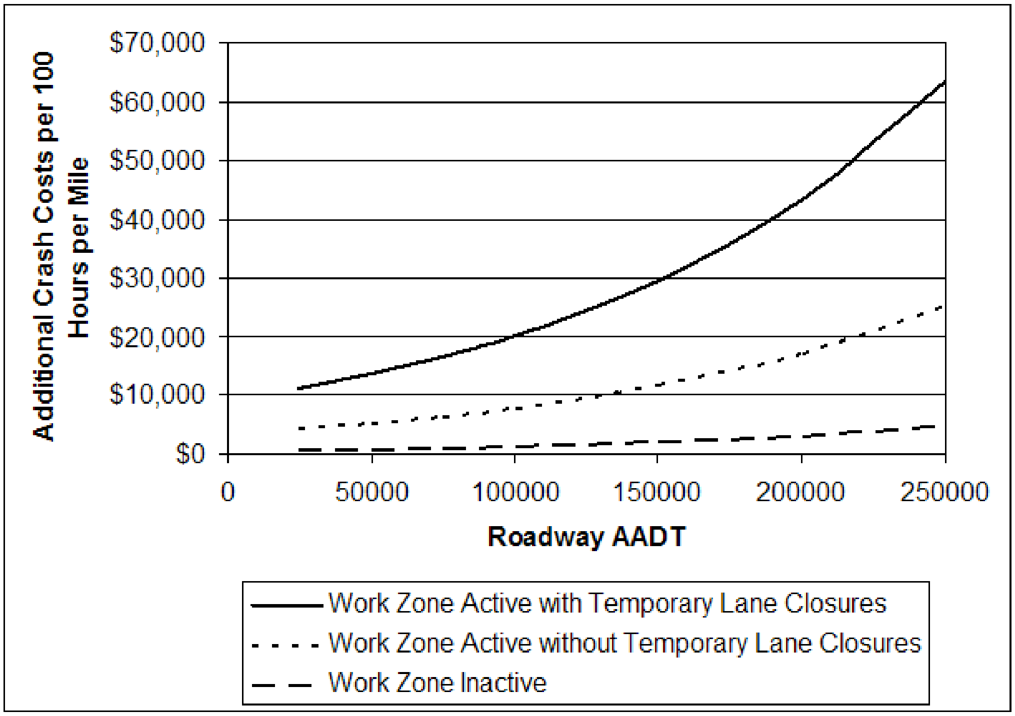


Figure 34. Effect of Strategies to Reduce Work Zone Frequency and Duration: Daytime Conditions (*16*).

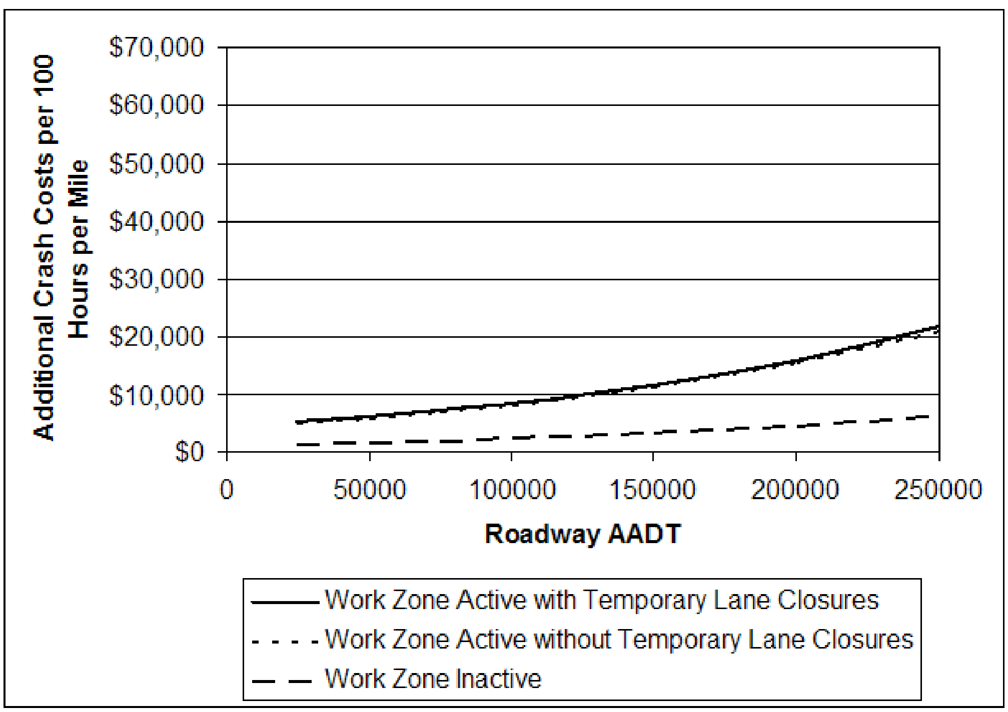


Figure 35. Effect of Strategies to Reduce Work Zone Frequency and Duration: Nighttime Conditions (*16*).

When and where it is possible to do so, completely closing a roadway section to allow construction or maintenance work to be performed eliminates the potential for traffic crashes to occur in the activity area. In addition, the elimination of interactions between construction vehicles/equipment and traffic often allows for larger workspaces and increased worker productivity, thus reducing the total duration of the work activity. It is possible that work quality can be improved as well. Closing one direction of a freeway and putting both directions of traffic on the other directional roadway via median crossovers is one example of this strategy. Likewise, closing one direction and moving traffic onto the adjacent frontage road around the work zone is another example. However, this strategy can entail the complete closure of both travel directions and detouring of traffic onto completely different roadways in the region.

From a safety assessment perspective, the amount by which traffic crashes in the work zone is reduced can be significant since both the additional crash costs due to the work zone and the crashes normally occurring on that roadway segment are eliminated. However, these reductions in crash costs may be offset to some degree by an increase in crash costs on the detour route(s) due to the additional traffic exposure that is placed on each route. Whereas this is not likely to be a significant concern when median crossovers or frontage road detours are employed, it may be more important if traffic is being completely detoured off of a freeway-type facility onto arterials and other surface streets. Normally, crashes occur more frequently on arterial streets than on freeways but are less severe. Consequently, a detailed analysis of a particular site and the feasible alternative routes would be required to assess whether there is a net crash cost benefit to a full roadway closure. Estimating the additional crash costs on these detour routes requires information on how much additional traffic is being carried on each route, the normal traffic volumes on those routes, and the expected crash rate.

The decision whether work must be performed at night should involve a comprehensive cost-effectiveness evaluation that should consider the implications of each alternative (including active night work) with respect to three key impact factors:

- Impact to the community and traffic (business operations, pedestrians and bicyclists, emissions, public transit, emergency services, noise effects, lighting and glare effects, traffic diversion impacts, etc.).

- Impact on safety (construction safety, traffic safety, and safety during maintenance efforts).
- Impact on constructability (contractor experience, temperatures, supervision capabilities, worker efficiency, lighting plan quality, and materials/equipment availability).

In the majority of cases, however, avoidance of adverse traffic impacts drives the decision of whether or not to work at night. Various criteria are used to determine when the threshold of maximum acceptable impacts is exceeded. Some agencies simply identify a maximum per-day or per-hour traffic volume per open lane that can exist if a lane closure is to be allowed. If the traffic volume during all or part of the time that the lane closure is being anticipated is higher than that threshold, it must be scheduled during a time when traffic volumes are lower. Other agencies use predicted estimates of delay or queue lengths to decide if work must be performed at night. Although congestion avoidance may be the primary factor compelling agencies and contractors to work at night, there is evidence that doing so does have a safety benefit as well to the motoring public. The extent of the expected savings when lanes are closed is illustrated graphically in Figure 36. Also shown are the expected savings of working at night when travel lanes do not need to be temporarily closed. For the former, the crash cost savings are substantial and increase exponentially at higher AADT levels. In contrast, there is little incentive from a safety standpoint to working at night if travel lanes do not need to be closed. As the figure illustrates, the difference in expected crash costs between working during the day versus at night are fairly small for most of the AADT range.

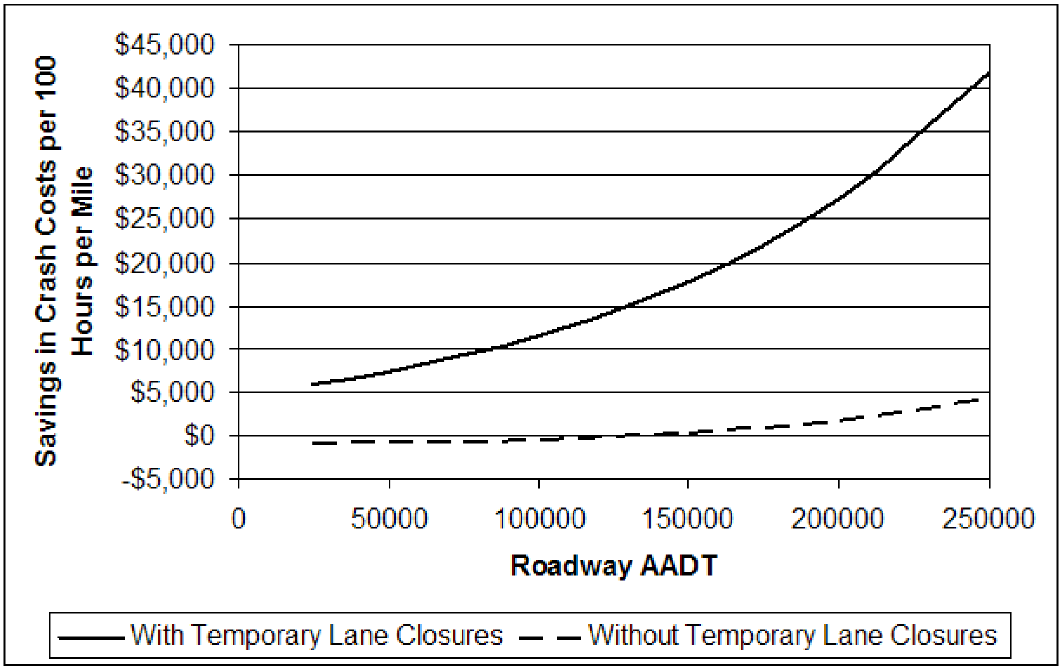


Figure 36. Example of Reduction in Crash Costs Achieved by Working at Night (*16*).

Transportation demand management (TDM) programs are one part of a comprehensive traffic management approach to improve safety and reduce delays in work zones (*20*). The goal of TDM is to reduce the total amount of traffic attempting to use the work zone and other routes in the corridor by encouraging various trip reduction techniques (carpooling/vanpooling, increased use of transit, increased bicycling/walking, etc.). In this way, vehicle exposure in the work zone is reduced, which improves safety. As example, the potential safety benefit of 10 and 20 percent trip reductions due to TDM techniques during times when work is active and lanes are temporarily closed is illustrated in Figure 37(*16*). TDM techniques work to reduce all crash costs on a facility, not only those additional costs that are attributable to the presence of the work zone. It must be kept in mind that these crash cost savings are achieved if the number of trips being made is reduced, not simply moved to other routes in the corridor.

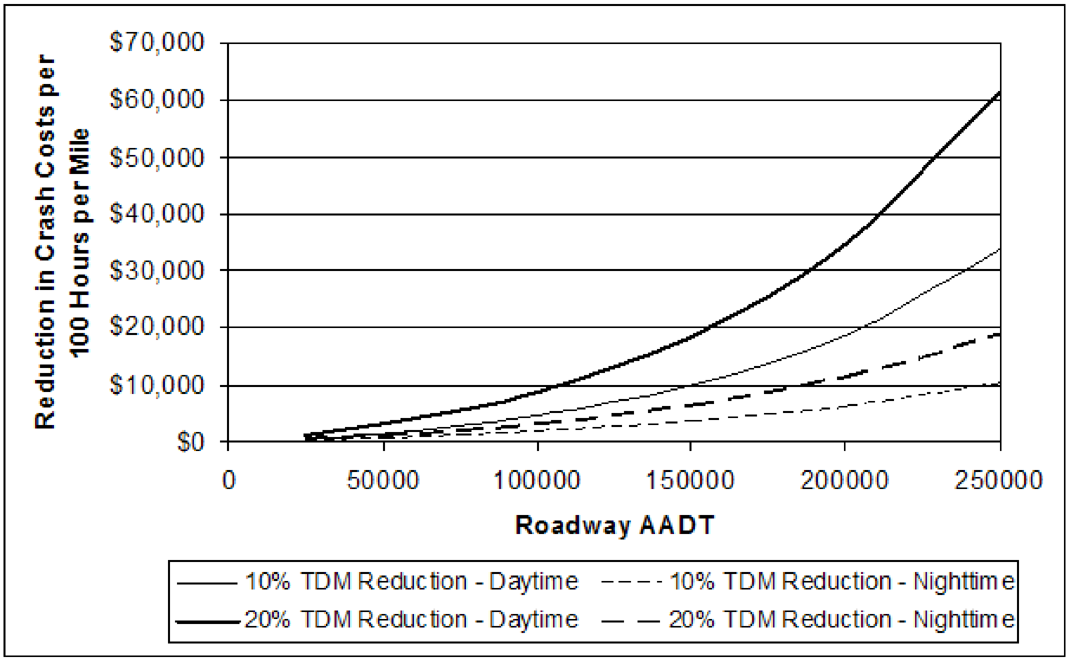


Figure 37. Example of Reduction in Crash Costs by Travel Demand Management Strategies during Work Activity with Temporary Lane Closures (*16*).

OTHER TRAFFIC CONTROL IMPROVEMENTS

Improved Worker and Vehicle Visibility

Ensuring that both workers and work vehicles are adequately visible to approaching motorists is believed to improve work zone safety and potentially reduce the likelihood of vehicle intrusions into the work area, especially those that occur because of deliberate driver decisions and actions to do so. Unfortunately, the magnitude of such crash reductions is not easily quantifiable. Consequently, only general recommendations can be provided.

The intent of the recent FHWA rulemaking on high-visibility vests is to ensure that workers are adequately visible to approaching motorists and to other workers operating construction equipment in and around the work zone (*21*). The regulations significantly improve worker visibility, especially at night. Ensuring that the visibility of vests is maintained and that vests that no longer perform as intended are removed from use is a key responsibility of highway agencies, including TxDOT. Guidance on vest conditions that are considered acceptable, marginal, or unacceptable (and thus should be discarded) is available (*22*).

With regard to work vehicles, visibility must be considered both when they are in operation and in use within the work space, as well as when they are not being used and are left out in or near the work site. For the former, the regular vehicle warning lights and supplemental special flashing beacons or other lights are used to warn motorists. For the latter, the use of retroreflective markings on the back and side of the vehicle enhances its visibility. Some agencies choose to have channelizing devices or barricades placed in front of parked vehicles to further ensure their visibility.

Various researchers have studied the design and placement of special flashing warning lights for construction and maintenance vehicles (*23-25*). TxDOT policy defines acceptable flashing warning light systems for use on TxDOT vehicles as well as other construction, maintenance, utility, and service vehicles statewide. Care must be exercised to ensure that the warning lights are not overpowering or blinding to motorists at night. Work vehicles should also be oriented such that their headlights are not pointed toward approaching traffic, especially when working in the right lane or shoulder of a multi-lane highway, as this can create significant confusion and erratic maneuvers by motorists (*26*).

Improving Driver and Worker Alertness

A number of strategies and technologies are available that strive to increase driver awareness and alertness in work zones (*20*). These include such things as portable changeable message signs, flags on warning signs, flashing warning lights on signs and channelizing devices, and sequential warning light systems on lane closure tapers. Certain work zone intelligent transportation system (ITS) applications can also improve driver alertness and awareness of work zone hazards. TxDOT requires flags on certain advance warning signs and PCMS use for certain work zone operations. Additional use of these and other devices are left up to the work zone designer or project engineer to determine. Overuse of such devices can reduce their credibility and effectiveness over time. Consequently, it is important that each application fulfills the basic MUTCD requirements for a traffic control device (*27*):

- Fulfill a specific need.
- Command attention.
- Convey a clear, simple meaning.

- Command respect from road users.
- Give adequate time for proper response.

Failure to follow these basic principles leads to the reduced credibility of these devices with the motoring public. If the devices are not perceived as credible, drivers simply ignore them and their effectiveness at alerting and improving awareness is lost.

Devices and strategies designed to increase alertness and awareness of workers include such things as:

- Back-up warning alarms on construction equipment.
- Use of spotters.
- Intrusion alarms.

Audible back-up alarms are required on construction equipment. Research is under way looking at the effectiveness of other types of alarms to help reduce the frequency of worker injuries due to being backed over by construction equipment. Spotters can be used to monitor and protect workers near construction equipment or can be used to monitor traffic approaching a work zone, and sound an alarm if an intrusion is going to occur. There have been a number of efforts to develop intrusion alarms that could be deployed in a work zone to automatically alert workers of an intrusion. Pneumatic tubes, infrared beams, and other detection devices have all been tried but with only limited success. False alarms were a problem in most cases, as was the time required to install and maintain the devices (*28*). As a result, most systems are no longer available. The only exception is a simple device shown in Figure 38 (*29*). The device is attached to a channelizing device. A CO_2 cartridge is punctured if the channelizing device is knocked over, activating an air horn that warns workers in the vicinity of a potential intrusion.

Figure 38. Example of Intrusion Warning Devices.

Speed Reduction Techniques

The final subcategory of techniques that are believed to offer the potential to improve work zone safety and reduce work zone intrusion potential are those techniques designed to reduce motorist speeds approaching and traveling through the work zone. Conceptually, slower speeds provide increased time to react to any unexpected situations that may arise, and reduce stopping distances. However, attempts to slow down vehicles excessively can increase speed differentials between vehicles, which can increase crash risk. Consequently, it is important that speed reduction techniques only be used where it is absolutely necessary to do so.

Techniques that have been used to reduce vehicle speeds include the following:

- Presence of law enforcement.
- Drone radar.
- Speed display trailers (including PCMS with radar).
- Citizen band (CB) radio information systems.
- Transverse rumble strips.
- Transverse pavement markings.
- Reduced lane widths with channelizing devices.

In a few cases, speed display trailers have resulted in speed reductions up to 10 mph (*30*). However, in most applications, techniques other than law enforcement presence typically reduce speeds by only a few miles per hour. It should be noted that even if the reduction in speed is rather small, these techniques may effectively alert drivers and so achieve some safety benefit.

The use of traffic law enforcement at a highway work zone is recognized as one of the most effective means available for reducing speeding, speed variability, and undesirable driving behaviors such as tailgating and unsafe lane changes, thereby improving traffic and worker safety in the work zone. The presence of work zone enforcement is also believed to raise driver awareness and level of alertness, reducing perception-reaction times in response to unexpected hazards encountered. A variety of enforcement philosophies and strategies have been used in work zones (overt versus covert enforcement, active enforcement versus traffic-calming techniques, etc.), depending on the needs of the highway agency. Specific reasons should exist for providing enforcement at a work zone. Enforcement costs are not insignificant, and represent an additional burden on enforcement agency manpower and equipment resources in a region, even when highway agency funds are being used to pay for such efforts. If enforcement is to be used, it should be address specific hazards, and the strategy used should be capable of minimizing those hazards. Hazards generally fall into one of two categories:

- Work activity hazards.
- Work zone design hazards.

Work activity hazards are present only during times when work is occurring, whereas work zone design hazards are typically present at all times (both when work is occurring and when the work zone is inactive). Engineering judgment is normally required to determine which work zones most need enforcement support. However, an analysis of potential savings in crash costs due to enforcement presence in work zones has yielded the recommendations found in Table 10. The recommended AADT values needed to offset the costs of dedicated enforcement depend on both the price of enforcement and the assumptions regarding their effectiveness in reducing work zone crashes (*31*). It should be noted that these values do not consider other types of benefits that enforcement presence in a work zone may create (i.e., increased traffic flow due to less aggressive driving, higher worker productivity and quality due to a sense of increased safety within the work space, etc.). Consequently, agencies may choose to justify enforcement use at even lower AADT levels than those shown.

Table 10. Comparison of Enforcement Benefits and Costs in Freeway Work Zones (*31*).

Enforcement Costs	AADT where Enforcement Benefits Are Approximately Equal to Enforcement Costs	
	Favorable-Benefit Scenario	Conservative-Benefit Scenario
$25 per hour		
Daytime work zone	5,000 vpd	20,000 vpd
Nighttime work zone	20,000 vpd	45,000 vpd
$50 per hour		
Daytime work zone	10,000 vpd	35,000 vpd
Nighttime work zone	35,000 vpd	100,000 vpd
$75 per hour		
Daytime work zone	15,000 vpd	50,000 vpd
Nighttime work zone	50,000 vpd	150,000 vpd
$100 per hour		
Daytime work zone	20,000 vpd	70,000 vpd
Nighttime work zone	65,000 vpd	200,000 vpd

vpd = vehicles per day

SUMMARY AND CONCLUSIONS

The goal of this project was to develop implementation guidance that the Texas Department of Transportation can use to make better decisions regarding when and where to use positive protection in work zones, and when to consider exposure control and other traffic control measures that could improve work zone safety. Researchers examined national and statewide practices regarding the use of positive protection in work zones. Researchers also used RSAP to examine crash cost reduction potential that could be achieved through the use of PCB under two different conditions:

- When intrusion crash costs alone (those involving workers, traffic control devices, work equipment, materials, etc.) would justify PCB use.
- When the combination of intrusion crash costs and costs of pavement drop-off considerations combine to justify PCB use.

An intrusion crash severity index was developed from the NYSDOT work zone crash data and used to model various configurations of work space and lateral drop-off location from the travel lanes. The RSAP analysis tool was also used to evaluate potential intrusion crash costs for short-term and short duration work zones where highway workers are on foot immediately adjacent to moving traffic. For these situations, any intrusions into a very short (i.e., 45 ft) work space around the work crew was treated as a fatality, and crash cost reductions achieved by having portable or mobile barriers protecting the work crew were estimated on a per-hour basis.

The positive protection crash cost benefits of providing TMAs for moving operations were also examined as part of this research. For that part of the analysis, recent work zone crash analyses were used to estimate rear-end crash cost frequencies between motorists and the back of a work vehicle. For each crash expected, the difference in crash cost severity with and without a TMA in place were computed and converted into expected crash cost reductions per hour of work operation.

The final topics examined were exposure control and other traffic control techniques encouraged by FHWA to potentially reduce the frequency of work zone intrusions and to make the work zone safer overall. Analysis results from recently-completed studies were synthesized to illustrate the potential crash cost savings associated with those techniques.

Based on the results of these various analyses, researchers drew the following findings and conclusions:

- For facilities where operating speeds are approximately 70 mph and work is occurring immediately adjacent (i.e., within 2 feet) to travel lanes, intrusion crash costs savings alone can justify PCB protection once the roadway ADT approaches 40,000 vpd over a year-long work zone, so long as there are constant hazards in the work space being protected by barrier. This ADT value can then be extrapolated to other work zone durations (i.e., equivalent to a 6-month work zone with an ADT of 80,000 vpd, a 2-year work zone on a 20,000 vpd facility, etc.). If all hazards are removed from the work space after each work shift, PCB use cannot be justified strictly on intrusion crash cost concerns. Similarly, if actual travel speeds are lower (i.e., 50 mph), PCB use for reducing intrusion crash cost potential alone does not appear to be justifiable at any ADT levels.
- For work zones in which drop-off conditions are also of concern, the analysis indicates that consideration of the potential for other types of intrusion crashes (in addition to drop-off crashes) does reduce the vehicle exposure thresholds at which PCB can be justified relative to current thresholds that consider drop-off conditions only. The extent to which the thresholds are affected depends on assumptions regarding the amount of time intrusion hazards exist in the work space. When intrusion hazards are present only during normal work activity on a typical work schedule, vehicle exposure thresholds are only slightly lower than they are for drop-off conditions alone. However, if the intrusion hazards in the work space will be there continuously (if there are equipment or materials that are left next to the travel lanes, for example), the vehicle exposure thresholds at which PCB can be justified will be 15 percent or more below those for drop-off conditions alone.
- Analysis of steel or mobile barrier technologies to create small, protected work spaces showed that the technologies are currently fairly expensive relative to the intrusion crash cost reductions that are possible, and so will generally be justifiable only on high-volume, high-speed facilities. It is expected that as these technologies

become more common and production increases, their prices will decrease. Even at their current prices, though, steel barrier appears capable of justifying its cost in terms of reduced intrusion crash cost potential within a year or two. In contrast, mobile barrier technology will require a longer time to recoup its investment cost but does appear to be able to do so for those agencies with a significant amount of high-volume, high-speed roadway under their jurisdiction.

- Analysis of rear-end crash potential with work vehicles in mobile and short-duration operations indicates that TMAs are highly effective in reducing rear-end crash severity and crash costs. Each crash with a TMA results in a crash cost savings of $174,490 relative to the crash costs that would have occurred if no TMA were present. Based on current TMA prices, agencies can recoup their costs in terms of reduced rear-end crash costs in less than a year of daytime work shifts on facilities serving 20,000 vpd or more and of nighttime work shifts on facilities serving 50,000 vpd or more.
- For work zones that do not serve enough traffic to warrant consideration of positive protection devices, a number of exposure control techniques and other traffic control measures are available to reduce intrusion crash risks. Techniques that reduce the total duration of a project are especially effective in reducing work zone crash costs. Working at night also reduces vehicle exposure and work zone crash costs that are incurred for a given duration of work. Reducing the total number of vehicle trips through the work zone via travel demand management is another way to reduce work zone crash costs. However, these types of techniques must actually reduce the number of vehicle-miles driven in the corridor. Techniques that divert traffic from the work zone to alternative routes in the corridor may also reduce work zone crash costs, but increase crash costs on those alternative routes due to increased vehicle exposure on those routes.
- Finally, the use of law enforcement in work zones is another technique that is believed to offer work zone crash cost reduction benefits (in addition to the other types of benefits of having enforcement present). The roadway ADT levels at which it is believed that enforcement presence is offset by reduced work zone crash costs varies by time of day, expected magnitude of crash cost reductions, and cost

of enforcement. Roadways with ADTs as low as 5,000 can justify enforcement use under a favorable set of assumptions. On the other hand, higher enforcement costs and a more conservative assumption regarding the effectiveness of enforcement can result in ADT thresholds of 100,000 vpd or higher in order to justify enforcement costs.

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APPENDIX A: TXDOT SURVEY OF POSITIVE PROTECTION USE

Greetings!

The Texas Transportation Institute, under TxDOT sponsorship, is conducting RMC 4 project 0 6163, "Improved Positive Protection Guidance for Work Zones." This brief survey is intended to gather information from TxDOT districts regarding current practices related to the use of positive protection on various road construction and maintenance projects. Please respond to the questions below at your convenience. If you have any questions regarding the information being requested, please contact:

Gerald Ullman
Texas Transportation Institute
Ph. (979) 845-9908
Email: g-ullman@tamu.edu

Thank you in advance for your assistance with this important research activity.

Contact Information of Survey Respondent

Name: ____

Job Title: ____

District: ____

Email: ____

Phone: ____

Address: ____

____

Part I: Use of Portable Concrete Barrier in Work Zones

1. Please provide the following information for any projects (up to 5) in your district during the past year where you utilized portable concrete barrier to separate the work area from traffic during all or part of the project.

Project No: _________ Route: _______________ Type of Project: _________________________

Project Duration: ______________________ Is the project ongoing now?__________________

Factors or reasons why you required PCB to be used: ___________________________________

____

____

Project No: _________ Route: _______________ Type of Project: ________________________

Project Duration: ______________________ Is the project ongoing now?__________________

Factors or reasons why you required PCB to be used: __________________________________

____

____

Project No: _________ Route: _______________ Type of Project: ________________________

Project Duration: ______________________ Is the project ongoing now?__________________

Factors or reasons why you required PCB to be used: __________________________________

____

____

Project No: _________ Route: _______________ Type of Project: ________________________

Project Duration: ______________________ Is the project ongoing now?__________________

Factors or reasons why you required PCB to be used: __________________________________

____

____

Project No: _________ Route: _______________ Type of Project: ________________________

Project Duration: ______________________ Is the project ongoing now?__________________

Factors or reasons why you required PCB to be used: __________________________________

____

____

2. For each of the projects you listed in question 1, what type(s) of end treatments did you use to protect motorists from the blunt end of the PCB? Why were these treatments selected?

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3. Have you had any projects in your district during the past year where thought was given to using PCB, but a decision not to use it was made for some reason? If so, please provide the following information for up to 3 such projects.

Project No: _________ Route: _______________ Type of Project: ________________________

Project Duration: ______________________ Is the project ongoing now?__________________

Factors why PCB was initially considered for use _____________________________________

____

Factors or reasons why it was eventually decided that PCB would not be used _______________

____

____

Project No: _________ Route: _______________ Type of Project: ________________________

Project Duration: ______________________ Is the project ongoing now?__________________

Factors why PCB was initially considered for use _____________________________________

____

Factors or reasons why it was eventually decided that PCB would not be used _______________

____

____

Project No: _________ Route: _______________ Type of Project: _________________________

Project Duration: _______________________ Is the project ongoing now?___________________

Factors why PCB was initially considered for use _______________________________________

____

Factors or reasons why it was eventually decided that PCB would not be used _______________

____

____

4. Have you used other types of barriers (steel, water-filled, etc.) instead of PCB on a project in the past 3 years? ___________

Part II: Use of Other Techniques to Improve Worker and Motorist Safety in Work Zones

5. What techniques or strategies have you implemented (other than what is required in the Texas MUTCD or the Texas Traffic Control Plan Standard Sheets) to improve worker and/or motorist safety? Examples include speed control strategies (payment for extra law enforcement, speed display trailers, etc.); enhanced signing, marking, or delineation; work zone intrusion alarms; requirements for larger lateral or longitudinal buffer areas adjacent to work areas; etc. Please identify up to 3 project(s) in your district during the past year where these techniques were or will be (for ongoing projects) employed.

Project No: _________ Route: _______________ Type of Project: _________________________

Project Duration: _______________________ Is the project ongoing now?___________________

Techniques or strategies used ____

Factors or reasons why the technique(s) were selected for this project _______________________

____

____

Project No: _________ Route: _______________ Type of Project: ________________________

Project Duration: ______________________ Is the project ongoing now?__________________

Techniques or strategies used ____

Factors or reasons why the technique(s) were selected for this project _____________________

____

____

Project No: _________ Route: _______________ Type of Project: ________________________

Project Duration: ______________________Is the project ongoing now?__________________

Techniques or strategies used ____

Factors or reasons why the technique(s) were selected for this project ______________________

____

____

Part III: Use of Truck-Mounted Attenuators

6. Do you require truck-mounted attenuators to be used on work or shadow vehicles in your district? ___________

7. What criteria does your district follow in determining whether or not a particular work operation requires the use of a truck-mounted attenuator?

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   ____

   ____

APPENDIX B: GUIDELINES ON THE USE OF POSITIVE PROTECTION IN WORK ZONES

INTRODUCTION

The decision whether to use positive protection to separate the work space from traffic requires consideration of a number of roadway and work zone characteristics, including (*1*):

- 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 (e.g., night work).
- Work area restrictions (including impact on worker exposure).
- Consequences from/to road users resulting from roadway departure.
- Potential hazard to workers and road users presented by device itself and during device placement and removal.
- Geometrics that may increase crash risks (e.g., poor sight distance, sharp curves).
- Access to/from work space.
- Roadway classification.
- Impacts on project cost and duration.

Efforts to reduce vehicle and worker exposure in work zones should also be considered, as should other traffic control devices and strategies which can improve the overall safety of the work zone for workers and for the traveling public.

POSITIVE PROTECTION JUSTIFICATION

Both FHWA regulations and TxDOT Work Zone Safety and Mobility guidelines state that 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:

(1) Work zones that provide workers no means of escape from motorized traffic (e.g., tunnels, bridges, etc.).
(2) Long duration work zones (e.g., two weeks or more) resulting in substantial worker exposure to motorized traffic.
(3) Projects with high anticipated operating speeds (e.g., 45 mph or greater), especially when combined with high traffic volumes.

(4) Work operations that place workers close to travel lanes open to traffic.
(5) Roadside hazards, such as drop-offs or unfinished bridge decks, that will remain in place overnight or longer.

PCB Use for Positive Protection

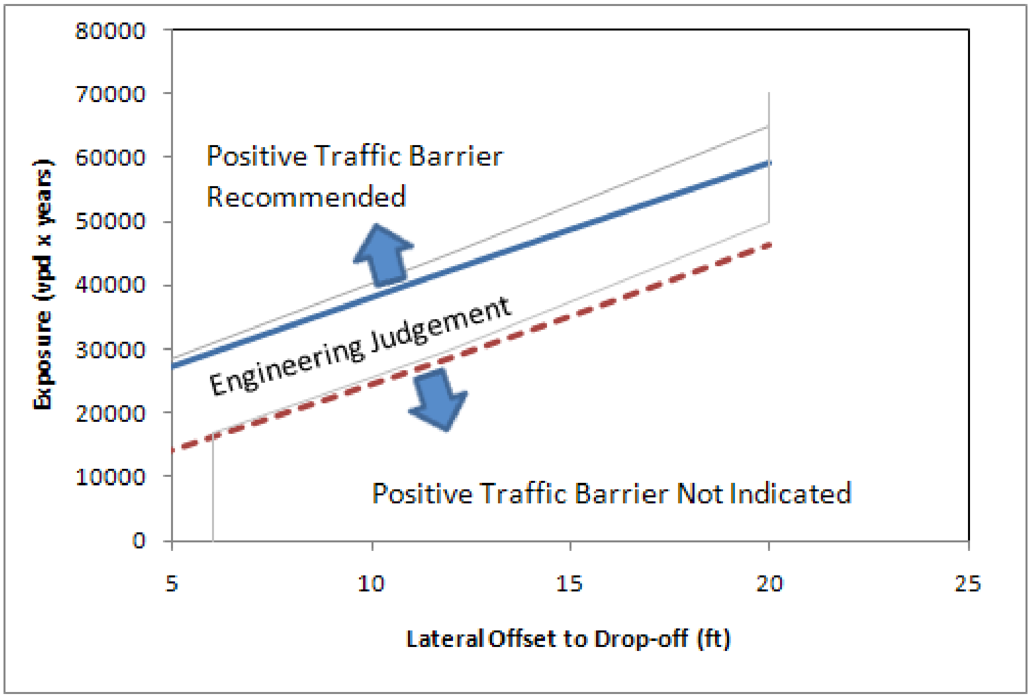
Previous positive barrier guidance targeted the protection of travelers from drop-off conditions only. In reality, positive protection can also protect workers from being hit by motorists who inadvertently enter the work space. In addition, positive protection can keep motorists from hitting stopped work vehicles or equipment, piles of material or debris, etc., within the work space as well.

Table B-1 identifies three conditions for which positive barrier use has been analyzed and found to be cost-beneficial. Positive barrier use can be justified solely on the basis of protecting the work space from intrusions, or on the basis of combined consideration of pavement drop-off and other work space intrusion cost reductions combined. If the latter, a distinction is made as to whether the work area is located closer to the travel lanes than the drop-off condition, or farther away.

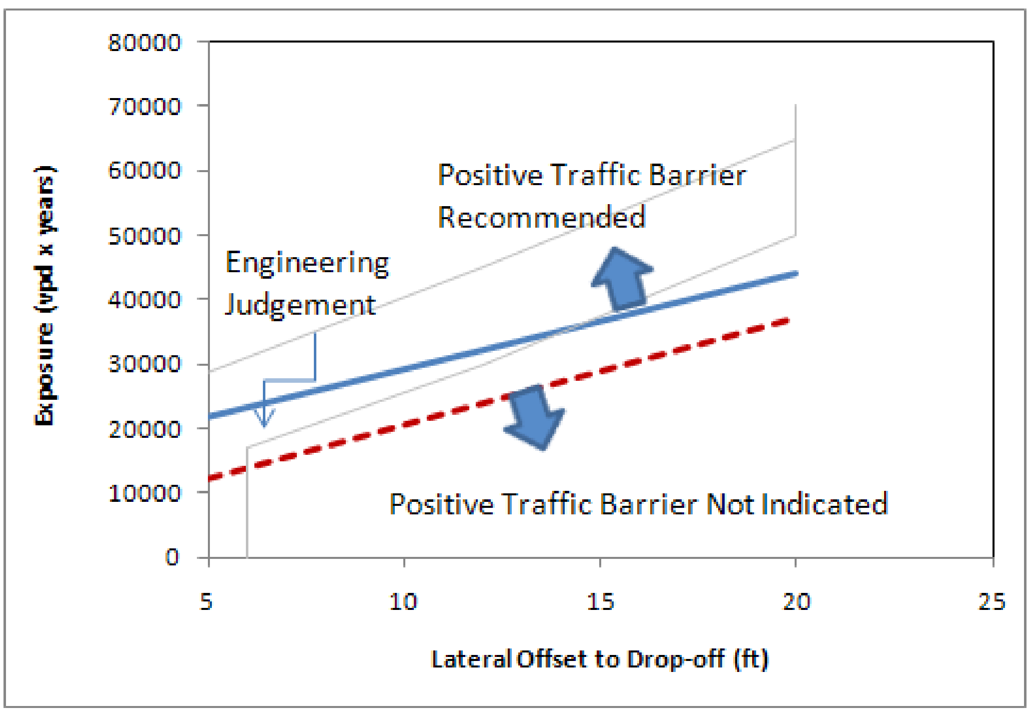
Table B-1. Portable Barrier Justification Criteria

Work Zone Condition	Justification Criteria
No drop-off condition present, but other intrusion hazards will be placed close to travel lanes and present continuously during the work zone	Justifiable if the operating speed on the facility is 65 mph or higher, and the expected vehicle exposure (the product of total roadway ADT and number of work zone years) exceeds 40,000 vehicle-years.
Drop-off condition present beyond area of work activity	Figure B-1[1]
Drop-off condition present between travel lanes and area of work activity	Figure B-2[1]

[1] The light-shaded lines in the figures represent previous positive barrier use thresholds based on drop-off considerations only

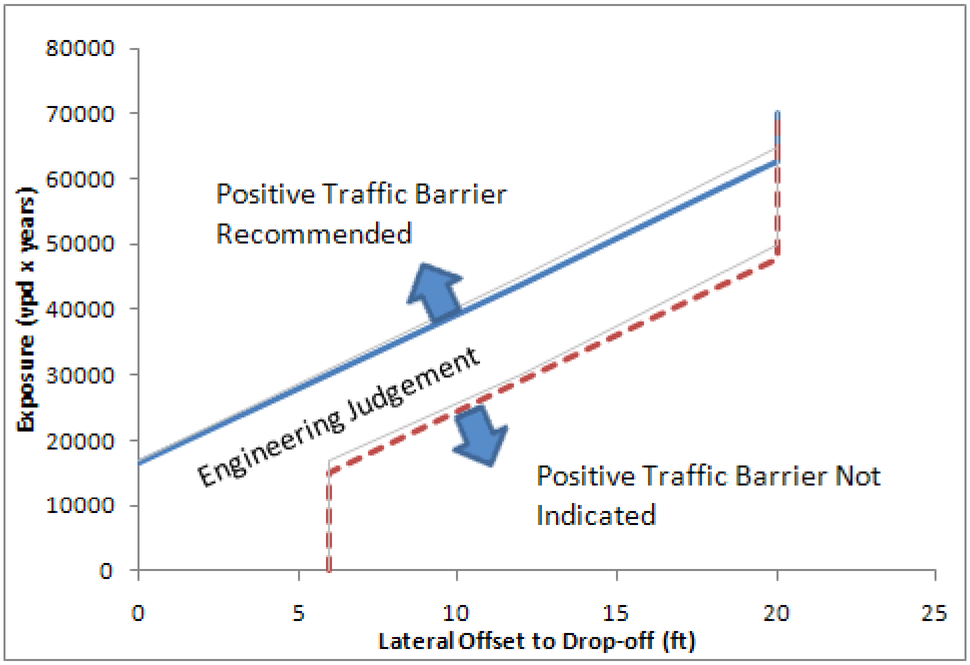


(a) Intrusion Crash Risks Exist 8 hours per day, 3–4 days per week

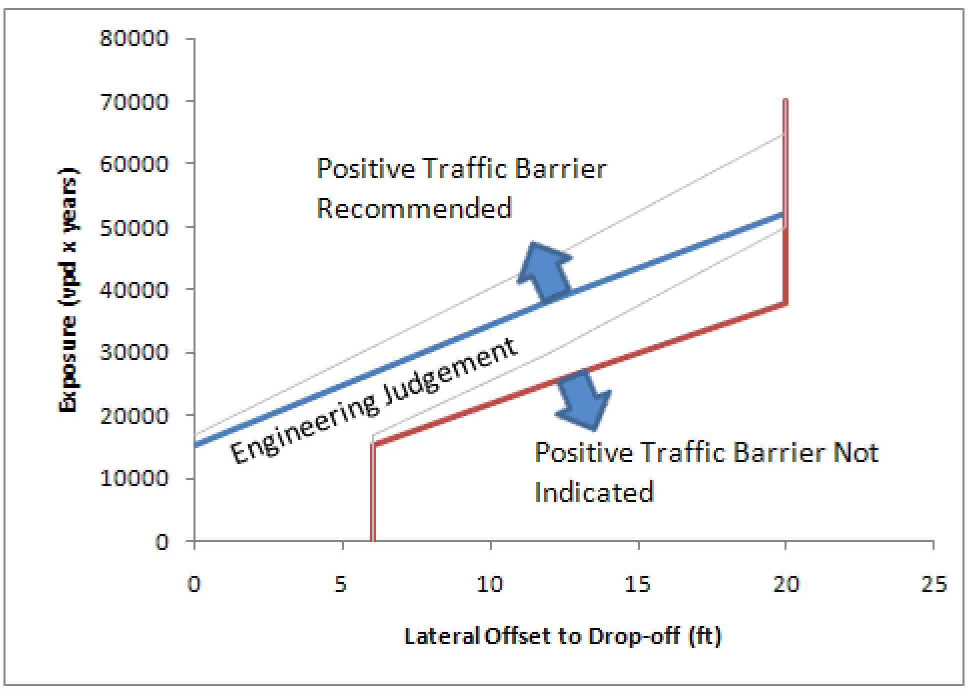


(b) Intrusion Crash Risks Exist Continuously (24/7)

Figure B-1. Recommended PCB Usage Guidance when Work Space Is in Front of the Drop-Off and Immediately Adjacent to the Travel Lanes.



(a) Intrusion Crash Risks Exist 8 hours per day, 3–4 days per week



(b) Intrusion Crash Risks Exist Continuously (24/7)

Figure B-2. Recommended PCB Usage Guidance when Work Space Is Beyond the Drop-Off.

The first criteria pertains to the situation where work area hazards will be continuously present in the work zone (even when work activity is not occurring) within 2 feet proximity to the travel lanes. For the other two conditions, the appropriate graph within each figure should be used, depending on whether work hazards are expected to be present only during typical work activity hours, or present at all times even when work is not occurring. These graphs would replace the single graph for pavement drop-off analyses now in use. In each case, the analyst would use the drop-off lateral distance and depth, along with the traffic exposure value, to determine whether the combined consideration of the drop-off and the presence of work hazards would justify barrier use.

The thresholds can be used for any duration work zone, by simply converting the estimated work-days to an equivalent fraction of a year and multiplying by the roadway ADT. It should be noted that, for simplicity purposes, overall two-way ADT values should be used when assessing the justification of barrier use in the work zone based on this guidance.

Portable Steel Barrier Use

For short-duration and short-term work zones, protection of a limited work space can be very important to the safety of the work crew. Presently, data is limited on both the effectiveness of steel barrier in protecting work space intrusions, as well as the costs. Therefore, Figure B-3 is provided as general guidance as to the cost-effectiveness of steel barrier under various assumptions of cost and roadway ADT.

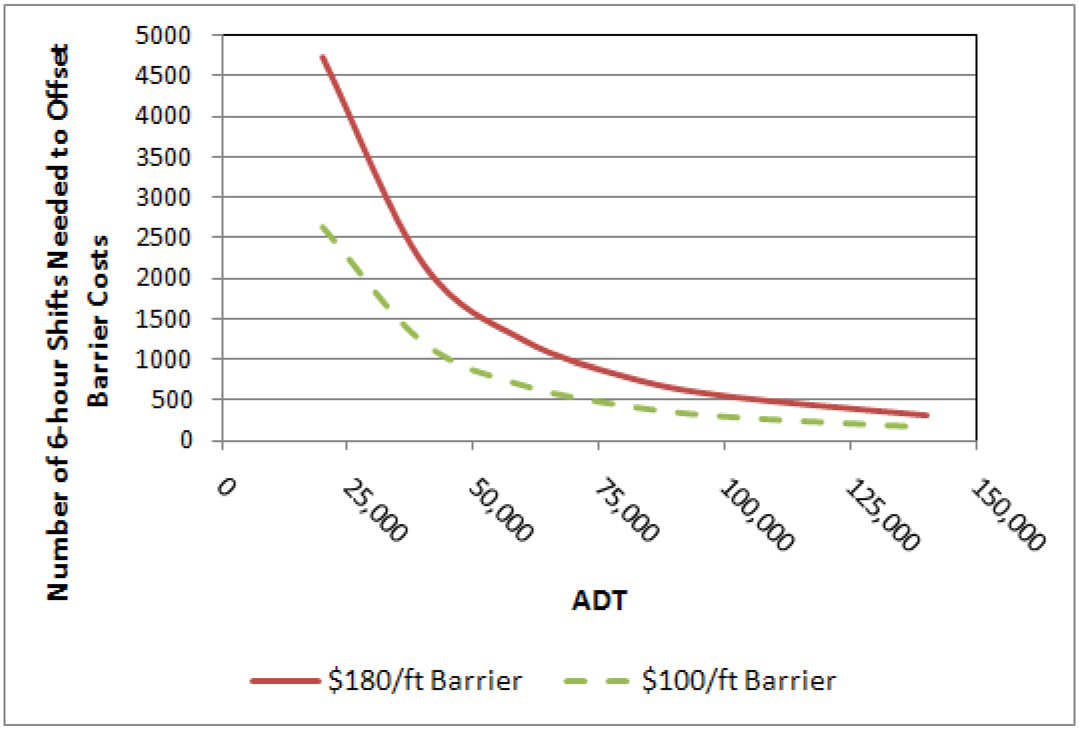


Figure B-3. Six-Hour Work Shifts to Offset Costs of Steel Barrier Use.

Mobile Barrier Use

Mobile barriers consist of a steel beam cage or wall attached to a semi-tractor trailer cab that can be towed to a location and then deployed around a small area to protect a work crew on foot near moving traffic. These devices can be highly-effective for short-duration and even mobile operations when workers are on foot in the work space. Currently, these devices cost approximately $200,000–250,000. Figure B-4 provides guidance on the cost-effectiveness of these devices.

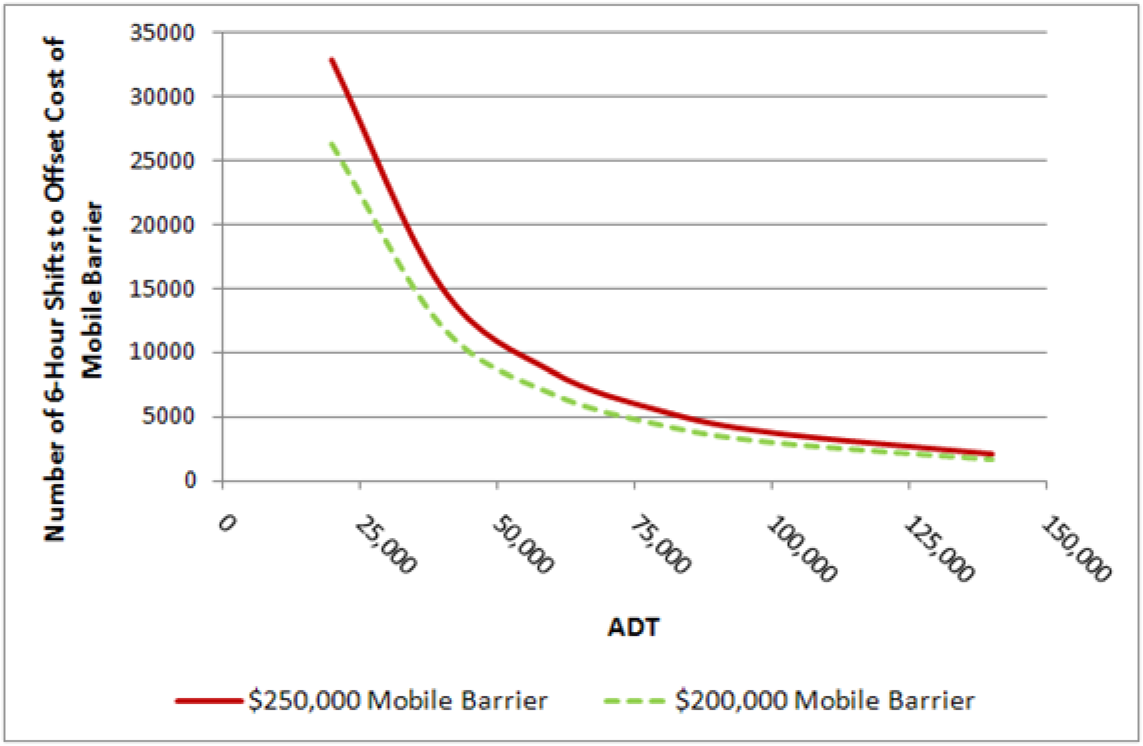


Figure B-4. Six-Hour Work Shifts to Offset Costs of Mobile Barrier Use.

Truck-Mounted Attenuators

The AASHTO Roadside Design Guide (*5*) provides general guidelines on priorities for using truck-mounted attenuators on work vehicles during mobile and other work operations as a function of roadway type. Analysis of rear-end crash frequency and severities involving work equipment with and without TMAs in use indicates substantial crash cost reductions achieved by their use. Figure B-5 provides cost-effectiveness information, assuming an approximate cost of $15,000 per TMA. Overall, TMAs can effectively return their investment in the form of reduced crash costs within a year of use on essentially all roadways during daytime operations, and on roadways with ADTs greater than 50,000 vpd for nighttime operations.

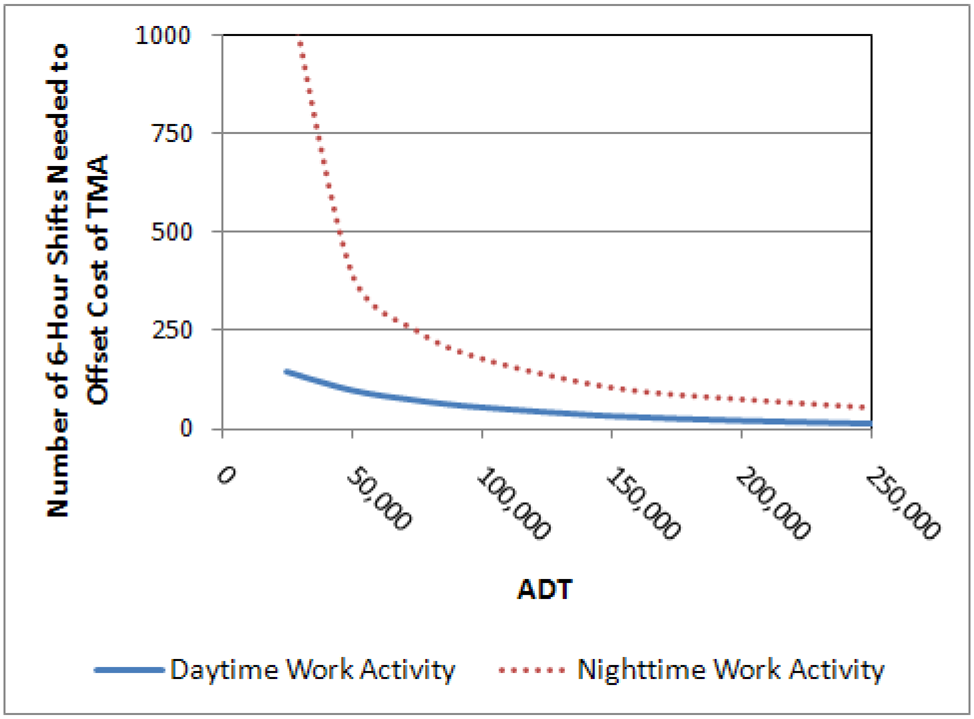


Figure B-5. Number of Work Shifts Needed to Offset TMA Use.

USE OF EXPOSURE CONTROL MEASURES

The fewer times motorists encounter work zones, the fewer chances there are for work-zone-related crashes to occur. Reducing the number of work zones, the length of time during which work zones are set up, and the adverse impact that work zones have on traffic will reduce the exposure of road users and workers to crashes.

Several strategies are available to control worker and vehicle exposure:

- Reducing work zone durations (via accelerated construction and contracting techniques) and number of work zones required through longer-lasting materials, or coordination of multiple maintenance activities into a single work operation.
- Full-time roadway closures.
- Nighttime road work.
- Demand management programs to reduce volumes through work zones.

These strategies also have implications in terms of traveler mobility as well as work productivity and quality. Therefore, engineering judgment must be used to determine whether some or all of these are appropriate for a given project.

USE OF LAW ENFORCEMENT

The use of traffic law enforcement at a highway work zone is recognized as one of the most effective means available for reducing speeding, speed variability, and undesirable driving behaviors such as tailgating and unsafe lane changes, thereby improving traffic and worker safety in the work zone. The presence of work zone enforcement is also believed to raise driver awareness and level of alertness, reducing perception-reaction times in response to unexpected hazards encountered. Specific reasons should exist for providing enforcement at a work zone. Enforcement costs are not insignificant, and represent an additional burden on enforcement agency manpower and equipment resources in a region, even when highway agency funds are being used to pay for such efforts. If enforcement is to be used, it should be to address specific hazards, and the strategy used should be capable of minimizing those hazards.

Table B-2 shows the recommendations made after researchers analyzed the potential savings in crash costs due to enforcement presence in work zones. The recommended annual average daily traffic (AADT) values needed to offset the costs of dedicated enforcement depend on both the price of enforcement and the assumptions regarding their effectiveness in reducing work zone crashes. It should be noted that these values do not consider other types of benefits that enforcement presence in a work zone may create (i.e., increased traffic flow due to less aggressive driving, higher worker productivity and quality due to a sense of increased safety within the work space). Consequently, a project engineer can justify enforcement use at even lower AADT levels than those shown.

Table B-2. Comparison of Enforcement Benefits and Costs in Freeway Work Zones.

Enforcement Costs	ADT where Enforcement Benefits Are Approximately Equal to Enforcement Costs	
	Favorable-Benefit Scenario	Conservative-Benefit Scenario
$25 per hour		
Daytime work zone	5,000 vpd	20,000 vpd
Nighttime work zone	20,000 vpd	45,000 vpd
$50 per hour		
Daytime work zone	10,000 vpd	35,000 vpd
Nighttime work zone	35,000 vpd	100,000 vpd
$75 per hour		
Daytime work zone	15,000 vpd	50,000 vpd
Nighttime work zone	50,000 vpd	150,000 vpd
$100 per hour		
Daytime work zone	20,000 vpd	70,000 vpd
Nighttime work zone	65,000 vpd	200,000 vpd

vpd = vehicles per day