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16. Abstract
In this report, Texas Transportation Institute researchers documented the efforts undertaken to investigate and categorize the different types of work zone intrusion crashes that occur on California roadways, and to conduct a detailed comparative critique of how each of the various countermeasures available may mitigate those types of work zone intrusions. Researchers used the New York State Department of Transportation work zone incident database and telephone surveys of California Department of Transportation and highway contractor personnel in California to gain insights into the frequency, characteristics, and crash sequences that comprise vehicle intrusion crashes at California work zones. Intrusion crashes make up a relatively small portion of crashes at work zones, and comprise a greater proportion of nighttime crashes than daytime crashes, although most intrusion crashes happen during daytime work operations. The biggest share of vehicle intrusion crashes occurs at lane closure operations. Intrusion crashes also occur at mobile operations, flagging operations, and during traffic control set-up and removal activities. When intrusions crashes occur, they most often involve collisions with work vehicles/equipment or work materials/debris rather than with a highway worker. In addition, a significant portion of intrusion crashes are the result of deliberate driver decisions and actions to enter the work area.

Several countermeasures were identified to address intrusion crashes. Some emphasize increased attention to current procedures or possible expansion of procedures, and are fairly low cost to implement. Others are technological countermeasures, and can have fairly significant costs associated with them. An assessment of implementation costs to possible reduction in work zone intrusion crash costs was performed and is documented in the report. Based on these findings, researchers developed guidance on which work zone intrusion countermeasures are most appropriate for a given set of roadway conditions and planned work zone activities (included as an appendix).

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WORK ZONE INTRUSION COUNTERMEASURE IDENTIFICATION, ASSESSMENT, AND IMPLEMENTATION GUIDELINES

Report FHWA/CA10-1102

TEXAS TRANSPORTATION INSTITUTE
THE TEXAS A&M UNIVERSITY SYSTEM
COLLEGE STATION, TEXAS

in cooperation with the
Federal Highway Administration and the
California Department of Transportation

WORK ZONE INTRUSION COUNTERMEASURE IDENTIFICATION, ASSESSMENT, AND IMPLEMENTATION GUIDELINES

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Performed in cooperation with the
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EXECUTIVE SUMMARY

Vehicle intrusion crashes in highway work zones injure both vehicle occupants and workers, and so are of concern to both the California Department of Transportation (Caltrans) and highway contractors. Whereas efforts to warn workers of a vehicle intrusion have existed for some time, less consideration has been given to efforts that reduce the frequency of intrusions in the first place. Many driver behavior modification strategies and technologies exist that could raise the awareness of drivers approaching a work zone or modify their speed selection, and potentially reduce intrusion crash frequency and severity. However, it is likely that such relative benefits will vary depending on the characteristics of the intrusion crashes targeted, roadway and work zone conditions, and so on.

In this report, researchers documented the efforts undertaken to investigate and categorize the different types of work zone intrusion crashes that occur on California roadways, and to conduct a detailed comparative critique of how each of the various countermeasures available may mitigate those types of work zone intrusions. Researchers used the New York State Department of Transportation (NYSDOT) work zone incident database and telephone surveys of Caltrans and highway contractor personnel in California to gain insights into the frequency, characteristics, and crash sequences that comprise vehicle intrusion crashes at California work zones. Researchers examined the narratives of the various intrusion crashes to try to identify the main categories of crash scenarios that occurred. Prototypical crash sequences were developed around four basic work zone operation categories:

- lane and shoulder closure operations,
- flagging operations,
- mobile operations, and
- traffic control set-up and removal operations.

Within each of these basic work zone situations, several different sequences leading to work zone intrusion crashes were defined. These sequences were differentiated on whether or not the action taken appeared to be a deliberate decision on the part of the driver, then on the primary contributing actions or factors leading to the intrusion. Researchers then identified potential reasons that could have contributed to the occurrence of the work zone intrusion crash sequences and matched possible strategies and technologies that could be deployed to mitigate these crashes. More than 40 possible countermeasures, split between procedural strategies and

technology deployments, were identified. These countermeasures were then critiqued based on feasibility and practicality of deployment, and potential for mitigating intrusion crashes. For several of the countermeasures, a cost-effectiveness comparison of implementation costs to crash cost reduction potential was performed.

Based on the assessment of intrusion crash characteristics, the following conclusions can be drawn:

- Intrusion crashes make up a relatively small portion of crashes at work zones (7.5 percent of traffic crashes that occur during daytime work operations, 12.4 percent of traffic crashes during nighttime work operations).
- Although intrusion crashes comprise a greater proportion of nighttime crashes than daytime crashes, most (69.9 percent) intrusion crashes happen during daytime work operations.
- The biggest share (58.7 percent) of vehicle intrusion crashes occurs at lane closure operations. Intrusion crashes also occur at mobile operations, flagging operations, and during traffic control set-up and removal activities, but each of these make up less than 10 percent of the intrusion crashes.
- When intrusions crashes occur, they most often involve collisions with work vehicles/equipment or work materials/debris; only about 17 percent of intrusion crashes involve a collision with a highway worker.
- A significant portion of intrusion crashes are the result of deliberate driver decisions and actions to enter the work area. The relative frequency of such deliberate events differs by type of work operation in place, but ranges from 22 to 63 percent of all intrusion crashes occurring at those types of operations.

Researchers identified a number of procedural and technological countermeasures viewed as viable for addressing work zone intrusion crashes. Several countermeasures, especially those that emphasize increased attention to current procedures or possible expansion of procedures, are fairly low cost to implement. Technological countermeasures, on the other hand, can have fairly significant costs associated with them. Several countermeasures that do involve some costs of implementation were further examined as part of this research. Based on that analysis, the following items are the most easily justified:

- use of larger channelizing devices,
- reducing the spacing of transverse barricades or channelizing devices in closed travel lanes, and
- speed display trailers.

The next two items meet cost-effectiveness criteria once traffic volumes reach moderate levels:

- drone radar devices and
- closer spacing of channelizing devices.

At still higher traffic volume levels, the following countermeasures can be justified:

- temporary transverse rumble strips,
- steel (portable) barrier,
- automated traffic control device placement and retrieval devices, and
- use of enforcement.

Finally, the following items are more difficult to justify on the basis of their crash cost reduction potential, but may be appropriate for other reasons in certain situations:

- sequential warning light systems,
- flagger replacement devices, and
- truck-mounted positive protection devices.

Guidance on which work zone intrusion countermeasures are the most appropriate for a given set of roadway conditions and planned work activities is provided in Appendix A.

CHAPTER 1:
INTRODUCTION

STATEMENT OF THE PROBLEM

Vehicle intrusion crashes in highway work zones injure both vehicle occupants and workers, and so are of concern to both the California Department of Transportation (Caltrans) and highway contractors. Whereas efforts to warn workers of a vehicle intrusion have existed for some time, less consideration has been given to efforts that reduce the frequency of intrusions in the first place. Many driver behavior modification strategies and technologies exist that could raise the awareness of drivers approaching a work zone or modify their speed selection, and potentially reduce intrusion crash frequency and severity. However, it is likely that such relative benefits will vary depending on the characteristics of the intrusion crashes targeted, roadway and work zone conditions, and so on. Therefore, research was needed to investigate and categorize the different types of work zone intrusion crashes that occur on California roadways, and to conduct a detailed comparative critique of how each of the various countermeasures available may mitigate those types of work zone intrusions. In addition, researchers developed guidance for temporary traffic control designers and field personnel regarding which work zone intrusion countermeasures are most appropriate for a given set of roadway conditions and planned work zone activities.

CONTENTS OF THIS REPORT

This report describes the methodology and results of the analyses conducted to provide Caltrans with improved guidance on using driver behavior modification strategies and technologies to reduce vehicle intrusion crashes in work zones. Appendix A contains the guidance regarding which work zone intrusion countermeasures are most appropriate for a given set of roadway conditions and planned work zone activities.

CHAPTER 2:
EXTENT AND CHARACTERISTICS OF WORK ZONE INTRUSION CRASHES

One of the primary difficulties in using typical statewide crash databases is the lack of information typically recorded by the investigating officer regarding the work zone itself. This lack of detail makes it nearly impossible to accurately assess specific work zone influences upon crash occurrence or severity. This lack of detail also limits the extent to which certain types of crashes, such as vehicle intrusions, can be targeted for further study.

In the mid 1980's, the Construction Division of the New York State Department of Transportation (NYSDOT) initiated a program to compile detailed information on traffic crashes and worker construction accidents that occur on their construction projects. Since the mid 1990's, this program has been used by Department staff and contractors to generate reports for nearly all traffic crashes and worker construction accidents. These reports are supplemented by standard police accident reports for many traffic crashes, and some worker accidents as well. A detailed database is maintained by NYSDOT that is used to generate annual reports of work zone incidents, track overall safety trends, and to prepare special reports addressing specific safety issues. One of the data fields (crash type) includes specific codes to identify intrusion crashes involving workers, construction vehicles and equipment, or construction materials and debris. Officially, NYSDOT defines an intrusion crash in the database as a vehicle or object which penetrates the actual work space within the work zone and strikes one of the above items listed.

Researchers used the NYSDOT work zone incident database and telephone surveys of Caltrans and highway contractor personnel in California to gain insights into the frequency, characteristics, and crash sequences that comprise vehicle intrusion crashes at California work zones (NYSDOT was the only agency with such a database available). Overall, researchers obtained six years of NYSDOT work zone traffic crash data (2000 to 2005), received 306 responses from Caltrans and highway contractor field personnel to an online survey developed to gauge the extent of work zone intrusions in California, and interviewed 62 on-line survey respondents who indicated that they had specific in-depth knowledge of one or more intrusion incidents.

INTRUSION CRASH TRENDS IN THE NYSDOT WORK ZONE ACCIDENT DATABASE

Overall, the NYSDOT data indicate that vehicle intrusions into a work space comprise only a small portion of all crashes that occur in work zones. As shown in Table 1, intrusions make up only 7.5 percent of daytime work zone crashes in the database when work is occurring, and 12.4 percent of work zone crashes that occurred at night during work activities. (A small subset of intrusion crashes [4 percent] also occurred during hours when work activity was not occurring). Interestingly, the percentages of intrusion crashes are less than what are defined as non-intrusion crashes occurring with workers, construction equipment, or construction debris (e.g., a crash involving a worker conducting a task outside the actual work space). In addition, impacts with truck-mounted attenuators (TMAs) on work vehicles were also higher at night (2.7 percent during the day and 9.8 percent at night). It should be noted that these data do not indicate that the frequency or rates of intrusion crashes are higher at night; rather, these data only imply that a slightly higher percentage of crashes which do occur at night do involve work zone intrusions.

Table 1. Types of Traffic Crashes in the NYSDOT Work Zone Crash Database.

Key Crash Types	Daytime Work Operations, Daytime Crashes (n=1762)	Nighttime Work Operations, Nighttime Crashes (n=315)
Rear End	49.0%	35.6%
Other Multi-Vehicle	16.8%	14.3%
Single Vehicle Run-Off-Road	9.4%	9.8%
Intrusion Impacts with Workers, Equipment, or Debris	**7.5%**	**12.4%**
Non-intrusion Impacts with Workers, Equipment, or Debris	10.8%	15.6%
Impacts with TMA	2.7%	9.8%
Other Miscellaneous Types	3.8%	2.5%

Part of the reason for the different percentages of intrusion crashes (as well as the TMA and non-intrusion crashes with workers, construction vehicles/equipment, or materials/debris) during the day versus night may be the fact that more night work activities are preformed with only channelizing devices separating the work space and traffic, whereas a greater proportion of

work performed during the day occurs behind barriers. Another possible explanation is that traffic congestion levels are generally less at night, so that crashes that do result occur in and near the work area. In contrast, more of the crashes that occur during the day when congestion levels are higher may occur upstream of the work area where approaching traffic first reaches the queues and other traffic disturbances caused by the downstream work zone.

Referring back to Table 1, the most common crash type occurring in work zones was the rear-end collision between two or more vehicles. It should be noted, however, that the percentage of this type of crash was significantly higher during the day (49.0 percent) than at night (35.6 percent). Taken together, these percentages are consistent with the notion that work zones during the daytime hours more often lead to congested traffic conditions and thus a higher percentage of rear-end crashes. At night, queues and congestion are less likely to form, and so a shift occurs towards a higher percentage of crashes that occur in and around the actual work space (intrusions, non-intrusion impacts with construction workers and equipment, impacts with truck-mounted attenuators, etc.).

Focusing explicitly on the intrusion crashes, Table 2 identifies the types of work zones where these crashes occurred. By far, the most common type of work zone where an intrusion crash occurred was a lane closure, associated with 58.7 percent of the intrusion crashes in the NYSDOT database. The remaining proportion of crashes coded as intrusions were then distributed among those involving work on the shoulder or median without any lane closures (8.9 percent), traffic control setup and removal activities (7.7 percent), mobile operations (6.5 percent), activities involving flaggers (6.5 percent), work activities involving minor traffic control such as debris pickup (4.5 percent), and full roadway closures (4.5 percent). Intrusions at full roadway closures typically represent a driver failing to exit the roadway at the designated detour point. All other types of work zone operations combined comprised the final 2.7 percent of the intrusion crashes that occurred.

In Table 3, the distribution of intrusion crashes between daytime and nighttime periods is presented. One sees that most of the crashes that occurred in both categories were during daytime hours. Although a higher percentage of all intrusion crashes occured at night (refer back to Table 1), the absolute number of intrusion crashes was more frequent during daytime periods.

Table 2. Types of Work Zones Where Crashes Occurred.

Type of Work Zone Operation	Percent of Intrusion Crashes (n=249)
Lane Closures	58.7%
Work on Shoulder or Median	8.9%
Traffic Control Setup and Removal Activities	7.7%
Mobile Operations	6.5%
Activities Involving Flaggers	6.5%
Work Activities Involving Minor Traffic Control	4.5%
Full Roadway Closures	4.5%
Other Miscellaneous Operations	2.7%

Table 3. Crashes by Time of Day.

Time of Intrusion Crashes	Percent of Intrusion Crashes
Daytime	69.9%
Nighttime	30.1%

In Table 4, the relative percentage of each type of item struck during the intrusion event (workers, construction vehicle or equipment, or construction materials or debris) is summarized. In the intrusion crashes of interest in this analysis, one sees that impacts with workers occurs less frequently than the other types of impacts (15.7 percent). More of the collisions occur with construction vehicles or equipment in the work space (49.0 percent) and construction material or debris (35.3 percent).

Table 4. Items Struck in Crashes.

Item Struck	Percent of Intrusion Crashes
Worker	15.7%
Construction Vehicle or Equipment	49.0%
Construction Material or Debris	35.3%

Table 5 illustrates the severity of crashes documented in the NYSDOT database. Approximately forty-four percent of intrusion crashes involve an injury or fatality, while 56.2 percent are property damage only.

Table 5. Crash Severity.

Crash Severity	Percent of Intrusion Crashes
Severe (Injury & Fatalities)	43.8%
Property Damage Only	56.2%

In summary, the NYSDOT database does provide an overall indication of the extent and characteristics of work zone highway intrusion crashes. In addition to these general statistics, the database has a detailed narrative for most of the crash records, which can be used to establish some general chain-of-event sequences that characterize these crashes. However, before presenting these sequences, researchers conducted a series of telephone interviews to gather experiences about work zone intrusion crashes in California. The purpose of these interviews was to determine whether the experiences and general trends of work zone intrusions in California were similar to those in New York, such that the statistics computed from the NYSDOT database can be considered as a good surrogate of the California experiences. The results of these interviews are summarized in the next section.

SURVEY OF CALTRANS AND HIGHWAY CONTRACTOR PERSONNEL

On-Line Survey to Gauge Extent of Intrusion Experiences

In December 2007, researchers developed and sent out a phase I on-line survey to gather Caltrans and highway contractor field personnel input into work zone intrusion experiences. The identification of respondents is summarized in Table 6. Researchers received a total of 306 responses. Fifty percent of the responses came from Caltrans maintenance personnel, 22 percent from Caltrans construction personnel, 13 percent from Caltrans employees who did not specify a department, 7 percent from highway contractors, and remaining participants were unidentified individuals. Responses were received from all districts except District 9 and District 12.

Table 6. Summary of On-Line Survey Respondents.

Respondent Self-Description	Number of Respondents	Percentage of Total
Caltrans Maintenance	152	50%
Caltrans Construction	68	22%
Caltrans (no further description)	42	13%
Contractor	21	7%
No identification information given	23	8%
Total	306	100%

Of those responding, 76 percent reported seeing or experiencing one or more intrusions over the past five years, with less than half of these respondents (41 percent) reporting some type of injury to a worker or motorist. Each respondent reported observing or experiencing an average of 6.5 intrusions over the past five years, or slightly more than one per year per respondent. If those who reported no intrusions are excluded from the dataset, the average increases to 8.5 intrusions over the past five years (i.e., 1.7 intrusions per year per respondent). There was no difference between the average number of intrusion events reported by contractors and by Caltrans employees.

Detailed Telephone Survey of Intrusion Experiences

After the on-line survey responses were tabulated and examined, a detailed telephone survey instrument was developed for a more in-depth assessment of the conditions present at the time of the intrusion, contribution factors, etc. This telephone survey instrument is included in Appendix A. A decision was made to interview 62 respondents who indicated that they had specific in-depth knowledge of one or more intrusions. Of these, 39 respondents were able to provide detailed descriptions of the intrusion event. The telephone surveys were conducted during the period from January to April 2008. The in-depth interview information was gathered from 9 Caltrans construction employees, 26 Caltrans maintenance employees, and 4 contractors. Since about two-thirds of these respondents were Caltrans maintenance employees, the number of intrusion events reported during maintenance work was much larger than those reported during construction work. Thus, in the analysis that follows TTI researchers did not stratify by work activity type.

Some of the respondents were able to describe more than one intrusion event. Unfortunately, many of the eyewitnesses were not able to provide as specific information about

intrusion events as others. Their recollection of events was more anecdotal in nature. In addition, some of their accounts did not actually result in an intrusion crash, but were descriptions of hazardous situations that could have resulted in an intrusion crash.

Interestingly, one of the more common descriptions provided by the interviewees was that of a motorist who "intentionally" penetrated into a work zone with their vehicle. Interview respondents hypothesized several different motivations for why the motorists had chosen to intrude into the work zones. In some cases, motorists were reported to have "cut through" the work zones to reach an intended cross street or driveway. Other motorists simply moved into the closed lane or shoulder to read a map, talk on the phone, or look for items in the vehicle. In one instance, a motorist stopped in an active lane closure on the freeway to ask a worker for directions. These deliberate actions that resulted in an intrusion were not included in the tabulations below, unless they appeared to have occurred accidentally because the motorist was confused and made an incorrect travel path choice decision.

Upon completion of the more in-depth interviews, the researchers were able to catalog 30 different intrusion events. Twenty seven vehicle intrusions were recalled by those interviewed, versus three object intrusions. Two object intrusion events occurred on the freeway and involved heavy trucks; one was a lost load of cardboard and the other was a flat tire. One state highway object intrusion event was a light truck tire. Other objects were mentioned by respondents as intruding into the work zone from a passing vehicle, such as a pickup truck bed liner, but details about the event were not available and thus not included in this analysis. Other anecdotal information included the intentional throwing of items, such as glass beverage bottles, by passing motorists who had been delayed by the construction and/or maintenance activities.

Table 7 contains the resulting distribution of intrusion events by roadway type and time of day. Almost two-thirds of the intrusion events documented occurred on freeway facilities. Based on the sample information, most intrusion events (80 percent) occurred during daytime hours, similar to the findings from the NYSDOT database analysis. More nighttime intrusion events occurred on freeways than on state highways, but this is not surprising since the current trend is to conduct night work on higher volume facilities that would most likely result in congestion if the work was conducted during the day.

Table 7. Percent of Intrusion Events by Facility Type and Time of Day.

Time of Day	Facility Type		Total (n=30)
	Freeway (n=19)	State Highway (n=11)	
Daytime	47%[c]	33%[e]	80%
Nighttime	17%[d]	3%	20%
Total (n=30)	64%[a]	36%[b]	100%

[a] Two events were object intrusions involving debris from heavy trucks.
[b] One event was an object intrusion involving a tire.
[c] One event involved an impaired driver.
[d] Two events involved an impaired driver.
[e] Two event involved an impaired driver and occurred during pilot car operations.

Five of the 30 events studied (17 percent) involved impaired drivers; however, only two of these five events occurred at night. During each of these two nighttime impaired driver intrusions, a California Highway Patrol (CHP) officer was onsite, and the intrusion occurred downstream from the officer's position, implying that not even enforcement presence was enough to inhibit this type of intrusion event. The remaining three impaired driver events occurred during daytime hours. Two of these daytime intrusion events occurred on state highways during pilot car operations when an impaired driver attempted to pass another vehicle by using a closed lane. In fact, one of the impaired drivers attempted to pass the pilot car itself.

Researchers further stratified the intrusion events by the type of work zone operation in Table 8. Stationary lane closures, mobile operations, shoulder closures, and work activities beyond the shoulders make up the majority of intrusions reported on freeways. During mobile operations, the intrusion crashes that occur are typically vehicles which strike a TMA on the back of the first work vehicle in the work convoy. On state highways, the predominant activity where intrusion crashes occur are alternating one-way flow operations on two-lane highways using flaggers to stop traffic at each end of the work zone. Stationary lane closures (for multi-lane roadways) and mobile operations on state highways also comprise a significant portion of intrusion crashes. The numbers are again similar to those computed from the NYSDOT database, although the latter did have a slightly higher percentage of intrusion events occurring at lane closure operations. Again, the discrepancy between these data sources could be due to the high number of Caltrans maintenance personnel included in the telephone survey and the fact

that many maintenance activities are often accomplished without formal lane closures. The NYSDOT database, in contrast, contains a large number of crashes that occurred at construction operations when highway contractors were present.

Table 8. Distribution of Intrusion Events by Facility Type and Work Zone Setup.

Work Zone Setup	Freeway (n=19)	State Hwy (n=11)	Totals (n=30)
Stationary Lane Closure	37%[a]	19%	30%
Mobile Operation	21%[b]	19%	20%
Ramp Closure	5%	0%	3%
Shoulder Closure	16%[c]	8%	13%
Work Beyond Shoulder	21%	8%	17%
Alternating One-Way Traffic Flow Operations on Two-Lane Highways	0%	46%	17%
Total	100%	100%	100%

[a] Three nighttime events
[b] Two nighttime events
[c] One nighttime event

The frequency of intrusion events occurring when work is being performed beyond the shoulder is somewhat surprising, because workers are typically located some distance from the open travel lanes. Of these five events in the Caltrans surveys, one occurred when a worker who was preparing to set up traffic control devices (TCDs) prior to initiating a work activity was struck by an errant vehicle. In another event, a heavy truck struck a TCD which broke apart and then hit a worker. The remaining three events resulted from passing vehicles departing the roadway for unknown reasons and striking work vehicles, causing one passenger fatality. Although the overall sample size is limited, the information does indicate the need to consider more than just work activities that occur in the actual travel lanes.

Flagging operations were another category of work activities noted by the interviewees where vehicle intrusions had occurred. It is generally assumed that many worker/vehicle conflicts occur at flagger positions during lane closures on two-lane roadways. Interestingly, however, only one of five intrusion events at alternating one-way operations occurred at the flagger location. During this one event, a motorist drove past the flagger without making eye contact and was stopped by another worker upon approaching the work activity area. Instead, the majority of the intrusion events during these operations occurred within the work zone while

following a pilot car. In addition to the two impaired driver incidents previously discussed, the remaining incidents involved flying object debris, and one motorist's failure to properly follow a pilot car. In this case, it is not understood whether the driver's failure to follow the pilot car was intentional or due to driver confusion or inattentiveness.

Table 9 presents the distribution of intrusion events identified during the telephone survey by location within the work zone. Almost half of the intrusion events that were described occurred in the work activity area, which is the area in where the workers are usually located. It was also interesting to note that there were three intrusion events (10 percent) that occurred during work zone setup, or establishment of the work zone traffic control. This number is consistent with the percentages found for this type of event in the NYSDOT database. One of the events occurred during cone placement, and involved a worker fatality. The worker was riding in a bucket at the rear of the cone vehicle, and the bucket was struck by an errant vehicle, ejecting the worker. The worker was then struck by another vehicle. Although rare, events of this type typically result in worker fatalities or severe injuries.

Table 9. Distribution of Intrusion Events by Location in Work Zone.

Area of Work Zone	Percent (n=30)
During Traffic Control Setup	10%[a]
Advance Warning Area	3%
Transition Area	30%
Buffer Space	7%
Work Activity Area	47%
Termination Area	3%
Total	100%

[a] One fatality

It must also be remembered that eyewitness account surveys cannot fully capture events that may occur elsewhere in the work zone. For example, if an errant vehicle intrudes into a transition area which is not visible by workers, does not strike any objects, and does not require assistance or attention in order to re-enter the traffic flow, this event would be undetected and not included in any eyewitness data.

Table 10 shows the distribution of worker injuries that resulted from work zone intrusions, as recalled by the interviewees. Almost one-third of the events resulted in some type of worker injury or fatality, consistent with statistics computed from the NYSDOT database.

Table 10. Distribution of Vehicle Intrusion Events by Facility Type and Worker Injury.

Worker Injury	Percent (n=30)
Fatality	7%
Some Injury	23%
No Injury	70%
Total	100%

An intruding vehicle will often strike a work vehicle, a worker on foot, a fixed object, or TCD once it enters the work zone. Table 11 shows the distribution of intrusion events by the first object struck. Overall, one sees that 50 percent of the intrusions involved an impact with a work vehicle, where 17 percent of the intrusions overall involved an impact with a worker on foot. These values are very consistent with those determined from the NYSDOT database and reported in Table 5. In many cases, an energy absorbing device, such as a TMA, was in use on the work vehicle and thus any worker injury was reduced or eliminated.

Table 11. Distribution of Vehicle Intrusion Events by Facility Type and Primary Object Struck.

Object Struck	Freeway (n=30)	State Hwy (n=11)	Both Roadway Types Combined (n=30)
Work Vehicle	63%[a]	27%	50%
Worker On Foot	11%[b]	27%	17%
Other Vehicle	5%	9% 7%	
Fixed Object or TCD Object	16%	9% 13%	
Nothing	5%	27%	13%
Total	100%	100% 100%	

[a] One event was a primary strike to work vehicle, ejected worker struck by other vehicle, causing worker fatality
[b] One worker fatality

There does appear to be a difference in these trends by roadway type, however. Whereas nearly two-thirds of the freeway intrusions involved an impact with a work vehicle, only 27 percent of those occurring on state highways involved a work vehicle impact. Conversely, only 11 percent of the intrusions at freeway work zones involved a worker on foot, compared 27 percent of intrusions on state highways. In other words, intrusion crashes on state highways are equally likely to involve a work vehicle or a worker on foot; on freeways, intrusion crashes are about 6 times more likely to involve a work vehicle than a worker on foot. Whether this is due to a higher density of work vehicles at freeway sites as compared to work zones on state highways, or other reasons, cannot be determined from these data.

Finally, researchers noted that five events described by the interviewees involved a primary strike to a worker, compared to four events that involved a secondary strike to a worker following an initial impact with a work vehicle, some construction materials or devices, or another vehicle. In several instances, the initial impact occurred outside of the work space (i.e., was not an initial intrusion event). Two of the events involving workers were fatalities, and the other seven resulted in some injury to the worker. As previously described, the first fatal event occurred when a worker was riding in a bucket at the back of a vehicle setting cones, and the bucket was struck. The worker was ejected and struck by another vehicle. The second fatal event occurred during the day when an impaired driver penetrated a line of channelizing devices, entered a work activity area and killed a worker.

Summary

Overall, the data that could be obtained through the telephone interviews was found to be less detailed and precise than that contained in the NYSDOT database. This was to be expected, as researchers were asking survey respondents to recall events that may have occurred many months or even years in the past. Even though the level of detail was less, the results of this analysis suggest that the general trends in work zone intrusion crashes identified in the NYSDOT database were consistent with those experienced by Caltrans personnel and highway contractors working for Caltrans. Consequently, researchers believe it is appropriate and acceptable to use the data from the NYSDOT database regarding intrusion crashes and non-intrusion crashes involving workers, construction vehicles or equipment, and construction materials or debris in conjunction with the information collected from the telephone interviews in identifying and

quantifying the common chain-of-event sequences that characterize those types of crashes. The derivation and description of those sequences are discussed in the following section.

COMMON WORK ZONE INTRUSION CRASH SEQUENCES

Researchers examined the narratives of the various intrusion crashes in the NYSDOT database as well as the discussions from the Caltrans interviews to try and identify the main categories or crash scenarios that occurred. For many of the crashes, the available narrative did not provide significant detail or insights that could be used for this purpose. For example, many of the narratives simply stated "vehicle 1 entered the closed lane and struck a construction vehicle/worker/material," which is of limited value in attempting to understand how and why the intrusion occurred. However, other narratives were much more detailed, and did allow researchers to collate and establish several prototypical sequences that occurred multiple times in the database.

For purposes of this technical memorandum, the prototypical sequences have been developed around four basic work zone operation categories:

- lane and shoulder closure operations (Figure 1),
- flagging operations (Figure 2),
- mobile operations (Figure 3), and
- traffic control set-up and removal operations (Figure 4).

As noted in the previous sections, these operations comprise 58.7 percent, 6.5 percent, 6.5 percent, and 7.7 percent, respectively, of the work zone intrusion crashes documented in the NYSDOT database. The interviews with Caltrans and highway contractor personnel also indicated that these operations were commonly associated with intrusion events. A fifth category of intrusions at miscellaneous operations did not yield any meaningful crash sequence trends that differed substantively from those developed from the above four work zone situations.

Within each of these basic work zone situations, several different sequences leading to work zone intrusion crashes were defined. These sequences were first differentiated on whether or not the action taken appeared to be a deliberate decision on the part of the driver. Next, the primary contributing action or factor leading to the intrusion was identified. Finally, some differentiation was made within some of the key contributing actions or factors to further describe the overall crash sequence of the intrusion event.

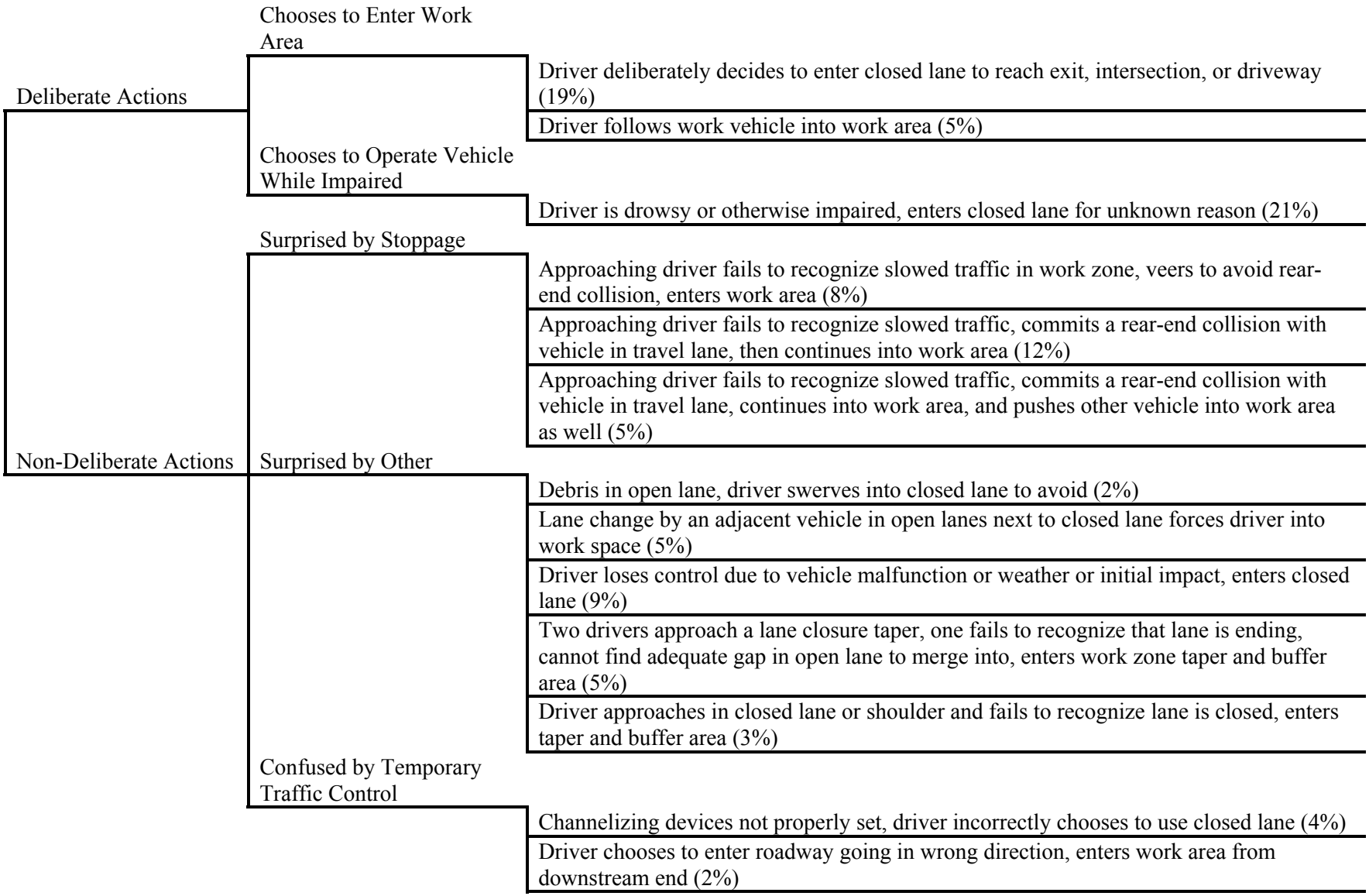


Figure 1. Vehicle Intrusion Crash Sequences: Lane Closure Operations.

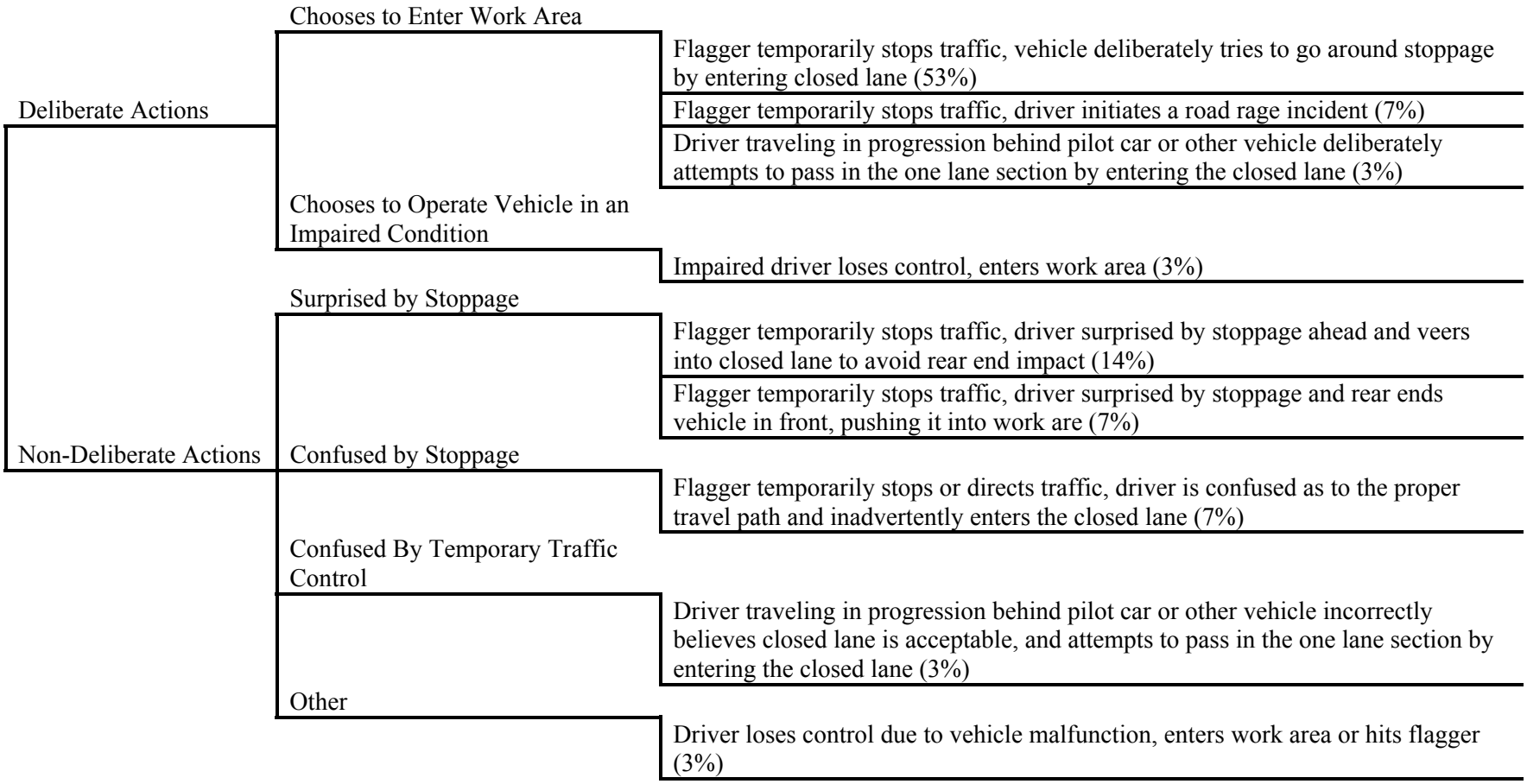


Figure 2. Vehicle Intrusion Crash Sequences: Flagging Operations.

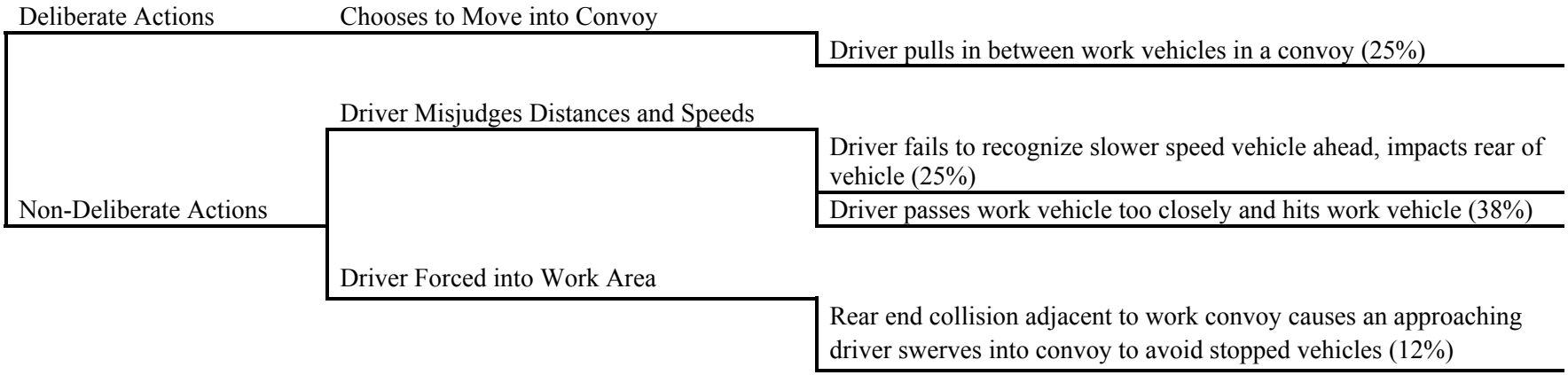


Figure 3. Vehicle Intrusion Crash Sequences: Mobile Operations.

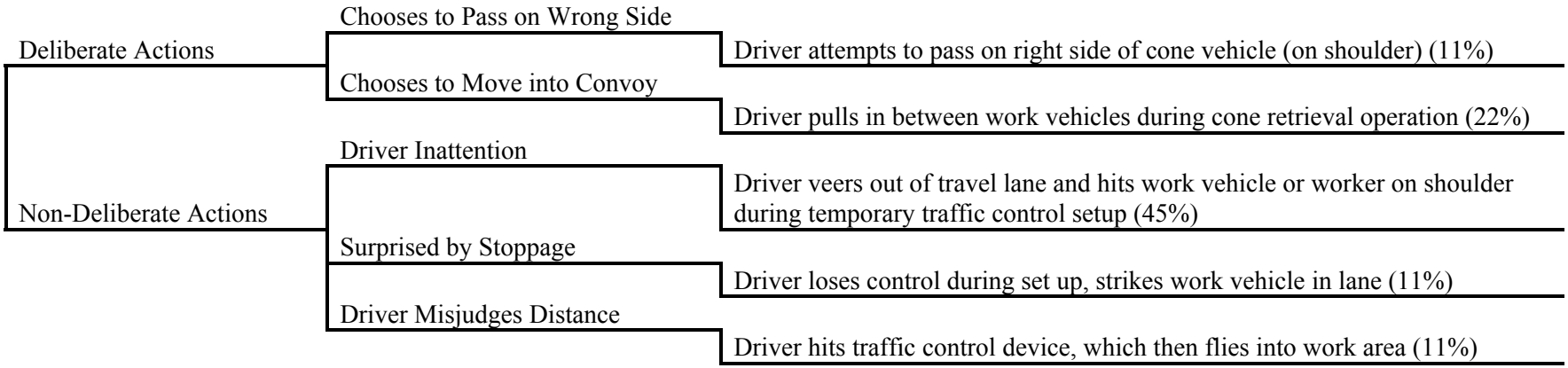


Figure 4. Vehicle Intrusion Crash Sequences: Traffic Control Set-Up and Removal Operations.

Typical Work Zone Intrusion Scenarios at Lane Closure Operations

The largest frequency of work zone intrusion events occurred at lane closure operations. Figure 1 presents the crash sequence analysis tree for these operations. The relative frequency of these individual crash sequences for this type of work zone operation is shown as percentages next to each statement at the right side of the figure (the percentages add to 100).

Overall, the researchers concluded that deliberate decisions and actions on the part of the driver account for almost one-half of the intrusion events that occur at lane closure operations. In most instances, the deliberate action taken is the decision to drive impaired, accounting for 21 percent of all lane closure intrusion events. Another 19 percent of the intrusions occurred because it appeared that drivers deliberately chose to enter the closed lane to reach a desired exit, intersection, or driveway. Finally, intrusions by drivers who simply followed a work vehicle into the closed lane accounted for 5 percent of the intrusions at lane closure operations in the database.

The remaining intrusions at lane closure operations were judged by researchers to have not been the result of a deliberate decision by the driver. Rather, drivers were either confused or surprised by the work zone situation, which led to driving decisions and behaviors that ultimately resulted in one or more vehicles intruding into the work zone. Specifically, one-fourth of the intrusions at lane closure operations occurred because drivers were surprised by a stoppage of traffic in the travel lane. The surprise condition then resulted in a driver veering directly into the work zone to avoid a rear-end collision with the vehicle immediately in front (8 percent of lane closure intrusions), in a driver actually having a rear-end collision with another vehicle in the travel lane and then continuing into the work zone (12 percent of lane closure intrusions), or in a driver colliding (rear-end) with another vehicle and then pushing that vehicle into the work zone as well (5 percent of lane closure intrusions).

Another one-quarter of the lane closure intrusions were caused by other “surprises” that eventually led to drivers entering the closed lane. In 9 percent of the lane closure intrusions, a vehicle malfunction/weather event/impact with a traffic control device or other factor causes a driver to lose control of the vehicle and enter the closed lane somewhere within the length of work zone. In another 5 percent of the intrusions, a vehicle operating in an adjacent lane swerved towards a second vehicle, causing the second vehicle to swerve away from that first

vehicle and into the closed lane. In 2 percent of the lane closure intrusions, debris in the travel lanes caused a driver to swerve into the closed lane.

Two crash sequences identified under the "surprised by other" category of events involved vehicles approaching the merging taper of the lane closure that ended up entering the closed travel lane. In 5 percent of the lane closure intrusions, two vehicles operating next to one another approached the taper, forcing the vehicle in the lane to be closed through the taper and into the closed lane area. In another 3 percent of the lane closure intrusions, a vehicle approaching the taper ran through the taper and into the closed lane area when there was not another vehicle nearby that appeared to force this maneuver (i.e., the intruding driver could have changed lanes into the open lane, but did not).

The final categories of lane closure intrusions appeared to be the result of advance signing or channelizing devices that were not set properly (devices missing, spacing too far apart, etc.) which confused drivers into entering the closed lane. In 2 percent of the lane closure intrusions, drivers entered the roadway downstream of the lane closure traveling in the wrong direction, and entered the work zone and the closed lane from the downstream direction.

Typical Work Zone Intrusion Scenarios at Flagging Operations

The crash sequences identified for vehicle intrusions at flagging operations are presented in Figure 2. For this particular work operation, researchers determined that 66 percent of the vehicle intrusions that occurred were the result of deliberate decisions and actions on the part of the motorist to enter the closed lane and work area. Motorists who decided to try to go around the flagger that has stopped them for the work operation was the most common crash sequence in this category. However, there were instances (3 percent of flagging intrusions) where the intrusion occurred in the work zone area during pilot car operations, as a driver deliberately entered the closed lane to pass the pilot car.

The remaining one-third of the flagging operation intrusions appeared to be the result of non-deliberate actions by the motorists. As was the case for lane closure operations, the stoppage of traffic flow surprised some approaching drivers, who then veered around the queue to avoid a rear-end impact (14 percent of flagging intrusions) or actually ran into the vehicle in front and pushed it into the work area (7 percent of flagging intrusions). There were also instances (7 percent of the flagging intrusions) that appeared to be caused by confusion on the

part of the motorist as to the directions being given by the flagger. In addition, similar to the sequence described under the deliberate actions, 3 percent of the flagging intrusions occurred during pilot car operations where the accident narrative indicated that the driver was confused and attempted to pass the progression of vehicles by traveling in the closed lane (exactly how the field personnel knew the driver was confused and not making a deliberate decision to use the closed lane was not evident from the narrative).

Typical Work Zone Intrusion Scenarios at Mobile Operations

Figure 3 illustrates the crash sequences identified for intrusions into mobile operations. For those intrusions that were deliberately performed by the driver, all occurred because the driver chose to pass the upstream work vehicle and then incorrectly enter the closed lane within the work convoy moving down the roadway (25 percent of the mobile operation intrusions were of this type).

For the remaining mobile operation intrusions that were judged to be non-deliberate actions, misjudgment by the driver approaching a work convoy appeared to be responsible two-thirds (63 percent) of the mobile operation intrusions. Twenty-five percent of the mobile operation intrusions were actually rear-end collisions between the approaching vehicle and the upstream work vehicle, while another one-third (38 percent of mobile operation intrusions) were vehicle impacts with the sides of the work vehicles (presumably because the drivers misjudged the distance between their vehicle and the work vehicle). Another 12 percent of the mobile operation intrusions occurred because other vehicles in the open lanes around the work convoy were stopped for some reason, and an approaching driver veered into the work convoy area to avoid a rear-end collision with those stopped vehicles.

Typical Work Zone Intrusion Scenarios at Traffic Control Set-Up and Removal Operations

Similar to the trends observed for mobile operations, a smaller proportion of vehicle intrusions that occurred during traffic control set-up and removal operations (33 percent) were the result of deliberate actions by the motorists (see Figure 4). Most of these (22 percent) occurred because drivers pulled their vehicles into the convoy of work vehicles during a cone retrieval operation, with a few others resulting from drivers who decided to try to pass the traffic control vehicle on the right shoulder during installation or removal activities. The intrusions that

were not deliberate actions by motorists (67 percent of the intrusions during traffic control set-up and removal) appeared to be due to either driver inattention that led to their failure to maintain their vehicle in the travel lane, to drivers being surprised by the stoppage of traffic in the travel lane around the set-up and removal activity, or to drivers hitting a traffic control device which then entered into the work area and struck a worker.

CONCLUSIONS

Based on the results of the NYSDOT database analysis and telephone surveys of Caltrans and highway contractor personnel in California, researchers gained a number of insights into the frequency, characteristics, and crash sequences that comprise vehicle intrusion crashes at California work zones. The following bullet list summarizes these key points.

- Intrusion crashes make up a relatively small portion of crashes at work zones. During daytime operations, 7.5 percent of traffic crashes that occur involve some type of vehicle intrusion into the work area. This percentage does increase somewhat at night (12.4 percent).
- Although intrusion crashes comprise a greater proportion of nighttime crashes than daytime crashes, most of the intrusion crashes that do occur (69.9 percent) happen during daytime work operations.
- Based on the NYSDOT database, the biggest share (58.7 percent) of vehicle intrusion crashes occurs at lane closure operations. Intrusion crashes also occur at mobile operations, flagging operations, and during traffic control set-up and removal activities, but each of these make up less than 10 percent of the intrusion crashes. These same work operations were also cited during interviews with Caltrans and highway contractor personnel in California, although the relative percentages were slightly different.
- When intrusions crashes occur, they most often involve collisions with work vehicles/equipment or work materials/debris; only 15.7 percent of intrusion crashes in the NYSDOT database involved a collision with a highway worker. For the Caltrans/highway contractor interviews, 17 percent of the intrusion events documented involved an impact with a worker, which tend to be fairly severe events.

- A significant portion of intrusion crashes are the result of deliberate driver decisions and actions to enter the work area. The relative frequency of such deliberate events differs by type of work operation in place, but ranges from 22 to 63 percent of all intrusion crashes occurring at those types of operations.
- Depending on the type of work operation in place on a roadway, researchers identified between 2 and 10 different crash sequences that were not deliberate actions by drivers which ultimately resulted in an intrusion crash.

CHAPTER 3:
STRATEGIES AND TECHNOLOGIES TO REDUCE WORK ZONE INTRUSION CRASHES

Next, researchers identified potential reasons that could have contributed to the occurrence of the work zone intrusion crash sequences discussed in Chapter 2 and matched possible strategies and technologies that could be deployed to mitigate these crashes. The objective of the task was to identify all potential countermeasures that could possibly address a particular intrusion crash sequence, regardless of its potential costs and practicality. In Chapter 4, researchers discuss their critique of each scenario/countermeasure combination on the basis of potential likelihood for crash reduction, cost of implementation, operation, and maintenance, and practicality of implementation.

Table 12 through Table 15 show the results of the countermeasure brainstorming process for the intrusion crash sequences for the following four basic work zone operation configurations, respectively:

- lane closure operations,
- flagging operations,
- mobile operations, and
- traffic control set-up and removal operations.

For brevity, researchers combined similar crash sequences in these tables when the assumed contributing factors and potential countermeasures were the same. Thus, in some cases the events (and the percentages) listed in the tables do not exactly match those shown in Chapter 2.

As expected, several of the intrusion crash countermeasures identified may be used to address more than one crash sequence. The following sections include a more detailed discussion of the comprehensive list of possible intrusion crash countermeasures identified by researchers. When available, researchers included data regarding the benefits of the technologies and strategies.

Table 12. Potential Countermeasures for Vehicle Intrusions into Lane Closure Operations.

Category	Event	Assumed Factor	Potential Countermeasures
Driver surprised by stoppage	Approaching driver fails to recognize slowed traffic, collision or collision avoidance results in a vehicle entering the closed lane (25%)	• Inadequate sight distance for driver perception and reaction • Driver fails to recognize closing speed	• Upstream queue end warning (real time information or general warning) • Conduct work at night or on weekends • Dynamic speed display trailers • Enforcement presence (real, automated, or drone radar) • Alter work area access point and internal TCP procedures • Enhanced vehicle warning light system • Positive protection
Driver surprised by other	Driver loses control of vehicle, enters closed lane (9%)	• Driver loses control	• Positive protection
	Driver fails to recognize lane closure, enters taper and buffer (8%)	• Driver is inattentive • Inadequate sight distance for driver perception and reaction	• Early merge system • Dual advanced signing • Overhead CMS • Ensure adequate sight distance to taper • Sequential warning light system (night operations only) • Closer or continual spacing of TCDs • Larger, more visible channelizing devices • Upstream queue end warning (real time information or general warning) • Positive protection
	Lane change by adjacent vehicle forces driver into closed lane (5%)	• Collision avoidance	• Lane changing restrictions • Positive protection
	Driver swerves to avoid debris in open lane, enters closed lane (2%)	• Collision avoidance	• Positive protection • Continuous patrol or monitoring of work zone
Driver chooses to enter work area	Driver deliberately decides to enter closed lane to reach exit, intersection, or driveway (19%)	• Delay avoidance • Driver does not know another way to reach destination	• Enforcement presence (real) • Closer or continual spacing of TCDs • Transverse TCDs • Shorter operation length to avoid blocking ramp or driveway • Advance notification of alternate routes, closure location, and duration • Positive protection
	Driver follows work vehicle into work area (5%)	• Access point is geometric continuation of expected travel path • Driver is inattentive • Delay avoidance	• Reconfiguring access point • Ensure use of existing vehicle systems (e.g., turn signals, hazard lights, beacons) • “DO NOT FOLLOW” signs (static or dynamic) • Construction entrance signing (static or dynamic) • Enforcement presence (real, automated, or drone radar)

Table 12. Potential Countermeasures for Vehicle Intrusions into Lane Closure Operations (continued).

Category	Event	Assumed Factor	Potential Countermeasures
Driver chooses to operate vehicle while impaired	Driver enters closed lane (21%)	• Driver is under influence of alcohol or drugs • Driver is drowsy	• Enforcement presence (real, automated, or drone radar) • Closer or continual spacing of TCDs • Transverse TCDs • Temporary transverse rumble strips • Sequential warning light system (night operations only) • Positive protection
Driver is confused by TTC	Channelizing devices not properly set, driver incorrectly chooses to use closed lane (4%)	• Driver is confused by TTC	• Proper set-up and maintenance of TTC
	Driver chooses to enter roadway going in wrong direction, enters work area from downstream end (2%)	• Driver is confused by TTC	• Closer or continual spacing of TCDs • Transverse TCDs • Downstream spotter

TCP = traffic control plan; TCD = traffic control device; CMS = changeable message sign; TTC = temporary traffic control

Table 13. Potential Countermeasures for Vehicle Intrusions into One-Way Flagging Operations on Two-Lane Two-Way Roadways.

Event	Assumed Factor	Potential Countermeasures
Driver ignores flagger instruction, enters closed lane (60%)	• Delay avoidance	• Enforcement presence (real) • Transverse TCDs/LCDs • Advance notice of work activity • Replace flagger with police officer • Limit lane closure length
Driver enters closed lane to pass pilot vehicle or another vehicle in progression (3%)	• Delay avoidance	• Closer or continual spacing of TCDs • Transverse TCDs • Limit lane closure length • Enforcement (real) • Positive protection
Impaired driver enters work area (3%)	• Driver is under influence of alcohol or drugs • Driver is drowsy	• Enforcement presence (real or drone radar) • Closer or continual spacing of TCDs • Transverse TCDs • Temporary transverse rumble strips
Approaching driver fails to recognize stopped traffic, collision or collision avoidance results in a vehicle entering the closed lane (21%)	• Inadequate sight distance for driver perception and reaction • Failure to recognize closing speed	• Temporary transverse rumble strips • Advance warning messages on PCMSs • Dynamic speed display trailers • Enforcement presence (real, automated, or drone)
Driver uncertain of correct travel path at flagger station, inadvertently enters the closed lane (7%)	• Driver is confused by TTC	• Transverse TCDs/LCDs
While travelling in progression, driver incorrectly believes that the closed lane is open and enters it to pass pilot vehicle or other vehicle (3%)	• Driver is confused by TTC	• Closer or continual spacing of TCDs • Transverse TCDs • Positive protection
Driver loses control of vehicle, enters work area or hits flagger (3%)	• Loss of control	• AFADs • Portable traffic signal system • Positive protection

TCD = traffic control device; LCD = longitudinal channelizing device; PCMS = portable changeable message sign; AFAD = automated flagger assistance device

Table 14. Potential Countermeasures for Vehicle Intrusions into Mobile Operations.

Event	Assumed Factor	Potential Countermeasures
Driver fails to recognize slower speed of work vehicle ahead, impacts work vehicle (63%)	• Inadequate sight distance for driver perception and reaction • Failure to recognize closing speed	• New messages on truck-mounted CMSs to indicate slow-moving vehicles • Truck-mounted dynamic speed display showing truck speed • Adjust spacing between advance warning vehicle and work convoy as needed to maintain sight distance to work convoy • Enforcement presence (real, automated, or drone radar) • Positive protection
Driver enters convoy (25%)	• Intentional • Driver is confused (does not know that he/she should not enter convoy)	• Reduce spacing between work vehicles • Work vehicle in front of workers on foot • New messages on truck-mounted CMSs to discourage vehicles from entering work convoy • Positive protection
Rear-end collision adjacent to work convoy, approaching vehicle swerves into convoy to avoid initial collision (12%)	• Inadequate sight distance for driver perception and reaction • Failure to recognize closing speed	• Adjust spacing between advance warning vehicle and work convoy as needed to maintain sight distance to work convoy • Enforcement presence (real, automated, or drone radar) • Positive protection

CMS = changeable message sign

Table 15. Potential Countermeasures for Vehicle Intrusions into Traffic Control Set-Up and Removal Operations.

Event	Assumed Factor	Potential Countermeasures
Driver attempts to pass work vehicle on shoulder (11%)	• Delay avoidance	• Additional work vehicle on shoulder
Driver enters between work vehicles (22%)	• Intentional • Driver is confused (did not know he/she should not enter convoy)	• Reduce spacing between work vehicles • Work vehicle in front of workers on foot • New messages on truck-mounted CMSs to discourage vehicles from entering work convoy • Positive protection
Driver veers out of travel lane and hits work vehicle or worker on shoulder (44%)	• Driver is inattentive	• Enforcement presence (real, automated, or drone radar) • Enhanced vehicle warning light system • Automated TCD set-up/removal • Positive protection
Driver loses control, strikes work vehicle in lane (11%)	• Loss of control	• Automated TCD set-up/removal • Positive protection
Driver strikes TCD, which then flies into work area (11%)	• Intentional • Driver is inattentive • Driver loses control • Driver is confused by TTC • Collision avoidance	• Enforcement (real, automated, or drone radar) • Positive protection • Follow proper TTC set-up and removal procedures

CMS = changeable message sign; TCD = traffic control device; TTC = temporary traffic control

POTENTIAL COUNTERMEASURES FOR INTRUSIONS INTO LANE CLOSURE OPERATIONS

As shown in Table 12, intrusions into stationary lane closures occur for a variety of reasons. Almost 50 percent of these events occurred because the driver was either surprised by slowed or stopped traffic or by some other unexpected event (e.g., lane closure, lane changes by other vehicles, etc.). In another 24 percent of these events, it appears that drivers deliberately entered the lane closure in order to avoid delay, because they did not know another way to reach their destination, or because they just kept following a work vehicle. While 21 percent of lane closure intrusions may be linked to driver impairment, another 6 percent may be a result of drivers being confused by the temporary traffic control set-up.

Researchers identified a large number of potential countermeasures that may be used to reduce intrusions into lane closure operations (Table 12). For ease of discussion, researchers will discuss the countermeasures that can be used throughout the entire work zone first, followed by those that can be applied in the advance warning area, transition area, and activity area, respectively.

Entire Work Zone

The following countermeasures can be used to decrease the potential for intrusion crashes throughout the entire lane closure operation:

- ensure proper set-up and maintenance of temporary traffic control,
- continual patrol or monitoring of open travel lanes, and
- provide enforcement (real, automated, or drone radar).

For the majority of the lane closure intrusion events described above, the information contained in the NYSDOT database did not allow researchers to determine whether or not the temporary traffic control was properly set-up. Nevertheless, researchers were able to verify that the temporary traffic control was improperly set-up in 4 percent of these events. For the remainder of the events, researchers assumed that the temporary traffic control was correct and that the intrusion crash was due to some other factor. Obviously, proper set-up and maintenance of temporary traffic control is important for the safety of both motorists and workers; it appears that failures to properly implement temporary traffic control do contribute to a small proportion of intrusions that occur.

In a small number of the lane closure intrusion crashes (2 percent), debris in the open travel lane caused drivers to swerve into the closed lane. Continuous patrol or monitoring of the work zone may be used to ensure that debris or other road conditions do not present hazards for passing motorists.

Police presence may also reduce the occurrence of intrusions into lane closure operations by drawing attention to the work zone and reducing speeds. Previous research (*1*,*2*) has shown enforcement to be the most effective method of speed control available in work zones. However, the relationship between speed reductions and the occurrence of intrusion crashes is unknown. The most commonly mentioned enforcement approaches in the literature include (*3*):

- Circulating (also referred to as mobile) patrols – These can be accomplished in both marked and unmarked patrol vehicles. In addition, determination of violators can occur through the use of radar units mounted in the vehicle or by physically following the vehicle and noting the speed required to maintain a consistent following distance. Speed reductions with circulating patrols typically range from 2 to 4 mph (*3*).
- Stationary patrols – These can also be accomplished in both marked and unmarked vehicles. This technique can be accomplished with a single officer and vehicle, or with multiple officers and vehicles. If the former, the lone officer has full responsibility for identifying violators, engaging in pursuit, and then stopping the violator and issuing the citation. In the latter, one officer identifies violators, and then notifies additional officer(s) downstream who stop the violator and issue the citation. Speed reductions with stationary patrols typically range from 3 to 12 mph (*3*).
- Police traffic controllers – This technique requires the officer to be positioned outside of their vehicle. The officer does not necessarily perform specific traffic control duties such as stopping vehicles, indicating to drivers where to travel, etc. (although they could). Rather, the emphasis is simply on being visible, establishing eye contact, and using other non-verbal communication techniques (i.e., the "slow down" hand signal) with the approaching driver to improve compliance, since the officer generally does not engage in pursuit if a violation

occurs. Speed reductions when police traffic controllers are used typically range from 3 to 14 mph (*3*).

Whereas the use of automated speed enforcement is fairly common in Europe, and is being used sparingly in a few local jurisdictions across the U.S., its application to work zones has just begun (*4*,*5*). Currently, the Washington State Department of Transportation (WSDOT) is conducting a pilot project utilizing automated speed enforcement cameras mounted in a small sport utility vehicle parked next to the highway to cite drivers driving too fast through construction work zones. Automated enforcement programs are also operational in Illinois and in Maryland (*5*). This technology is used to electronically identify violators and to capture an image of the vehicle imbedded with speed/location/date/time information about the violation. The registered owner of the vehicle is determined via the license plate number, and a citation is issued and mailed to the owner of the vehicle. In a recent study of this system in Illinois, speed data were collected at the speed-radar photo enforcement (SPE) device and a location 1.5 miles downstream in the work zone. The results showed that SPE is effective in reducing the average speed and increasing compliance with the work zone speed limit. The reduction in the mean speed varied from 3 to 6 mph near the SPE; however, the speed reduction at the downstream location was not significant (1 to 3 mph) (*6*). These systems can be fairly expensive to initiate and operate. Of course, the potential does exist to issue a larger number of citations than can normally be accomplished by a uniformed officer located at the site, and thus offset the costs of operation.

Drone radar can be used to imply the presence of enforcement in the work zone area. Drone radar devices emit radio signals that activate radar detectors used by the traveling public. These devices are commercially available and are typically mounted on work vehicles, arrow panels, or portable changeable message signs (PCMSs). Although actual speed reductions may be small, this device may effectively alert drivers to an upcoming change in the highway environment when their radar detector is activated (*7*,*8*).

Advance Warning Area

The advance warning area is an area where drivers are often surprised by traffic queues or other hazards. These types of events may be a result of a driver being inattentive, failing to recognize their closing speed, or having inadequate sight distance for the perception of and

reaction to the surprising queue or hazard. Several advance warning area enhancements may have increased "attention getting" ability, which may reduce the opportunity for inattentive drivers to commit intrusions:

- ensure adequate sight distance to lane closure taper;
- use dual advanced signing;
- use overhead changeable message sign (CMS) to warn drivers of upcoming or current work zone conditions;
- use temporary transverse rumble strips;
- use an early merge system;
- consider working at night or on weekends;
- use an upstream queue end warning (real time information or general warning);
- use dynamic speed display (DSD) trailers; and
- provide advance notification of work activity, alternate routes, closure location and duration.

As part of the initial patrol through the work zone, sight distance should be checked using speeds at which vehicles normally travel on that roadway. Early detection of sight distance issues may prevent intrusions, particularly where traffic control devices may simply be extended beyond upstream horizontal or vertical curvature.

According to the *Caltrans Standard Plans for Construction of Local Streets and Roads* (*9*), dual advance warning signing (i.e., warning signs on both sides of the roadway) are required for lane closures on freeways and expressways when less than half of the available lanes remain open to traffic (i.e., going from three lanes to one lane open). However, dual advance warning signing is not required when at least half of the travel lanes remain open (i.e., going from three lanes to two lanes open). Assuming a right lane is closed, dual signing provides a better opportunity for drivers in the left lane to see advance warning signs that might otherwise be blocked from their view by traffic in the right lane, particularly on a roadway with higher volumes of truck traffic. In addition, dual signing notifies drivers in the open travel lanes of the right lane closure in hopes that they will remain in the open travel lanes and not enter the right lane upstream of the lane closure. Overhead changeable message signs, which are more likely to be visible from all traffic lanes, can also be used to warn drivers of the upcoming work zone conditions.

Temporary transverse rumble strips may also be used to alert drivers that they are approaching a work zone by generating audible and tactile warnings. Temporary transverse rumble strips are typically used in long-term maintenance work zones. Conventional rumble strips adhere to the pavement surface and are often placed in an array of several strips placed perpendicular to traffic at 18 inch intervals. More recently, portable plastic rumble strips have been developed. These devices are weighted, may be used without an adhesive, and are suitable for shorter duration work (Figure 5). Previous research (*10*,*11*,*12*) has shown that temporary transverse rumble strips in work zones typically result in a 2 to 5 mph speed reduction. Even when only very small speed reductions are achieved, temporary transverse rumble strips may effectively alert drivers to an upcoming change in the highway environment, and thus achieve a safety benefit.

Figure 5. Portable Plastic Rumble Strips.

The early merge system (also known as a dynamic no passing zone) encourages drivers to exit the closed lane as soon as possible and thus is intended to reduce the number of forced merges near the beginning of the lane closure. The early merge system uses intelligent transportation systems (ITS) sensors to monitor traffic in the open lane on the approach to the work area. As shown in Figure 6, advance warning signs are used to display no passing messages (e.g., "NO PASSING WHEN FLASHING" or "LEFT LANE DO NOT PASS WHEN FLASHING"). These types of messages are intended to discourage "queue-jumpers" from merging into the open lane at the beginning of the lane closure and causing additional delay to those who merged early. Thus, the early merge system aims to reduce aggressive driving and

unsafe merge maneuvers. A study in Michigan (*13*) found that the average peak period travel time delay decreased by over 30 percent, the average number of stops and duration of stops were decreased, and the number of aggressive driving maneuvers (late merges) during peak hours was significantly reduced. Early merge systems may be used for lane closures on high speed facilities under low volume conditions. For a two-to-one lane closure, volumes should be between 2,000 and 3,000 vehicles per hour; for a three-to-two lane closure, volumes should be between 3,000 and 3,800 vehicles per hour (*14*).

Figure 6. Example of Early Merge Advance Warning Sign.

Drivers often misjudge their closing speed when approaching a queue or other hazard. Several available countermeasures may help with this problem. When possible, the schedule of work should be reviewed to determine if the work can be performed during night and/or weekend periods when traffic volumes may be lower. When backups are expected, an upstream queue end warning system can monitor the speed of vehicles within and upstream of a work zone. When reduced speeds are detected, an upstream PCMS or other warning system (such as static signs with flashers) are activated to warn drivers of the slower-moving traffic ahead. Warnings messages may include "BE PREPARED TO STOP," "SLOW TRAFFIC AHEAD," or may give the actual speed of the slower-moving traffic (e.g., "30 MPH TRAFFIC AHEAD"). A study in Texas (*15*) found that a queue end warning system reduced the number of vehicle conflicts, such as sudden breaking and forced lane changes to avoid rear-end crashes, by 2 to 7 percent. Speed variance was also significantly reduced, which may reduce the potential for rear-end crashes and result in safer traffic operations.

Dynamic speed display (DSD) trailers showing the speed of approaching vehicles (i.e., "YOUR SPEED" signs) paired with a regulatory or advisory speed limit sign allows drivers to see their own speed and compare it to the recommended vehicle speed for the work zone (Figure 7). DSD trailers have been shown to reduce speeds by 2 to 10 mph and decrease the percent of vehicles exceeding the speed limit (*16*,*17*,*18*). Even when only very small speed reductions are achieved, DSD trailers may effectively alert drivers to an upcoming change in the highway environment, and thus achieve a safety benefit. DSD trailers are more effective at locations where the sign supports a clear and real need for a driver to reduce their speed or where the perception of regular enforcement exists. The effect of DSD trailers over time (especially if left at a location continuously and not enforced) is uncertain but believed to diminish as drivers become more accustomed to their presence in the work zone.

Figure 7. DSD Trailer.

Another innovative use of DSD trailers was evaluated on Interstate 80 near Lincoln, Nebraska (*19*). The system deployed consisted of three DSD trailers placed at approximately one-quarter mile intervals in advance of the work zone. Each trailer was equipped with a light-emitting diode (LED) speed display, a radar unit that measured the speed of the downstream traffic, two flashing strobes to warn drivers of stopped or slow-moving traffic, a "SPEED OF TRAFFIC AHEAD" sign mounted over the speed display, and a "USE EXTREME CAUTION WHEN FLASHING" sign mounted beneath the speed display. When slow or stopped traffic was detected, the speed of the downstream traffic was displayed and the strobe lights were

activated. When no slowdown was present, the strobe lights were off and either the speed of the downstream traffic or the work zone speed limit, which ever was lower, was displayed. The results of the evaluation indicated that the speed messages were effective at reducing the speed of vehicles approaching queued traffic. In addition, drivers began decelerating sooner and reduced their speed over a longer distance.

Unfortunately, some drivers deliberately choose to enter the closed lane in order to bypass congestion or reach an exit, intersection, or driveway. Providing advance notification of lane closures via PCMS, highway advisory radio (HAR), or other media will allow drivers to make more informed decisions (e.g., take an alternate route, avoid roadway during lane closure times, etc.) and thus potentially reduce work zone intrusions. If no alternate routes are available, information regarding the lane closure duration and location can still be provided.

Transition Area

The transition area is where lane closures begin. As shown in Table 12, 8 percent of intrusion incidents into the taper occur because the driver fails to recognize the lane closure. While several of the potential countermeasures discussed in the previous section are also used to alert drivers about an upcoming lane closure, there are three additional countermeasures that may be used in the lane closure taper itself:

- use larger channelizing devices,
- use closer-space or continual traffic control devices, and
- use a sequential warning light system.

National Cooperative Highway Research Program (NCHRP) Report 476 (*20*) contains guidelines for identifying the special problems associated with night work that require safety enhancements above and beyond the minimum requirements specified in the Manual on Uniform Traffic Control Devices (MUTCD) (*21*). During lane closures, positive guidance at decision points becomes more critical for drivers at night. Therefore, channelizing devices that are larger and more visible than those required for daytime applications are desirable. In addition, channelizing devices should be closely spaced to more clearly define closed lanes at night. Table 16 shows the channelizing device spacing in tapers recommended for use by NYSDOT to discourage work zone intrusions in lane and shoulder closures. With larger channelizing devices, such as drums, the close device spacing appears to create a more continuous array of retroreflective devices and thus

reduces the risk of drivers entering the closed lane (deliberately and non- deliberately). To date, no evaluations of these channelizing device enhancements have been conducted.

Table 16. Channelizing Device Spacing in Tapers (20).

Estimated Operating Speed (mph)	Maximum Spacing (ft)
20	20
30	30
40+	40

In some situations, it may be desired to provide continuous delineation of the taper (i.e., no spacing between devices). This can be accomplished with longitudinal channelizing devices (LCDs). LCDs are lightweight, deformable channelizing devices that can be connected together to form a solid line of traffic control devices. LCDs look similar to water-filled barrier, but they are not positive protection devices. LCDs may be used instead of a line of cones, drums, or barricades. However, currently no guidance is provided regarding the work zone configurations and conditions where LCDs should be considered in lieu of these other devices (*21*). Ongoing research at the Texas Transportation Institute (TTI) is being conducted to determine whether LCDs used in a continuous line application in work zones improve safety and operations relative to the use of other types of channelizing devices.

At night, a sequential warning light system can also be attached to the drums that form the lane closure taper. This warning light system is composed of a series of synchronized individual flashing warning lights that produce the perception of light that “moves” repeatedly in a sequential manner from the beginning of the taper to the end of the taper (Figure 8). TTI research (*22*) showed that this system significantly reduced the percent of both passenger vehicles and trucks in the closed lane 1000 ft upstream of the lane closure.

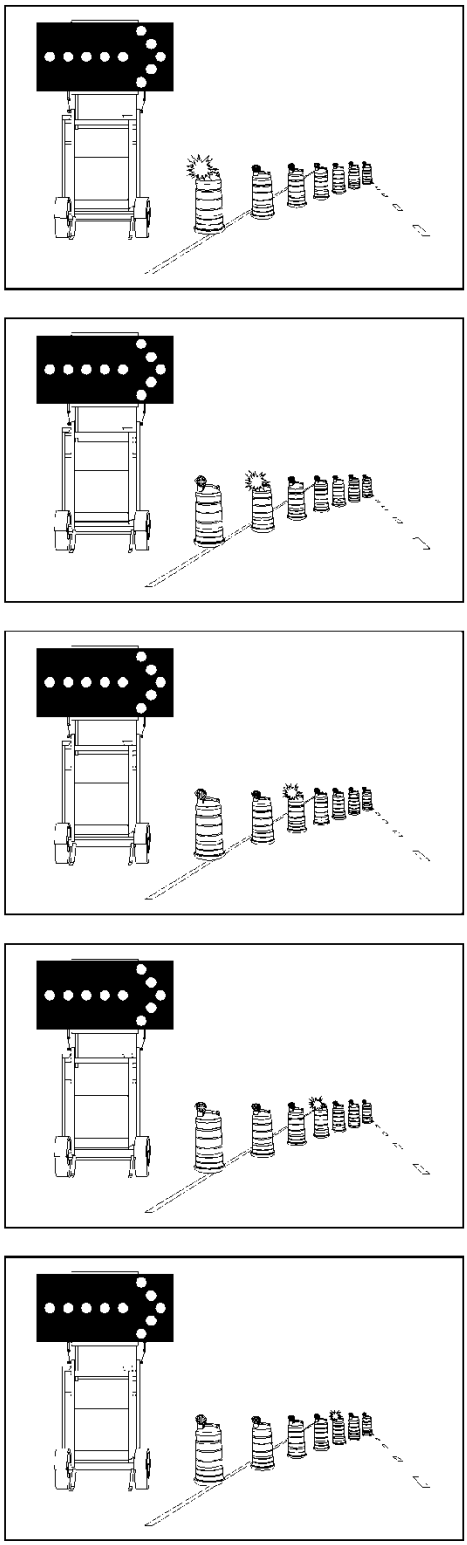


Figure 8. Sequential Warning Light System.

Activity Area

The activity area is where work takes place; thus, workers and equipment are located in this area. Obviously, positive protection can be used to reduce work zone intrusions into the activity area. However, traditional positive protection devices (e.g., concrete barrier) are not feasible with shorter term operations. 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 (Figure 9). 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 progresses down the roadway. To date, steel barrier has not been extensively deployed. Consequently, its effectiveness and practicality have not been verified. However, steel barrier is expected to reduce vehicle intrusions into the work area.

Figure 9. Example of Steel Barrier.

Other intrusion countermeasures that can be used in the activity area are:

- use closer-spaced or continual traffic control devices,
- use transverse traffic control devices,
- limit the length of lane closures to avoid blocking ramps or driveways,
- implement lane change restrictions, and
- use a downstream spotter.

Closer or continual spacing of traffic control devices can also be used throughout the lane closure to improve delineation of the proper travel path and prohibit drivers from entering the closed lane. When travel lanes are closed for long distances it may appear that no work activity is taking place. Thus, impaired or careless drivers who enter the closed lane may travel some distance before encountering the work operation or some other hazard. Channelizing devices placed transversely across the closed lanes can be used to warn errant drivers who may have moved into the closed travel lane without realizing it was still an active closure. NCHRP Report 476 (*20*) recommends that transverse traffic control devices be located approximately every 750 ft so that an obstacle is presented to a driver about every 10 seconds for vehicles traveling 45 to 50 mph. While Caltrans currently requires transverse traffic control devices in lane closures on freeways and expressways (*9*), these devices are spaced more than twice the distance (2000 ft) recommended in the NCHRP report. However, to date the use of transverse traffic control devices has not been evaluated so it is uncertain how the device spacing impacts the probability of an intrusion crash.

Transverse traffic control devices also prohibit drivers who deliberately enter the closed lane to bypass congestion or access exits, driveways, etc. from progressing down the roadway inside the closed lane. In addition, when feasible, limiting the length of the lane closure may reduce delay and decrease the number of access points blocked; thereby, hopefully reducing the need for drivers to deliberately enter the lane closure.

Researchers attributed a small portion of the lane closure intrusion events (5 percent) to vehicle conflicts that occur when vehicles change lanes adjacent to the closed lane. Lane changing restrictions (i.e., not allowing vehicles to change lanes while traveling through the work zone) may reduce vehicle conflicts and thus potentially decrease the chance of an intrusion.

Occasionally, drivers enter the roadway going in the wrong direction and enter the closed lane from the downstream end (2 percent of lane closure intrusion events). While closer or continual spacing of traffic control devices and transverse traffic control devices can also be used to deter the occurrence of these types of events, detection of this type of event by a downstream spotter may enhance worker safety. Although the intrusion may not be prevented, the spotter may be able to provide a warning to other workers or possibly stop the intruding vehicle before any injuries occur.

Typically, work area access points are short openings with little or no area for trucks to decelerate or accelerate. Thus, drivers sometimes fail to recognize the slow speed of work vehicles trying to enter or exit the work area. In addition, drivers occasionally follow the trucks into the work area. Potential countermeasures for these types of intrusions include:

- reconfigure access point;
- alter internal traffic control plan procedures to prevent truck slow-down in active travel lane;
- use construction entrance signing (static or dynamic);
- use "DO NOT FOLLOW" signs (static or dynamic);
- ensure that work vehicle warning lights are used when appropriate (e.g., turn signals, hazard lights, beacons, etc.); and
- use enhanced vehicle warning light system.

In some cases, the work area access points are located such that they appear to be a continuation of the expected travel path. Reconfiguring the access point to make it more apparent that the construction entrance is not the intended travel path may reduce the chance that drivers will inadvertently follow the work trucks into the work area. In addition, altering the layout of the access point, as well as internal traffic control plan procedures (i.e., the coordination of the flow of construction vehicles, equipment, and workers), can allow work trucks to enter and exit the work area at higher speeds; thus, alleviating the need for them to decelerate and accelerate in an active travel lane.

Static or dynamic construction entrance signing located near or immediately upstream of the access point may also be used to notify drivers about trucks entering and exiting the roadway. Example messages include:

- "CONSTRUCTION ENTRANCE,"
- "WORK ZONE VEHICLES ONLY,"
- "TRUCKS ENTERING ROADWAY/REDUCE SPEED,"
- "TRUCKS ENTERING 1000 FT/BE PREPARED TO STOP," and
- "TRUCKS EXITING 2000 FT/DO NOT FOLLOW TRUCKS."

Static or dynamic "DO NOT FOLLOW" signing can also be located near access points or on the back of work vehicles to tell drivers not to follow work vehicles into the work area. In

addition to the fifth example message above, the following messages may be used "DO NOT FOLLOW INTO WORK AREA" and "CONSTRUCTION VEHICLE DO NOT FOLLOW."

Typically, the messages discussed above are displayed to drivers whether or not a truck is actually entering or exiting the work area. Work zone ITS may be used to activate messages on a PCMS only when trucks are detected; thus, hopefully improving the driver's trust of the message. Static signs with flashing beacons may also be used to display more real-time messages. When a truck is detected, the beacons would flash; otherwise the beacons would remain off.

There are several types of construction vehicle enhancements that can be utilized to deter intrusion crashes. Specific operational procedures, such as requiring the use of turn signals, hazard lights, and beacons by construction vehicle drivers, may provide additional information for drivers to anticipate the upcoming maneuvers of the work vehicle. Traditionally, amber warning lights have been used on work vehicles and equipment to alert drivers to potentially hazardous conditions. However, currently there are various types (e.g., light bars, arrow sticks, strobes, beacons, LEDs, etc.) and colors (e.g., blue and white) of warning lights available. Recently as part of NCHRP Project 13-02 (*23*), researchers developed guidelines for the selection and application of warning lights on roadway operations equipment. Recommended lighting requirements included:

- no specific type of light over another;
- the use of amber or white lighting on maintenance vehicles;
- lights should flash, with a pattern that alternates from one side of the vehicle to the other being preferable to a pattern in which lights on both sides of the vehicle flash at the same time; and
- positioning the lighting such that it appears against a portion of the vehicle and not against the sky (however, this limits the ability of the light to be seen from all directions; thus, it may be necessary to replicate lights in multiple directions).

POTENTIAL COUNTERMEASURES FOR INTRUSIONS INTO FLAGGING OPERATIONS

Flagging operations mainly occur on two-lane, two-way roadways where one lane of travel must be closed to conduct the work. Table 13 shows that intrusions into one-way flagging

operations can occur in several areas, including in the advance warning area (21 percent), at the flagging position (70 percent), and in the work area (9 percent). In the sections that follow, researchers will discuss the potential countermeasures that can be applied in the advance warning area, at the flagger station, and in the activity area, respectively.

Advance Warning Area

The intrusion incidents in the advance warning area were all attributed to the approaching driver failing to recognize stopped or slowed traffic. The following countermeasures should be considered to deter these types of intrusions:

- use temporary transverse rumble strips,
- use advance warning messages on PCMSs,
- use DSD trailers, and
- provide enforcement (real).

As mentioned in the lane closure discussion, temporary transverse rumble strips may be used to alert drivers that they are approaching a work zone by generating audible and tactile warnings. Recently in Florida (*24*) researchers found over an 8 mph reduction in speeds 600 ft upstream of the flagger when four sets of temporary transverse rumble strips were applied between 500 and 1500 ft upstream of the flagger.

PCMS messages may also be used to warn drivers of an upcoming work zone and slow or stopped traffic. As discussed in the lane closure section, there are several ways that DSD trailers can be used to inform drivers of the need to slow down and allow them to compare their speed to anticipated speeds of vehicles in front of them. Previous research (*16,17,18,25,26*) has shown that speed-related PCMS messages and DSD trailers provide reasonable speed reductions in the short-term (0 to 10 mph); however, their effect over time is uncertain. Enforcement in conjunction with these devices or by itself may also reduce the occurrence of intrusions at flagging operations.

Flagger Station

In addition to enforcement (real or drone radar) and temporary rumble strips, the following methods may be employed to reduce work zone intrusions at the flagger station:

- use closer-spaced or continual traffic control devices,
- use transverse traffic control devices/LCDs,
- provide advance notice of work activity,
- limit length of lane closures to avoid blocking driveways,
- replace flagger with police officer, and
- use automated flagger assistance devices.

Flaggers are often susceptible to strikes from both directions of traffic. As mentioned previously, closer spacing of traffic control devices, transverse traffic control devices and LCDs may be used to improve delineation of the lane closure and prohibit drivers from entering the closed lane. These devices can also be used to block off access to the shoulder in order to discourage drivers from going around the closed lane on the shoulder.

In some cases, drivers ignore the flagger's instruction to stop and try to proceed into the open lane. Most likely these drivers are trying to avoid delay. Providing advance notice of the lane closure on PCMSs allows drivers to avoid the work zone if desired. In addition, limiting the length of the lane closure may reduce delays and thus decrease the potential for drivers to get impatient and try to go around the flagger. To further improve compliance with flagger instructions, uniformed officers may be located at the flagging station or used to direct traffic (i.e., be the flagger) in lieu of workers.

In lieu of a flagger, several devices can be used to control the right-of-way when a lane closure is needed on a two-lane, two-way road. Automated flagger assistance devices (AFADs) are portable traffic control systems designed to be operated by a flagger located off the roadway (*27*). One type uses a STOP/SLOW sign to control the right-of-way (Figure 10a), while the other type utilizes red and yellow lenses (Figure 10b). AFADs must be operated by a qualified flagger and the flagger operating the AFAD cannot leave the AFAD unattended at any time while the AFAD is controlling the right-of-way. However, AFADs can be remotely operated either by a single flagger, at one end of the lane closure or at a central location, or by two flaggers, one near each device's location. AFADs should not be used for long-term stationary work. Typical applications include bridge maintenance, haul road crossings, and pavement patching. There are concerns that AFADs may confuse drivers or garner less respect and thus result in decreased compliance.

a) STOP/SLOW AFAD

b) Red/Yellow Lens AFAD

Figure 10. Examples of AFADs.

Portable traffic signals are traffic signals mounted on trailers that can be used to control the right-of-way in a work zone (Figure 11). Communications between the signals are provided by hard wiring, radio frequency transceiver, or by preset timing. Thus, portable traffic signals can actually replace flaggers; thereby, removing flaggers from direct exposure to approaching traffic and allowing flaggers to perform other critical work tasks. Appropriate timing is critical to the success of portable traffic signals. Excessive wait time can lead to driver confusion and frustration, possibly resulting in decreased compliance. Portable traffic signals are appropriate for use in longer term work zones, as well as some short-term operations. Examples of typical applications include: long-term bridge construction, short-term pavement repair, and short-term bridge maintenance.

Figure 11. Portable Traffic Signal.

Activity Area

Surprisingly, some work zone intrusions during flagging operations occur when drivers attempt to pass a pilot car or vehicle while adjacent to the work activity area (6 percent). The nature of the events suggests that drivers may not understand that the lane is closed and not available for passing other vehicles. However, some of these events appear to be a result of drivers deliberately entering the closed lane. Possible countermeasures for intrusions into the activity area of flagging operations include:

- use closer-spaced or continual traffic control devices,
- use transverse traffic control devices,
- limit length of lane closures to avoid blocking driveways,
- use steel (portable) barrier, and
- provide enforcement (real).

All of these countermeasures have previously been discussed; thus, for brevity researchers will not repeat the information here.

POTENTIAL COUNTERMEASURES FOR INTRUSIONS INTO MOBILE OPERATIONS

Maintenance work is often accomplished using mobile operations which consist of one or more vehicles that move along the road intermittently or continuously at very slow speeds relative to the normal traffic stream. According to the *Caltrans Standard Plans for Construction*

of Local Streets and Roads (9), for mobile operations Caltrans currently requires both a shadow vehicle with a truck-mounted attenuator (TMA) in the blocked lane immediately upstream of the work vehicles and an advance warning vehicle on the shoulder upstream of the work convoy. Where sufficient shoulder is not available, the advance warning vehicle may encroach into the traffic lane staying as close to the edge of the shoulder as practical. On two-lane highways the advance warning vehicle has a truck-mounted "SLOW TRAFFIC AHEAD" sign (static or dynamic signs can be used). On multilane highways, the advance warning vehicle is required to have a truck-mounted CMS displaying "ROAD WORK AHEAD" and "LANE CLOSED AHEAD" when the outside or median lane is closed and "ROAD WORK AHEAD" and "INTERIOR/CENTER LANE CLOSED" when the interior lane is closed.

Even though Caltrans is currently using an advance warning vehicle and, in some instances, truck-mounted CMSs (both of which are considered intrusion countermeasures), the extent to which these countermeasures are actually present at intrusion crash locations is unknown. According to Table 8, 20 percent of the work zone intrusions in California occur in mobile operations (second only to lane closures, 30 percent). Furthermore, these intrusion events occur equally on both freeways and state highways (21 percent and 19 percent, respectively). Caltrans and highway contractor personnel stated that these mobile operation intrusions typically involve vehicles which strike the TMA on the back of the shadow vehicle (i.e., the first work vehicle encountered by drivers). This was also the primary reason for mobile operation intrusions in New York (63 percent). In addition, according to the NYSDOT database another 25 percent of mobile operation intrusions may be attributed to drivers pulling between the work vehicles (i.e., entering the work convoy).

Researchers identified the following potential countermeasures that may be used to reduce intrusions into mobile operations (Table 14):

- use effective messages on truck-mounted CMSs to indicate slow-moving vehicles or to discourage vehicles from entering the work convoy,
- use truck-mounted DSD showing truck speed,
- adjust spacing between advance warning vehicle and work convoy as needed to maintain adequate sight distance to work convoy,
- maintain close spacing between work vehicles in convoy,
- provide a work vehicle in front of workers on foot,

- use truck-mounted positive protection (intermittent operations only), and
- provide enforcement (real or drone radar).

TTI researchers believe that truck-mounted CMSs have superior target value and thus possibly provide more advance warning time to drivers than static signing. However, the amount and order of information presented, the legibility distance of the message, and the content of the message all impact the effectiveness of these devices. Research has shown the drivers require 2 seconds of reading time for each unit of information on a CMS (*28*). This implies that drivers need 2 seconds of reading time (once the message is legible) to adequately read and process the single-unit message (e.g., "SLOW TRAFFIC AHEAD") currently used with mobile operations on two-lane highways. For the two-unit message currently used on multi-lane highways (e.g., "ROAD WORK AHEAD" and "LANE CLOSED AHEAD"), drivers need 4 seconds of reading time.

Given that agencies have only limited control over vehicle speeds operating on a roadway, it is the design of the truck-mounted CMS message that must be adjusted so as to provide adequate legibility distances. Unfortunately, this is not easily accomplished on truck-mounted CMSs because the number of characters available per line is dependent upon the character height and the character height is dependent upon the number of message lines used. On a typical truck-mounted CMS, the height of the letters in two-line and three-line messages is only 10 inches and 6 inches, respectively. A recent TTI study (*29*) found that the 85th percentile legibility distance for 9-inch and 10.6-inch letter heights on an LED CMS were 228 ft and 324 ft, respectively. While researchers did not evaluate a 6-inch letter height, it can be assumed that this letter height would provide less than 200 ft of legibility distance. These limitations imply that new shorter messages (possibly using abbreviations) and multiple-phase messages should be developed for truck-mounted CMSs to ensure that the drivers have adequate time to read and react to the messages presented.

As shown in Table 14, the messages on the truck-mounted CMSs should be used to warn drivers that they are approaching a slow moving work convoy (driver misjudgment of the work vehicle's slower speed appeared to be responsible for over 60 percent of the mobile operation intrusions) or to discourage drivers from entering between the work vehicles (25 percent of the mobile operation intrusions were of this type). Researchers believe that drivers may not understand that the message "SLOW TRAFFIC AHEAD" is referring to a mobile work convoy,

since this message can also be used to warn drivers about congestion. Also, the two-phase message used for moving lane closures in the outside or median lanes ("ROAD WORK AHEAD" and "LANE CLOSED AHEAD") does not tell the driver which lane is closed; thus, the driver must wait until they can see the work convoy to make a driving decision. Use of the words "RIGHT" and "LEFT" may encourage drivers to move out of the closed lane further upstream of the work convoy.

Recently, TTI researchers conducted laboratory and field studies of candidate messages and deployment configurations of truck-mounted CMSs used in support of various mobile operations for the Wyoming Department of Transportation (*30*). Based on the evaluations, researchers identified the following key points that should be kept in mind when designing and displaying messages on truck-mounted CMS.

- The character heights typically used on truck-mounted CMS only provide enough sight distance to allow 2 units-of-information (or phrases) to be displayed in a message.
- For most applications, the two critical units that should be displayed on a truck-mounted CMS are: 1) a problem/roadwork descriptor and 2) an action statement.
- A message <u>cannot</u> contain more than 2 phases.
- Message elements should not flash or scroll.
- Abbreviations should be used when necessary to keep the message to two phases, and should be used in accordance with accepted practices.

Finally, the selection of message elements should be based on the identification of specific concerns for the type of operation and road. These concerns include (but are not limited to):

- communication of the convoy situation,
- communication of passing or action information,
- avoidance of paint tracking during striping, and
- speed differential.

Based on the findings of the Wyoming research and message design principles, researchers created the sampling of recommended messages for use on truck-mounted CMS during mobile operations in Table 17. These messages are defined by the type of work, road type, and identified concerns being addressed by the message.

Table 17. Recommended Messages for Use on Truck-Mounted CMS During Mobile Operations.

Operation	Road Type	Primary Concern	Phase 1 [a,b]	Phase 2 [b]
Striping	2-Lane, 2-Way	Convoy Recognition	# PAINT TRUCKS	DO NOT CUT IN
		Convoy Recognition & Tracking Paint	# PAINT TRUCKS	YELLOW [*or WHITE*] LINE WET
		Tracking Paint	YELLOW [*or WHITE*] LINE WET	DO NOT CUT IN
	Multi-lane	Convoy Recognition	# PAINT TRUCKS	DO NOT CUT IN
		Convoy & Passing Maneuver	# PAINT TRUCKS	STAY IN LFT [*or RGT*] LANE
		Tracking Paint	# PAINT TRUCKS	CNTRLINE [*or EDGELINE*] WET
Sweeping	2-lane, 2-way or Multi-lane	Debris/Dust Obstructing Vision	SWEEPING AHEAD	REDUCED VISION
	Multi-lane	Lane Encroachment	SWEEPING AHEAD	STAY IN LFT [*or RGT*] LANE
Workers Out of Vehicle	2-lane, 2-way or Multi-lane	Protection of Workers	# WORK TRUCKS	WATCH FOR WORKERS
		Reducing Vehicles Entering Convoy as Protection.	# WORK TRUCKS	DO NOT CUT IN

[a] Where there is a # symbol, the appropriate number of trucks that are present in the convoy should be inserted.
[b] Items in italics are alternatives to be used in place of other similar descriptors shown in the message. For example, "Yellow" could be interchanged with "White."

Truck-mounted DSDs indicating the speed of the work vehicle may also improve driver understanding of the speed differential between themselves and the work convoy. Previous TTI research (*31*) investigated this concept using two techniques: a "MY SPEED" DSD showing the speed of the work truck (Figure 12a) and a "YOUR SPEED/MY SPEED" combination DSD showing the speed of approaching vehicles and the speed of the work vehicle (Figure 12b). Unfortunately, neither of these displays was well understood by drivers. The "MY SPEED" display was misinterpreted as the speed of approaching vehicles by approximately one-third of the participants. There was also evidence that the combination display contained too much information for participants to correctly interpret.

a) "MY SPEED" DSD

b) "YOUR SPEED/MY SPEED" DSD

Figure 12. Truck-Mounted DSDs Evaluated in Previous TTI Research.

In Wisconsin (*32*), researchers investigated "YOU" and "ME" DSDs on the back of a work vehicle moving at slow speeds or stopped on a two-lane road (Figure 13). The "YOU" display showed the approaching driver's speed, while the "ME" display showed the work vehicle's speed. Field studies showed a 3 mph reduction in the average speed of vehicles approaching the work vehicle. However, motorist understanding of the devices was not investigated and TTI researchers believe that the "ME" display could be misunderstood by motorists (similar to the "MY SPEED" display). Changing the message shown with the display of the work vehicle's speed (e.g., SPEED OF WORK TRUCK) may increase comprehension; however, this would need to be evaluated in future research prior to implementation.

Figure 13. Truck-Mounted DSDs Evaluated in Wisconsin.

Besides ensuring that the truck-mounted CMS messages are properly designed, the advance warning vehicle needs to be located far enough upstream of the shadow vehicle to allow drivers time to complete the necessary actions prior to encountering the work convoy. Furthermore, in locations where there is limited sight distance, the spacing between the advance warning vehicle and the work convoy should be adjusted as needed to maintain adequate sight distance to the work convoy. For example, the advance warning vehicle should be positioned at the peak of a crest vertical curve until the work convoy progresses far enough down the roadway that drivers have adequate sight distance of the convoy once they top the hill.

Conversely, reducing the distance between the work vehicles within the work convoy may deter drivers from pulling between the work vehicles. However, protection vehicles with TMAs must maintain a minimum distance upstream of the next work vehicle to account for the roll-ahead movement that occurs when impacted.

In some mobile operations, workers may be on foot in front of a work vehicle. Recent research in Illinois (*33*) found that drivers begin returning to the closed travel lane as early as 50 ft beyond the work area. Thus, traffic returns to the closed lane at very short distance beyond the perceived end of the work area. An effective way to extend the work area length in front of workers on foot is to add another work vehicle downstream just past the work crew.

As discussed previously, in a mobile operation Caltrans currently requires a shadow vehicle with a TMA in the blocked lane immediately upstream of the work vehicles. 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. One example is the Caltrans-developed Balsi Beam (Figure 14), a steel beam “cage” currently 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. However, the Balsi Beam and other similar devices cannot be moved continuously down the road while workers are within the protection area, nor can it be moved or extended laterally across lanes.

Figure 14. Caltrans Balsi Beam.

Police presence in the work convoy may also reduce the occurrence of intrusions into mobile operations. A police vehicle could be located on the shoulder upstream of the work convoy to reduce rear-end crashes or in the closed lane downstream (or in front of) the shadow vehicle to deter drivers from entering the convoy. It is important to note that the police vehicle should not be located in the travel lane upstream of (or behind) the shadow vehicle, since they are not designed to physically protect the rear of the work convoy. Drone radar could also be used to mitigate intrusion crashes into mobile operations. Researchers discussed the benefits of active enforcement and drone radar in lane closure section and thus that information is not repeated here.

POTENTIAL COUNTERMEASURES FOR INTRUSIONS INTO TRAFFIC CONTROL SET-UP AND REMOVAL OPERATIONS

Drivers may be confused by temporary traffic control that is being changed as they pass by, particularly when channelizing devices are partially set. To avoid driver confusion, proper temporary traffic control set-up and removal procedures should be followed at all times. As shown in Table 15, drivers tend to commit the same types of intrusions during traffic control set-up and removal as seen with mobile operations and flagging operations that use pilot cars. This is not surprising, since traffic control set-up and removal is a type of mobile operation and is susceptible to vehicles entering the convoy (22 percent of intrusions into set-up and removal

operations). Researchers identified the following potential countermeasures that may be used to reduce intrusions into traffic control set-up and removal operations:

- use effective messages on truck-mounted CMSs to discourage vehicles from entering the work convoy,
- maintain close spacing between work vehicles in convoy,
- provide work vehicle in front of workers on foot,
- use additional work vehicle on shoulder,
- provide enforcement (real),
- use enhanced vehicle warning light system,
- use automated traffic control device set-up/removal, and
- use positive protection.

As with other types of mobile operations, using effective messages on truck-mounted CMSs, reducing the spacing between work vehicles, and adding a work vehicle in front of workers on foot in the closed travel lane are methods that can be used to discourage vehicles from entering the traffic control set-up/removal operation. During intermittent stops, the Caltrans-developed Balsi Beam or other similar devices could be use to protect workers.

In some instances, drivers may attempt to pass a work vehicle on the shoulder during set-up and removal operations (11 percent of intrusions). The addition of another work vehicle on the shoulder may be a suitable countermeasure to discourage this behavior.

The most common type of intrusion during set-up and removal operations occurs when a driver veers out of the travel lane and strikes a work vehicle or worker on the shoulder (44 percent). Researchers assumed that the primary contributing factor in these cases was driver inattentiveness. As discussed previously, enforcement (real or drone radar) is a countermeasure that should be considered in cases where a driver needs to be alerted to unexpected roadway conditions. Enhanced vehicle warning light systems on work vehicles may also be used to alert drivers.

The use of automated equipment to set-up and remove traffic control devices (i.e., cones and drums) may be desirable to keep workers from standing in the active travel lane during these operations. Although a driver may still veer out of the travel lane or accidentally lose control (11 percent of intrusions into set-up and removal operations) and strike a work vehicle, injury

severity could potentially be reduced by removing the worker from the pavement. Caltrans has already funded a significant amount of research on this topic.

Drivers may also strike a traffic control device, which flies into the work area (11 percent of intrusions into set-up and removal operations). Unfortunately, sometimes drivers deliberately hit traffic control devices in the vicinity of workers. Again, active enforcement near the work activity should reduce the occurrence of these deliberate actions.

SUMMARY

Within Chapter 3, researchers provided a detailed discussion of over 40 potential countermeasures (regardless of potential cost, practicality, or effectiveness) that could be used to mitigate the occurrence of the work zone intrusion crash sequences identified in Chapter 2. In all work zones, proper set-up and maintenance of temporary traffic control is important for the safety of both motorists and workers. In addition, continuous patrol or monitoring of all work zones may be used to ensure that debris or other road conditions do not present hazards for passing motorists. Two other potential countermeasures identified for all four types of work zone operations considered (lane closure operations, flagger operations, mobile operations, and traffic control set-up and removal operations) were enforcement presence (real or drone radar) and positive protection.

The majority of the remaining potential countermeasures were identified for lane closure situations (including flagging operations). However, about one-fourth of the countermeasures could be used to reduce work zone intrusions into mobile operations (including traffic control set-up and removal operations). Due to the potential for adverse effects, the following two countermeasures were removed from further consideration:

- truck-mounted DSD showing truck speed and
- enhanced vehicle warning light system.

CHAPTER 4:
WORK ZONE INTRUSION COUNTERMEASURE CRASH COST REDUCTION ANALYSES

INTRODUCTION

In this chapter, the methodology and results are presented for the work zone intrusion crash cost analyses. The intent these analyses is to provide some degree of objectivity and consistency in comparing the expected costs of intrusion countermeasure implementation under various work zone scenarios to the possible reduction in crash costs that may be realized by the implementation of the countermeasure. Conceptually, locations and conditions where potential crash cost reductions exceed countermeasure costs would be candidates for implementation, whereas locations and conditions where countermeasure costs exceed potential crash cost savings would not.

It must be emphasized here that these analyses should be considered as a general guide, a starting point for decision-makers regarding the types of conditions under which the potential countermeasures may prove cost-effective. In reality, it is difficult to predict with any certainty the crash costs expected for a particular work zone, let alone those that involve vehicle intrusions into the work area. Current crash prediction models generally use traffic volume, roadway type, and maybe one or two road geometric variables as independent variables. In reality, many other site characteristics can ultimately affect the likelihood and severity of a crash occurring at a location. Add to this the fact that decisions regarding how a particular work zone is set up or moved along the roadway can likewise influence crash frequency and severity, and one can see that the potential exists for large deviations from an "average" estimate. Consequently, the results of the analysis only provide order-of-magnitude indications of anticipated crash cost values.

COMPUTATION OF CRASH COSTS

Overview

A series of crash prediction models previously developed from other research studies were utilized in this analysis. For freeway facilities, the crash prediction models came from a traffic safety evaluation study of daytime and nighttime freeway work zones (*34*). California

was actually one of the states used in that study, and so a work zone crash prediction model directly applicable to California freeways was used. For other roadway types, work zone specific data were not available; only general crash prediction models were available (*35*, *36*). Researchers used these models to estimate crash frequencies on those types of facilities, and then applied crash modification factors to account for the increased risks experienced during work zone operations. The adjustment factors themselves came from the daytime and nighttime work zone study listed above, since similar factors for work zones on other facility types do not currently exist.

Methodology

Currently, most efforts to predict crash frequencies on a given roadway segment or to estimate the effectiveness of a particular countermeasure in reducing crash frequencies rely on Empirical Bayesian (EB) techniques. EB techniques increase the precision of estimation and correct for regression-to-the-mean bias (*37*). The technique involves the creation of a safety performance function (SPF), based on data from several roadway segments as a reference group, to provide a generalized estimate of the expected crash frequency as a function of roadway type, geometric features, and traffic volumes. In the absence of site-specific crash data, these SPFs are the estimated crash frequency expected on a given type of facility over a given time period.

Freeway/Expressway Facilities

For freeway facilities in California, separate SPFs were initially estimated for daytime and nighttime periods (6 am to 7 pm and 7 pm to 6 am) on freeways with 4 or 5 lanes, 6 or 7 lanes, and 8 or more lanes. The SPFs were negative binomial (NB) regression models (consistent with the state of the art in the safety field) developed with crash frequency as the dependent variable and site characteristics as independent variables. The analysis focused on total injury and fatal crashes and total property damage only (PDO) crashes. The model form was log-linear. With this model form, the expected crash frequency is related to the independent variables as follows:

$$Y = L * \exp(\beta_0 + \beta_1 X_1 + \beta_2 X_2 + ... \beta_n X_n) \quad (1)$$

where:

Y is the expected frequency of crashes per year;

L is the length of the section (miles);

X_1 through X_n are independent variables (e.g., traffic volume shoulder width, etc.); and

β_0 through β_n are coefficients that need to be estimated.

In a negative binomial model, the variance is related to the mean as follows:

$$Var(y_i) = E(y_i) + k(E(y_i))^2 \quad (2)$$

where:

$Var(y_i)$ is the variance,

$E(y_i)$ is the mean, and

k is the dispersion parameter.

For the models that were estimated, the CURE procedure (*38*) was used to determine if the functional form of the independent variables was reasonable. Models were estimated using PROC GLIMMIX in Statistical Analysis Software (SAS).

The SPF model coefficients developed through that effort can be found in the project documentation (*34*). These SPFs represented normal non-work zone conditions. A series of crash modification factors (CMFs) were then applied to these models to account for the increased crash risk that exists when a work zone is in place. Separate CMFs were developed for daytime and nighttime periods, and for each of the three following work periods:

- work activity occurring in the work zone, temporary lane closures in place;
- work activity occurring in the work zone, no temporary lane closures in place; and
- work zone inactive, no temporary lane closures in place.

The CMFs were developed for injury and fatal crashes, for property-damage-only (PDO) crashes, and for all crash severity types combined. The work zone CMFs are presented in Table 18. Generally speaking, the CMFs are higher for PDO crashes than for injury and fatal crashes. For inactive and active work zones when temporary lane closures are not in place, the nighttime CMFs are slightly higher than the daytime CMFs. However, when work activity with a temporary lane closure is required, the CMFs are approximately equal for both time periods, and are higher than for the other two work zone conditions. Multiplying the appropriate CMF by

the SPF provides an estimate of the crash frequencies expected on a given type of roadway for a given work zone condition.

These computations yielded the expected number of severe and PDO crashes under each of the three work zone conditions. Researchers also multiplied these expected crash values by CMFs to determine the expected number of intrusion crashes occurring under each work zone condition. These factors were taken from the analysis of the NYSDOT crash database described earlier in this report which indicated:

- 7.5 percent of daytime work zone crashes were intrusion crashes and
- 12.4 percent of nighttime work zone crashes were intrusion crashes.

Table 18. Freeway Work Zone Crash Modification Factors (*34*).

Work Zone Condition	Crash Modification Factor (CMF)	
	Nighttime	**Daytime**
Work Zone Active with Temporary Lane Closures[a]:		
PDO Crashes	1.748	1.808
Injury and Fatal Crashes	1.423	1.455
All Crashes Combined	1.609	1.663
Work Zone Active without Temporary Lane Closures:		
PDO Crashes	1.666	1.398
Injury and Fatal Crashes	1.414	1.174
All Crashes Combined	1.577	1.314
Work Zone Inactive without Temporary Lane Closures:		
PDO Crashes	1.330	1.196
Injury and Fatal Crashes	1.114	1.051
All Crashes Combined	1.237	1.127

[a] It is assumed that these crash modifications can also be used to characterize the increased crash risks that exist at mobile operations when located in an actual travel lane

The crash frequencies estimated using the appropriate SPF and work zone CMF were then multiplied by a per-crash cost value. The following recent crash cost values on facilities with operating speeds of 50 mph or higher were used (*39*):

- injury crash (fatality or injury) – $206,015 and
- PDO crash – $7,800.

The computations yielded estimates of the crash costs per year's worth of exposure under each work zone condition as a function of roadway average annual daily traffic (AADT). These yearly costs ultimately were then converted to an hourly cost to allow comparison to costs of the

various potential countermeasures under consideration. In most cases, the hourly intrusion crash costs values are relatively small.

For the freeway SPFs, researchers ultimately determined that the resulting hourly crash costs computed from the individual functions were so similar that it became unnecessary to retain separate functions by number of lanes and adjacent land use (rural versus urban). Consequently, a generalized function relating work zone crash costs per hour versus roadway AADT was developed for freeways, irrespective of the number of lanes on the freeway. Functions were estimated for the best-fit SPF model parameters, and also at the 5th and 95th percentile values of those parameters as a way to approximate confidence intervals around the cost functions for each work zone and time-of-day condition. The Appendix presents the resulting total and intrusion crash cost functions for freeway work zones in California.

Multilane Highways

For multilane highways, researchers relied on SPFs developed as part of ongoing research in support of a national Highway Safety Manual (*40*). These SPFs represent optimum conditions (12 foot lanes, 6 foot paved shoulders, and flat side slopes). Separate SPFs were available for divided and undivided multilane highways, using AADT as the key independent variable, as shown below:

- Divided Multilane Highways
  - Fatal and injury crashes per mile per year = $e^{(-8.772+0.939*Ln(AADT))}$
  - Total crashes per mile per year = $e^{(-9.776+1.171*Ln(AADT))}$
- Undivided Multilane Highways
  - Fatal and injury crashes per mile per year = $e^{(-9.832+1.008*Ln(AADT))}$
  - Total crashes per mile per year = $e^{(-10.235+1.190*Ln(AADT))}$

Unlike the separate freeway SPFs that were available for daytime and nighttime periods, the available multilane SPFs covered the entire 24-hour period each day. Researchers used the distribution of daytime to nighttime crashes documented in that reference (63 percent occurring daytime, 37 percent nighttime). Also, work zone CMFs were not available for either type of multilane highways. Researchers again used the freeway work zone CMFs to estimate total and intrusion work zone crashes on multilane highways. The resulting crash cost functions (best-fit and approximate 5th and 95th percentile confidence intervals) are also found in the Appendix.

Generally speaking, the crash costs per hour per mile for both the divided and undivided multilane highways tend to be less than those for freeway facilities at the same AADT level. The reason for this is that the HSM procedure also includes a separate SPF and methodology for estimating the crashes that occur at highway intersections on these facilities. For this analysis, the intersection crash costs were ignored because of a lack of available information as to average intersection spacing and how such spacing would play into typical work zone installations. Rather than unduly complicate the analysis, researchers propose simply to recognize the limitations of these functions as basic roadway segments and interpret and assess the likely potential of countermeasures being considered with this fact in mind.

Two-Lane, Two-Way Highways

For two-lane, two-way highway crashes, only a total crash SPF was available (*36*):

$$\text{Total crashes per mile per year} = 10^{-6}*\text{AADT}*365*e^{(-0.312)}$$

Of this total, 67.9 percent were estimated to be PDO and 32.1 were expected to be injury and fatal crashes. The same distribution procedure by time-of-day as was used for multilane highways was again used here. Similarly, the freeway work zone CMFs were also again used due to a lack of availability of two-lane, two-way work zone CMFs.

The Appendix once again provides the total and intrusion crash cost functions for two-lane highways that were used in this analysis. The influence of individual intersections were once again excluded from the analysis, and simply recognized when assessing the likelihood of a countermeasure being able to offset its costs through a reduction in crash costs. It should be noted that researchers were unable to define a reasonable standard error of the model parameters for the equation, and so were not able to approximate a confidence interval for the functions. Generally speaking, though, the lower traffic volumes on many rural two-lane highways yields crash costs in work zones that are very small on a per-hour basis.

RESULTS OF COUNTERMEASURE EVALUATIONS

The preliminary list of potential countermeasures identified in Chapter 2 served as the starting point of this analysis. Several items from that list were judged to be procedural

countermeasures that do not require significant additional expenditures or other agency/contractor resources, and so could and should be implemented as part of normal traffic control activities in most situations. In addition, some of the countermeasures identified had highly variable implementation costs, depending on the magnitude of the deployment and level of sophistication of the technology utilized (e.g., simple radar-activated warning sign at a specific location versus a complete work zone intelligent transportation system installed throughout the project). In general, not enough data exists as to the effectiveness in these widely-ranging designs to allow a reasonable cost-effectiveness assessment to be useful. Consequently, these types of countermeasures were not explicitly evaluated in this analysis. For those situations in which a traffic control designer were interested in assessing whether a particular countermeasure would be cost-effective for their particular work zone, the tables and graphs provided in the Appendix could be used to compare possible crash cost benefits directly with the costs of a particular countermeasure deployment being considered.

After eliminating several strategies as described, researchers examined the following list of 11 potential countermeasures in this cost-effectiveness assessment (expressed in terms of lowest to highest estimated hourly cost to deploy at a site):

- drone radar devices;
- use of larger channelizing devices;
- closer channelizing device spacing;
- more frequent spacing of transverse channelizing devices in closed lanes;
- temporary transverse rumble strips;
- sequential warning light system;
- speed display trailers;
- flagger replacement devices;
- steel (portable) barrier;
- use of automated traffic control channelizing device set-up and removal technology;
- truck-mounted positive protection systems;
- provision of law enforcement (i.e., COZEEP, MAZEEP); and
- Automated speed enforcement technology.

For these countermeasures, researchers approximated the hourly cost of deployment/use based on available literature, recent bid prices on the CALTRANS or other state DOT websites, or vendor estimates. For many of the intrusion countermeasures evaluated, their potential benefits extend beyond the reduction in intrusion crash potential. Consequently, it was appropriate to consider their total crash cost reduction potential as well as the potential intrusion crash cost reduction potential. These costs were then compared to the hourly crash cost functions described above. Two comparisons were made:

1. At what AADT level would deployment of the countermeasure be offset by the elimination of a reasonable estimate of possible reduction in intrusion crash costs?
2. At what AADT level would the deployment costs of the countermeasure be offset by a reasonable estimate of possible reduction in total crash costs during the particular work zone condition?

In this analysis, what was considered "reasonable" varied based on prior knowledge or expectations of how the countermeasure would affect driver behavior (and, intuitively, safety). For example, the increased use of law enforcement at work zones has been shown in various studies to result in actual crash reductions of 20 percent or more (*41*). However, these crash reductions were computed based on an analysis of the entire duration of the project, and so that reduction value may be very conservative for times when an enforcement vehicle and officer is actually present and visible in the work zone. In another case, the use of speed display trailers has not been evaluated in terms of their potential crash cost reduction benefits. However, operational studies have suggested that they can typically result in small (2-3 mph) reduction in speeds, although larger speed reductions have been observed in some instances (*42*). Recent crash modification analysis suggest that a 2 mph reduction in speeds on a facility typically operating at 70 mph can be expected to reduce injury crashes by approximately 9 percent (*43*). Presumably, some of these crashes are reduced in severity, whereas other crashes are eliminated entirely. In any event, taking these two findings together, researchers estimated (conservatively) that speed display trailers have the potential to reduce total work zone crash costs by up to 5 percent. Intuitively, some of these crashes would be intrusion crashes, but the actual extent to which such crashes would be reduced is unknown.

For other countermeasures, the potential crash cost reduction will come exclusively from a reduction in crash severity. Positive protection devices, such as the truck-mounted barriers or

steel barriers, are an example of these types of countermeasures. Crashes that may have been intrusions into the work area and resulted in severe injuries to workers and motorists are changed to impacts with the protection devices. Although the likelihood of some type of impact is not changed, it is assumed that the redirection of the vehicle from entering the work area will result in less severe injuries (on average) and in less property damage overall.

To simplify the assessment of possible countermeasures, four general levels of crash cost reduction potential were defined:

- **Limited** crash cost reduction potential – countermeasures in this category were expected to be able to reduce up to 33 percent of the intrusion crash costs at a work zone, or 3 percent of the total crash costs;
- **Minor** crash cost reduction potential – countermeasures in this category were expected to be able to reduce intrusion crash costs between 33 and 50 percent, or 5 percent of total crash costs at the work zone;
- **Moderate** crash cost reduction potential – countermeasures in this category were expected to be able to reduce intrusion crash costs by 75 percent, or total crash costs by 10 percent; and
- **Significant** crash cost reduction potential – countermeasures in this category were expected to be able to eliminate all intrusion crash costs, or reduce total crash costs by 25 percent.

Ultimately, none of the countermeasures evaluated were expected to completely eliminate intrusion crash costs. Only a few countermeasures, such as law enforcement presence, were expected to achieve significant reductions in overall crash cost potential. Referring back to the crash cost graphs in the Appendix, the fact that the confidence intervals of the crash cost estimates diverge so much at higher AADT values was also considered by researchers in the assessment. As a result, several possible countermeasures are considered plausible and are suggested for additional consideration at work operations on higher volume work zones, even if the comparison of implementation costs to the average crash cost functions does not strictly warrant a recommendation.

Table 19 summarizes the results of the analyses. From a cost-effectiveness perspective, **drone radar devices** are relatively inexpensive devices to deploy, costing $4 or less per hour of use (assuming the device can be used for at least 100 hours). Even assuming a very limited crash

Table 19. Cost-Effective Assessment of Intrusion Countermeasures.

Countermeasure	Approximate Implementation Cost per Hour per Mile	Expected Crash Cost Reduction	Minimum AADT Levels to be Potentially Cost Effective
Drone radar devices	$4	**Limited** – all crash types when work activities are occurring	Daytime work activities: 10k (all roadway types) Nighttime work activities: 40k (all roadway types)
Use of larger channelizing devices	$2	**Limited –** intrusion crashes at temporary lane closures	Work activities involving temporary lane closures: 10k (all roadway types)
Closer channelizing device spacing	$3	**Limited** – all crash types	Work activities with or without temporary lane closures: 10k (all roadway types) Inactive work zones: 50k (freeways and multilane highways)
Transverse channelizing devices at 750 foot spacing	$1	**Limited –** intrusion crashes where travel lanes are closed	Work activities with temporary lane closures: 3k (all roadway types)
Temporary transverse rumble strips	$10	**Limited** – all crash types	Freeway and multilane facilities: 60k
Sequential warning light system	$20	**Limited** – intrusion crashes due to failure to merge out of closed lane; could possibly increase overall driver awareness and attention slightly	Nighttime work activities with temporary lane closures: 75k (freeways and multilane highways)
Speed display trailers	$2	**Minor** – potential to affect all crash types	All roadway types: 10k
Flagger replacement devices	$2-40	**Limited** – primarily affects crash severity of flagger-involved intrusion crashes	Two-lane highways: 15k
Steel (portable) barrier	$20	**Moderate –** primarily affects intrusion crash severity; potential to affect all intrusion crash types	Daytime work activities: 50k (freeways and multilane highways) Nighttime work activities: 75k (freeways and multilane highways)
Enforcement	$75	**Significant –** potential to affect all types of crashes	Daytime operations: 20k (all roadway types) Nighttime operations : 50k (all roadway types)
Automated traffic control devices set-up and removal technology	$3500	**Minor** – primarily affects intrusion crash severity during TCD set-up and removal.	Difficult to justify based solely on intrusion crash costs
Truck-Mounted Positive Protection	$750	**Moderate** – primarily affects intrusion crash severity; potential to affect all intrusion crash types	Difficult to justify based solely on intrusion crash costs

k = 1000

cost reduction potential, these devices would be justifiable at work zones during periods of daytime work activity (with or without temporary lane closures present) once AADTs reach 10,000 vehicles per day (vpd) on any type of facility (freeways, multi-lane highways, or two-lane highways). During nighttime work operations, AADTs would need to be somewhat higher to be cost-effective (perhaps 40,000 vpd or more). The expectation is that the radar devices would be removed during periods of inactivity at the work zone, so that drivers do not become accustomed to their presence and disregard the signal.

The purpose of using **larger channelizing devices** (i.e., drums instead of cones) is that the larger devices can present a more imposing presence to a lane closure and reduce the potential for vehicles to run into the merging taper or to inadvertently enter into the closed lane once into the actual activity area. It is unlikely that larger devices can have much of an effect on non-intrusion crashes, so the categorization as "limited" effect is based exclusively on intrusion crash cost reduction potential. Based on this characterization, this strategy was also judged to be justifiable at work operations involving temporary lane closures (either day or night) once AADTs reach approximately 10,000 vpd, regardless of the type of roadway. For work operations that do not involve temporary lane closures, it is assumed that larger devices would be used on the shoulder or off of the paved travel surface if necessary anyway, and so there would not offer any incremental benefit.

Similarly, deployment of **channelizing devices at closer spacings** are intended to present a more imposing closure to motorists approaching and passing by a closed section of roadway. It is believed that closer spacing makes it more difficult for those attempting to deliberately intrude into the work area, and merging tapers will be more visually detectable to approaching motorists, reducing the potential for them to run through the taper and into the work activity area. The hourly costs of this strategy are also fairly small, and so can again be justified when work activities are occurring at about 10,000 vpd (day or night) for all roadway types. During periods of work inactivity, though, it appears that this strategy can be cost-effective when AADTs are about 50,000 vpd or higher (and thus more appropriate as a countermeasure on multilane facilities).

As another strategy to help curtail deliberate attempts to use closed travel lanes and/or reduce inadvertent travel in the closed lane, researchers examined the Caltrans procedures regarding the deployment of periodic **transverse channelizing devices or barricades**.

Currently, these devices are used in closed lanes on freeways and expressways every 2000 feet. Researchers examined the cost-effectiveness of decreasing that spacing to 750 feet, which is recommended elsewhere in the literature (*20*). Presently, the incremental cost to reduce the spacing would be less than $1 per hour per mile. At such a small incremental cost, this strategy can be justified at all freeway work zones that involve closed travel lanes, and could be expanded to other types of multilane highways, once AADTs reach 3,000 vpd.

Several agencies have looked at the use of **temporary transverse rumble strips**, installed upstream of work zones (either with or without lane closures) as a way to alert drivers and reduce the crash potential. Given that significant portion of intrusions do appear to be the result of a driver being surprised by a condition in the work zone and either swerving to avoid the hazard or hitting the hazard and then entering the work space, this technology is expected to have some effect on intrusions as well. However, the cost of temporary strips that are adhered to the pavement are fairly significant, estimated at $10 per hour for a one-week work zone (the adhesive strips are not easily reusable at different locations), but would decrease for longer-term work zones. Meanwhile, the strips are assumed to have a limited effect on all types of crash costs at the work zone. Consequently, the use of this technology appears to be justifiable primarily on higher-volume facilities (i.e., 60,000 vpd multilane highways and freeways). Again, as the duration of the work zone increases, the AADT threshold decreases. Also, if future research indicates a higher level of crash cost reduction potential, the AADT threshold would likewise decrease.

The **sequential warning light system** for temporary lane closures has been shown to be detected farther upstream of a nighttime lane closure and positively affect driver behavior. Assuming a reasonable replacement rate of about two or three lights per week to account for periodic hits by merging traffic, the device appears to involve an hourly cost of $20 per hour per mile of work zone (assuming that the system has an influence on safety over an approximate 0.5-mile segment of roadway), and is targeted primarily for nighttime lane closures on freeways and multilane highways. Its effectiveness in terms of crash reductions is assumed to be limited, in that it attempts to reduce those crashes that occur because drivers do not recognize the lane is closed until they are too close to the merging taper. The potential does exist for the technology to increase driver attention somewhat and reduce other types of crashes farther into the work zone, but the magnitude of this effect is not known. For situations where driver awareness and

response to traditional lane closures at night do not appear sufficient (and so the expected crash cost potential at the work zone is likely to be much higher than average), this system may be justifiable at higher AADT levels (i.e., 75,000 or more) at night.

Speed display trailers have been shown to be able to reduce speeds slightly. As discussed above, these devices have been categorized as having minor potential effectiveness in reducing all types of work zone crashes, including intrusion crashes. The device is estimated to have an hourly cost of about $2 per hour, based on current lease prices of these devices. Consequently, their use can be justified on all roadway types at AADTs of 10,000 vpd or higher.

On two-lane highways, intrusion crashes involving flaggers can be very serious. Consequently, **flagging replacement devices** were examined as part of this evaluation. These technologies include the use of automated flagger assistance devices (AFADs) and portable traffic signals. AFADs still require the use of a flagger (albeit removed from the path of approaching vehicles and so with a lower crash risk potential), whereas portable traffic signals operate without constant attention by a worker and so are more appropriate for long-term operations including times when work is not occurring). The estimated effectiveness of these technologies is limited, as they are designed to only address the flagger-involved intrusion crashes at the end locations of alternating one-lane operations on two-lane highways. Costs of these technologies are highly variable, depending on whether they are purchased or leased, their expected service lives, etc. For this analysis, a range of $2-$40 per hour per mile was used (this assumes the average length of the one-way section is one mile long). Based on these assumptions, AFADs at the lower range of the cost range could be justified on two-lane highways once AADTs reach or exceed 15,000 vpd. Systems at the higher end of the range would likely not be justifiable at any AADT level, as the potential crash cost savings would not offset implementation costs. Certainly, the potential does exist for the elimination of one flagger in some locations where a single flagger can control both directions of travel; such an operation would reduce the operating costs of the contractor and reduce the overall implementation cost of the device.

Steel (portable) barrier technology has recently been introduced in the U.S. The technology allows for much quicker installation and removal at projects where protection against vehicle intrusions is most important. The effectiveness of the technology is considered to be moderate, in that it can reduce a significant portion of intrusion crash costs in the vicinity of

workers and equipment operating near moving traffic by reducing the severity of such crashes (the frequency of these types of crashes is assumed to not be affected). Currently, the technology is fairly expensive to obtain, and is estimated to cost approximately $20 per hour per mile (if the technology is able to provide a 10-year service life). Even so, this technology appears to be justifiable on freeways and multilane highways during daytime operations when AADTs exceed 50,000 vpd and nighttime operations for AADTs exceeding 75,000 vpd.

The use of **law enforcement** has been shown to consistently reduce vehicle speeds when located within work zones, and the provision of enforcement in work zones has been associated with a substantial reduction in all types of work zone crashes, including intrusion crashes. A cost value of $75 per hour (which is believed to be the current approximate cost in California) was used in the analysis. The effectiveness of enforcement for crash reduction is estimated to be between 25 and 40 percent. Using these values, the analysis indicates that enforcement use in work zones can be justified on freeways and multilane highways during daytime operations when AADTs are as low as 20,000 vpd and at nighttime operations at AADTs as low as 50,000 vpd. Automated speed enforcement technology may be justifiable at even lower AADTs (due to the ability to offset operating costs with citation revenues), but requires enabling legislation in order to implement.

Automated channelizing device installation and removal technology has been of interest to Caltrans and other highway agencies and contractors in recent years. This technology is viewed positively for its ability to remove workers from the edge of the placement and retrieval vehicle (which presumably reduced the risk of injury to workers should an impact from an approaching vehicle occur or from having the worker fall from the vehicle). There are also potential efficiency savings with some of the technologies by reducing the number of workers required to put out and pick up TCDs. However, the overall effectiveness of the technology is believed to be minor in terms of reducing intrusion crash severity and costs (the frequency of vehicle crashes is assumed to remain the same). Because it affects potential crash costs over a very limited distance, it has a very high estimated hourly cost (assuming a 50-foot influence area for an hour each day over a 10-year service life). Consequently, it is very difficult to justify the use of the technology for vehicle intrusion crash reduction alone. However, the potential for reducing worker backovers and runovers by work equipment may justify its use under much less stringent conditions.

Finally, **truck-mounted barrier technology** has been designed to be driven to a particular worksite and protect workers in very close proximity to traffic in a very limited work space (generally 100 feet or less). Researcher perceive these devices as having moderate effect on intrusion crash costs, dramatically reducing the severity (but not frequency) of those vehicles intruding into the actual work space. Their ability to protect workers on foot is excellent, especially for those operations in extremely close proximity to moving traffic. Unfortunately, these technologies currently have a very high cost at this time (estimated to be equivalent to $750 per hour per mile of protection over a 10-year service life). Consequently, the devices currently are difficult to justify based on the type of crash cost analysis as was done for this report. A longer service life or other operational benefits (one vendor of this type of technology has anecdotal information to suggest that the device can improve traffic flow past the work site and reduce traffic delays slightly) would reduce the AADT threshold accordingly. However, it is likely that agencies making use of this technology will do so primarily with risk reduction to its highway workers on foot as a priority, rather than as a strictly economic decision.

SUMMARY

It is important to again reiterate the limitations of the analyses results presented in this section. Data were very limited in terms of the effectiveness of most countermeasures in crash reductions and so had to be assumed based on engineering judgment. Likewise, cost values for many of the countermeasures were unavailable and had to be assumed (along with service lives) in order to come up with a per-hour, per-mile estimate. Generalized safety performance functions were used for most roadway types, and cost modification factors due to various types of work zone operations under either daytime or nighttime conditions were available only for freeway facilities.

Those limitations notwithstanding, the evaluation indicates that there are several intrusion countermeasure strategies and technologies that appear justifiable from a crash cost reduction perspective. Although some of these countermeasures are justifiable on the basis of total crash cost reduction potential, each is believed to also have the potential to address some or all of the intrusion crash events that occur in work zones. Because they have very low hourly costs associated with them, the following items are the most easily justified:

- use of larger channelizing devices,

- reducing the spacing of transverse barricades or channelizing devices in closed travel lanes, and
- speed display trailers.

The next two items meet cost-effectiveness criteria once traffic volumes reach moderate levels:

- drone radar devices and
- closer spacing of channelizing devices

At still higher traffic volume levels, the following countermeasures can be justified:

- temporary transverse rumble strips,
- sequential warning light systems,
- flagger replacement devices,
- steel (portable) barrier, and
- use of enforcement.

Finally, the following items are more difficult to justify on the basis of their crash cost reduction potential, but may be appropriate for other reasons in certain situations:

- automated TCD placement and retrieval technology, and
- truck-mounted positive protection devices.

Obviously, meeting the justification criteria according the analysis just provided alone is not sufficient to implement any or all of the above proposed countermeasures. The analysis relates implementation costs, which are borne directly by a highway agency such as Caltrans, to user costs that are borne by the motoring public. Although some intrusions undoubtedly involve Caltrans or contractor workers and thus involve additional expenditures by the agency, the majority of crash costs are borne by society as a whole. Agency budgets must ultimately dictate when and where these countermeasures can be implemented. It is likely that many work zones where a countermeasure could be justified based on this analysis cannot be implemented because of a lack of sufficient agency funding.

CHAPTER 5:
CONCLUSIONS AND RECOMMENDATIONS

In this report, researchers documented the efforts undertaken to investigate and categorize the different types of work zone intrusion crashes that occur on California roadways, and to conduct a detailed comparative critique of how each of the various countermeasures available may mitigate those types of work zone intrusions. Researchers used the NYSDOT work zone incident database and telephone surveys of Caltrans and highway contractor personnel in California to gain insights into the frequency, characteristics, and crash sequences that comprise vehicle intrusion crashes at California work zones. Researchers examined the narratives of the various intrusion crashes to try to identify the main categories of crash scenarios that occurred. Prototypical crash sequences were developed around four basic work zone operation categories:

- lane and shoulder closure operations,
- flagging operations,
- mobile operations, and
- traffic control set-up and removal operations.

Within each of these basic work zone situations, several different sequences leading to work zone intrusion crashes were defined. These sequences were differentiated on whether or not the action taken appeared to be a deliberate decision on the part of the driver, then on the primary contributing actions or factors leading to the intrusion. Researchers then identified potential reasons that could have contributed to the occurrence of the work zone intrusion crash sequences and matched possible strategies and technologies that could be deployed to mitigate these crashes. More than 40 possible countermeasures, split between procedural strategies and technology deployments, were identified. These countermeasures were then critiqued based on feasibility and practicality of deployment, and potential for mitigating intrusion crashes. For several of the countermeasures, a cost-effectiveness comparison of implementation costs to crash cost reduction potential was performed.

Based on the assessment of intrusion crash characteristics, the following conclusions can be drawn:

- Intrusion crashes make up a relatively small portion of crashes at work zones (7.5 percent of traffic crashes that occur during daytime work operations, 12.4 percent of traffic crashes during nighttime work operations).
- Although intrusion crashes comprise a greater proportion of nighttime crashes than daytime crashes, most (69.9 percent) intrusion crashes happen during daytime work operations.
- The biggest share (58.7 percent) of vehicle intrusion crashes occurs at lane closure operations. Intrusion crashes also occur at mobile operations, flagging operations, and during traffic control set-up and removal activities, but each of these make up less than 10 percent of the intrusion crashes.
- When intrusions crashes occur, they most often involve collisions with work vehicles/equipment or work materials/debris; only about 17 percent of intrusion crashes involve a collision with a highway worker.
- A significant portion of intrusion crashes are the result of deliberate driver decisions and actions to enter the work area. The relative frequency of such deliberate events differs by type of work operation in place, but ranges from 22 to 63 percent of all intrusion crashes occurring at those types of operations.

Tables 20 and 21 provide a summary of the procedural and technological countermeasures researchers view as viable for addressing work zone intrusion crashes. Several countermeasures, especially those that emphasize increased attention to current procedures or possible expansion of procedures, are fairly low cost to implement. Technological countermeasures, on the other hand, can have fairly significant costs associated with them. Several countermeasures that do involve some costs of implementation were further examined as part of this research. Based on that analysis, the following items are the most easily justified:

- use of larger channelizing devices,
- reducing the spacing of transverse barricades or channelizing devices in closed travel lanes, and
- speed display trailers.

Table 20. Summary of Intrusion Countermeasures for Stationary Operations.

Type of Work Operation	Countermeasure Category	Procedural Strategy
Stationary - Procedural	Low-cost/no-cost to implement (advance planning and policy-setting is key)	• Alter work area access point and internal TCP procedures to prevent truck slow-down in active travel lane • Limit lane closure length to avoid blocking ramp or driveway • Reconfigure construction vehicle access point to minimize impacts to traffic or confuse following drivers • Ensure adequate sight distance to merging and shifting tapers • Ensure use of existing vehicle warning systems (e.g., turn signals, hazard lights, beacons, etc.) • Proper setup and maintenance of TTC • Utilize CMS when available upstream of the work zone to warn drivers
	Moderately low cost (consists of commonly-available signs, devices, or lights)	• Increased use of dual advance signing • Closer or continual spacing of channelizing devices • Enhanced vehicle warning light system • Lane changing restrictions • Larger, more visible channelizing devices • Transverse TCDs • Upstream queue end warning (general warning on static signs)
	Staffing solutions (involve additional personnel or reallocation of personnel)	• Replace flagger with police officer • Use of a flagger at the access point • Downstream spotter • Continuous patrol or monitoring of work zone • Enforcement presence
	Moderate expense	• Improve advance information to drivers through traveler information systems or other means
Stationary - Technology	Moderate expense	• AFADs • Portable traffic signals • Construction entrance signing (dynamic) • "DO NOT FOLLOW" truck-mounted signs • Dynamic speed display trailers • Sequential warning light system (night operations only) • Early merge system • Temporary transverse rumble strips • Upstream queue end warning (real time/dynamic)
	Moderately high expense	• Steel barrier (positive protection)

TCP = Traffic Control Plan; TTC = Temporary Traffic Control; CMS = Changeable Message Sign; TCDs = Traffic Control Devices; AFADs = Automated Flagger Assistance Devices

Table 21. Summary of Intrusion Countermeasures for Mobile Operations or Traffic Control Device Set-up and Removal Activities.

Type of Work Operation	Countermeasure Category	Procedural Strategy
Mobile - Procedural	Low-cost/no-cost to implement (advance planning and policy-setting is key)	• Additional work vehicle positioned on shoulder • Adjust spacing between advance warning vehicle and work convoy as needed to maintain adequate sight distance to work convoy • Follow proper TTC set-up and removal procedures • Utilize messages on truck-mounted CMSs to discourage vehicles from entering work convoy • Utilize messages on truck-mounted CMSs to indicate slow-moving vehicles • Reduce spacing between work vehicles • Utilize CMS when available upstream of the work zone to warn drivers
	Moderately low cost (consists of commonly-available signs (static), devices, or lights)	• Enhanced vehicle warning light system
	Staffing solutions (involve additional personnel or reallocation of personnel)	• Use of enforcement
Mobile – Technology	High expense	• Automated TCD setup & removal technology • Truck mounted positive protection

TTC = Temporary Traffic Control; CMS = Changeable Message Sign; TCDs = Traffic Control Devices

The next two items meet cost-effectiveness criteria once traffic volumes reach moderate levels:

- drone radar devices and
- closer spacing of channelizing devices.

At still higher traffic volume levels, the following countermeasures can be justified:

- temporary transverse rumble strips,
- sequential warning light systems,
- flagger replacement devices,
- steel (portable) barrier, and
- use of enforcement.

Finally, the following items are more difficult to justify on the basis of their crash cost reduction potential, but may be appropriate for other reasons in certain situations:

- automated TCD placement and retrieval technology, and
- truck-mounted positive protection devices.

Guidance on which work zone intrusion countermeasures are the most appropriate for a given set of roadway conditions and planned work activities is provided in Appendix A.

CHAPTER 6:
REFERENCES

1. G.L. Ullman and D.R. Riesland. *Catalog of Work Zone Speed Control Methods*. Research Report FHWA/TX-89/1161-2. Texas Transportation Institute, College Station, Texas, May 1990.
2. Richards, S.H. and C.L. Dudek. Implementation of Work Zone Speed Control Measures. In *Transportation Research Record 1086*. TRB, National Research Council, Washington, DC, 1986, pp. 36-42.
3. Ullman, G.L., S.D. Schrock, M.A. Brewer, P. Sankar, J.E. Bryden, M. Corkran, C.W. Hubbs. *Traffic Enforcement Strategies in Work Zones, Interim Report,* NCHRP Project No. 3-80, June 2006.
4. Blackburn, R.R. and D.T Gilbert. *Photographic Enforcement of Traffic Laws*. NCHRP Synthesis of Highway Practice 219. TRB, National Research Council, Washington, D.C., 1995.
5. Benekohal, R.F., M. Chitturi, A. Hajbabaie, M. Wang, and J.C. Medina. *Automated Speed Photo Enforcement Effects on Speeds in Work Zones*. In *Transportation Research Record 2055*, TRB, National Research Council, Washington, DC, 2008, pp. 11-20.
6. Medina, J.C., R.F. Benekohal, A. Hajbabaie, M. Wang, and M.V. Chitturi. Downstream Effects of Speed Photo-Radar Enforcement and Other Speed Reduction Treatments in Work Zones. In *Transportation Research Record 2107*. TRB, National Research Council, Washington, DC. 2009. pp. 24-33.
7. Ullman, G.L. Effect of Radar Transmissions on Traffic Operations at Highway Work Zones. In *Transportation Research Record 1304*, TRB, National Research Council, Washington, DC, 1991, pp. 261-269.
8. Eckenrode, R.T., W.A. Sarasua, J.H. Mattox III, J.H. Ogle, and M. Chowdhury. Revisiting the Use of Drone Radar to Reduce Speed in Work Zones. In *Transportation Research Record 2015*, TRB, National Research Council, Washington D.C., 2007, pp. 19-27.
9. Standard Plans (U.S. Customary Units). California Department of Transportation, May 2006. Available at http://www.dot.ca.gov/hq/esc/oe/project_plans/highway_plans/stdplans_US-customary-units_06/viewable_pdf/2006-Std-Plns-for-Web.pdf. Accessed January 7, 2009.
10. Meyer, E. *Guidelines for the Application of Removable Rumble Strips*. Report No. K-TRAN: KU-02-3. The University of Kansas, Lawrence, Kansas, August 2006.
11. Andrew, L.B. and J.E. Bryden. *A Work Zone Intrusion Initiative to Reduce Highway Construction Accidents.* Presented at the 80th Annual TRB meeting, January 2001.
12. Morgan, R.L. *Temporary Rumble Strips*. Report FHWA/NY/SR-03/140, New York State Department of Transportation, July 2003.
13. *Intelligent Transportation Systems in Work Zones: A Case Study, Dynamic Lane Merge System Reducing Aggressive Driving and Optimizing Throughput at Work Zones in Michigan*. Report No. FHWA-HOP-04-033, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., October 2004. Available at http://ops.fhwa.dot.gov/wz/technologies/michigan/index.htm. Access December 8, 2009.
14. *ITS Safety and Mobility Solutions: Improving Travel Through America's Work Zones*. American Traffic Safety Services Association, Fredericksburg, Virginia, 2008.

15. Pesti, G., P. Wiles, R.L. Cheu, P. Songchitruksa, J. Shelton, and S. Cooner. *Traffic Control Strategies for Congested Freeways and Work Zones*. Research Report FHWA/TX-08/0-5326-2. Texas Transportation Institute, College Station, Texas, October 2008.
16. McCoy, P.T., J.A. Bonneson, and J.A. Kollbaum. Speed Reduction Effects of Speed Monitoring Displays with Radar in Work Zones on Interstate Highways. In *Transportation Research Record 1509*, TRB, National Research Council, Washington D.C., 1995, pp. 65-72.
17. Fontaine, M.D., P.J. Carlson, and H.G. Hawkins, Jr. *Evaluation of Traffic Control Devices for Rural High-Speed Maintenance Work Zones: Second Year Activities and Final Recommendations*. Report No. FHWA/TX-01/1879-2. Texas Transportation Institute, College Station, Texas, October 2000.
18. Chen, Y., X. Qin, D.A. Noyce, and C. Lee. *Evaluation of Strategies to Manage Speed in Highway Work Zones*. Presented at the 86th Annual TRB meeting, January 2007.
19. Pesti, G. *Alternative Way of Using Speed Trailers: Evaluation of the D-25 Speed Advisory Sign System*. Presented at the 84th Annual Transportation Research Board Meeting, Washington, D.C., January 2005.
20. Bryden, J.E. and D. Mace. *Guidelines for Design and Operation of Nighttime Traffic Control for Highway Maintenance and Construction*. NCHRP Report 476. TRB, National Research Council, Washington, D.C., 2002.
21. *Manual on Uniform Traffic Control Devices for Streets and Highways*. 2003 Edition with Revisions Number 1 and 2 Incorporated. Federal Highway Administration, Washington, D.C., November 2004. Available at http://mutcd.fhwa.dot.gov/. Accessed January 21, 2009.
22. Finley, M.D., G.L. Ullman, and C.L. Dudek. *Work Zone Lane Closure Warning Light System*. Texas Transportation Institute, College Station, Texas, September 1999.
23. Gibbons, R.B., S.E. Lee, B. Williams, and C.C. Miller. *Selection and Application of Warning Lights on Roadway Operations Equipment*. NCHRP Report 624. TRB, National Research Council, Washington D.C., 2008.
24. Evaluation of Temporary Removable Rumble Strips for Speed Reduction 09-1970 McAvoy, D., P.T. Savolainen, V. Reddy, J.B. Santos, and T.K. Datta. Presented at the 88th Annual Transportation Research Board Meeting, January 11-15, 2009, Washington, D.C.
25. Garber, N.J. and S.T. Patel. Control of Vehicle Speeds in Temporary Traffic Control Zones (Work Zones) Using Changeable Message Signs with Radar. In *Transportation Research Record 1509*, TRB, National Research Council, Washington D.C., 1995, pp. 73-81.
26. Wang, C., K.K. Dixon, and D. Jared. Evaluating Speed-Reduction Strategies for Highway Work Zones. In *Transportation Research Record 1824*, TRB, National Research Council, Washington D.C., 2003, pp. 44-53.
27. *Manual on Uniform Traffic Control Devices for Streets and Highways*. 2009 Edition. Federal Highway Administration, Washington, D.C., December 2009. Available at http://mutcd.fhwa.dot.gov/. Accessed December 18,2009.

28. Dudek, C.L. and R. D. Huchingson. *Manual on Real-Time Motorist Information Displays*. Report No. FHWA-IP-86-16. Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., August 1986.
29. Ullman, G.L., B.R. Ullman, C.L. Dudek, and N.D. Trout. *Legibility Distances of Smaller Character Light-Emitting Diode (LED) Dynamic Message Signs for Arterial Roadways*. Texas Transportation Institute, College Station, Texas, July 2004.
30. Ullman, B.R., N.D. Trout, and G.L. Ullman. *Recommended Messages for Truck-Mounted Changeable Message Signs During Mobile Operations.* Report FHWA-WY-09-07F. Texas Transportation Institute, College Station, Texas, November 2009.
31. Finley, M.D., B.R. Ullman, and N.D. Trout. *Traffic Control Devices and Practices to Improve the Safety of Mobile and Short Duration Maintenance Operations*. Report 0-4174-2. Texas Transportation Institute, College Station, Texas, December 2004.
32. Notbohm, T., A. Drakopoulos, and G. Vergou. *Smart Work Zone Deployment Initiative Wisconsin Evaluations: Mobile/Stationary Speed Boards (You/Me Boards) Wisconsin Evaluation*. Summer 2001.
33. Steele, D.A., and W.R. Vavrik. *Improving the Safety of Moving Lane Closures*. Report ICT-09-049. Applied Research Associates, Inc., Champaign, Illinois, June 2009.
34. Ullman, G.L., M.D. Finley, J.E. Bryden, R. Srinivasan, and F.M. Council. *Traffic Safety Evaluation of Nighttime and Daytime Work Zones*. NCHRP Report 627. TRB, National Research Council, Washington, DC, 2008.
35. Lord, D., S.R. Geedipally, B.N. Persaud, S.P. Wasington, I. van Schalkwyk, J.N. Ivan, C. Lyon, and T. Jonsson. *Methodology to Predict the Safety Performance of Rural Multilane Highways*. NCHRP Web-Only Document 126. February 2008. Accessible at http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_w126.pdf.
36. Hughes, W., K. Eccles, D. Harwood, I. Potts, and E. Hauer. *Development of a Highway Safety Manual.* NCHRP Web-Only Document 62. March 2004. Accessible at http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_w62.pdf.
37. Hauer, E., D. W. Harwood, F. M. Council, and M. S. Griffith. Estimating Safety by the Empirical Bayesian Method: A Tutorial. *Transportation Research Record 1784*, Transportation Research Board, National Research Council, Washington, D.C., 2002, pp. 126-131.
38. Hauer, E., and J. GBamfo. Two Tools for Finding what Function Links the Dependent Variable to the Explanatory Variables. In *Proceedings of the ICTCT 1997 Conference*, Lund, Sweden, 1997.
39. F. Council, E. Saloshnja, T. Miller, and B. Persaud. *Crash Cost Estimates by Maximum Police-Reported Injury Severity within Selected Crash Geometries*. Report No. FHWA-HRT-05-051. Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., October 2005.
40. Lord, D. S.R. Geedipally, B.N. Persaud, S.P. Washington, I. van Schalkwyk, J.N. Ivan, C. Lyon, and T. Jonsson. *Methodology to Predict the Safety Performance of Rural Multilane Highways.* NCHRP Web-Only Document 126. TRB, National Research Council, Washington, DC. February 2008.
41. JHK & Associates. *Traffic Safety in Highway Construction Zones "Enhanced Enforcement Services."* Prepared for California Department of Transportation, Sacramento, CA, November 1990.

42. Fontaine, M.D. and P.J. Carlson. Evaluation of Speed Displays and Rumble Strips at Rural Maintenance Work Zones. In *Transportation Research Record 1745*, TRB, National Research Council, Washington, DC, 2001, pp. 627-38.
43. Harkey, D.L., R. Srinivasan, J. Baek, F.M. Council, K. Eccles, N. Lefler, F. Gross, B. Persaud, E. Hauer, and J. Bonneson. *Accident Modification Factors for Traffic Engineering and ITS Improvements*. NCHRP Report 617. TRB, National Research Council, Washington, DC, 2008.

APPENDIX A:
WORK ZONE INTRUSION COUNTERMEASURES IMPLEMENTATION GUIDELINES

INTRODUCTION

Vehicle intrusion crashes in highway work zones injure both vehicle occupants and workers, and so are of concern to both the California Department of Transportation (Caltrans) and highway contractors. Whereas efforts to warn workers of a vehicle intrusion have existed for some time, less consideration has been given to efforts that reduce the frequency of intrusions in the first place. This document provides guidance on which work zone intrusion countermeasures are most appropriate for a given set of roadway conditions and planned work zone activities. The guidance provided herein is based on research conducted under Caltrans Contract 65A0248, *Errant Motorists' Intrusions into Highway Work Zones*. The methodology and results of the analyses conducted to develop this guidance is documented in the final technical report (*1*).

OVERVIEW OF WORK ZONE INTRUSION CRASHES

Based on the results of the New York State Department of Transportation (NYSDOT) database analysis and telephone surveys of Caltrans and highway contractor personnel in California, a number of insights into the frequency, characteristics, and crash sequences that comprise vehicle intrusion crashes at California work zones can be obtained. For example:

- Intrusion crashes make up a relatively small portion of crashes at work zones(7.5 percent of traffic crashes that occur during daytime work operations, 12.4 percent of traffic crashed during nighttime work operations.
- Although intrusion crashes comprise a greater proportion of nighttime crashes than daytime crashes, most of the intrusion crashes that do occur (69.9 percent) happen during daytime work operations.
- The biggest share (58.7 percent) of vehicle intrusion crashes occurs at lane closure operations. Intrusion crashes also occur at mobile operations, flagging operations, and during traffic control set-up and removal activities, but each of these make up less than 10 percent of the intrusion crashes.
- When intrusions crashes occur, they most often involve collisions with work vehicles/equipment or work materials/debris; only about 17 percent of intrusion crashes typically involve a collision with a highway worker.
- A significant portion of intrusion crashes are the result of deliberate driver decisions and actions to enter the work area. The relative frequency of such deliberate events differs by type of work operation in place, but ranges from 22 to 63 percent of all intrusion crashes occurring at those types of operations.

Table 1 shows the main work zone intrusion crash sequences that occur. Mobile operations are activities that move continuously or intermittently along the roadway (including traffic control set-up and removal activities), whereas stationary activities include lane closure and flagging operations. The majority of intrusion crashes in mobile operations occur when a driver fails to recognize the slower speed of the work vehicle, when a driver enters between the work vehicles in a convoy, or when a driver veers out of the travel lane onto the shoulder where work is occurring. Similarly, almost one-fourth of intrusion crashes in stationary operations occur when a driver fails to recognize slowed or stopped traffic upstream or within a lane

closure. In addition, a large portion of intrusion crashes in stationary operations can be attributed to drivers deliberately choosing to enter the close lane and impaired drivers.

Table 1. Work Zone Intrusion Crash Sequences for Mobile and Stationary Operations.

Type of Work Operation	Work Zone Intrusion Crash Sequence (Percent of Category)
Mobile	Driver fails to recognize slower speed of work vehicle and strikes work vehicle (29.4%)
	Driver enters between work vehicles in a convoy and strikes worker or work vehicle (23.5%)
	Driver veers out of travel lane and strikes worker or work vehicle on shoulder (23.5%)
	Driver attempts to pass work vehicle on shoulder (5.9%)
	Driver loses control and strikes worker or work vehicle in lane (5.9%)
	Driver swerves into work convoy to avoid impacting rear-end collision adjacent to work convoy (5.9%)
	Driver strikes traffic control device, which then flies into work area and strikes worker (5.9%)
Stationary	Driver deliberately decides to enter the closed lane (27.0%)
	Driver fails to recognize slowed or stopped traffic, collision or collision avoidance results in driver entering the closed lane (23.3%)
	Impaired driver enters closed lane (17.6%)
	Driver loses control and enters closed lane (7.5%)
	Driver fails to recognize lane closure and enters taper and buffer space (6.9%)
	Driver enters closed lane due to improper setup of channelizing devices (4.4%)
	Lane change by adjacent driver forces another driver into the closed lane (3.8%)
	Driver follows work vehicle into work area (3.8%)
	Driver swerves to avoid debris and enters closed lane (1.9%)
	Driver uncertain of correct travel path or believes closed lane is open and inadvertently enters the closed lane (1.9%)
	Drivers enters the roadway in the wrong direction and enters closed lane at the downstream end (1.9%)

WORK ZONE INTRUSION COUNTERMEASURE IMPLEMENTATION GUIDELINES

Based on the above assessment of intrusion crash sequences and (in some cases) underlying causes, a comprehensive list of work zone intrusion countermeasures was developed that are most appropriate for a given set of roadway conditions and planned work zone activities. The guidance is divided into two parts: one that addresses procedural countermeasures and one that focuses on technology countermeasures. Procedural countermeasures are techniques that are generally accepted as good practice. Most of these strategies do not require significant additional expenditures or other agency/contractor resources, and so should be implemented as part of normal traffic control activities. The purpose of mentioning them in this document is to emphasize their importance in reducing intrusion crash potential, as the data suggests that many intrusion crashes can be attributed to not following accepted procedures and protocols. Meanwhile, technology countermeasures are innovative devices that can be used to reduce the frequency of work zone intrusion crashes; however, the additional cost and practicality of implementation must be considered.

For those procedural and technology countermeasures for which typical implementation costs and data regarding the potential incremental benefit of the countermeasure could be identified (or a reasonable assumption made), researchers conducted an analysis to determine the conditions for which the countermeasure would be most cost-effective. This analysis was based on typical crash frequencies (total crashes and intrusion crashes depending on the expected effectiveness of the countermeasure), crash costs, and expected crash reduction (frequency and severity) for various roadway types and average annual daily traffic (AADT) levels. Additional information about the crash cost reduction analysis can be found in Chapter 4 of the final technical report (*1*).

Procedural Countermeasures

This section contains brief descriptions and application criteria (where available) for the following procedural countermeasures:

- follow proper temporary traffic control set-up and removal procedures;
- continually monitor open travel lanes and traffic control devices while the work zone is in place**;**
- ensure that work vehicle warning lights are used when appropriate (e.g., turn signals, hazard lights, beacons, etc.);
- consider working at night or on weekends;
- provide law enforcement (i.e., COZEEP, MAZEEP);
- use effective messages on truck-mounted changeable message signs (CMSs) during mobile operations;
- use advance warning vehicle to warn drivers about work convoy around horizontal curves and at crest vertical curves;
- maintain close spacing between work vehicles in convoy;
- use additional work vehicle on shoulder;
- provide a work vehicle in front of workers on foot;
- ensure adequate sight distance to lane closure taper;

- use dual advanced signing in advance of lane closures;
- use overhead CMSs to warn drivers of upcoming or current work zone conditions;
- use larger channelizing devices;
- provide advance notice of work activity, alternate routes, closure location, and closure duration;
- use closer-spaced or continual traffic control devices;
- use transverse traffic control devices;
- limit the length of lane closures to avoid blocking ramps or driveways;
- implement lane change restrictions;
- reconfigure work area access point;
- alter internal traffic control procedures to prevent truck slow-down in active travel lane; and
- use a downstream spotter.

Some of these countermeasures are applicable to all work zones, while others are only applicable to either mobile or stationary operations. While most of these countermeasures are generally accepted as good practice and may even be currently used by Caltrans, data suggests that many intrusion crashes can be attributed to not following accepted procedures and protocols. Thus, these procedural strategies are discussed in this guidance document to emphasize their importance in reducing intrusion crash potential.

Most of these strategies do not require significant additional expenditures or other agency/contractor resources, and so should be implemented as part of normal traffic control activities. For a few of the procedural countermeasures, researchers were able to determine conditions for which the countermeasure would be most cost-effective.

Following Proper Traffic Control Device Set-Up and Removal Procedures

The intrusion data indicate that drivers can become confused by temporary traffic control that is only partially set or is being changed as they pass by and inadvertently move into a closed travel lane or work activity area. To avoid driver confusion, proper temporary traffic control set-up and removal procedures should be followed at all times. Periodic reviews of traffic control crews should be made to ensure that they are adhering to established protocols, such as:

- putting out advance warning signs first,
- not running across travel lanes to put out signs, and
- picking up channelizing devices in reverse order of installation.

Continually Monitoring Open Travel Lanes and Traffic Control Devices

In a small number of the lane closure intrusion crashes, debris in the open travel lane caused drivers to swerve into the closed lane. In addition, careless placement or movement of a traffic control device into an open lane can also lead to errant motorist behavior and intrusion into a closed travel lane. Therefore continuous patrolling and monitoring of the work zone should occur to ensure that debris or other road conditions do not present hazards for passing motorists.

Ensure That Work Vehicle Warning Lights are Used When Appropriate

Some intrusion crashes result from drivers following a work vehicle into the work area. Emphasis should be placed on work vehicle operators to following standard operational procedures when entering work areas and use turn signals, hazard lights, and beacons to provide additional information for drivers to anticipate the upcoming maneuvers of the work vehicle. Failure to activate these devices for this purpose invites indecision and confusion by motorists. In cases where the hazard lights and beacons are already activated because the vehicle is traveling slowly, activation of the turn signal is even more important.

Consider Working at Night or On Weekends

Over 50 percent of all intrusion crashes occurred because a driver failed to recognize slowed or stopped traffic within or upstream of a lane closure or the slow speed of a mobile work convoy. When possible, the schedule of work should be reviewed to determine if the work can be performed at night and/or over weekend periods when traffic volumes may be lower and such slowdowns are less likely. The following National Cooperative Highway Research Program (NCHRP) documents are useful resources to review when considering night work:

- NCHRP Report 475: A Procedure for Assessing and Planning Nighttime Highway Construction and Maintenance (*2*);
- NCHRP Report 476: Guidelines for Design and Operation of Nighttime Traffic Control for Highway Maintenance and Construction (*3*); and
- NCHRP Report 627: Traffic Safety Evaluation of Nighttime and Daytime Work Zones (*4*).

Provide Law Enforcement

The provision of enforcement has been shown to consistently reduce vehicle speeds when located within work zones, and the provision of enforcement in work zones has been associated with a substantial (20 percent or more) reduction in all types of work zone crashes. It is expected that enforcement can likewise reduce the likelihood of intrusion crashes. Although enforcement use does involve a fairly substantial hourly cost to the highway agency, the benefits appear to outweigh costs once traffic volumes reach moderate levels. Based strictly on an expected crash cost reduction (*1*), enforcement use in work zones can be justified on freeways and divided multilane highways during daytime operations when the AADT exceeds 20,000 vehicles per day (vpd) and at nighttime operations when the AADT exceeds 50,000 vpd. Because enforcement can also provide other types of benefits not included explicitly in these computations, its use at even lower traffic volume levels may be justifiable in some instances.

Use Effective Messages on Truck-Mounted Changeable Message Signs during Mobile Operations

Maintenance work is often accomplished using mobile operations which consist of one or more vehicles that move along the road intermittently or continuously at very slow speeds relative to the normal traffic stream. Even though Caltrans currently uses an advance warning vehicle, shadow vehicle, and in some instances truck-mounted CMSs (all of which are considered intrusion countermeasures) (*5*), 20 percent of the work zone intrusions in California

occur in mobile operations. These intrusions typically involve vehicles which strike the truck-mounted attenuator (TMA) on the back of the shadow vehicle (i.e., the first work vehicle encountered by drivers) or drivers pulling between the work vehicles (i.e., entering the work convoy).

Truck-mounted CMSs have superior target value and thus possibly provide more advance warning time to drivers than static signing. However, the amount and order of information presented, the legibility distance of the message, and the content of the message all impact the effectiveness of these devices. Even though Caltrans currently uses truck-mounted CMSs, the messages displayed may not be optimum for warning drivers that they are approaching a slow moving work convoy (driver misjudgment of the work vehicle's slower speed appeared to be responsible for approximately 30 percent of the mobile operation intrusions) or for discouraging drivers from entering between the work vehicles (approximately 25 percent of the mobile operation intrusions were of this type). The following principles should be followed when designing and displaying messages on truck-mounted CMSs:

- The character heights typically used on truck-mounted CMS only provide enough sight distance to allow 2 units-of-information (or phrases) to be displayed in a message.
- For most applications, the two critical units that should be displayed on a truck-mounted CMS are a problem/roadwork descriptor and an action statement.
- A message cannot contain more than 2 phases.
- Message elements should not flash or scroll.
- Abbreviations should be used when necessary to keep the message to two phases, and should be used in accordance with accepted practices.

Specific recommended messages for use on truck-mounted CMSs during mobile operations are shown in Table 2 (*6*). These messages are defined by the type of work, road type, and identified concerns being addressed by the message.

Use Advance Warning Vehicle to Warn Drivers about Work Convoy around Horizontal Curves and at Crest Vertical Curves

When used, the advance warning vehicle needs to be located far enough upstream of the shadow vehicle to allow drivers time to complete the necessary actions prior to encountering the work convoy. In mountainous and rolling terrain locations where there is limited sight distance, it is important that the driver of the advance warning vehicle continually monitor the spacing to the convoy. The advance warning vehicle should lag back around horizontal curves and at the peak of a crest vertical curve until the work convoy progresses far enough down the roadway that drivers have adequate sight distance of the convoy once they top the hill. The advance warning vehicle can then proceed quickly down the curve to catch up with the convoy.

Table 2. Recommended Messages For Use on Truck-Mounted CMS During Mobile Operations.

Operation	Road Type	Primary Concern	Phase 1 [a,b]	Phase 2 [b]
Striping	2-Lane, 2-Way	Convoy Recognition	# PAINT TRUCKS	DO NOT CUT IN
		Convoy Recognition & Tracking Paint	# PAINT TRUCKS	YELLOW [*or WHITE*] LINE WET
		Tracking Paint	YELLOW [*or WHITE*] LINE WET	DO NOT CUT IN
	Multi-lane	Convoy Recognition	# PAINT TRUCKS	DO NOT CUT IN
		Convoy & Passing Maneuver	# PAINT TRUCKS	STAY IN LFT [*or RGT*] LANE
		Tracking Paint	# PAINT TRUCKS	CNTRLINE [*or EDGELINE*] WET
Sweeping	2-lane, 2-way or Multi-lane	Debris/Dust Obstructing Vision	SWEEPING AHEAD	REDUCED VISION
	Multi-lane	Lane Encroachment	SWEEPING AHEAD	STAY IN LFT [*or RGT*] LANE
Workers Out of Vehicle	2-lane, 2-way or Multi-lane	Protection of Workers	# WORK TRUCKS	WATCH FOR WORKERS
		Reducing Vehicles Entering Convoy as Protection.	# WORK TRUCKS	DO NOT CUT IN

[a] Where there is a # symbol, the appropriate number of trucks that are present in the convoy should be inserted.
[b] Items in italics are alternatives to be used in place of other similar descriptors shown in the message. For example, "Yellow" could be interchanged with "White."

Maintain Close Spacing between Work Vehicles in Convoy

Similar to the previous statement, it is important that the distance between the work vehicles within the work convoy be minimized to the extent allowed by the work operation in order to deter drivers from pulling between the work vehicles. Of course, protection vehicles (with or without TMAs) must maintain a minimum distance upstream of the next work vehicle to account for the roll-ahead movement that occurs when impacted.

Use Additional Work Vehicle on Shoulder

In some instances, drivers deliberately attempt to pass a work vehicle or convoy on the shoulder. To reduce the likelihood of this occurring, another work vehicle can be used on the shoulder to discourage this behavior. If this technique is used, drivers of all work vehicles should decide beforehand how any shoulder discontinuities will be handled, agreeing on when and where the shoulder vehicle will move into the travel lane and then back over to the shoulder.

Provide a Work Vehicle in Front of Workers on Foot

In mobile operations, workers may be on foot in front of a work vehicle for crack sealing, pothole patching, etc. Unfortunately, traffic typically returns to the closed lane at very short

distance beyond the perceived end of the work area. An effective way to extend the work area length in front of workers on foot is to add another work vehicle downstream just past the work crew. The work vehicle should be immediately in front of the workers, and the shadow vehicle should stay back just far enough to provide sufficient roll-ahead distance before reaching the workers. If these vehicles are properly spaced, the distance between the shadow and lead vehicles would be small enough to discourage a passing vehicle from moving into the work area, yet would be long enough to keep the shadow vehicle from running into the workers should an approaching vehicle strike the back of the shadow vehicle.

Ensure Adequate Sight Distance to the Lane Closure Taper

As part of the initial patrol through the work zone, sight distance to the lane closure taper should be checked using speeds at which vehicles normally travel on that roadway. Early detection of sight distance issues may prevent intrusions, particularly where traffic control devices may simply be extended beyond upstream horizontal or vertical curvature. The amount of sight distance should always exceed the stopping sight distance for the facility. However, on higher-volume roadways, it is desirable to provide more than this amount to allow extra time for vehicles in the closed lane to find suitable gaps in the open lane traffic stream before reaching the merging taper.

Use Dual Advanced Signing in Advance of Lane Closures

Currently, Caltrans requires dual advance warning signing (i.e., warning signs on both sides of the roadway) for lane closures on freeways and expressways when less than half of the available lanes remain open to traffic (i.e., going from three lanes to one lane open) (*5*). However, dual advance warning signing may also be useful under less restrictive conditions, as it can provide a better opportunity for drivers in the left lane to see advance warning signs that might otherwise be blocked from their view by traffic in the right lane, particularly on a roadway with higher volumes of truck traffic. In addition, dual signing notifies drivers in the open travel lanes of the lane closure in hopes that they will remain in the open travel lanes and not enter the closed lane upstream of the lane closure.

Use Overhead CMSs to Warn Drivers of Upcoming or Current Work Zone Conditions

Overhead CMSs, which are more likely to be visible from all traffic lanes, should be used whenever available upstream of a work zone to warn drivers of upcoming or current conditions. Field personnel should make sure that the transportation management center (TMC) operators who have responsibility for the CMS are aware of the work zone and have whatever information needed (e.g., which lane is closed, how long the work zone will be in place, etc.) to create and display a useful, effective message for approaching motorists.

Use Larger Channelizing Devices

The purpose of using larger channelizing devices (i.e., drums instead of cones) is that the larger devices can present a more imposing appearance at a lane closure and reduce the potential for vehicles to run into the merging taper or to inadvertently enter into the closed lane once into the actual activity area. This strategy does appear to be justifiable at work operations involving temporary lane closures (either day or night) once the AADT reaches approximately 10,000 vpd,

regardless of the type of roadway. For work operations that do not involve temporary lane closures, it is assumed that larger devices would be used on the shoulder or off of the paved travel surface, if necessary, and so there would not be any incremental benefit.

Provide Advance Notice of Work Activity, Alternate Routes, Closure Location, and Closure Duration

Unfortunately, a substantial proportion of drivers deliberately choose to enter a closed lane or ignore a flagger's instruction to stop, which leads to 27 percent of the intrusion crashes that occur. It is hypothesized that many of these drivers make such decisions because they are in a hurry or are unaware of how they should reach their intended destination (an exit, intersection, or driveway). Providing advance notification of lane closures, detours, alternative routes, etc. via overhead CMS, portable changeable message signs (PCMSs), highway advisory radio (HAR), or other media will allow drivers to make more informed decisions (e.g., take an alternate route, avoid roadway during lane closure times, etc.) and thus potentially reduce work zone intrusions. If no alternate routes are available, information regarding the lane closure duration and location can still be provided to prepare the driver about the change in travel patterns that will be required.

Use Closer-Spaced or Continual Traffic Control Devices

Closer spacing of traffic control devices than is currently required is intended to present a more imposing closure to motorists approaching and passing by a closed section of roadway. It is believed that closer spacing makes it more difficult for those attempting to deliberately intrude into the work area and makes the merging taper more visually detectable to approaching motorists, reducing the potential for drivers to pass through the taper and into the work activity area. The hourly costs of this strategy are fairly small, and so can be justified when work activities are occurring on all types of roadways with about 10,000 vpd (day or night). During periods of work inactivity, it appears that this strategy can also be cost-effective when the AADT is about 50,000 vpd or higher (and thus more appropriate as a countermeasure on multilane facilities).

In locations where deliberate intrusions into the lane closure are unusually high, it may be desired to provide continuous delineation (i.e., no spacing between traffic control devices). This may be accomplished with longitudinal channelizing devices (LCDs), which can be connected together to form a solid line of traffic control devices. While LCDs look similar to water-filled barrier, they do not provide positive protection. As would be expected, it will be more expensive to create a wall using LCDs, so they are most appropriate for conditions in which a substantial intrusion problem is occurring or anticipated (such as when a high-volume exit ramp may be temporarily closed during a paving operation or maintenance activity, for example).

Use Transverse Traffic Control Devices

Another strategy to help curtail deliberate attempts to use closed travel lanes and/or reduce inadvertent travel in the closed lane is the use of periodic transverse channelizing devices or barricades (*5*). Currently, Caltrans procedures are to use these devices in closed lanes on freeways and expressways every 2000 feet. Researchers examined the cost-effectiveness of decreasing that spacing to 750 feet, which is recommended elsewhere in the literature (*3*).

Presently, the incremental cost to reduce the spacing would be less than $1.00 per hour per mile. At such a small incremental cost, this strategy can be justified at all freeway work zones that involved closed travel lanes, and could be expanded to other types of multilane highways, once the AADT reaches 3,000 vpd.

Limit the Length of Lane Closures to Avoid Blocking Ramps or Driveways

When feasible, the length of a lane closure should be as short as feasible in order to reduce delay and decrease the number of access points blocked, thereby reducing the need for drivers to deliberately enter the lane closure.

Implement Lane Change Restrictions

A small portion of the lane closure intrusion events can be attributed to vehicle conflicts that occur when vehicles change lanes adjacent to the closed lane, and force the vehicle next to the closed lane into the work area. In locations where more than one travel lane remains open, lane changing restrictions (i.e., not allowing vehicles to change lanes while traveling through the work zone) should be used to reduce vehicle conflicts and thus potentially decrease the chance of an intrusion.

Reconfigure Work Area Access Point

Typically, work area access points are short openings with little or no area for trucks to decelerate or accelerate. Therefore, drivers sometimes fail to recognize the slow speed of work vehicles trying to enter or exit the work area, and are forced to swerve into the work area to avoid a collision. In addition, drivers occasionally follow the trucks into the work area on purpose, failing to recognize that they are following a work vehicle off of the travel lanes. In some of these situations, it may be that the work area access points are located such that they appear to be a continuation of the expected travel path. Reconfiguring the access point to make it more apparent that the construction entrance is not the intended travel path should be considered in order to reduce the chance that drivers will inadvertently follow the work trucks into the work area.

Alter Internal Traffic Control Procedures to Prevent Truck Slow-Down in Active Travel Lane

In addition to reconfiguring the access point, it may be possible to alter the internal traffic control plan procedures (i.e., the coordination of the flow of construction vehicles, equipment, and workers), to allow work trucks to enter and exit the work area at higher speeds; thus, alleviating the need for them to decelerate and accelerate in an active travel lane.

Use a Downstream Spotter

Occasionally, drivers enter the roadway going in the wrong direction and enter the closed lane from the downstream end. This can especially be problematic in work activity areas located near entrance or exit ramps. Detection of this type of event by a downstream spotter (i.e., a worker that understands the potential for this type of intrusion event and can keep a look out for its occurrence) may enhance worker safety. Although the intrusion may not be prevented, the

spotter may be able to provide a warning to other workers or possibly stop the intruding vehicle before any injuries occur.

Technologies

In addition to the procedural strategies previously discussed, technologies can be used to further reduce the frequency work zone intrusion crashes. For each of the following technologies, researchers developed guidance sheets that provide a brief description of each technology, its effectiveness (if known), general cost information, application criteria, and other considerations:

- automated traffic control device set-up and removal technology,
- drone radar devices,
- flagger replacement devices,
- sequential warning light system,
- speed display trailers,
- steel (portable) barrier,
- temporary transverse rumble strips,
- truck-mounted positive protection systems,
- construction entrance signing,
- "DO NOT FOLLOW" signing,
- early merge system,
- upstream queue end warning, and
- automated speed enforcement technology.

For the first eight of these technology countermeasures, researchers were able to determine conditions for which the countermeasure would be most cost-effective. Unfortunately, some of the technology countermeasures cannot easily be justified on the basis of their crash cost reduction potential. However, the following limitations of the analysis must be considered.

- Data were very limited in terms of the effectiveness of most countermeasures in crash reductions and so had to be assumed based on engineering judgment.
- Cost values for many of the countermeasures were unavailable and had to be assumed (along with service lives) in order to come up with a per-hour, per-mile estimate.

Considering these limitations and the fact that these technologies may be appropriate for other reasons in certain situations (e.g., work zones where a higher frequency of intrusion crashes are expected to occur or are occurring), researchers included them in this guidance document.

Due to highly variable implementation costs and lack of adequate data regarding the potential incremental benefit of the countermeasure, researchers could not assess the conditions for which the last five technology countermeasures would be most cost-effective. Thus, general application criteria are discussed.

AUTOMATED TRAFFIC CONTROL DEVICE SET-UP AND REMOVAL TECHNOLOGY

Description:
The use of automated traffic control device set-up and removal equipment keeps workers from standing in the active travel lane during these operations or from leaning out over the work vehicle to place or pickup devices. Although a driver may still strike the automated vehicle in the active travel lane, the risk of injury and injury severity could potentially be reduced by having the worker off the pavement. The automated cone-setting truck concept was initially developed in California, and Caltrans is currently using cone-setting trucks on a limited basis.

Effectiveness:
Automated traffic control device technology is viewed positively since it does prevent workers from being on foot during traffic control device set-up and removal. There also might be potential efficiency savings with some of the technologies by reducing the number of workers required to put out and pick up traffic control devices. Overall, the effectiveness of the technology is believed to be minor in terms of reducing intrusion crash severity and costs (the frequency of vehicle crashes is assumed to remain the same).

Cost:
The cost to purchase a cone-setting truck ranges from $36,000 to $110,000 for the vehicle and machine. Recognizing that this technology is used for only a limited (i.e., 15 minutes or less) amount of time at the beginning and again at the end of a work shift, researchers estimated the pro-rated cost of its use during set up and take down to be equivalent to about $3500 per hour.

Suggested criteria:
Based on an intrusion crash cost reduction analysis, it is difficult to justify the use of automated traffic control device technology on can be justified under any conditions. However, the potential for reducing worker backovers and runovers by work equipment may justify its use under highest-risk working conditions.

Other considerations:
- Maintenance costs also need to be considered in decisions whether to use this technology.
- Potential for worker(s) to be ejected from automated vehicle if the vehicle is struck should be evaluated.

DRONE RADAR

Description:

Drone radar devices emit radio signals that activate radar detectors used by the traveling public. Therefore, drone radar can be used to imply the presence of enforcement in the work zone area. These devices are commercially available and are typically mounted on work vehicles, arrow panels, or changeable message signs.

Effectiveness:

Drone radar reduces the number of vehicles traveling at excessive speeds (i.e., 10 mph or more over the speed limit) by 6 to 33 percent. However, drone radar only typically reduces mean vehicle speeds by 2 to 3 mph. This device may also effectively alert drivers to an upcoming change in the highway environment when their radar detector is activated.

Cost:

Drone radar devices cost approximately $400 per unit. Solar power units can be purchased for an additional cost.

Suggested Criteria:

Based on a crash cost reduction analysis, drone radar devices are justifiable at work zones during periods of daytime work activity (with or without temporary lane closures present) once the average annual daily traffic reaches 10,000 vehicles per day. During nighttime work operations, the average annual daily traffic needs to be somewhat higher to be cost-effective (e.g., 40,000 vehicles per day).

Other considerations:

- Drone radar devices should be removed during periods of inactivity at the work zone, so that drivers do not become accustomed to their presence and disregard the signal.

FLAGGER REPLACEMENT DEVICES

Description:
In lieu of a flagger, several devices can be used to control the right-of-way when a lane closure is needed on a two-lane, two-way road. Automated flagger assistance devices (AFADs) are portable traffic control systems designed to be operated by a flagger located off the roadway. There are two types of AFADs. One type uses a remotely controlled STOP/SLOW sign to control the right-of-way, while the other type utilizes remotely controlled red and yellow lenses and a gate arm to control right-of-way.

Portable traffic signals are traffic signals mounted on trailers that can be used to control the right-of-way in a work zone. Communications between the signals are provided by hard wiring, radio frequency transceiver, or by preset timing. Thus, portable traffic signals can actually replace flaggers; thereby, removing flaggers from direct exposure to approaching traffic and allowing flaggers to perform other critical work tasks.

Effectiveness:
AFADs allow flaggers to be positioned off the roadway away from moving traffic; thereby, reducing the likelihood of a flagger getting struck by a vehicle. AFADs might also increase the sight distance to the lane closure. However, there are concerns that AFADs may confuse drivers or garner less respect and thus result in decreased compliance.

Replacing flaggers with portable traffic signals is expected to eliminate crashes where vehicles strike flaggers and improve the efficiency of the operation. Appropriate timing is critical to the success of portable traffic signals. Excessive wait time can lead to driver confusion and frustration, possibly resulting in decreased compliance.

Cost:
An AFAD costs between $7500 and $13,500 (dependent upon system type). A portable traffic signal costs between $28,000 and $80,000 (dependent upon system type and additional components desired).

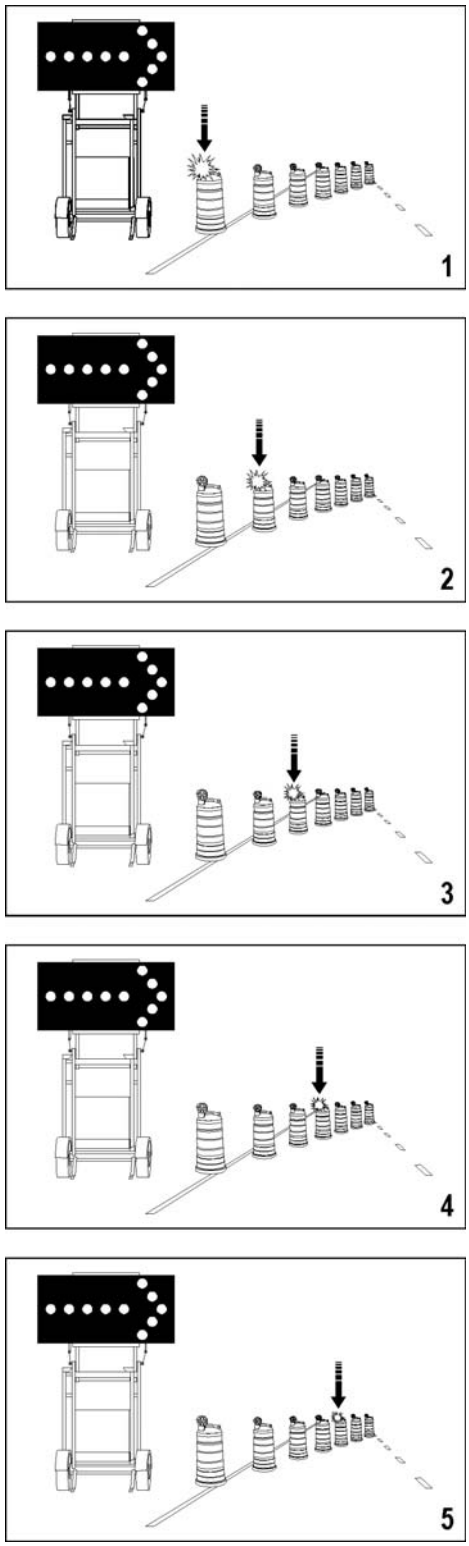
Selection criteria:
These two technologies would be expected to address only the flagger-involved intrusion crashes at the end locations of alternating one-lane operations on two-lane highways. In addition, costs of these technologies can be fairly high. Certainly, the use of portable traffic signals at many locations is based on reduced flagger labor costs to continuously staff a work zone for many days, and so its potential as an intrusion crash countermeasure is a secondary benefit. For AFADs, however, safety is a primary decision criteria (although some locations may be effectively operated by two AFADs and a single flagger positioned to see both ends of the work zone). Those considering the use of AFADs should consult the discussion in the technical report (*1*) about assessing implementation costs and comparing that value to the potential crash cost reduction that could be achieved. At the low range of costs for such devices, it does appear that they can be justifiable once AADTs reach about 15,000 vpd.

Other considerations:

- AFADs are included in the recently released *2009 Manual on Uniform Traffic Control Devices* (MUTCD).
- AFADs shall only be used in situations where there is only one lane of approaching traffic in the direction to be controlled.
- AFADs should not be used for long-term stationary work.
- AFADs must be operated by a qualified flagger and the flagger operating the AFAD cannot leave the AFAD unattended at any time while the AFAD is controlling the right-of-way. However, AFADs can be remotely operated either by a single flagger, at one end of the lane closure or at a central location, or by two flaggers, one near each device's location.
- Portable traffic signals are appropriate for use in longer term work zones, as well as some short-term operations.
- If a portable traffic signal malfunctions and switches to flashing red operation, drivers must be able to see whether there is another vehicle on the opposite approach.

SEQUENTIAL WARNING LIGHT SYSTEM

Description:
Lane closures require drivers to physically move out of a closed lane; thus, it is important to positively indicate the direction the driver should travel, especially at night when visibility is reduced and lane closures may not be expected. A sequential warning light system is comprised of a series of individual flashing warning lights that are attached to channelizing drums in the merging taper. The lights are synchronized to produce the perception of a light that repeatedly "moves" in a sequential manner from the beginning to the end of the merging.



Effectiveness:
Field studies at a nighttime work zone in Texas resulted in a 7 percent reduction in the number of passenger vehicles and a 12 percent reduction in the number of commercial vehicles in the closed lane 1000 ft upstream of the lane closure when the sequential warning light system was used. However, its effectiveness in terms of crash reductions is assumed to be limited, in that it attempts to reduce those crashes that occur because drivers do not recognize the lane is closed until they are too close to the merging taper. The potential does exist for the technology to increase driver attention somewhat and reduce other types of crashes farther into the work zone, but the potential for this to occur is not known.

Cost:
Each individual warning light costs approximately $150, so it would cost about $2000 to implement the system in a merging taper designed for 60 mph (13 lights). Batteries may be an additional cost.

Selection criteria:
Based on the device's limited potential effectiveness, coupled with a fairly high hourly cost, implies that this technology could currently be justifiable only on higher volume facilities (i.e., AADTs of 75,000 or more) at night.

Other considerations:

- Language allowing the use of sequential warning light systems was included in the recently released *2009 Manual on Uniform Traffic Control Devices* (MUTCD).

SPEED DISPLAY TRAILERS

Description:
Speed displays are dynamic message signs that use radar to measure and record the speed of approaching vehicles. The measured speed and speed limit are then displayed to passing drivers in an effort to decrease speeds and increase compliance with the work zone speed limit. Speed displays mounted on trailers are portable and thus can be deployed at any roadside location that provides sufficient room.

Effectiveness:
Speed display trailers have been shown to reduce speeds by 2 to 10 mph and decrease the percent of vehicles exceeding the speed limit. These devices may also alert drivers to an upcoming change in the highway environment. However, minor potential effectiveness in reducing all types of work zone crashes, including intrusion crashes is expected.

Speed display trailers are more effective at locations where the sign supports a clear and real need for a driver to reduce their speed or where the perception of regular enforcement exists. The effect of speed display trailers over time (especially if left at a location continuously and not enforced) is uncertain but believed to diminish as drivers become more accustomed to their presence in the work zone.

Cost:
Speed display trailers cost between $5500 and $20,000 (dependent upon the type of technology used and additional components desired) and can be leased for approximately $50 a week.

Selected criteria:
Based on a crash cost reduction analysis, speed display trailers can be justified on most types of roadways once traffic demands reach 10,000 vehicles per day or higher.

Other considerations:
- When used, a plan should be established for moving the speed display trailers on a regular basis in order to keep them from losing their effectiveness over time.
- As roadways get wider, the angle at which vehicle speeds are being measured by the sign increases which introduces a measurement error into the system. In extreme cases, the reported speed on the trailer can be several miles an hour slower than the actual speed of the vehicle. Roadways with high traffic volumes are not particularly useful for speed display trailers, as there are too many vehicles in the range of the radar at any one time to establish a clear speed measurement. This results in erratic sign operation and a loss of effectiveness.

STEEL (PORTABLE) BARRIER

Description:

Many work activities are short-term and so cannot practically be protected by temporary concrete 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.

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.

Effectiveness:

To date, steel barrier has not been extensively deployed. Consequently, its effectiveness and practicality have not been verified. However, moderate effectiveness is expected since it can reduce a significant portion of intrusion crash costs in the vicinity of workers and equipment operating near moving traffic by reducing the severity of such crashes (the frequency of these types of crashes is assumed to not be affected).

Cost:

Portable steel barriers cost approximately $180 per foot.

Selection criteria:

Based on a crash cost reduction analysis, steel barrier may be justifiable on freeways and multilane highways during daytime operations when the average annual daily traffic exceeds 50,000 vehicles per day and during nighttime operations for average annual daily traffic levels exceeding 75,000 vehicles per day. As prices for the product decrease, the minimum AADT level required would likewise decrease.

Other considerations:

- 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.

TEMPORARY TRANSVERSE RUMBLE STRIPS

Description:
Temporary transverse rumble strips can be used to alert drivers that they are approaching a work zone by generating audible and tactile warnings. They are typically used in long-term maintenance work zones. Most rumble strips adhere to the pavement surface and are often placed in an array of several strips placed perpendicular to traffic at 18 inch intervals. More recently, portable plastic rumble strips have been developed. These devices are weighted, may be used without an adhesive, and are suitable for shorter duration work.

Effectiveness:
Previous research shows that temporary transverse rumble strips in work zones can result in a 2 to 5 mph speed reduction. Given that a significant portion of intrusions do appear to be the result of a driver being surprised by a condition in the work zone and either swerving to avoid the hazard or hitting the hazard and then entering the work space, this technology is expected to have some effect on intrusions as well. In addition, temporary transverse rumble strips are assumed to have a limited effect on all types of crash costs at the work zone.

Cost:
For conventional rumble strips, cost is approximately $6500 for standard array (consisting of 3 sets). For portable plastic rumble strips, cost is $1250 per device. Depending upon the pattern, an array of portable plastic rumble strips may cost between $7500 and $22,500.

Suggested criteria:
Based on a crash cost reduction analysis, the use of this technology appears to be justifiable primarily on higher-volume facilities (i.e., 60,000 vehicles per day on freeways and multilane highways). As the duration of the work zone increases, the average annual daily traffic threshold decreases.

Other considerations:
- May cause an unexpected hazard for motorcyclists and bicyclists.
- Should not be used on sharp horizontal or vertical curves.
- Noise generated by rumble strips may lead to complaints from nearby residents, particularly when deployed for an extended period of time.
- At higher speeds and volumes, some portable rumble strips may move slightly with each strike, making routine monitoring and realignment necessary.

TRUCK-MOUNTED POSITIVE PROTECTION SYSTEMS

Description:
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 (TMAs) 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. One example is the Caltrans-developed Balsi Beam, a steel beam "cage" currently 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.

Effectiveness:
To date, the Balsi Beam and other similar devices have not been extensively deployed. Consequently, their effectiveness and practicality have not been verified. However, they are expected to have a moderate effect on intrusion crash costs, reducing the severity (but not frequency) of those vehicles intruding into the actual work space.

Cost:
The Balsi Beam and other similar devices cost between $171,000 and $250,000 to purchase.

Suggested criteria:
Based on an intrusion crash cost reduction analysis alone, it is difficult to justify truck-mounted positive protection systems under any volume conditions. Better information on service life and crash costs when the technology is deployed will be needed before a better estimate of appropriate deployment conditions can be made. Still, it is likely that agencies making use of this technology will do so primarily with risk reduction to its highway workers on foot as a priority, rather than as a strictly economic decision.

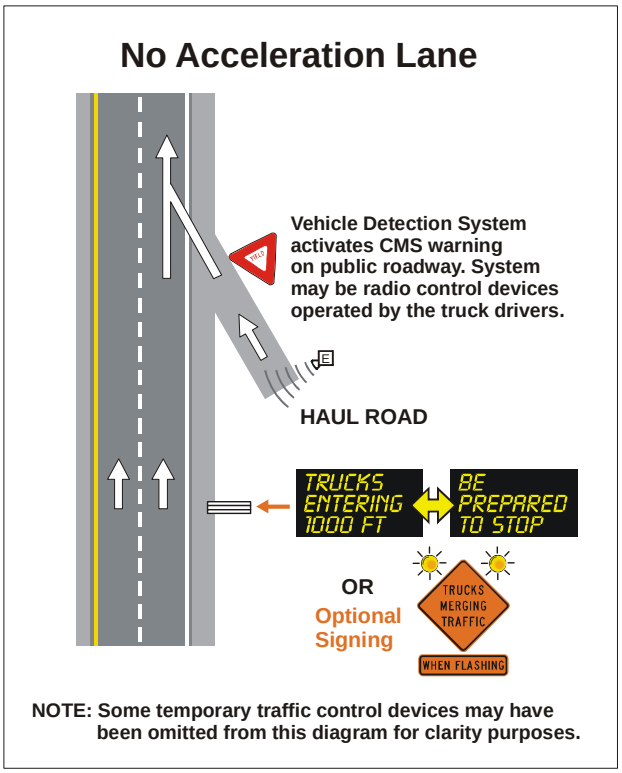
Other considerations:
- The Balsi Beam and other similar devices cannot be moved continuously down the road while workers are within the protection area, nor can it be moved or extended laterally across lanes.

CONSTRUCTION ENTRANCE SIGNING

Description:
Sometimes drivers fail to recognize the slow speed of work vehicles trying to enter or exit the work area and must take evasive actions to avoid hitting the work vehicle. Static or dynamic construction entrance signing can be located near access points to warn drivers that a work vehicle is entering or exiting the travel lanes. Example messages include:

- "TRUCKS ENTERING ROADWAY/REDUCE SPEED,"
- "TRUCKS ENTERING 1000 FT/BE PREPARED TO STOP," and
- "TRUCKS EXITING 2000 FT/DO NOT FOLLOW TRUCKS."

Typically, these signs are displayed to drivers whether or not a truck is actually entering or exiting the work area. Work zone intelligent transportation systems may be used to activate messages on portable changeable message signs (PCMS) only when trucks are detected; thus, hopefully improving the driver's trust of the message. Static signs with flashing beacons may also be used to display more real-time messages. When a truck is detected, the beacons would flash; otherwise the beacons would remain off.



Effectiveness:
Static and dynamic construction entrance signing can alert drivers to work vehicles that are slowly decelerating or accelerating in preparation to enter or exit the work area. Thus, construction entrance signing has the potential to decrease crashes involving work vehicles and secondary crashes upstream (i.e., rear-end crashes due to queuing). Providing real-time information allows drivers to associate the message with an actual event, increasing awareness and trust of the system.

Cost:
Static warning signs cost approximately $250 each. PCMS cost approximately $5500 each, but can be leased for approximately $11.00 an hour. An installed static sign assembly with flashing beacons costs approximately $2500 and radar vehicle detection systems cost approximately $6500. The cost of work zone intelligent transportation systems varies and is highly dependent upon the technology used.

Suggested criteria:
Due to highly variable implementation costs and lack of adequate data regarding the potential incremental benefit of the countermeasure, a cost-effectiveness assessment could not be conducted. However, some type of construction entrance signing should be considered at locations where work vehicles are expected to enter or exit the active travel lanes with little or no area for the vehicles to decelerate or accelerate, especially on high speed, rural roadways and if sight distance is limited.

Other considerations:

- It is normally preferable to separate construction access and egress from high-speed travel lanes to avoid creating high-speed differentials between work vehicles and motorists. If such separation cannot be accomplished, improving driver awareness of the presence of exiting and entering work traffic is the next logical alternative.

"DO NOT FOLLOW" SIGNS

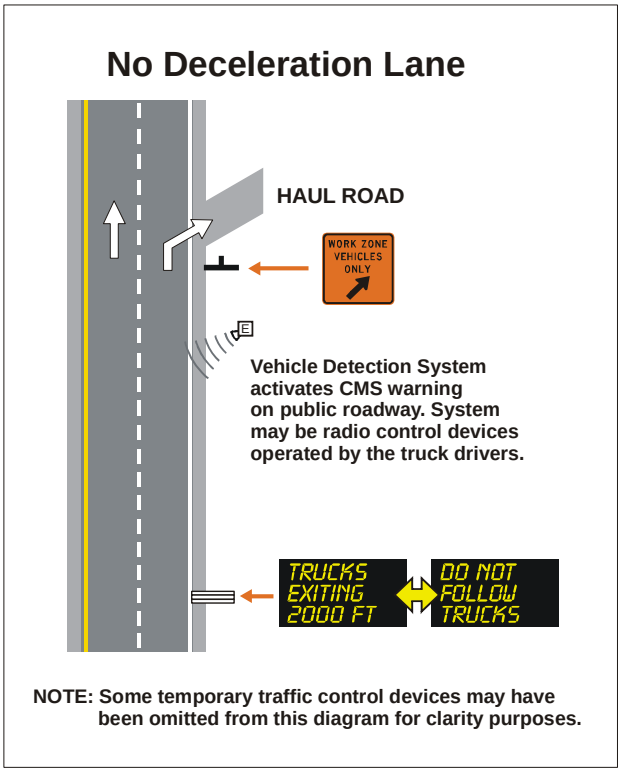
Description:

Sometimes drivers follow work vehicles into the work area, especially at night. Static or dynamic "DO NOT FOLLOW" signing can be located near construction entrances or on the back of work vehicles to warn drivers not to follow work vehicles into the construction area.

Example messages include:

- "CONSTRUCTION VEHICLE DO NOT FOLLOW,"
- "DO NOT FOLLOW INTO WORK AREA," and
- "TRUCKS EXITING 2000 FT/DO NOT FOLLOW TRUCKS."

Work zone intelligent transportation systems may be used to activate messages on portable changeable message signs (PCMS) only when trucks are detected; thus, hopefully improving the driver's trust of the message.



Effectiveness:

Static and dynamic "DO NOT FOLLOW" signs tell drivers not to follow work vehicles into the work area. Therefore, these signs have the potential to reduce vehicle intrusions into the work area and conflicts between drivers and workers. Providing real-time information allows drivers to associate the message with an actual event; hopefully increasing their awareness and trust of the system.

Cost:

Static warning signs cost approximately $250 each, while truck-mounted changeable message signs cost approximately $8000 each. Portable changeable message signs (PCMS) cost approximately $5500 each, but can be leased for approximately $11.00 an hour. Radar vehicle detection systems cost approximately $6500. The cost of work zone intelligent transportation systems varies and is highly dependent upon the technology used.

Suggested criteria:

Due to highly variable implementation costs and lack of adequate data regarding the potential incremental benefit of the countermeasure, a cost-effectiveness assessment could not be conducted. However, "DO NOT FOLLOW" signage should be considered at locations where

construction entrances appear to be continuations of the expected travel path or where drivers repeatedly enter the work area behind work vehicles.

Other considerations:

- It is normally preferable to separate construction access and egress from high-speed travel lanes to avoid creating high-speed differentials between work vehicles and motorists. If such separation cannot be accomplished, improving driver awareness of the presence of exiting and entering work traffic is the next logical alternative.

EARLY MERGE SYSTEM

Description:
The early merge system (also known as a dynamic no passing zone) encourages drivers to exit the closed lane as soon as possible and thus is intended to reduce the number of forced merges near the beginning of the lane closure. The early merge system uses intelligent transportation systems sensors to monitor traffic in the open lane on the approach to the work area. Advance warning signs are used to display no passing messages (e.g., "NO PASSING WHEN FLASHING" or "LEFT LANE DO NOT PASS WHEN FLASHING"). These types of messages are intended to discourage "queue-jumpers" from merging into the open lane at the beginning of the lane closure and causing additional delay to those who merged early. Thus, the early merge system aims to reduce aggressive driving and unsafe merge maneuvers.

Effectiveness:
An early merge system may be used to discourage last minute lane changes near the beginning of the lane closure, reduce aggressive driving, and reduce unsafe merge maneuvers. It also provides significant advance warning so drivers have adequate distance to merge prior to reaching the beginning of the lane closure. A Michigan Department of Transportation (MDOT) study showed that average peak period travel time delay decreased by over 30 percent, the average number of stops and duration of stops were decreased, and the number of aggressive driving maneuvers (late merges) during peak hours was significantly reduced.

Cost:
The complexity of each system varies, so cost is a function of the number of signs required, the type of detection and communication methods employed, duration of use, and whether the system is leased or purchased. MDOT leased an early merge system for use over two six-month periods at a cost of $120,000. The system consisted of five sign trailers, each with microwave sensors, wireless radio communications and solar, rechargeable power systems.

Suggested criteria:
Due to highly variable implementation costs and lack of adequate data regarding the potential incremental benefit of the countermeasure, a cost-effectiveness assessment could not be conducted. However, early merge systems may be used for lane closures on high speed facilities under low volume conditions. Based on previous research, for a two-to–one lane closure, volumes should be between 2,000 and 3,000 vehicles per hour; for a three-to-two lane closure, volumes should be between 3,000 and 3, 800 vehicles per hour.

Other considerations:

- Best suited for commuter traffic and sufficient project duration to allow drivers to adapt to the system.
- Enforcement is necessary to ensure compliance with the early merge system.
- If the system is leased, the transportation agency does not have to maintain the equipment or store it after use.

UPSTREAM QUEUE END WARNING

Description:
When backups are expected, an upstream queue end warning system can monitor the speed of vehicles within and upstream of a work zone. When reduced speeds are detected, an upstream portable changeable message sign (PCMS) or other warning system (such as static signs with flashers) are activated to warn drivers of the slower-moving traffic ahead. Warnings messages may include "BE PREPARED TO STOP," "SLOW TRAFFIC AHEAD," or may give the actual speed of the slower-moving traffic (e.g., "30 MPH TRAFFIC AHEAD").

Effectiveness:
A study in Texas found that a queue end warning system reduced the number of vehicle conflicts, such as sudden breaking and forced lane changes to avoid rear-end crashes, by 2 to 7 percent. Speed variance was also significantly reduced, which may reduce the potential for rear-end crashes and result in safer traffic operations.

Cost:
A PCMS costs approximately $5500, but can be leased for approximately $11.00 an hour. The complexity of each system varies, so cost is a function of the number of signs required, the type of detection and communication methods employed, and duration of use. An installed static sign assembly with flashing beacons costs approximately $2500 and radar vehicle detection systems cost approximately $6500.

Typical Application(s):
Due to highly variable implementation costs and lack of adequate data regarding the potential incremental benefit of the countermeasure, a cost-effectiveness assessment could not be conducted. However, upstream queue end warning systems should be considered at lane closures with recurring or occasional congestion, high traffic volumes, relatively long queues, and stop-and-go conditions.

Other considerations:
- Care should be taken to assess the length of queues that occur, and position the sign upstream to ensure viewing before reaching the sign. If queues of several miles are expected, it may be necessary to have more than one sign positioned upstream, and additional sensors used to determine approximate queue length in order to activate the sign closest to the upstream end of the queue.

AUTOMATED SPEED ENFORCEMENT TECHNOLOGY

Description:
This technology is used to electronically identify speed violators and to capture an image of the vehicle imbedded with speed, location, date, and time information about the violation. The registered owner of the vehicle is determined via the license plate number, and a citation is issued and mailed to the owner of the vehicle.

Effectiveness:
In a recent study of this system in Illinois, speed data were collected at the speed-radar photo enforcement device and a location 1.5 miles downstream in the work zone. The results showed that this technology is effective in reducing the average speed and increasing compliance with the work zone speed limit. The reduction in the mean speed varied from 3 to 6 mph near the vehicle. However, the speed reduction at the downstream location was not as significant (1 to 3 mph).

Cost:
The costs of this technology include vehicle purchase and maintenance, speed enforcement technology, and staffing to operate the technology, review violations, and process and mail citations. The costs of the technology can vary widely depending on the number of vehicles used, technology used, etc. For programs in Illinois and Maryland, it appears that operating costs are approximately $400 per hour. The revenues received depend on the fine structure, citation threshold, and other factors. In Washington, it is estimated that revenues are approximately equal to operating costs.

Suggested Criteria:
Assuming that revenues generated do offset the costs of operation, this technology could be justified at all types of work zones.

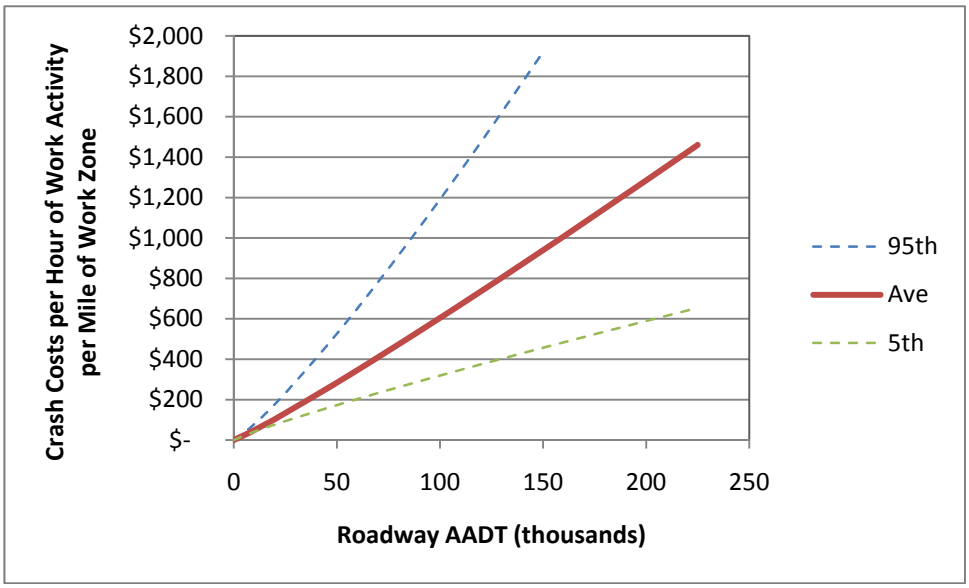
Other considerations:

- This technology requires enabling legislation to allow its use.
- Automated speed enforcement can be a lightning rod for public outcry against invasion of privacy, big brother concerns, and government use of the technology for revenue enhancement purposes. Agencies should be prepared to address these and other concerns in an objective and up front manner.

REFERENCES

1. Ullman, G.L., M.D. Finley, and L.T. Theiss. *Work Zone Intrusion Countermeasure Identification, Assessment, and Implementation Guidelines*. Report No. FHWA/CA10-1102. Texas Transportation Institute, College Station, Texas, May 2010.
2. Bryden, J.E., and D. J. Mace. *A Procedure for Assessing and Planning Nighttime Highway Construction and Maintenance.* NCHRP Report 475. Transportation Research Board, National Research Council, Washington, D.C., 2002.
3. Bryden, J.E., and D. J. Mace. *Guidelines for Design and Operation of Nighttime Traffic Control for Highway Maintenance and Construction.* NCHRP Report 476. Transportation Research Board, National Research Council, Washington, D.C., 2002.
4. Ullman, G.L., M.D. Finley, J.E. Bryden, R. Srinivasan, and F.M. Council. *Traffic Safety Evaluation of Nighttime and Daytime Work Zones.* NCHRP Report 627. Transportation Research Board, National Research Council, Washington, D.C., 2008.
5. Standard Plans (U.S. Customary Units). California Department of Transportation, May 2006. Available at http://www.dot.ca.gov/hq/esc/oe/project_plans/highway_plans/stdplans_US-customary-units_06/viewable_pdf/2006-Std-Plns-for-Web.pdf. Accessed January 7, 2009.
6. Ullman, B.R., N.D. Trout, and G.L. Ullman. *Recommended Messages for Truck-Mounted Changeable Message Signs During Mobile Operations.* Report FHWA-WY-09-07F. Texas Transportation Institute, College Station, Texas, November 2009.

APPENDIX B:
CRASH COST FUNCTIONS



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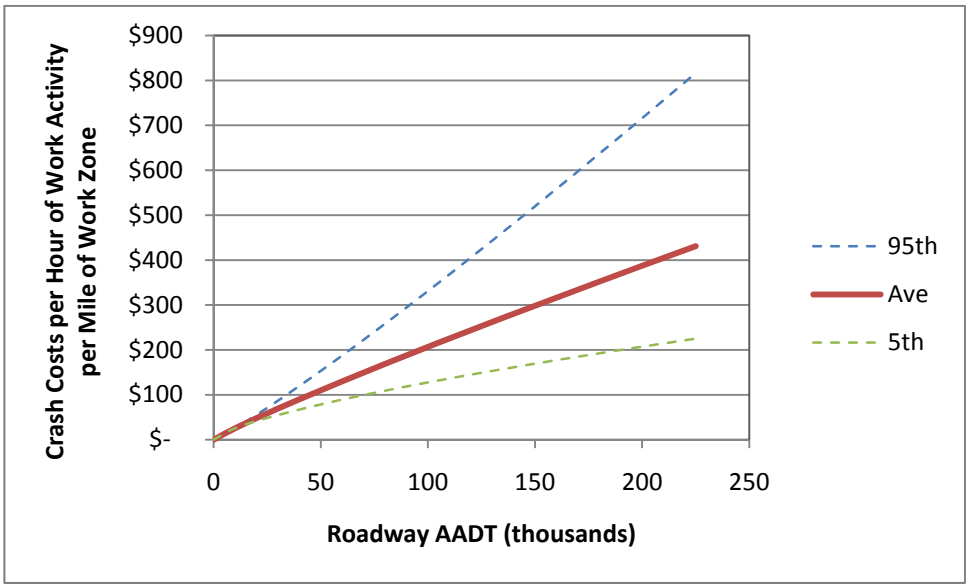
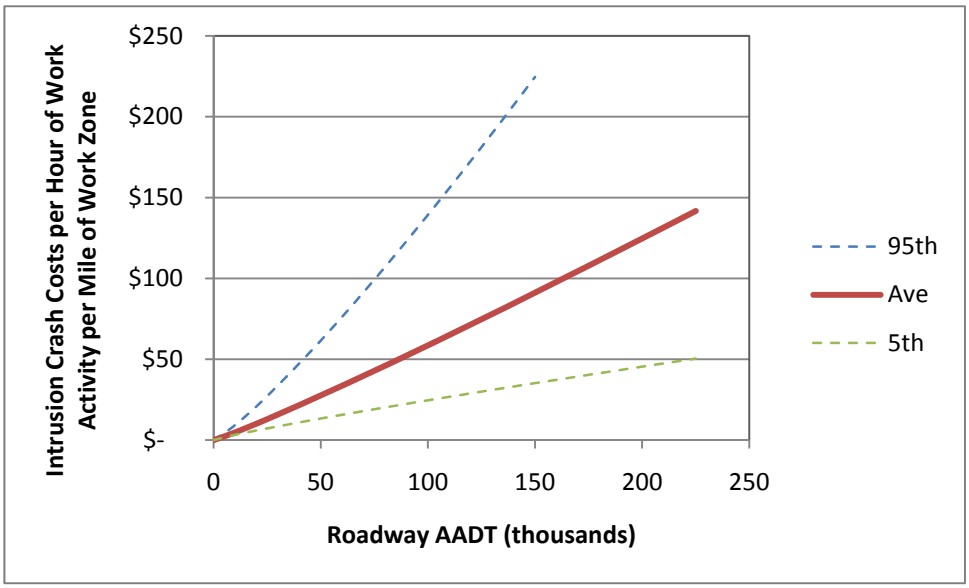


(b) Nighttime

Figure A-1. Total Crash Cost Functions for Freeway Facilities: Work Zone Active with Temporary Lane Closures.



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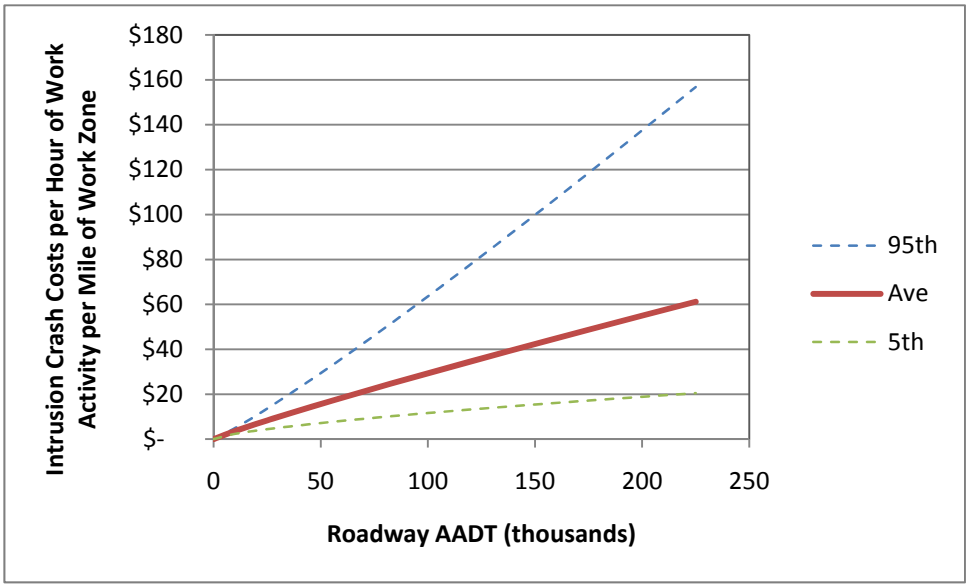

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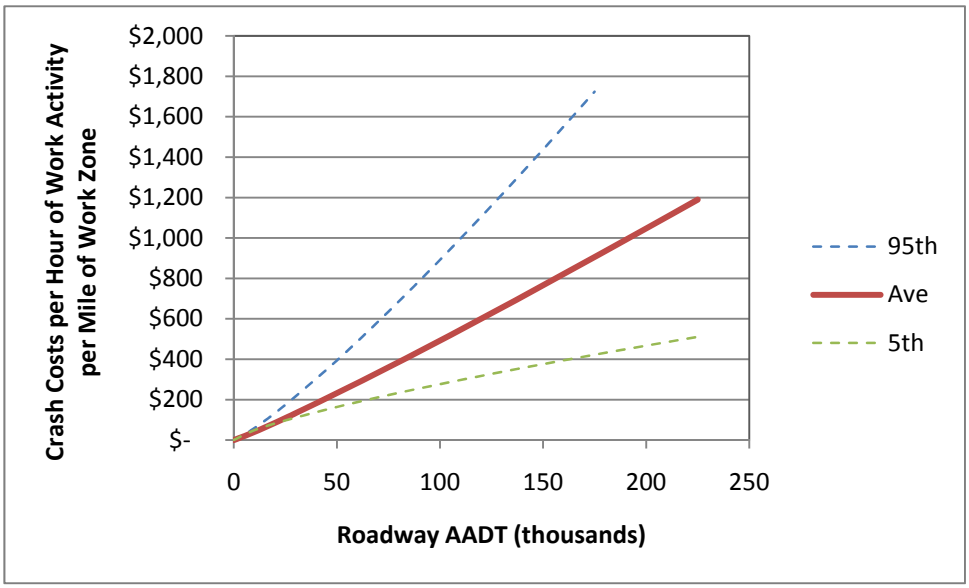
Figure A-2. Intrusion Crash Cost Functions for Freeway Facilities: Work Zone Active with Temporary Lane Closures.



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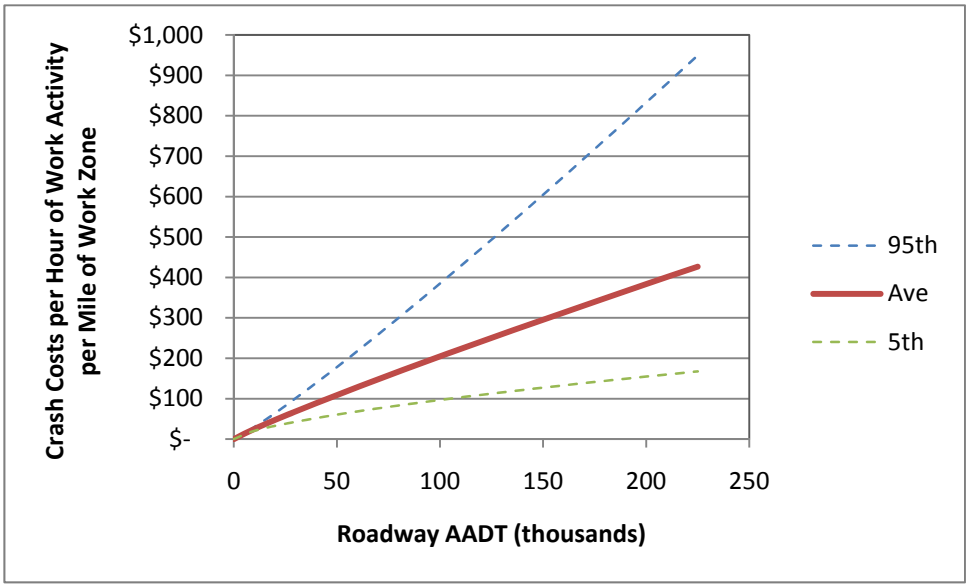

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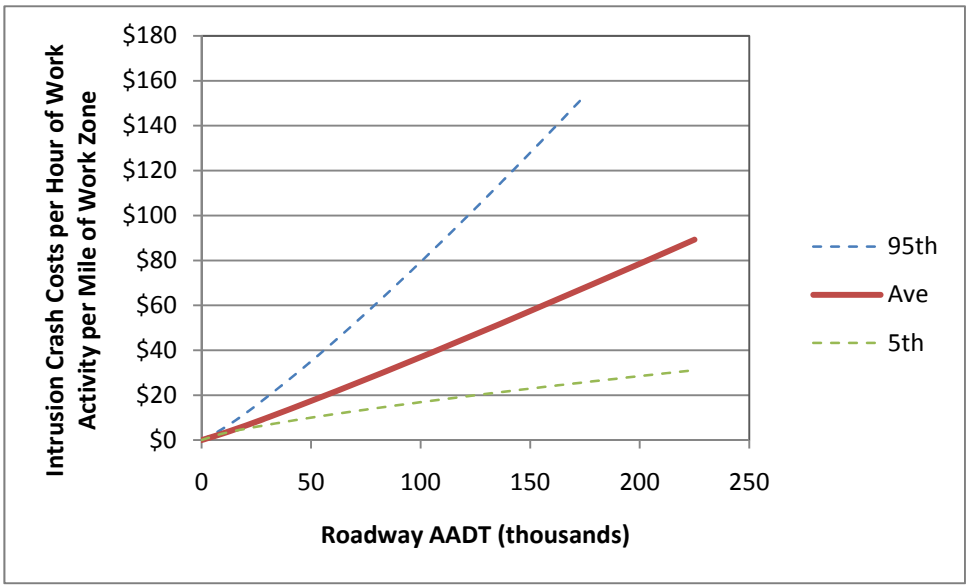
Figure A-3. Total Crash Cost Functions for Freeway Facilities: Work Zone Active without Temporary Lane Closures.



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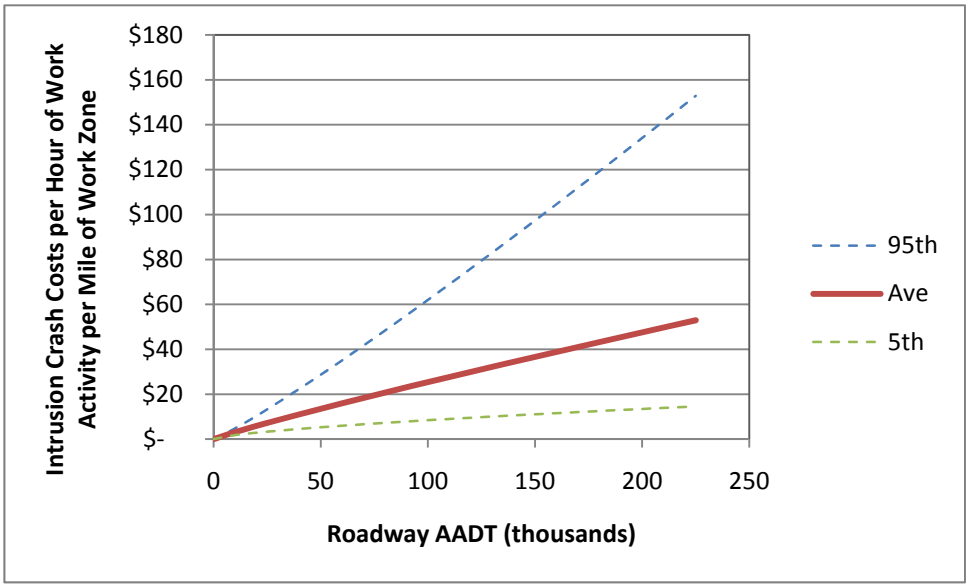

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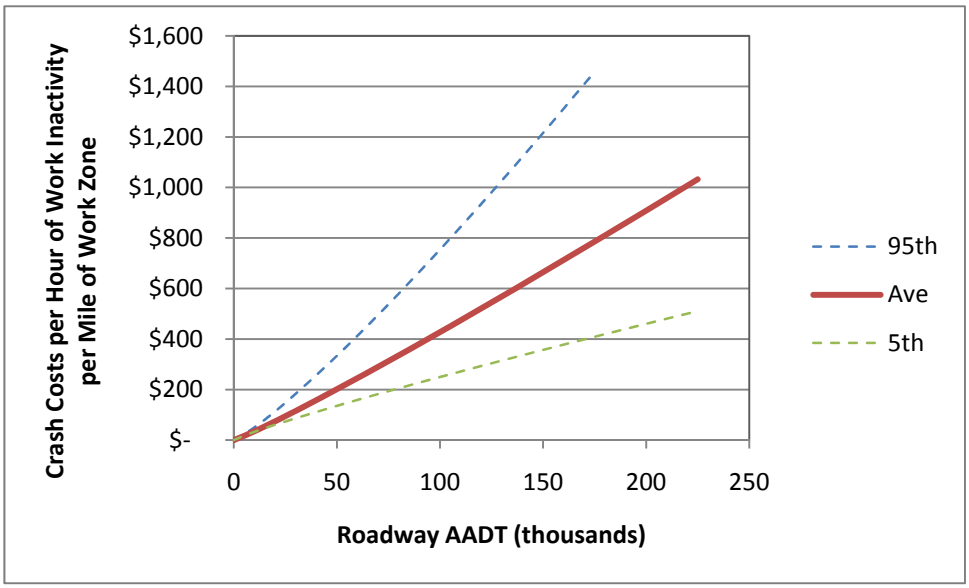
Figure A-4. Intrusion Crash Cost Functions for Freeway Facilities: Work Zone Active without Temporary Lane Closures.



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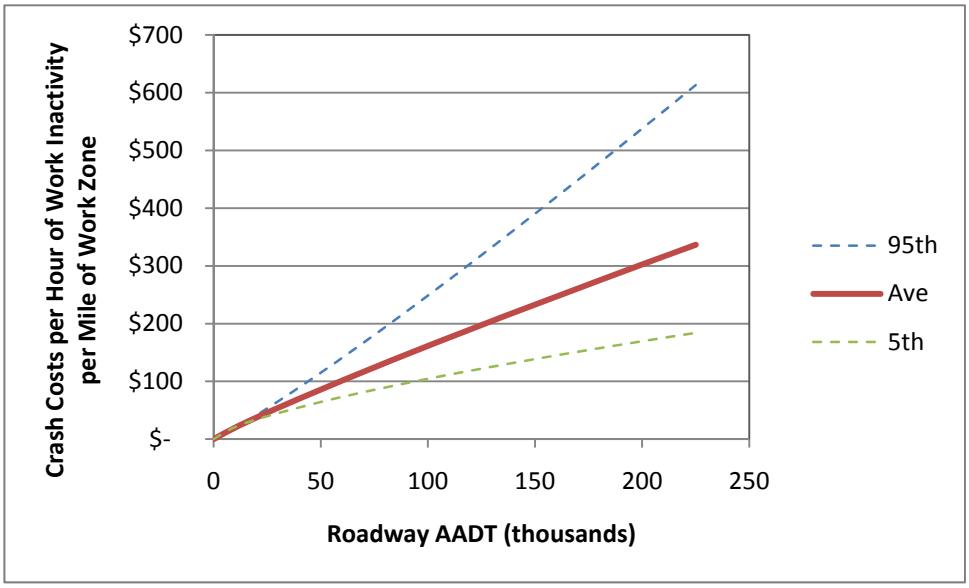

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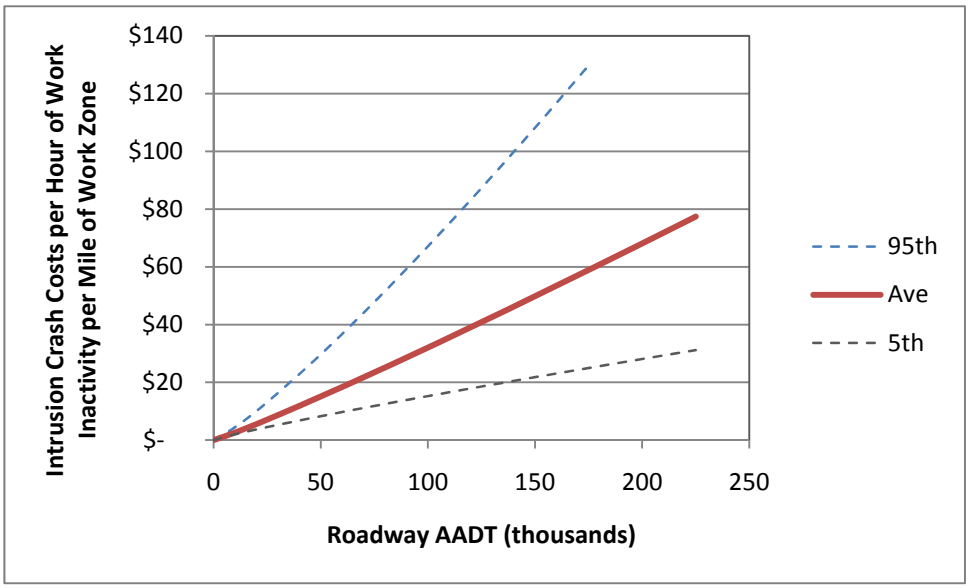
Figure A-5. Total Crash Cost Functions for Freeway Facilities: Work Zone Inactive without Temporary Lane Closures.



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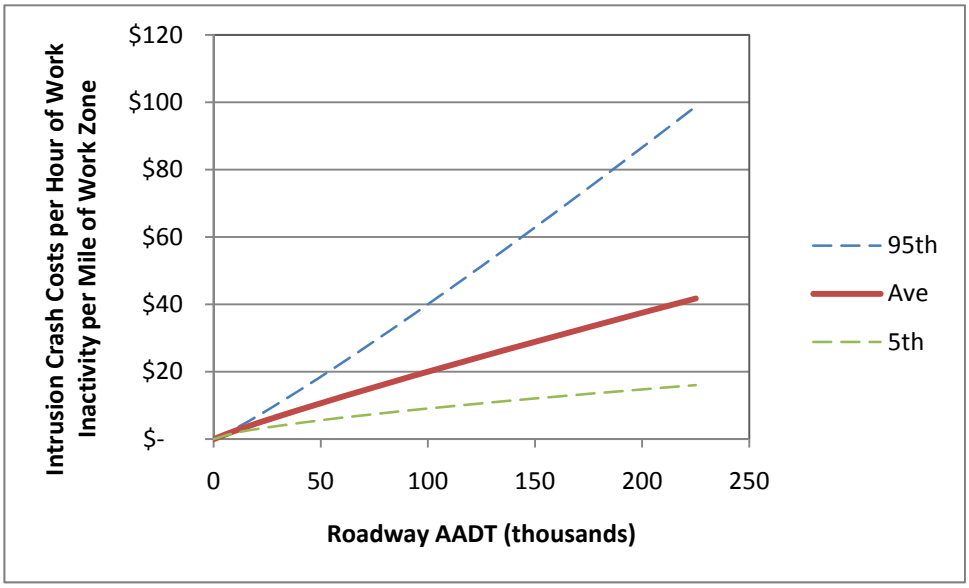

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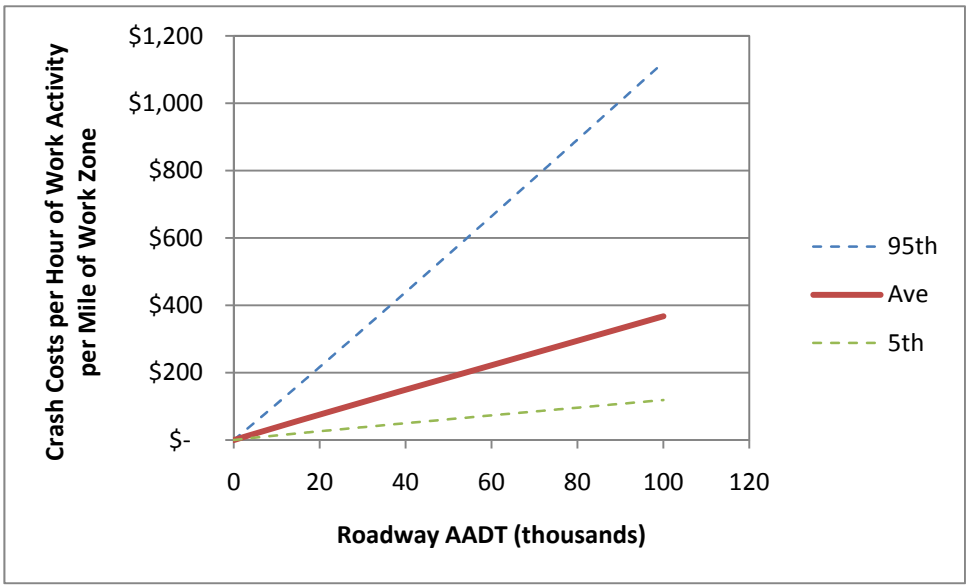
Figure A-6. Intrusion Crash Cost Functions for Freeway Facilities: Work Zone Inactive without Temporary Lane Closures.



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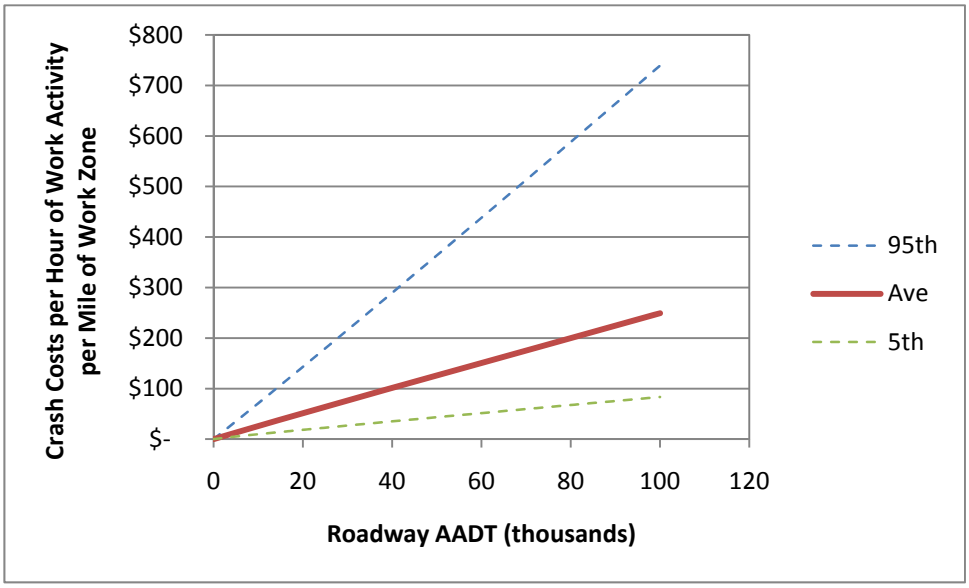

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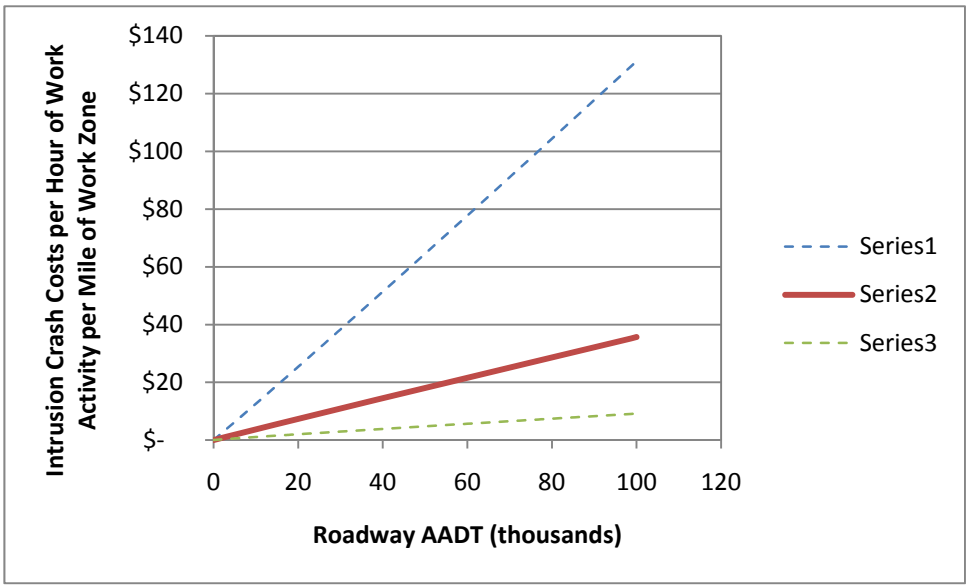
Figure A-7. Total Crash Cost Functions for Multi-Lane Divided Roadway Segments Between Intersections: Work Zone Active with Temporary Lane Closures.



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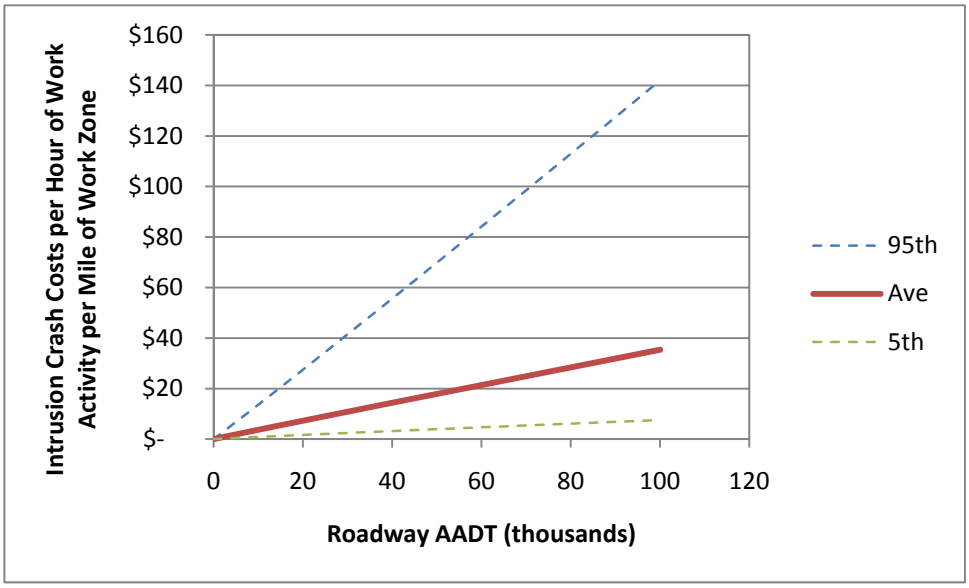

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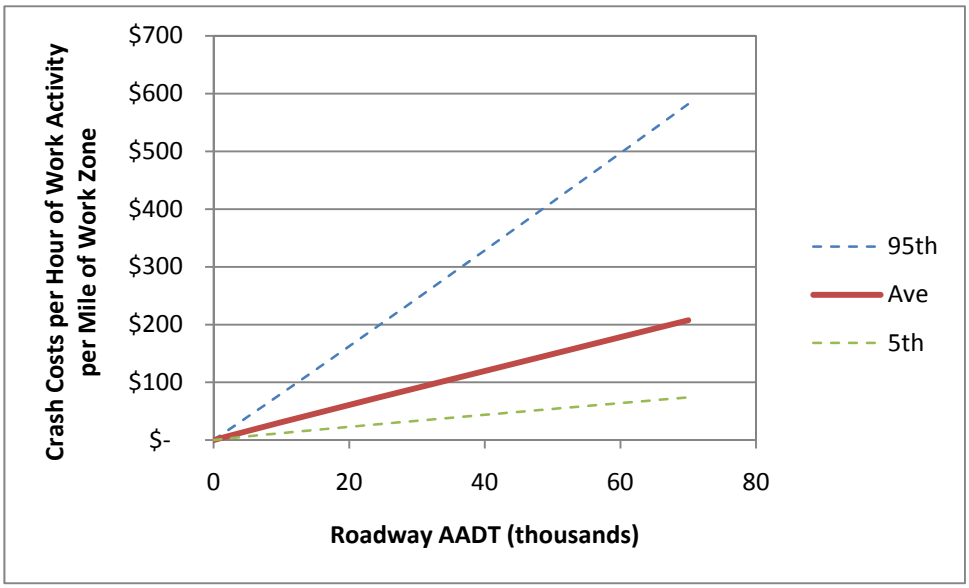
Figure A-8. Intrusion Crash Cost Functions for Multi-Lane Divided Roadway Segments Between Intersections: Work Zone Active with Temporary Lane Closures.



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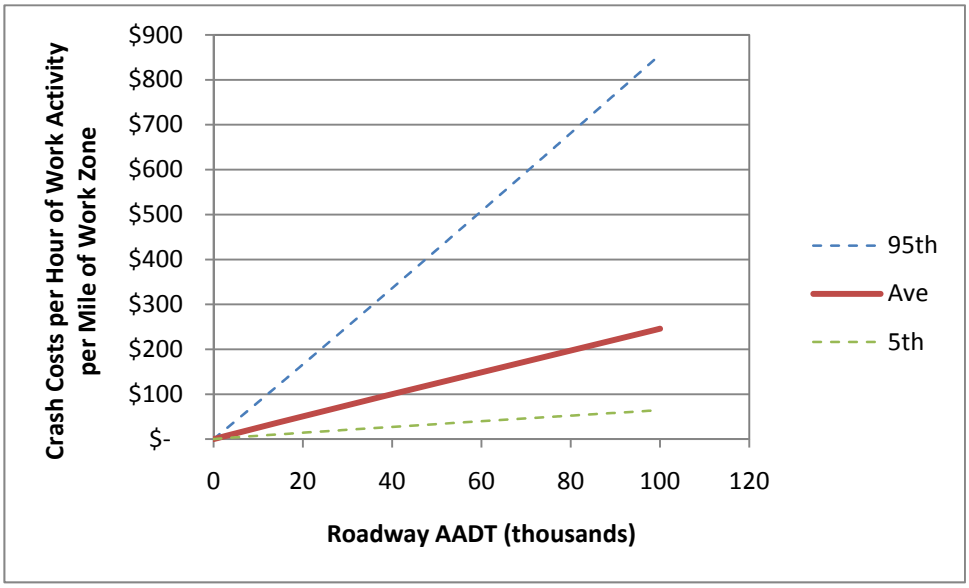

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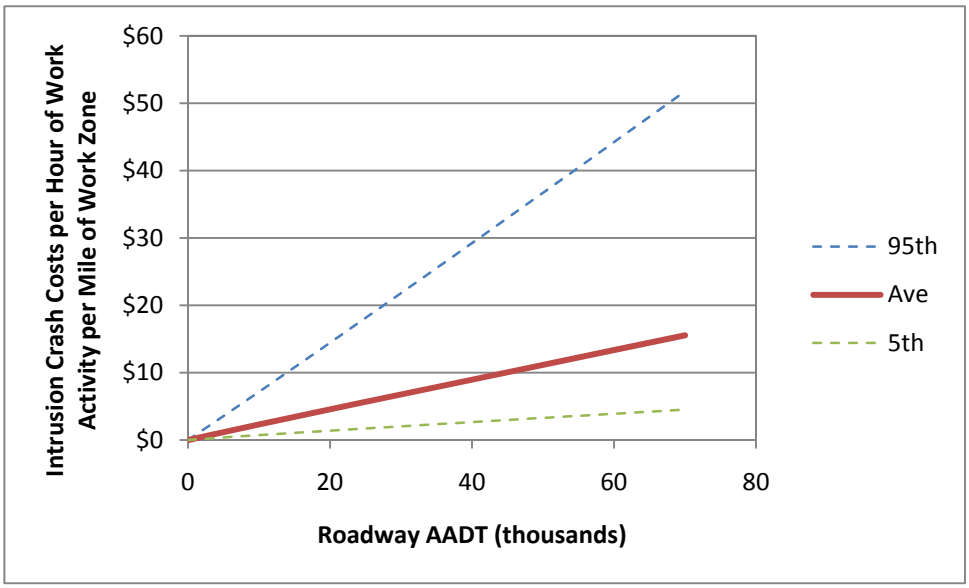
Figure A-9. Total Crash Cost Functions for Multi-Lane Divided Roadway Segments Between Intersections: Work Zone Active without Temporary Lane Closures.



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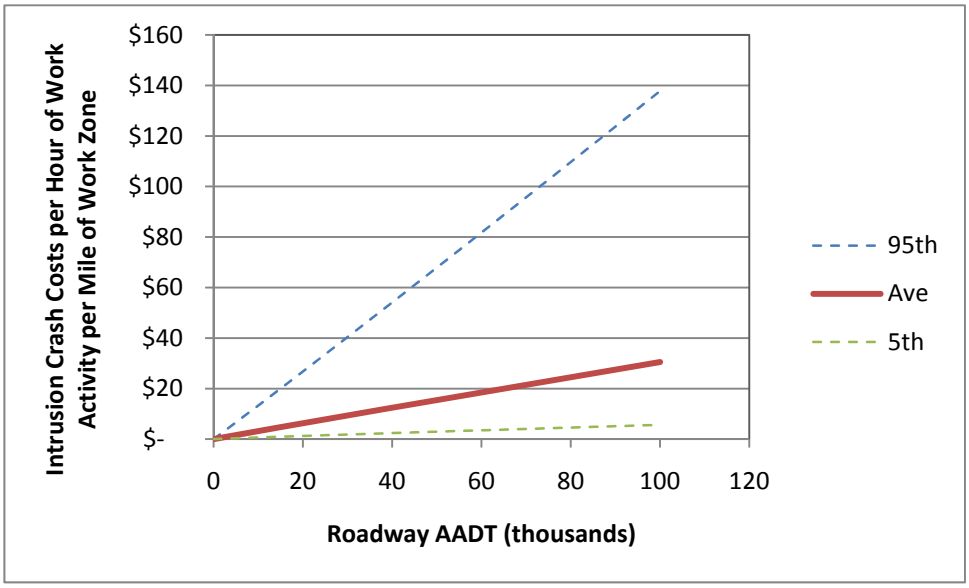

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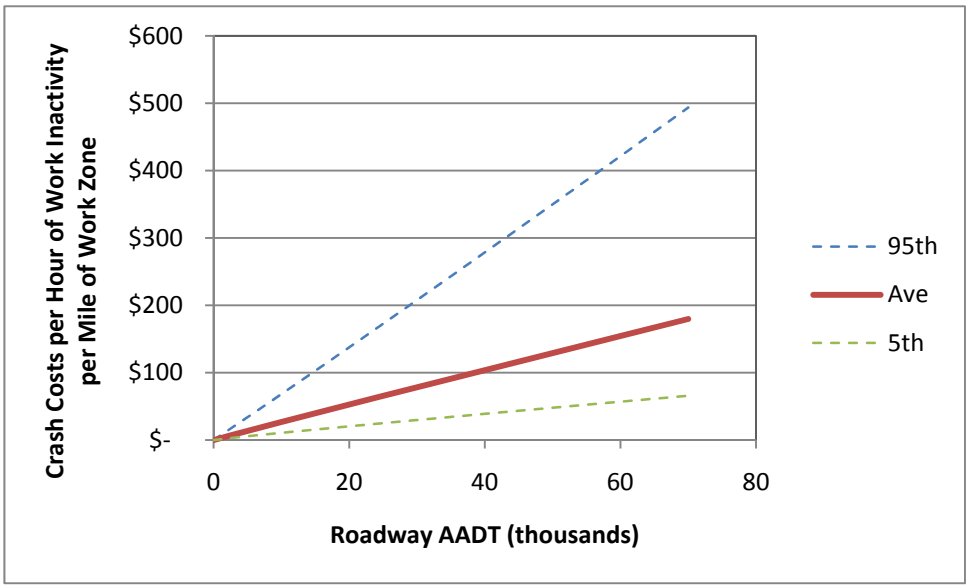
Figure A-10. Intrusion Crash Cost Functions for Multi-Lane Divided Roadway Segments Between Intersections: Work Zone Active without Temporary Lane Closures.



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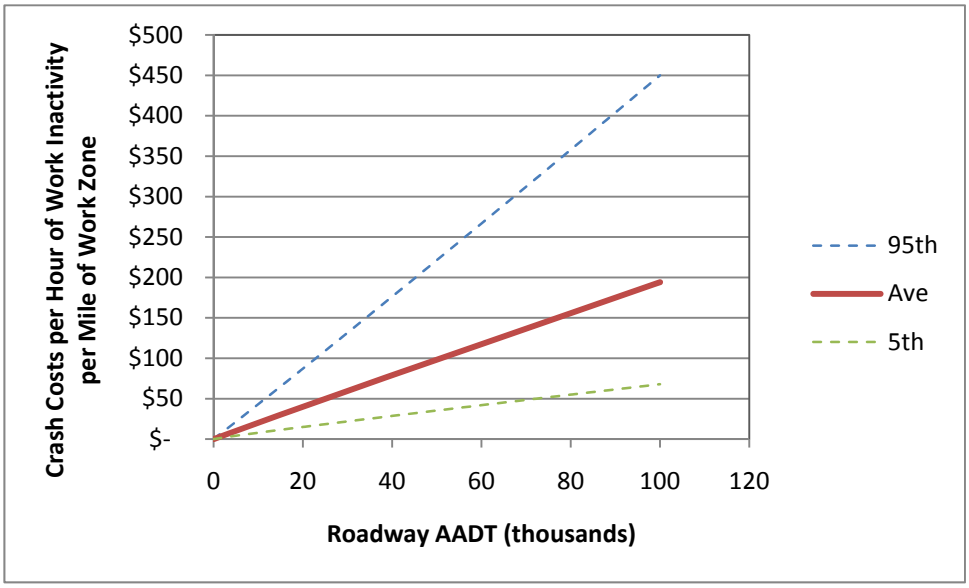

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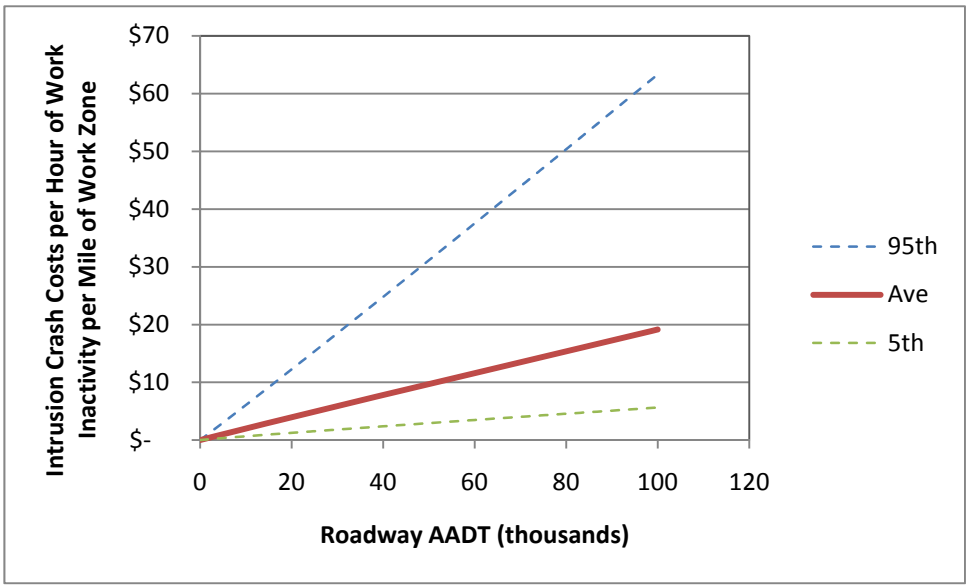
Figure A-11. Total Crash Cost Functions for Multi-Lane Divided Roadway Segments Between Intersections: Work Zone Inactive without Temporary Lane Closures.



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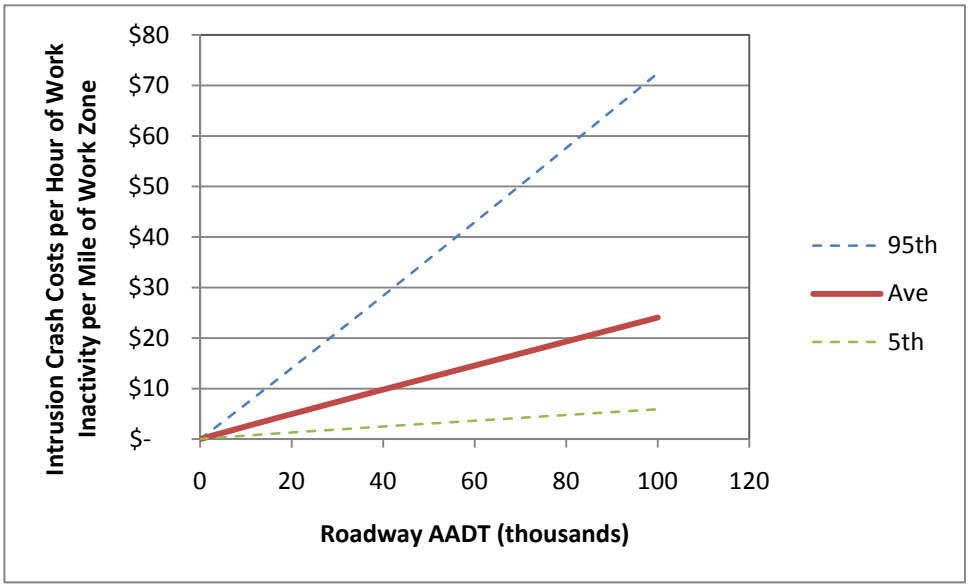

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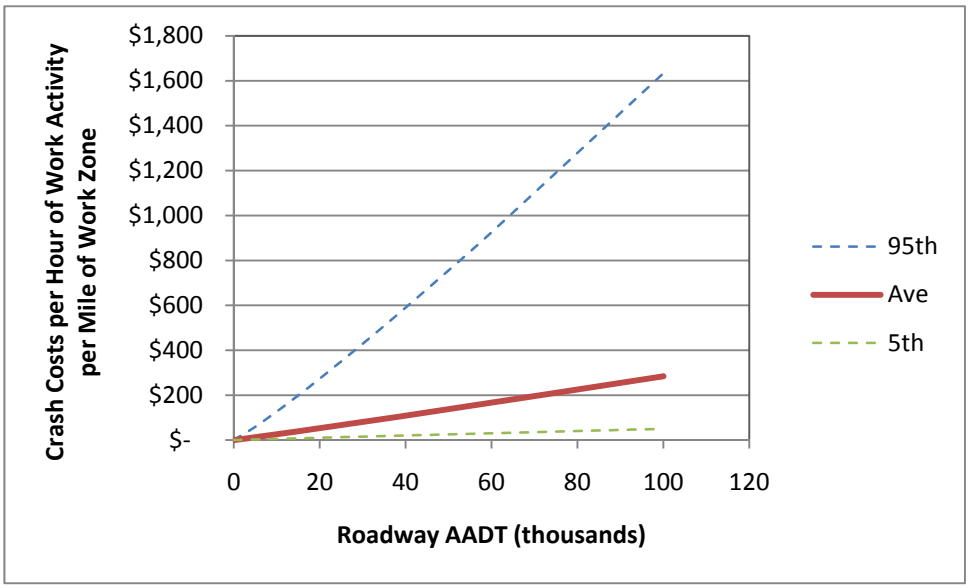
Figure A-12. Intrusion Crash Cost Functions for Multi-Lane Divided Roadway Segments Between Intersections: Work Zone Inactive without Temporary Lane Closures.



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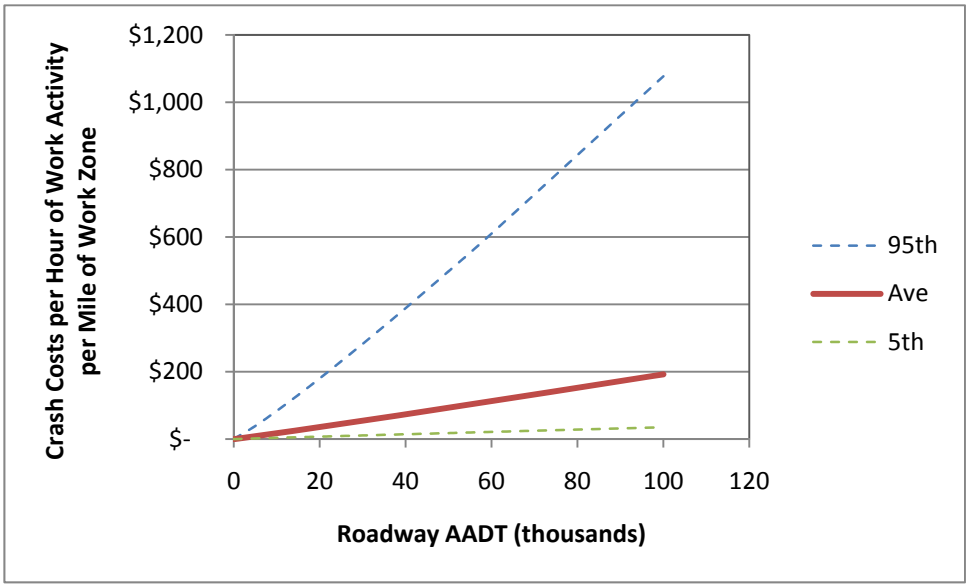

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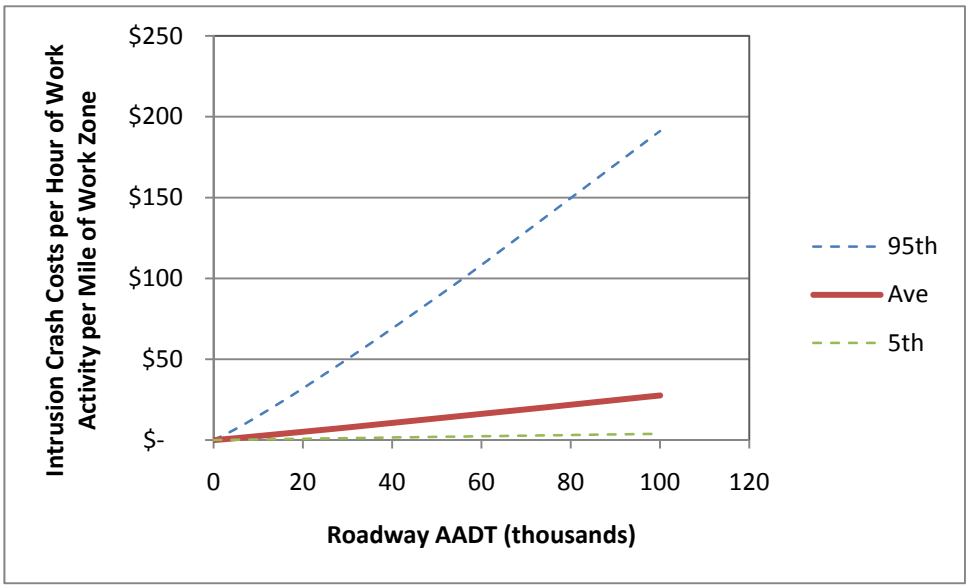
Figure A-13. Total Crash Cost Functions for Multi-Lane Undivided Roadway Segments Between Intersections: Work Zone Active with Temporary Lane Closures.



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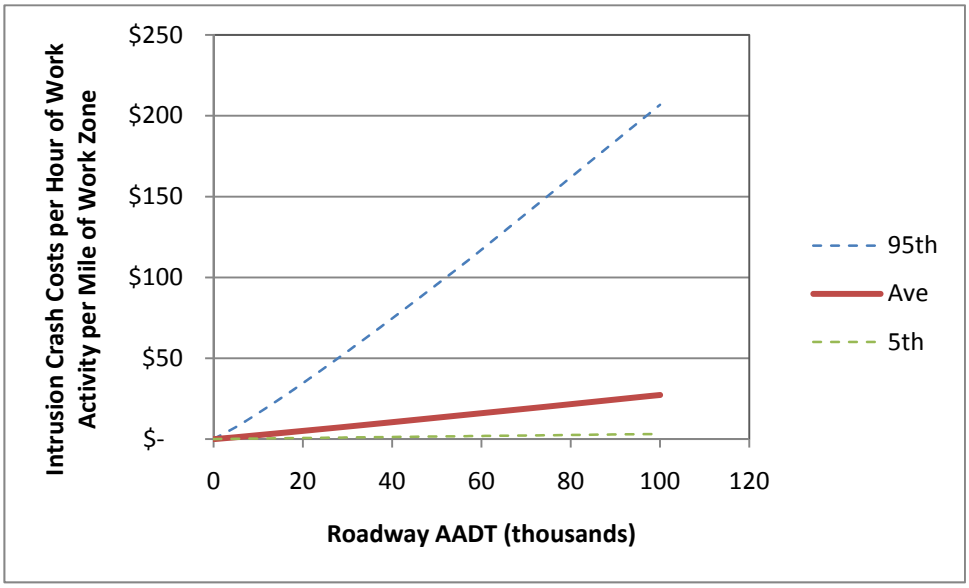

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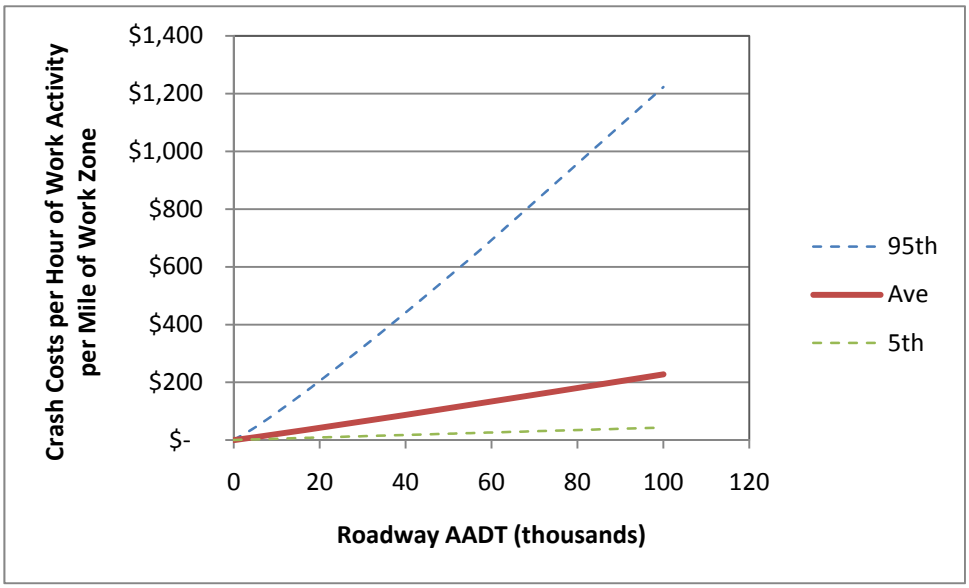
Figure A-14. Intrusion Crash Cost Functions for Multi-Lane Undivided Roadway Segments Between Intersections: Work Zone Active with Temporary Lane Closures



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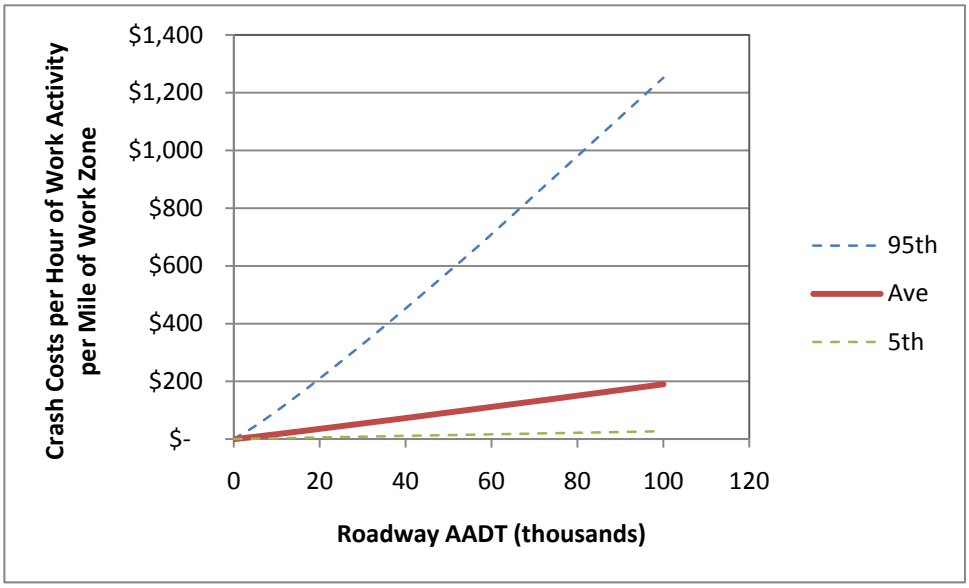
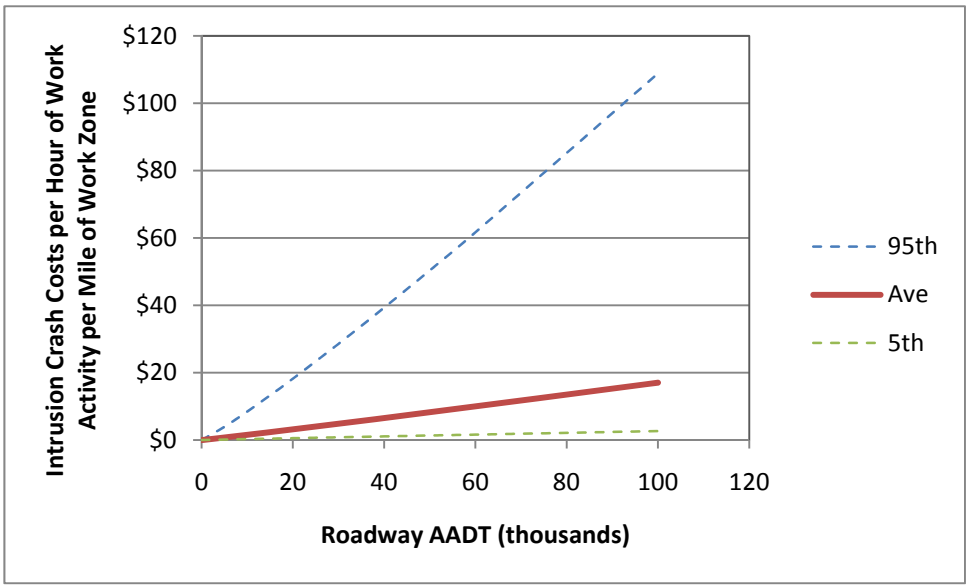
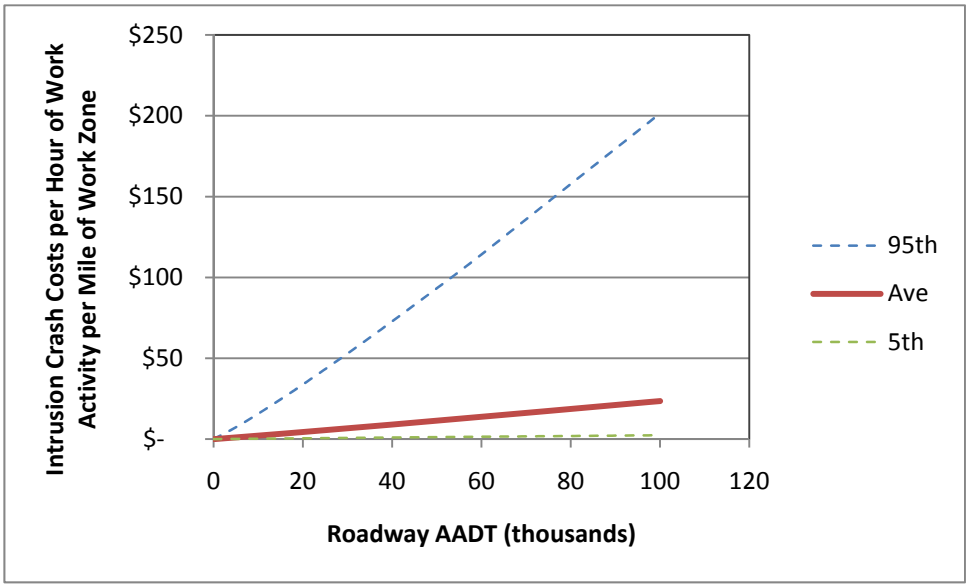


(b) Nighttime

Figure A-15. Total Crash Cost Functions for Multi-Lane Undivided Roadway Segments Between Intersections: Work Zone Active without Temporary Lane Closures.

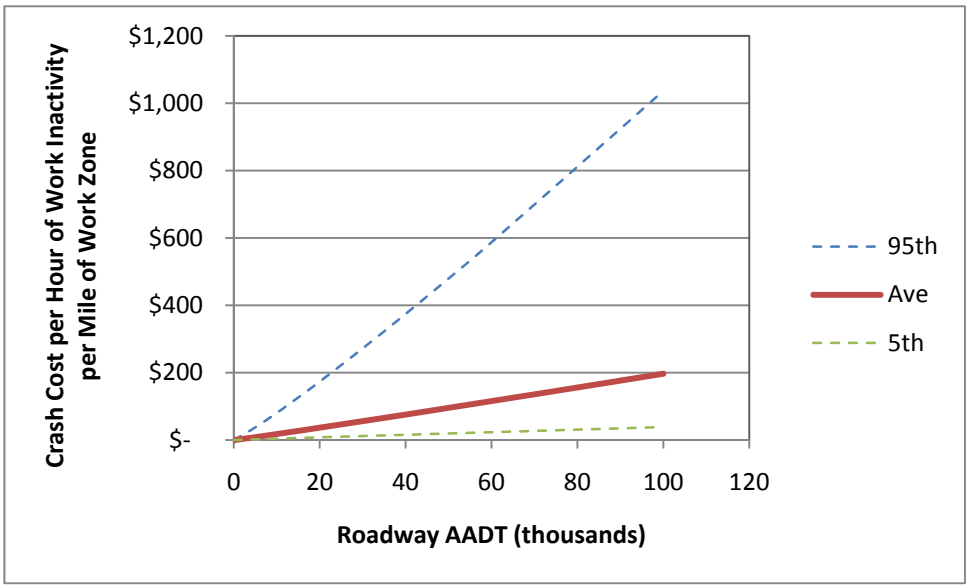


(a) Daytime

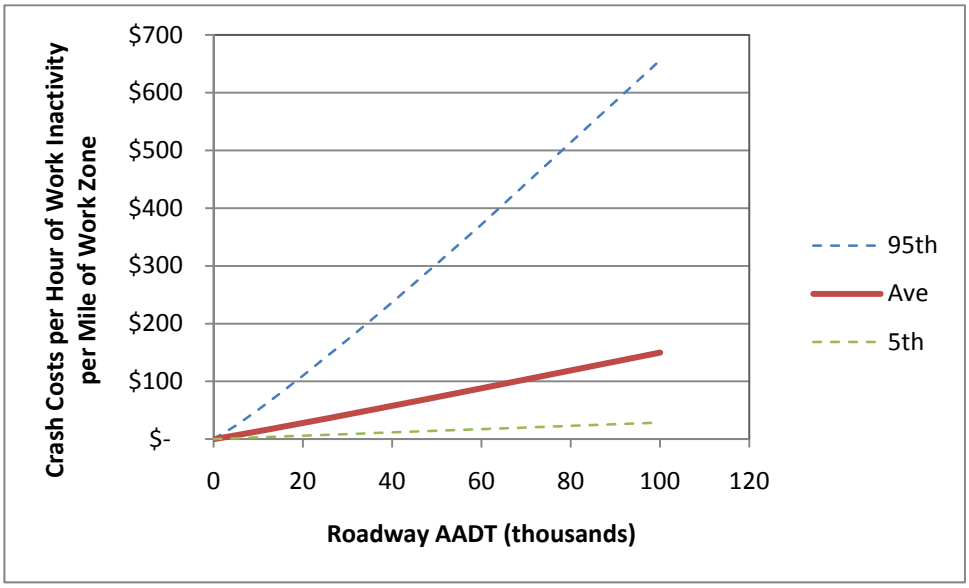


(b) Nighttime

Figure A-16. Intrusion Crash Cost Functions for Multi-Lane Undivided Roadway Segments Between Intersections: Work Zone Active without Temporary Lane Closures.

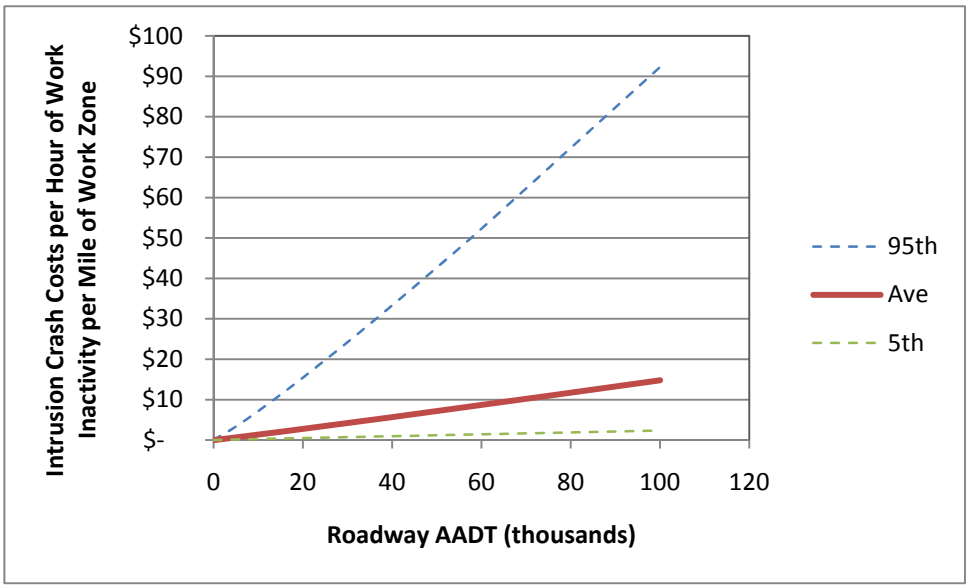


(a) Daytime

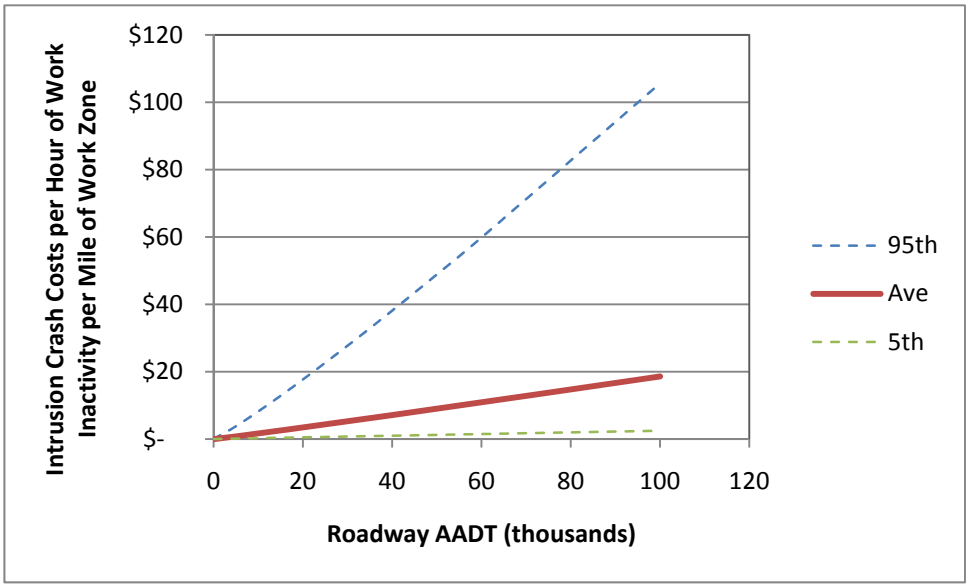


(b) Nighttime

Figure A-17. Total Crash Cost Functions for Multi-Lane Undivided Roadway Segments Between Intersections: Work Zone Inactive without Temporary Lane Closures.



(a) Daytime



(b) Nighttime

Figure A-18. Intrusion Cost Functions for Multi-Lane Undivided Roadway Segments Between Intersections: Work Zone Inactive without Temporary Lane Closures.

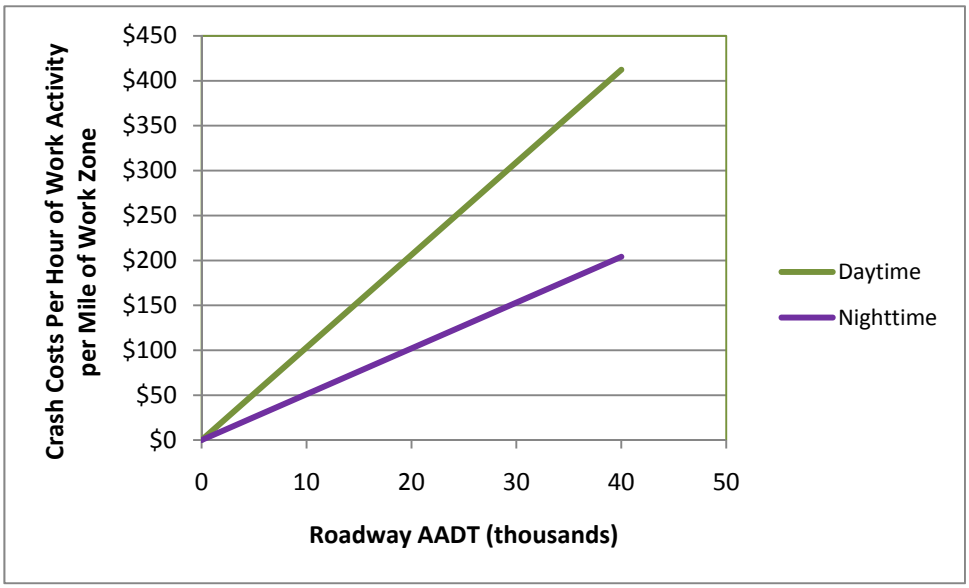


Figure A-19. Total Crash Cost Functions for Rural Two-Lane Highway Segments Between Intersections: Work Zone Active with Temporary Lane Closures.

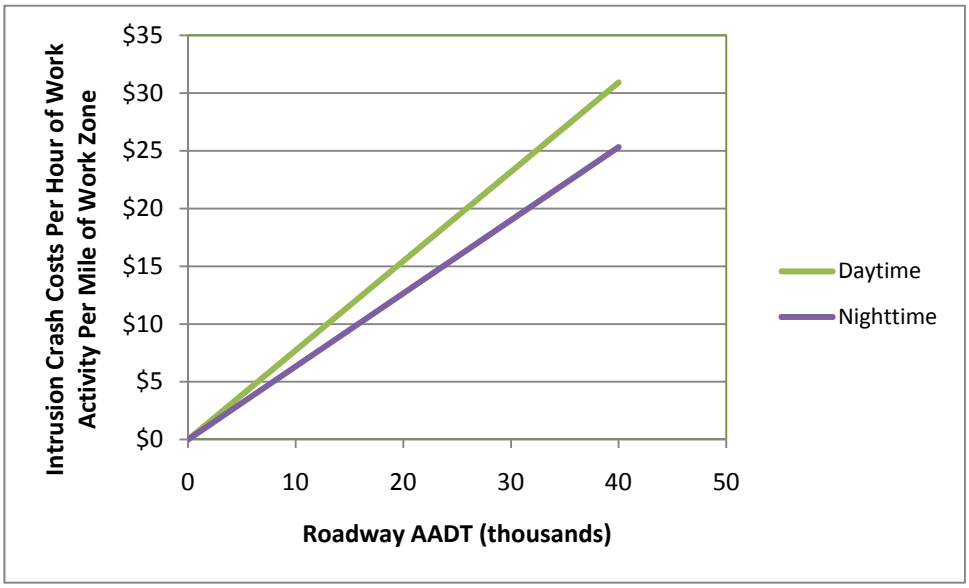


Figure A-20. Intrusion Crash Cost Functions for Rural Two-Lane Highway Segments Between Intersections: Work Zone Active with Temporary Lane Closures.

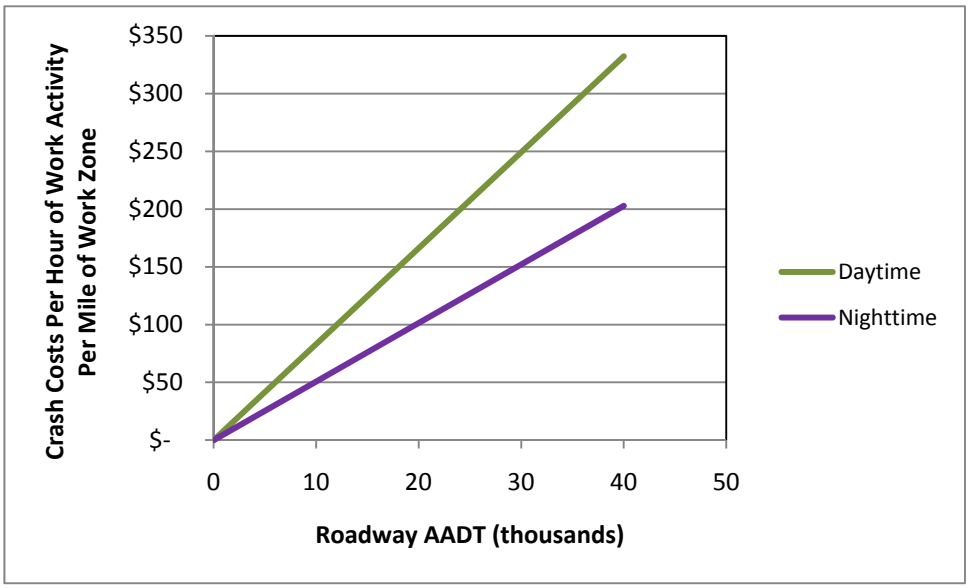


Figure A-21. Total Crash Cost Functions for Rural Two-Lane Highway Segments Between Intersections: Work Zone Active without Temporary Lane Closures.

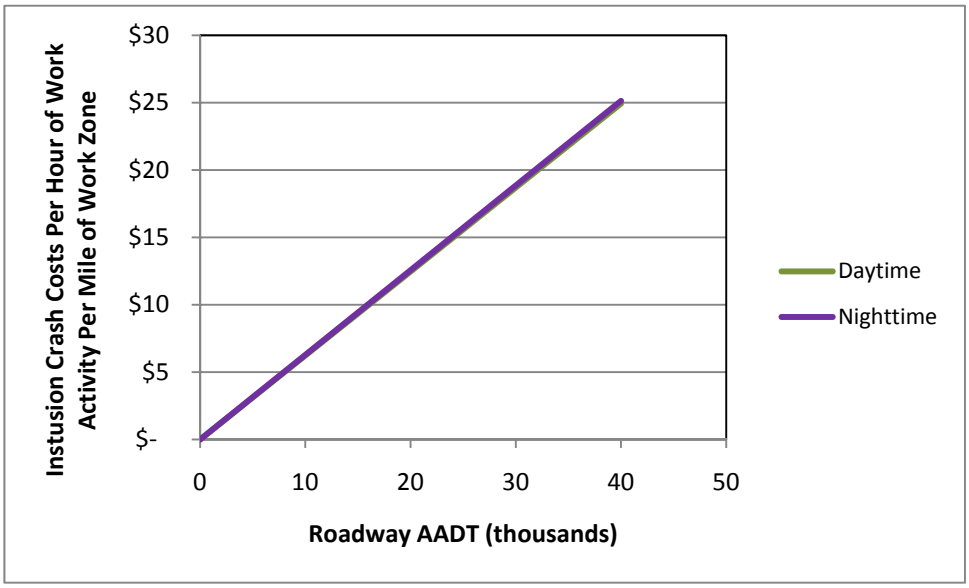


Figure A-22. Intrusion Crash Cost Functions for Rural Two-Lane Highway Segments Between Intersections: Work Zone Active without Temporary Lane Closures.

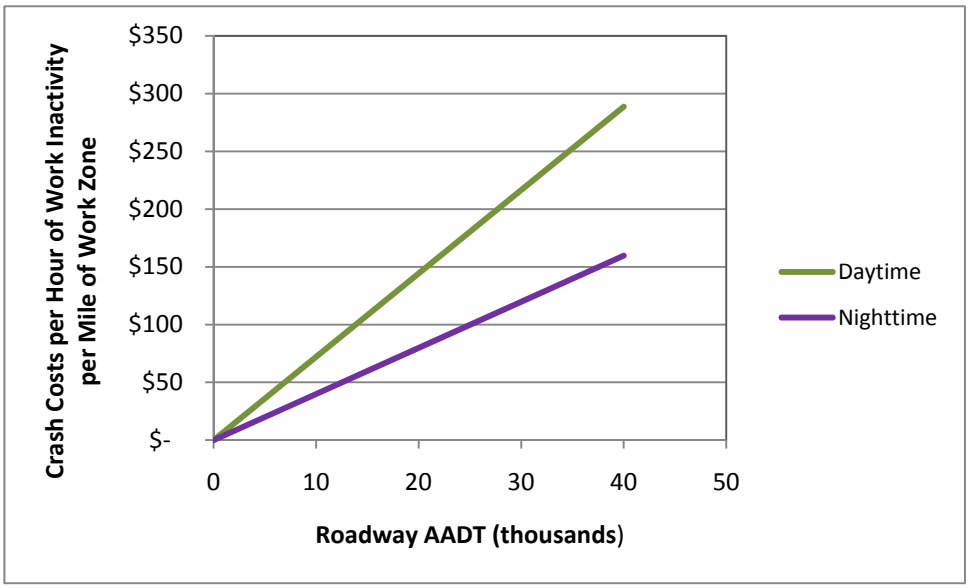


Figure A-23. Total Crash Cost Functions for Rural Two-Lane Highway Segments Between Intersections: Work Zone Inactive without Temporary Lane Closures.

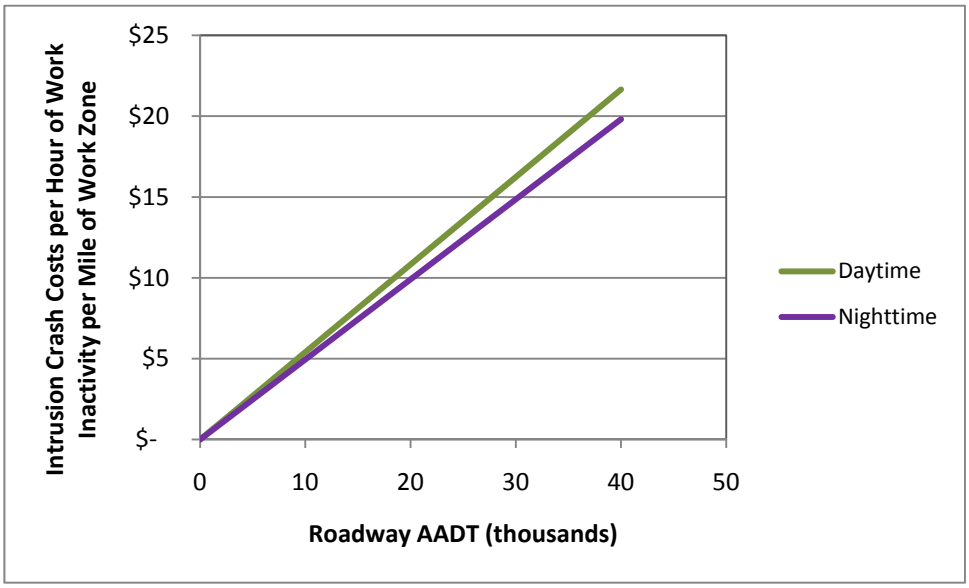


Figure A-24. Intrusion Crash Cost Functions for Rural Two-Lane Highway Segments Between Intersections: Work Zone Inactive without Temporary Lane Closures.