Technical Report Documentation Page

1. Report No. FHWA/TX-10/0-5771-P1	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle IMPLEMENTATION GUIDE FOR MONITORING WORK ZONE SAFETY AND MOBILITY IMPACTS		5. Report Date August 2008 Published: September 2009 6. Performing Organization Code
7. Author(s) Gerald L. Ullman, Richard J. Porter, and Ganesh Karkee		8. Performing Organization Report No. Product 0-5771-P1
9. Performing Organization Name and Address Texas Transportation Institute The Texas A&M University System College Station, Texas 77843-3135		10. Work Unit No. (TRAIS) 11. Contract or Grant No. Project 0-5771
12. Sponsoring Agency Name and Address Texas Department of Transportation Research and Technology Implementation Office P.O. Box 5080 Austin, Texas 78763-5080		13. Type of Report and Period Covered Product: September 2006 – August 2008 14. Sponsoring Agency Code

15. Supplementary Notes

Project performed in cooperation with the Texas Department of Transportation and the Federal Highway Administration.
Project Title: Developing a Work Zone Safety and Mobility Performance Monitoring Plan for Texas
URL: http://tti.tamu.edu/documents/0-5771-P1.pdf

16. Abstract

This implementation guide describes the conceptual framework, data requirements, and computational procedures for determining the safety and mobility impacts of work zones in Texas. Researchers designed the framework and procedures to assist district-level personnel who have responsibility for work zone safety and mobility impact reviews of significant projects as required by Texas Department of Transportation (TxDOT) policy.

In this guide, researchers describe the types of impact monitoring and analysis that can occur as part of on-going project activities and those that can be performed during post-project reviews. Analysis procedures are presented to assist in determining which projects should be targeted for regular reviews of crash data during the project, as well as the increase in crash frequency that is indicative of unusual safety concerns that should be investigated further through field observations. Researchers also present analysis procedures to guide district personnel in determining the queue lengths, individual vehicle delays, and total vehicle-hours of delay that are created during temporary lane closures in a project.

17. Key Words Work Zone, Temporary Traffic Control, Performance Measures, Traffic Impacts		18. Distribution Statement No restrictions. This document is available to the public through NTIS: National Technical Information Service Springfield, Virginia 22161 http://www.ntis.gov	
19. Security Classif.(of this report) Unclassified	20. Security Classif.(of this page) Unclassified	21. No. of Pages 46	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

IMPLEMENTATION GUIDE FOR MONITORING WORK ZONE SAFETY AND MOBILITY IMPACTS

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Product 0-5771-P1
Project 0-5771
Project Title: Developing a Work Zone Safety and Mobility Performance Monitoring Plan for Texas

August 2008
Published: September 2009

Texas Transportation Institute
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College Station, Texas 77843-3135

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Section 1

Overview

The Federal Highway Administration (FHWA) final rule on work zone safety and mobility requires states to implement work zone performance monitoring programs (*1*). Areas that the FHWA believes should be encompassed by such a program include:

- delay,
- user costs,
- exposure,
- safety, and
- public perception.

This implementation guide describes a plan for monitoring the safety and mobility impacts of selected work zones within Texas. The intent of the plan is to provide objective data that district safety review team (DSRT) personnel can use during both ongoing (phase 3) and post-project (phase 4) reviews of significant project transportation management plans (TMPs) as defined by the Texas Department of Transportation (TxDOT) work zone safety and mobility policy (*2*). Ultimately, these data could also be consolidated across multiple districts to provide regional or even statewide assessments of work zone policies and TMP procedures and identify areas for further improvement.

Section 2
A Work Zone Safety and Mobility Monitoring Plan

Description

A work zone safety and mobility monitoring plan involves the collection and analysis of roadway, work zone, and traffic data during a particular project. Public perception information, obtained either in terms of complaints received or as results of formal surveys of motorists, businesses, or nearby residents can supplement these data.

Ongoing (Phase 3) Monitoring of Work Zone Impacts

Work Zone Safety

Ongoing project monitoring is an integral part of the TxDOT work zone policy. Regular inspections of temporary traffic control at the project, using Form 599, allow for the quick identification and correction of traffic control deficiencies. The policy encourages the districts to establish a district safety review team to monitor and periodically review available information regarding the relative levels of safety at each project. The information may include completed Form 599s, project diary notes, field observations, public complaints, and monitoring and evaluation of available crash data. Of these, ongoing monitoring and assessment of crash data provides the most direct indicator of safety impacts.

Work zone crash data monitoring and assessment does require a manpower investment. The DSRT or other district staff assigned to safety monitoring responsibilities will need to receive crash information from each project of interest in real-time or near real-time. Personnel will need to compile and analyze these data, and the DSRT may need to conduct follow-up field visits to identify or diagnose possible safety problems implied by data analysis results. The state crash records information system (CRIS) can facilitate this monitoring process.

(continued…)

Work Zone Safety (*continued*)

The level of safety monitoring that is possible depends on the duration and length of project as well as the amount of traffic using the roadway. Longer duration and lengthier projects on high-volume roadways may allow for quarterly or even monthly assessments of safety performance or may allow the project to be divided into subsections to more closely assess the safety implications of a particular work zone strategy or temporary design feature. Conversely, shorter projects of less duration may not be conducive at all to active monitoring of safety using available crash data. Even if a project is not conducive to formal monitoring of crash data on a periodic basis, an abnormally high frequency of crashes occurring in a relatively short period of time may be indicative of a safety problem. Section 3 provides procedures for identifying projects suitable for ongoing safety monitoring using crash data, identifying appropriate monitoring parameters (monitoring frequency, possible assessment by subsections), and identifying when a project is experiencing an abnormally high number of crashes.

Work Zone Mobility

A reduction in available travel lanes reduces roadway capacity to a level below the traffic demand attempting to pass through the work zone will create work zone mobility impacts. The capacity reduction creates a traffic queue, which results in motorist delays and additional road user costs. Queues can also increase the frequency of rear-end traffic crashes.

Queues can occur on all projects, regardless of whether or not they are designated as significant by current TxDOT policy. In fact, short-term lane closures (as defined in the *Texas Manual of Uniform Traffic Control Devices* [TMUTCD]) performed either during the day or at night are the most frequent causes of traffic queues in work zones (*3*).

The creation of queues is undesirable, but sometimes unavoidable. Work zone mobility monitoring and assessment provides objective data to aid in project management efforts to limit the occurrence of unnecessary queues or queues during restricted time periods. In fact, such monitoring allows for computation of actual road user costs created by time period restriction violations and could be useful in assessing liquidated damages, contractor penalties, or lane rental rates associated with the temporary lane closures. Mobility monitoring can also ensure the proper positioning of appropriate temporary traffic control features warning of the lane closure and of possible slowdowns upstream of any queues that develop.

(continued…)

Work Zone Mobility (*continued*)

For projects located on facilities where electronic surveillance is present, project personnel must document the location and time periods of the lane closures. District personnel can then estimate queue lengths, individual user delays, and total vehicular delay for each lane closure period from the speeds and volumes from sensor locations upstream of the lane closure. For projects located outside the limits of a surveillance system (or if work zone requires the traffic sensors in the section to be deactivated), field personnel must provide the monitoring. Fortunately, procedures exist to allow simple documentation of the start and end times of any traffic queue formation, as well as the periodic estimate of the length of the queue between these times. The analyst then estimates speeds and delays based on the queue length data. Section 4 provides these procedures, as well as those for using traffic surveillance data for monitoring purposes.

Post-Project (Phase 4) Assessment of Work Zone Impacts

Work Zone Safety

Whereas monitoring efforts during a project (phase 3) simply focus on the detection of an unusually large number of crashes that may be indicative of the need for corrective actions within the project itself, assessment efforts in the post-project period serve two purposes:

- establishing how work zone projects overall affect crash expectations (i.e., what increase in crash frequencies is "normal" for this type of project on this type of facility), and
- evaluating how particular strategies or features used within work zones are affecting crashes (i.e., how much of an effect the strategy or feature has upon safety).

Initially, it may be possible to identify general trends across similar projects by simply comparing absolute frequencies to historical averages obtained during phase 3 monitoring. For example, a district may find that most of the widening projects on freeways in its district experience a 20 – 40 percent increase in crash frequency relative to the three prior years on those same freeway segments. This range could serve as the threshold that future phase 3 monitoring of freeway widening projects are compared against to determine if there is a potential problem. Likewise, a district may find that each widening project in the vicinity of a high-volume entrance ramp experiences an increase in crashes that far exceeds this 40 percent "normal" range. Upon further investigation, the district notes that all such projects have had their acceleration lanes significantly shortened during the project.

(continued…)

Work Zone Safety (*continued*)

Although such qualitative assessments may be useful for periodic district or regional reviews, there will be instances where district personnel desire more specific numeric estimates. These efforts typically require the use of comparison sites and fairly complex analysis techniques (e.g., Empirical Bayes) that are best handled by those with formal training in this area.

Work Zone Mobility

A post-project (phase 4) assessment of mobility impacts for a particular project should differentiate between the time periods in which they occurred. The analyst should define measures on the basis of a pre-determined acceptable threshold of impacts. Examples of these types of performance measures are summarized below (note that shaded values are simply examples of the types of thresholds that could be established based on district, regional, or statewide preference).

- Vehicle-hours of delay
  - Total per project during lane closure activity
  - Average per hour of (daytime, nighttime, weekend) lane closure
  - Percent that occurred when delays exceeded 20 minutes per vehicle (stratified according to daytime, nighttime, weekend lane closure period)
  - Percent that occurred when lane closure queue lengths were 0.5 miles or longer (stratified according to daytime, nighttime, weekend lane closure period)
- Individual vehicle delay (minutes per vehicle)
  - Average per hour of (daytime, nighttime, weekend) lane closure
  - Percent of lane closure hours when individual vehicle delay exceeded 20 minutes per vehicle (stratified according to daytime, nighttime, weekend lane closure period)
- Queues caused by lane closures (miles)
  - Average length per hour of (daytime, nighttime, weekend) lane closure
  - Percent of (daytime, nighttime, weekend) lane closure hours creating a queue
  - Percent of (daytime, nighttime, weekend) lane closure hours creating a queue > 0.5 miles

(continued…)

Work Zone Mobility (*continued*)

The district should assess these measures on an individual project basis to evaluate the effectiveness of the overall TMP. Then, the measures can be aggregated across multiple projects of similar types to achieve district or regional indicators, if desired. In addition, the district should compute performance measures that indicate t mobility impacts experienced across the district or region project workload, e.g.:

- percent of projects where average vehicle-hours of delay per hour of (daytime, nighttime, weekend) lane closure exceeds 100 vehicle-hours; and
- percent of projects with more than five percent of (daytime, nighttime, weekend) lane closure hours creating a queue.

Section 3
Procedures for Monitoring Work Zone Crashes

Introduction

This section provides guidance on three topics:

- determining the suitability of a project to be monitored using crash data,
- determining appropriate assessment intervals and subsection lengths for the project, and
- determining whether the crash frequency over a particular assessment period indicates an unusual reduction in safety within the project.

Generally speaking, safety is defined relative to the number of crashes or crash consequences (e.g., crashes by type or severity) *expected* to occur on a roadway segment, intersection, etc., during a specified time period and is estimated based on a "long-term average" of crash frequency or crash consequences over some time period. This average value is compared to the crashes actually occurring to determine whether there is evidence that a possible safety concern exists.

Data Requirements

The procedures in this section require the following information:

- an estimate of the crash rate for the segment under normal operating conditions where the work zone project will be located,
- the annual average daily traffic (AADT) expected through the project [or an estimate of the average daily traffic (ADT) obtained through a short-term traffic count at the site],
- the project segment length, and
- the duration of the project.

The segment length may be the length of the entire project or the length of a specific segment within the work zone boundaries. Analyzing shorter segment lengths with homogenous features can help assess whether changes in specific geometric and traffic control variables are having a significant effect on safety. Similarly, monitoring work zones frequently (e.g., every month) can more quickly capture possible safety concerns relative to changes in work phasing, specific work activities, and possibly the associated temporary traffic control strategies. However, sample size and statistical power become controlling issues in both cases.

Determining Project Suitability for Crash Data Monitoring

A district can use Figures 3-1 through 3-4 to determine the likelihood of detecting a significant increase in crash frequency at a particular project of a given length after a given period of time. The graphs represent a very high level (100 percent) increase in crashes from what is normally expected on the roadway segment in order to differentiate between work zones where a possible safety concern exists and work zones with only a small or moderate increase in crash risk such as typically occurs when a roadway undergoes rehabilitation and/or reconstruction.

To begin, one must determine the normal crash rate for the facility on which the project will be located. National numbers suggest that freeway and other access-controlled facilities experience approximately one crash per million vehicle miles (mvm). Crash rates on other roadway types are usually higher than this value. However, districts should use actual crash rate data for the project segment of interest in lieu of these national estimates whenever possible, using the following equation:

$$\text{Normal crash rate} = 365 \bullet (\Sigma \# \text{ crashes}_{\text{year } i} \bullet \text{AADT}_{\text{year } i})/1000000$$

where,

i represents each of the three years of data immediately preceding the onset of work on the project.

A district should select the figure that most closely corresponds to the normal crash rate for the project segment. The AADT of the roadway segment expected during the project and the length of the project are used to assess the minimum monitoring interval of the project for which a crash increase of 100 percent or more could be judged as significant and deemed worthy of further assessment by field personnel (as opposed to being just a random occurrence). If the project duration is less than the minimum monitoring interval required to detect a significant increase in crashes, there is limited value in monitoring the crash experiences in real-time during the project.

Determining Appropriate Assessment Intervals and Subsection Lengths

Districts can also use Figures 3-1 through 3-4 to assess how quickly significant crash increases can be identified on a particular project (i.e., the monitoring interval that can be used). Likewise, the figures allow districts to assess whether the overall project can be divided into subsections and monitored on a real-time basis. An example later in this section illustrates how this assessment can be performed.

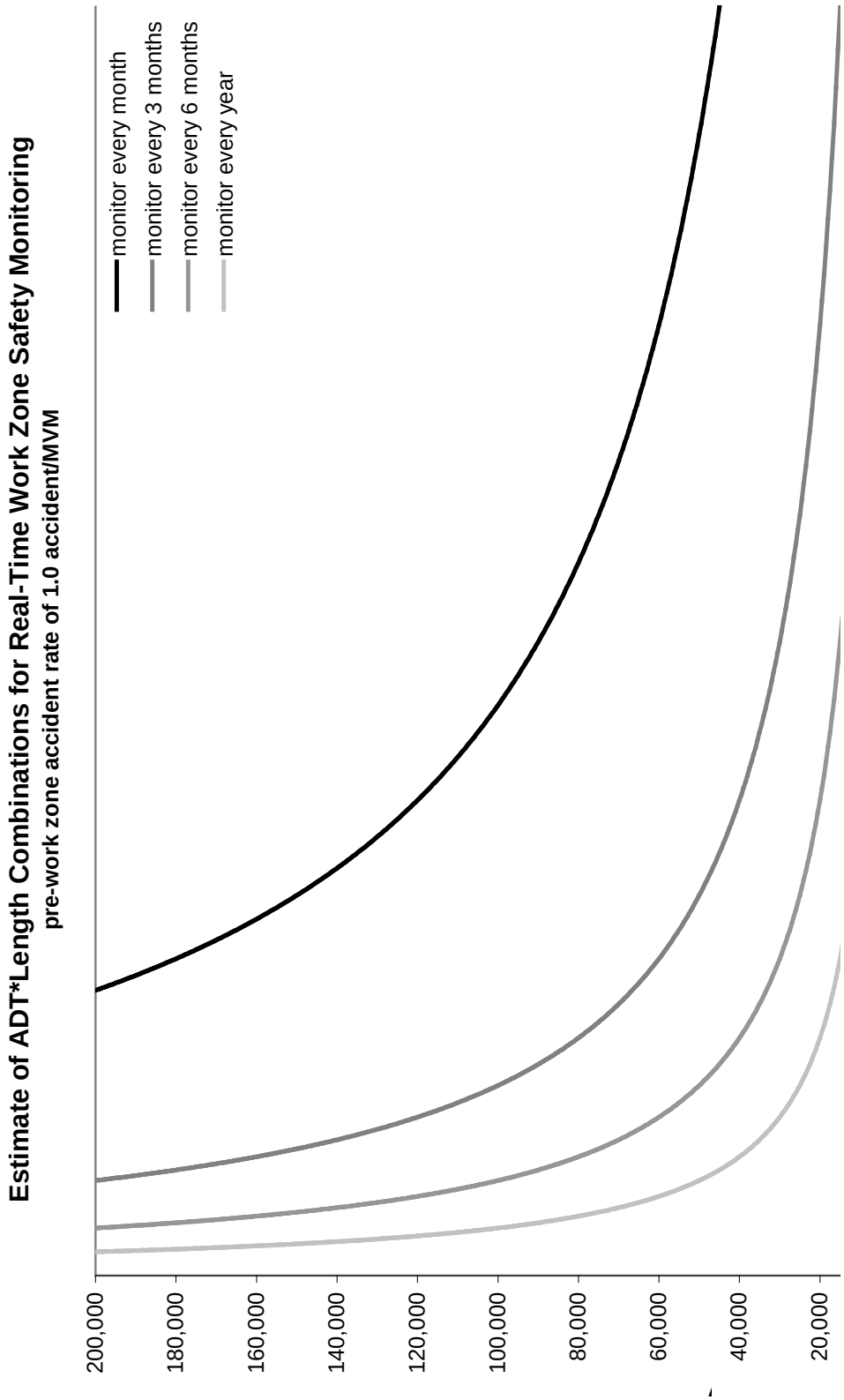


Figure 3-1. ADT and Project Length Combinations That Allow Detection of Significant Increases in Crashes during the Project (Pre-Project Crash Rate of 0.5 Crashes/MVM).

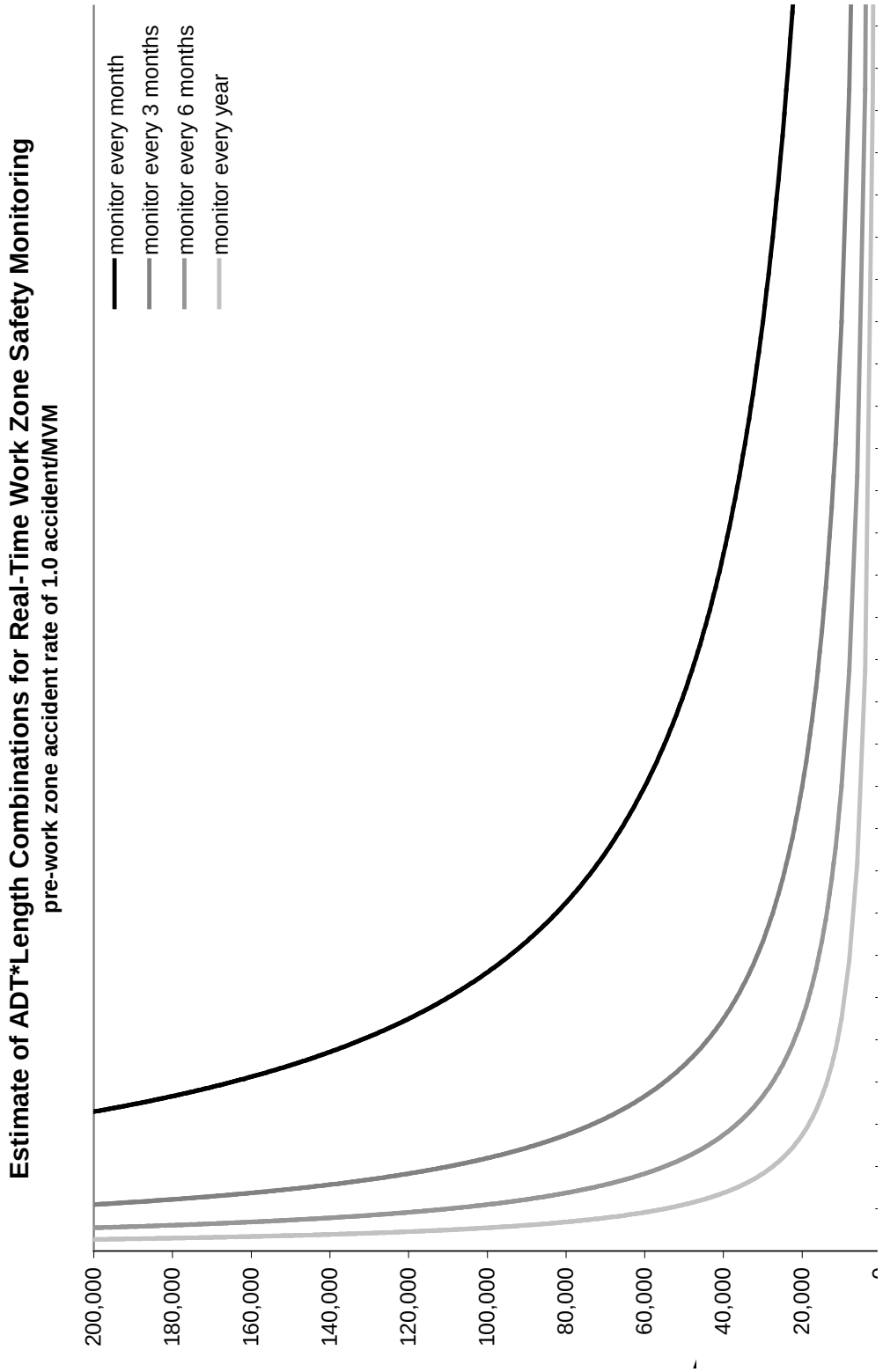


Figure 3-2. ADT and Project Length Combinations That Allow Detection of Significant Increases in Crashes during the Project (Pre-Project Crash Rate of 1.0 Crashes/MVM).

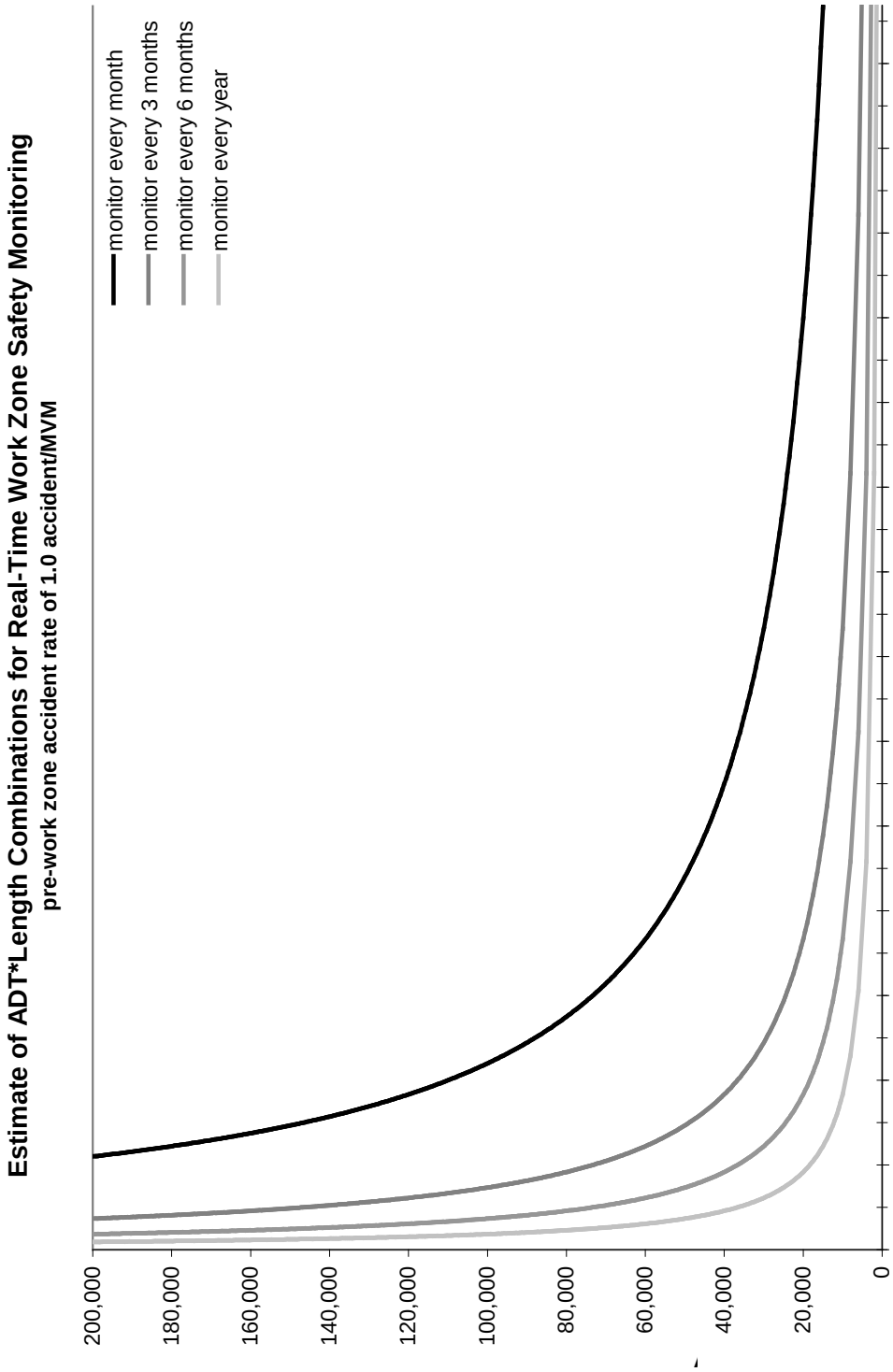


Figure 3-3. ADT and Project Length Combinations That Allow Detection of Significant Increases in Crashes during the Project (Pre-Project Crash Rate of 1.5 Crashes/MVM).

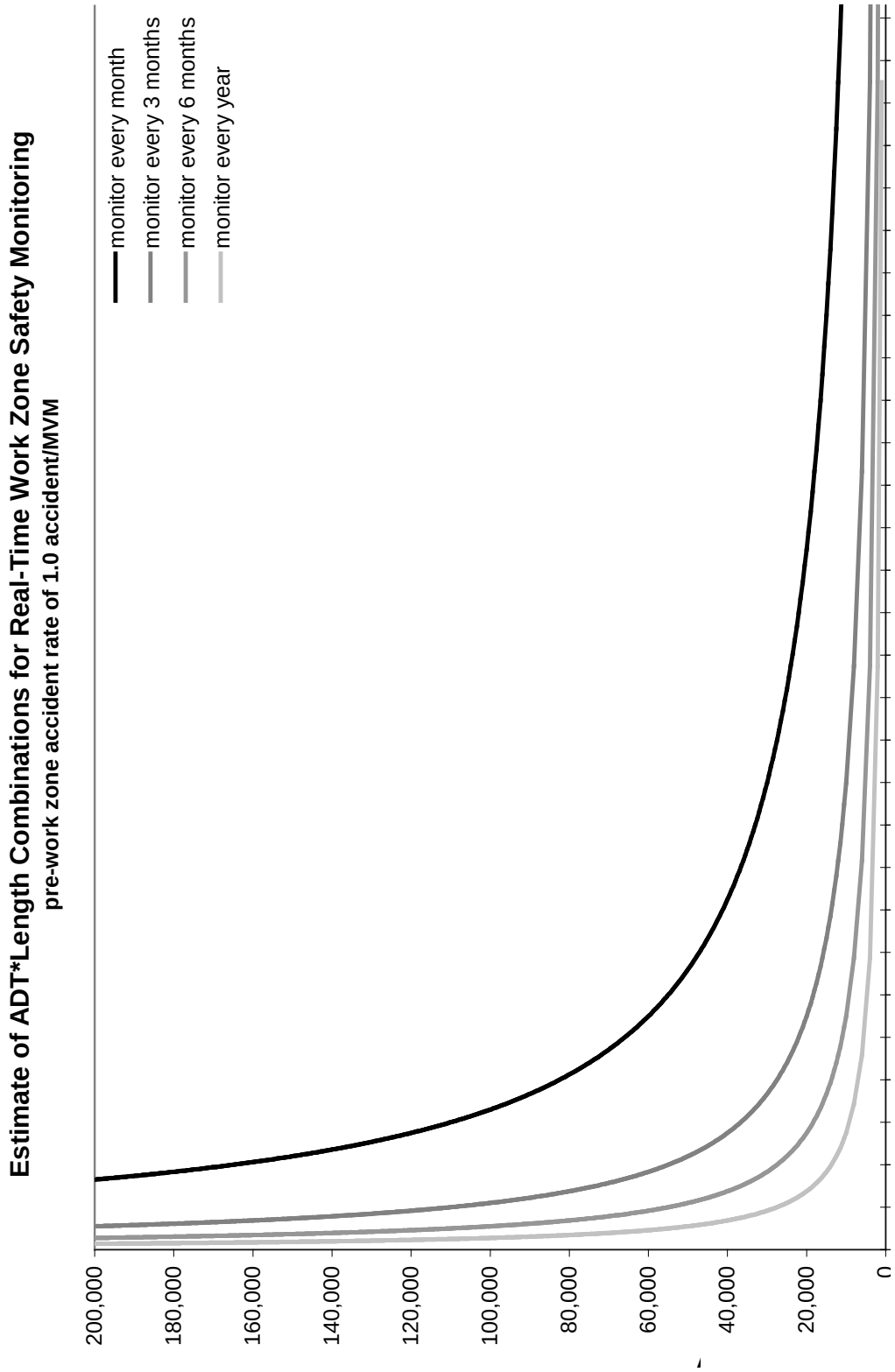


Figure 3-4. ADT and Project Length Combinations That Allow Detection of Significant Increases in Crashes during the Project (Pre-Project Crash Rate of 2.0 Crashes/MVM).

Identifying Unusually High Increases in Crashes during the Project

Whereas the previous figures in this section help determine which projects are best-suited to ongoing safety monitoring using crash data, districts must also determine whether the crashes occurring at a project far exceed what is "normal" or expected for that work zone, indicating possible safety concerns that need to be investigated more thoroughly. To accomplish this, districts compare the crashes actually occurring over the monitoring period of interest to the previous three-year average number of crashes on that roadway segment.

Three computational steps are required:

Step 1: Determine the number of crashes occurring in the project segment during the period of interest.

Step 2: Estimate what would have been the crashes expected in the segment during the same time period had the work zone not been there.

Step 3: Use Figure 3-5 to determine whether the crashes actually occurring are significantly higher than what is expected.

To estimate the crashes normally expected in the segment, the total number of crashes in the three-year period before the project begins is adjusted to account for any changes in traffic demand occurring over time:

$\pi = 0.33 \bullet rtf \bullet \Sigma$crashes in three-year period before the work zone begins

where,

r_{tf} = ratio of AADT in the current year to that of the average AADT in the three-year before period.

Historically, research has shown that crash rates increase between 20 and 40 percent when a work zone is present, depending on project characteristics, roadway type, etc. Therefore, Figure 3-5 shows three threshold levels of significance. The lower line represents the threshold number of crashes that would need to occur in the work zone before any indication of a crash rate increase would exist. Meanwhile, the upper two lines represent the crash frequency that would be required to indicate an increase that is 20 or 40 percent higher than what would normally be expected, respectively. In other words, actual crash frequencies that fall above these lines indicate a greater-than-typical increase in crashes, which would imply possible safety concerns that a district should investigate more thoroughly.

Districts should consult the appendix for additional details on this procedure, if desired.

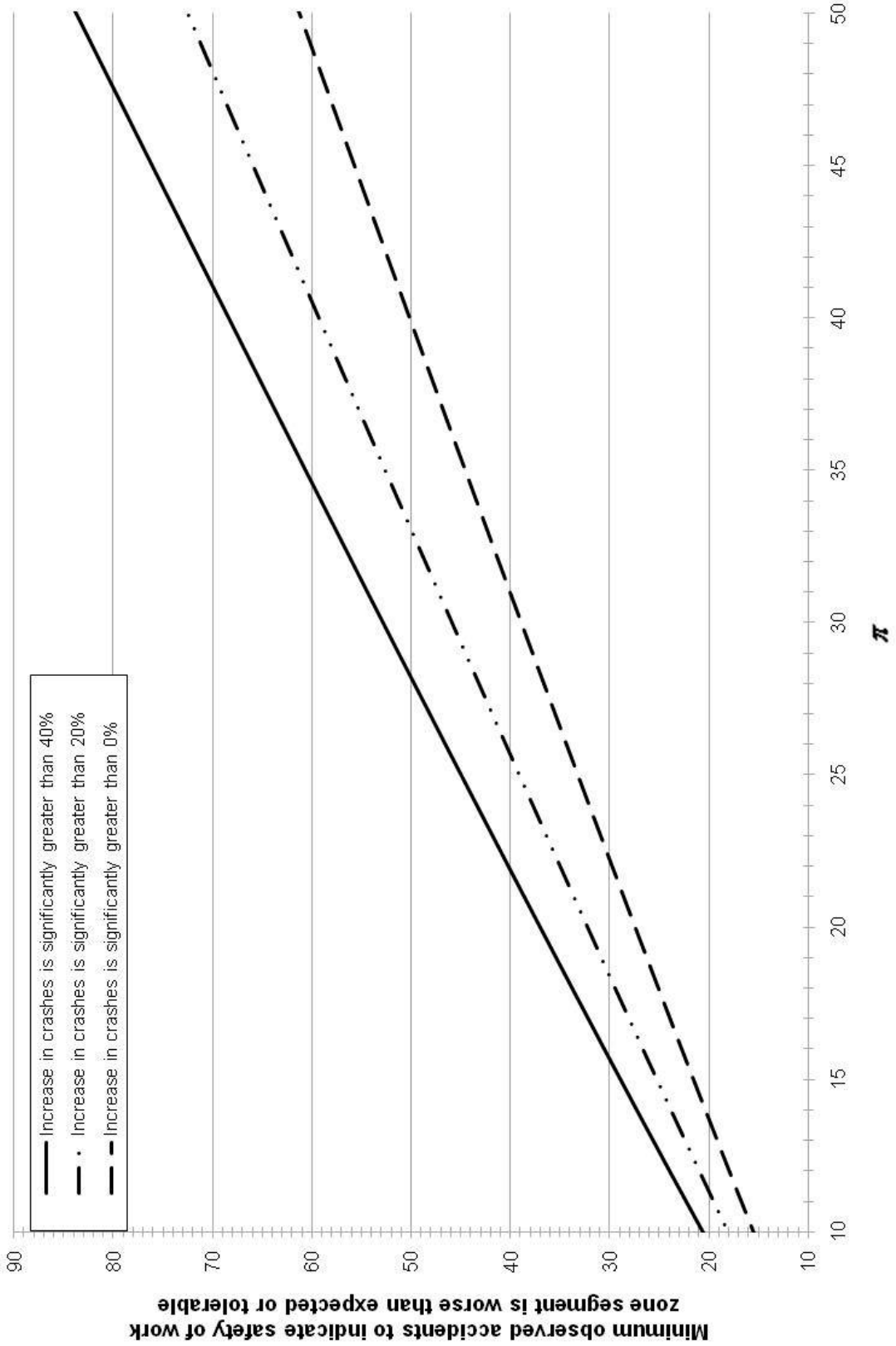


Figure 3-5. Number of Crashes during the Project Evaluation Period That Indicate a Significant Reduction in Safety.

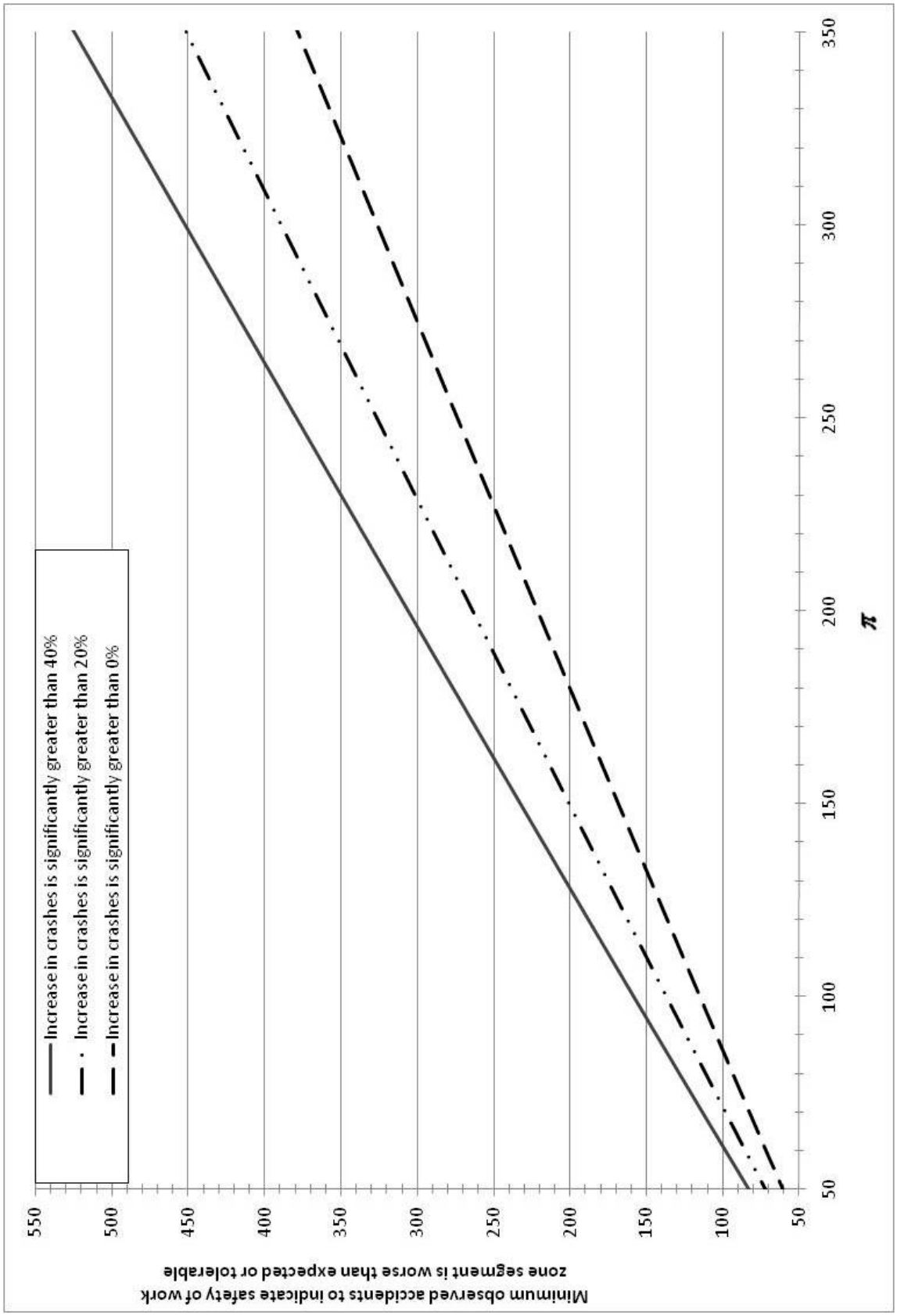


Figure 3-5. Number of Crashes during the Project Evaluation Period That Indicate a Significant Reduction in Safety (Continued).

Example

A 3.5-mile pavement rehabilitation project is located in both directions of a six-lane divided freeway with an ADT of approximately 120,000 vehicles per day. The project began on August 1, 2007, and the district has the first three months of crash data available (see Table 3-1). A district engineer wishes to determine if the work zone experienced significantly greater numbers of crashes, more than what the district typically experiences for that type of project (a 20 percent increase in this district is typical). The district engineer compares the data on a monthly and quarterly basis. Traffic volumes remained fairly constant over the last four years, including daily volumes through the work zone.

Table 3-1. Number of Crashes in Work Zone for Both Directions of Travel.

Month	Number of Crashes
August 2004	8
September 2004	7
October 2004	18
August 2005	15
September 2005	10
October 2005	14
August 2006	15
September 2006	23
October 2006	25
August 2007	21
September 2007	17
October 2007	21

August comparison:

Number of crashes actually occurring = 21

$$\pi = 0.33 r_{tf} K = 0.33 \bullet 1 \bullet (8 + 15 + 15) = 12.5$$

Using Figure 3-5, the minimum number of crashes that would indicate an increase of more than 20 percent is 22. Therefore, crashes on this segment were not higher than normally expected in August for this type of work zone.

August–October comparison:

Number of crashes actually occurring = 21+17+21 = 59

$$\pi = 0.33 r_{tf} K = 0.33 \bullet 1 \bullet (8 + 7 + 18 + 15 + 10 + 14 + 15 + 23 + 25) = 44.6$$

Again using Figure 3-5, the minimum number of crashes that would indicate an increase of more than 20 percent is 65. Therefore, there is not enough evidence to conclude that safety on this segment was worse than what the district typically experiences on this type of project during that three-month time period.

Section 4
Procedures for Monitoring Work Zone Mobility

Introduction

In this section, two approaches to monitoring travel mobility impacts at work zones are described:

- Approach 1: Collecting and analyzing work zone mobility data obtained from electronic traffic surveillance systems during temporary lane closures.
- Approach 2: Collecting and analyzing work zone mobility data obtained from field personnel estimates of traffic queues during temporary lane closures.

In both instances, the analyst determines three primary performance measures:

- queue lengths and durations,
- total vehicle delay, and
- average individual delay.

Data Requirements

Both approaches require the following data:

- Work zone project information
  - Project milepoint limits
  - Begin and end date
    - For entire project
    - For each major construction phase
  - Roadway cross-section within the work zone
- Daily project activity
  - Begin and end times of work activity
  - Begin and end times of each lane closure
  - Number of lanes closed during each closure
  - Location and direction of travel for each lane closure

Construction plans or contract documents typically contain the necessary project information. Meanwhile, project inspectors will normally document daily project activity in the inspector diary (although in some cases, the district may need to emphasize the importance of specific documentation of the temporary lane closure details to the inspectors at the start of the project).

(continued…)

Data Requirements (*continued*)

When using an electronic traffic surveillance system (Approach 1), mobility monitoring of the work zone requires the following data:

- Location of traffic sensors within and upstream of the project limits (working sensors are needed for a distance of at least two miles upstream of lane closure locations to determine the extent of queue buildup.
- Hourly summaries of volumes and speeds at each sensor are needed during time of work activity and temporary lane closures (and for one hour afterwards to allow for the possible need for queue dissipation after removing the closure). Shorter time periods (e.g., 15-minute intervals) could also be used, if desired, but would increase the computational workload required.

Mobility monitoring of projects not located within the limits on an electronic traffic surveillance system (Approach 2) requires estimates of hourly traffic volumes and queuing patterns:

- If actual traffic count data are not available, project personnel must obtain an AADT estimate for the roadway segment along with an estimate of the hour-by-hour distribution of that AADT over a 24-hour period (from automatic traffic recorder or similar data in the region).
- During each temporary lane closure period, project personnel will need to manually record the following:
    - Time when a traffic queue starts to build at the work zone (this may be the same as the begin time of the temporary lane closure). If the queue begins at a location other than the transition taper of the temporary lane closure, project personnel must also document the begin point of the queue.
    - Periodically (hourly is preferable) during the times when a queue is present, project personnel must record the approximate length of the queue, and the time of the estimate.
    - Project personnel can collect these data on simple forms, such as illustrated in Table 4-1. Table 4-2 shows an example of how the table might be completed for the first few lane closure periods of a project.

Table 4-1. Queue Length Documentation Form.

Project: _____

Date	Times of Work Activity				Times of Work Activity with Lane Closures					Queuing During Work Activity with Lane Closures							
	Time Begin	Time End	Dir of Travel	Loc of Work	Time Begin	Time End	Dir of Travel	Loc of Closure	# Lns Closed	Time Q Begins	Time Q Ends	Q Length @ Hr 1	Q Length @ Hr 2	Q Length @ Hr 3	Q Length @ Hr 4	Q Length @ Hr 5	Q Length @ Hr 6

Notes:
Estimates of queue lengths approximately every hour are desired. However, the time can be adjusted slightly as necessary, as long as the reporting time is noted.
Locations of work and lane closures can be noted using mile markers, stations, etc.

Table 4-2. Example of Queue Length Documentation Form Data Entry.

Project: __I-45 (03-245BR5)_____

Date	Times of Work Activity				Times of Work Activity with Lane Closures					Queuing During Work Activity with Lane Closures							
	Time Begin	Time End	Dir of Travel	Loc of Work	Time Begin	Time End	Dir of Travel	Loc of Closure	# Lns Closed	Time Q Begins	Time Q Ends	Q Length @ Hr 1	Q Length @ Hr 2	Q Length @ Hr 3	Q Length @ Hr 4	Q Length @ Hr 5	Q Length @ Hr 6
5/18	8 am	6 pm	NB	MM 33													
5/19																	
5/20	8 pm	6 am	NB	MM 31	9 pm	4 am	NB	MM 31	1	9 pm	1 am	2 mi @ 9:30 pm	2.5 mi @ 10 pm	1.5 mi @ 11:15 pm	1.0 mi @ 12 pm		

Notes:
Estimates of queue lengths approximately every hour are desired. However, the time can be adjusted slightly as necessary, as long as the reporting time is noted
Locations of work and lane closures can be noted using mile markers, stations, etc.

Computations – Electronic Traffic Surveillance System Approach

After obtaining the work zone and electronic surveillance data, the following steps are required to calculate estimated delays and queues associated with each work activity period in which a temporary lane closure was employed:

Step 1: Compare Speeds and Volumes between Sensors to Determine Duration and Extent of Queuing

Beginning with the first sensor located upstream of the temporary lane closure, identify the hour when the lane closure began. Next, examine the average speeds each hour after that period. Average speeds below 30 mph can be used to indicate queue presence at a sensor location. Perform this assessment at each sensor location in sequence upstream until reaching a sensor where speeds are not below 30 mph during the hours of the lane closure. Assume that the upstream end of the queue is midway between that sensor and the next sensor downstream.

Figure 4-1 illustrates this process. Sensors are located 0.2 miles, 0.8 miles, and 1.3 miles upstream of the temporary lane closure. Project diary information indicates that the lane closure began at 9:00 am and ended at 3:30 pm. The analysis of speeds at the upstream sensor locations indicates that a queue began to develop at approximately 11:30 am at the first sensor and then grew upstream and reduced speeds at the second sensor at about 12:30 pm. The queue did not extend back to the third sensor, since speeds never did drop below 30 mph at that location during the hours of work activity. Therefore, the estimated queue lengths each hour were:

11:30 am	0 (queue begins)
12:00 pm	0.2 + (0.6/2) = 0.5 miles
1:00 pm	0.2 + 0.6 + (0.5/2) = 1.05 miles
2:00 pm	1.05 miles
3:00 pm	1.05 miles
3:30 pm	1.05 (lane closure ends)
4:00 pm	0 (queue ends)

(continued…)

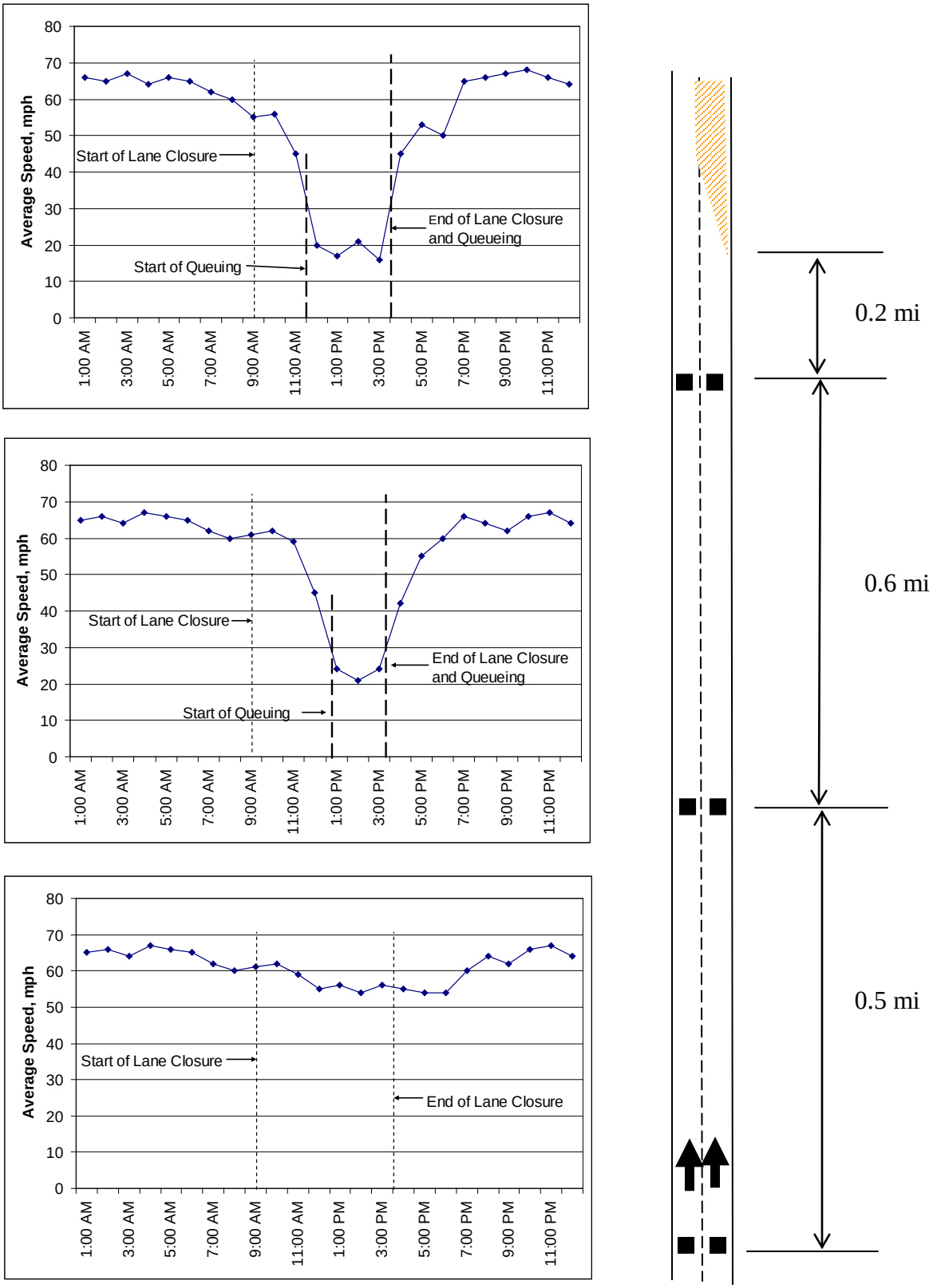


Figure 4-1. Example of Sensor Speed Analysis to Determine Duration and Length of Queue.

Computations – Electronic Traffic Surveillance System Approach (*continued*)

Step 2: Estimate Average Travel Times Through the Queue Each Hour

Estimate the average travel time through the queue by computing the travel time required to traverse each segment of the queue that is accounted for by a sensor location and then summing over all segments. For the illustration in Figure 4-1, assume that speeds at sensor 1 represent the 0.5 miles in queue immediately upstream of the closure, and sensor 2 represent the next 0.55 miles upstream. For each hour that a queue exists, divide these distances by average speeds measured at each sensor to determine the average travel time through each segment, and then sum the segment travel times to determine the total travel time in queue:

	Sensor 1 (0.5 mile coverage)		Sensor 2 (0.55 mile coverage)		Total Travel Time In Queue (min)
Hour	Speed (mph)	Travel Time (min)	Speed (mph)	Travel Time (min)	
12:00 pm	20	1.5	NA	NA	1.5
1:00 pm	17	1.8	24	1.4	3.2
2:00 pm	21	1.4	21	1.6	3.0
3:00 pm	16	1.9	24	1.4	3.3

User delay is then estimated by subtracting travel times that normally occur on that segment of roadway at the same time of day without the lane closure (based on an assumption of normal travel speeds) from the total time in queue. For the Figure 4-1 illustration, assuming that speeds during the day typically average 65 mph, the travel time over the 0.5 and 0.55 mile distances represented by each sensor location would be 0.4 and 0.5 minutes, respectively. Therefore, average vehicle delay through the queue each hour would be 1.1 minutes in the first hour (1.5 minutes – 0.4 minutes) and between 2.1 and 2.4 minutes (3.0 to 3.3 minutes – 0.9 minutes) for the next three hours.

Step 3: Compute Total Vehicle Delays through the Queue Each Hour

After estimating average delays per vehicle for each hour that the queue is present, one computes the total vehicle-hours of delay by multiplying the normal hourly volume by these average delay values. Normal volumes are used rather than those actually measured by the sensors in the queue. These sensors measure queue discharge rates rather than approach volumes. More importantly, there is likely to be considerable real-time diversion that naturally occurs at the site that will significantly reduce the approach volumes on that facility. Although actual volumes on that roadway are lower, volumes on other routes in the corridor or region will experience increases. More importantly, the alternative route taken by each of those diverting motorists will take longer than would have normally occurred if they had used that facility as planned (without a temporary lane closure present). Therefore, for purposes of simplicity, researchers recommend that the same average delay values be applied to both those vehicles passing through the queue and work zone and those diverting to other routes.

(continued…)

Computations – Electronic Traffic Surveillance System Approach (*continued*)

If the begin and end times of the lane closure and queue do not occur exactly on the hour, extrapolation techniques should be used to estimate the delays during that portion of an hour. Assuming that the hourly volumes on the facility are as shown below, the total vehicular delay experienced during this lane closure activity would be the following:

Hour	Normal Hourly Volume (vph)	Average Delay per Vehicle (min)	Total Vehicle-Hours of Delay
11:30 am – 12:00 pm	2100	1.1	19.3*
12:00 – 1:00 pm	2300	1.1	42.2
1:00 – 2:00 pm	2450	2.3	93.2
2:00 – 3:00 pm	2500	2.1	87.5
3:00 – 3:30 pm	2600	2.4	52.0*
	TOTAL		294.2

* The hourly volume multiplied by the average delay per vehicle is then halved for each of these 30-minute periods when a queue is present.

Computations – Manual Queue Length Estimation Approach

Although electronic traffic surveillance data does allow for a detailed queue and delay analysis of each temporary lane closure that occurs on a project, the vast majority of roadway miles statewide are not instrumented with sensors to support this type of analysis. Situations without electronic surveillance data where temporary lane closures create traffic queues and delays require the use of manual estimation procedures. The queue length estimates collected using the form in Table 4-1 provides the main source of mobility impact data.

The steps associated with this computational approach are as follows:

Step 1: Estimate Normal Hourly Volumes on Roadway during Hours of Lane Closure

For most roadway locations, only AADT planning-level estimates will be available for use. One must first divide these 24-hour count estimates into hourly directional volumes. Often, one can apply the hourly distribution values from automatic traffic recorder (ATR) stations on similar types of facilities in the vicinity of the project to the AADT number at a location. The directional split of traffic will also need to be included in the computations. Usually, one can assume a 50/50 split by direction.

Step 2: Estimate the Capacity of the Work Zone

The 2000 *Highway Capacity Manual* (HCM) uses the following equation to estimate the traffic capacity of a short-term lane closure (*4*):

(continued…)

Computations – Manual Queue Length Estimation Approach (*continued*)

$c_a = (1{,}600 + I - R) \bullet f_{HV} \bullet N$

where,

c_a = work zone capacity (vehicles per hour)
I = work activity intensity adjustment (± 160 passenger cars per hour per lane)
R = volume on ramps within 500 ft of the lane closure (passenger cars per hour)
f_{HV} = adjustment for heavy vehicles
N = number of lanes open through the work zone

For the computations presented in this guide, an approximation of 1500 vehicles per hour per lane will usually suffice.

Step 3: Estimate the Normal Capacity of the Roadway

The HCM also provides procedures to estimate the normal traffic-carrying capacity of the roadway segment. Again, for the degree of accuracy targeted through these computations, the following approximations will usually suffice:

For 65- and 70-mph roadways:

2200 vehicles per hour per lane * number of lanes on the facility

For 60-mph roadways:

2000 vehicles per hour per lane * number of lanes on the facility

Step 4: Estimate Average Speed in Queue and Average Delay per Vehicle through Queue

The following equation, as used in the Queue and User cost Evaluation for Work Zones (QUEWZ) program, produces an estimate of the average speed in queue as a function of the normal roadway capacity and the capacity through the work zone (*5*):

$$\text{Average Speed in Queue} = \left(\frac{\textit{Free Flow Speed}}{2}\right)\left(1 - \left(1 - \frac{\textit{Work Zone Capacity}}{\textit{Normal Roadway Capacity}}\right)^{\frac{1}{2}}\right)$$

Substituting the suggested capacity estimates into the equation yields the following average speed in queue values:

(continued…)

Computations – Manual Queue Length Estimation Approach (*continued*)

Average Speed in Queue: 70-mph Roadways

Number of Lanes Open in Work Zone	Total Number of Lanes Per Direction of Travel		
	2	3	4
1	6.6	4.8	3.6
2		10.5	7.5
3			12.0

Average Speed in Queue: 65-mph Roadways

Number of Lanes Open in Work Zone	Total Number of Lanes Per Direction of Travel		
	2	3	4
1	6.1	3.9	3.1
2		9.2	6.6
3			10.5

(continued…)

Computations – Manual Queue Length Estimation Approach (*continued*)

Average Speed in Queue: 60-mph Roadways

Number of Lanes Open in Work Zone	Total Number of Lanes Per Direction of Travel		
	2	3	4
1	6.3	4.0	3.0
2		8.8	6.3
3			10.2

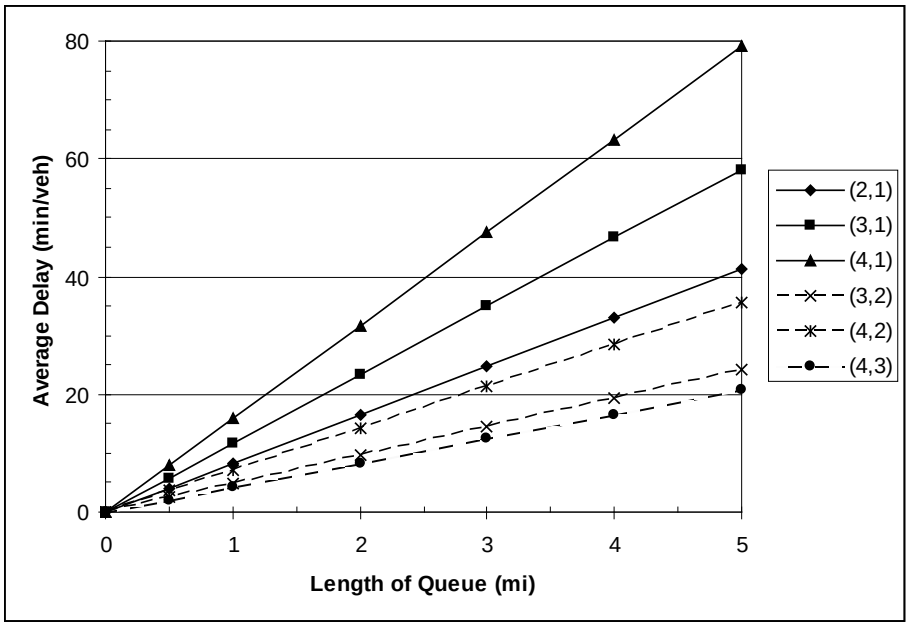
Assuming that these speeds are maintained, on average, through the entire length of queue documented on the forms, one can estimate average delays per vehicle as a function of the length of queue documented by the field personnel during the temporary lane closure period. Figures 4-2 through 4-4 are provided to simplify the computations.

Step 5: Compute Total Vehicle Delays through the Queue Each Hour

After estimating the average delay per vehicle due to the queue, one computes the total vehicle-hours of delay by multiplying the normal hourly volume by these average delay values. If the begin and end times of the lane closure and queue do not occur exactly on the hour, extrapolation techniques should be used to estimate the delays during that portion of an hour. Finally, this value should be added to the delay that occurs because vehicles travel slower through the length of work zone once passing through the queue. Figure 4-5 illustrates the additional delay that would be generated as a function of the length of the work zone, assuming that a vehicle travels at the speed equal to a capacity flow rate through the work zone. In most instances, the delays generated by the queue upstream of the work zone will far exceed any delays created by slower speeds through the work zone itself.

(continued…)

Computations – Manual Queue Length Estimation Approach (*continued*)



Note: (x,x) indicates (number of roadway lanes, number lanes open in work zone)

Figure 4-2. Effect of Queue Length on Average Delay (70-mph Roadways).

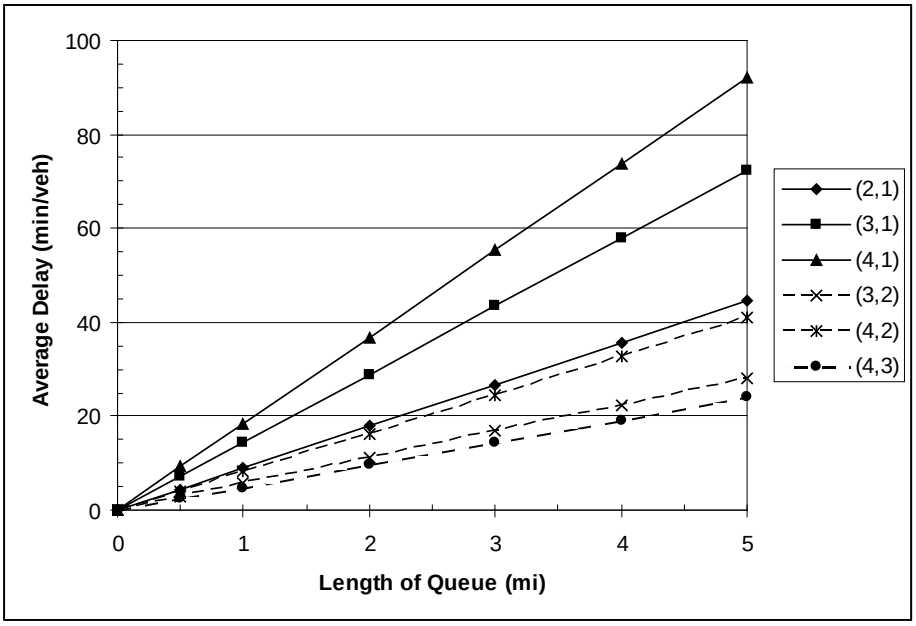


Figure 4-3. Effect of Queue Length on Average Delay (65-mph Roadways).

(continued…)

Computations – Manual Queue Length Estimation Approach (*continued*)

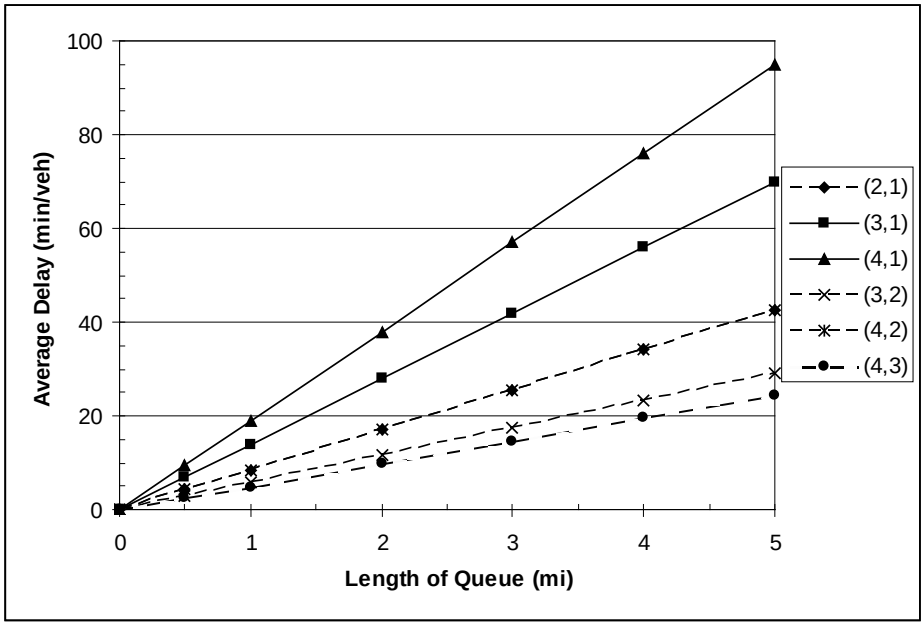


Figure 4-4. Effect of Queue Length on Delay (60-mph Roadways).

Figure 4-5. Effect of Work Zone Length on Average Delay.

Section 5

References

1. Work Zone Safety and Mobility. Code of Federal Regulations, Title 23, Part 630—Preconstruction Procedures, Subpart J. U.S. Government Printing Office, Washington, DC, September 9, 2004.
2. Work Zone Safety and Mobility Guidelines. Texas Department of Transportation, Austin, TX, July 2007.
3. *Texas Manual on Uniform Traffic Control Devices*. Texas Department of Transportation, Austin, TX, 2006.
4. *Highway Capacity Manual*. Transportation Research Board, National Research Council, Washington, DC, 2000.
5. Memmott, J.L. and C.L. Dudek. *Model to Calculate the Road User Costs at Work Zones*. Report No. FHWA/TX-83/20+292-1. Texas Transportation Institute, College Station, TX, September 1982.

Section 6

Appendix: Analyzing Work Zone Segments for Safety and Mobility Impacts

This section describes a procedure for analyzing work zone segments to determine if safety has declined more than the district expected or considers tolerable compared to normal operating conditions. A number of alternative comparisons can be made, especially with respect to defining safety during normal operating conditions. The one presented here is a commonly used comparison and is a balance between using recent data and accounting for seasonal fluctuations in extraneous crash-influencing factors (e.g., traffic, weather, and light conditions). The following data are needed:

- The number of accidents observed during the work zone period of interest on the work zone segment of interest (L);
- The total number of accidents on the same segment and during the same calendar period for three years prior (K);
- An estimate of the ratio of traffic in the work zone to traffic on the same segment and during the same calendar period for three years prior (r_{tf});
- The typical percent increase in crashes the district experiences in work zones of this type or is willing to tolerate ($\theta\%_{tolerable}$).

Four computational steps are then required:

Step 1: Estimate the safety of the work zone segment during the period of interest (λ) and the variance of that estimate

$$\lambda = L$$

$$VAR\{\lambda\} = L$$

(*continued…*)

Step 2: Estimate what would have been the safety of the segment during the same time period had the work zone not been there (π) and that variance of the estimate

$$\pi = 0.33 r_{tf} K$$

$$VAR\{\pi\} = 0.1089 r_{tf}{}^{2} K$$

One estimates the value for π using a "three-year average" of the crash frequency on the same segment and during the same calendar period while accounting for changes in traffic volumes. If traffic has grown and is greater in the work zone than on the same segment for the three years prior, r_{tf} will be greater than 1. If traffic has decreased as a result of general trends or implementation of travel demand management strategies introduced as part of the temporary traffic management plan, then r_{tf} will be less than 1. If no information on traffic volumes is available, a value of 1.0 should be used for r_{tf} .

Step 3: Estimate the tolerable work zone safety given the maximum safety reduction the district expects or is willing to accept ($\lambda_{tolerable}$) and the variance of that estimate

$$\lambda_{tolerable} = \left(\frac{\theta\%_{tolerable}}{100\%} + 1 \right) \bullet \pi$$

$$VAR\{\lambda_{tolerable}\} = \left(\frac{\theta\%_{tolerable}}{100\%} + 1 \right)^{2} \bullet VAR\{\pi\}$$

(continued…)

Step 4: Determine if the safety of the work zone segment during the period of interest (λ) is worse than the expected or tolerable work zone safety ($\lambda_{tolerable}$)

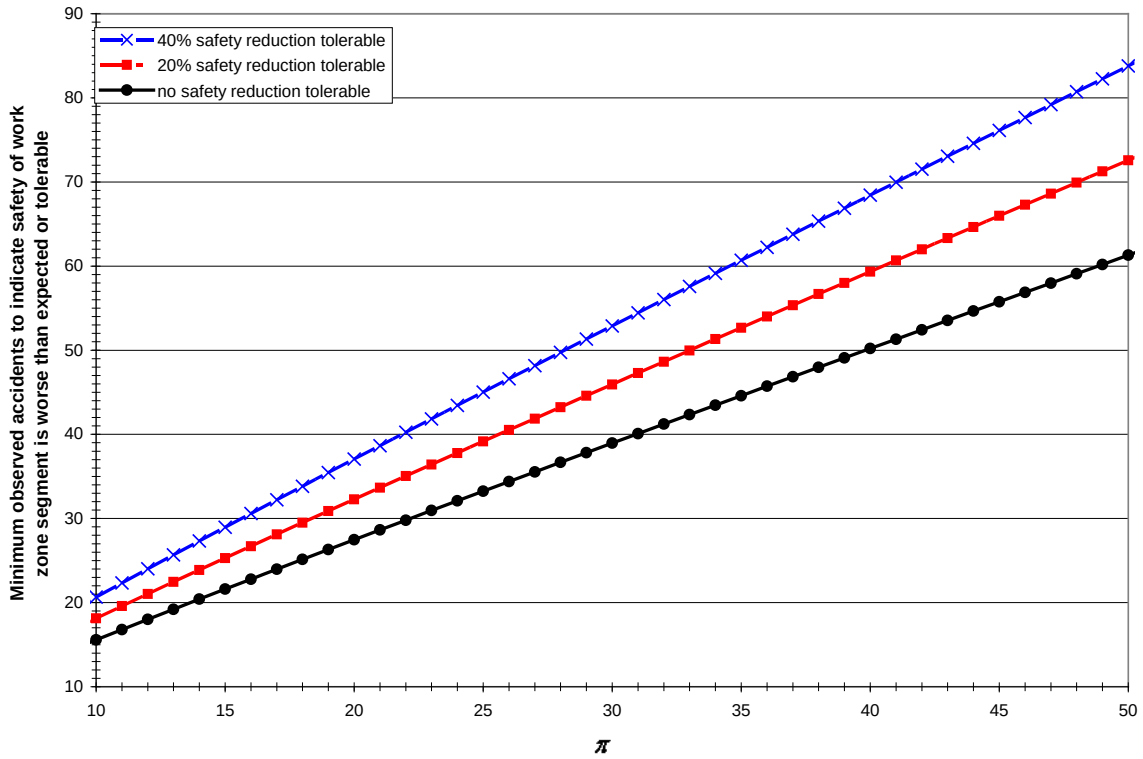
$\lambda > \lambda_{tolerable} + 1.282\sqrt{VAR\{\lambda\} + VAR\{\lambda_{tolerable}\}}$	Safety of the work zone segment during the period of interest is worse than expected or tolerable.

$\lambda \leq \lambda_{tolerable} + 1.282\sqrt{VAR\{\lambda\} + VAR\{\lambda_{tolerable}\}}$	There is not enough evidence to conclude that safety of the work zone segment during the period of interest is worse than expected or tolerable (with caveat explained below).

The use of 1.282 indicates that if we conclude the safety of the work zone segment during the period of interest (λ) is worse than the expected or tolerable work zone safety ($\lambda_{tolerable}$), the conclusion will be correct at least 90 percent of the time. With this confidence level, there is a chance (especially with small sample sizes) that we will conclude the safety of the work zone segment during the period of interest is not worse than the expected or tolerable work zone safety and be wrong. We can reduce the chance of the latter occurrence by decreasing our level of confidence in the first conclusion. However, this will then flag a larger number of work zone segments as being less safe than expected or tolerable. Seeing that each district will address work zone safety through a number of non-quantitative procedures (e.g., development and application of detailed work zone design and temporary traffic control guidance, formal inspections [e.g., Form 599 inspections], and informal inspections), a 90 percent confidence level is used to try to identify the most extreme safety changes with the highest level of confidence.

Steps 3 and 4 can be accomplished graphically using Figure A-1. The x-axis represents the safety of the segment during the time period of interest had the work zone not been there (π). Values on the y-axis indicate the minimum number of work zone accidents observed during the analysis period ($\lambda = L$) that would indicate safety has been reduced greater than expected or tolerable. Relationships are shown for three levels of tolerable safety reductions.

(continued…)



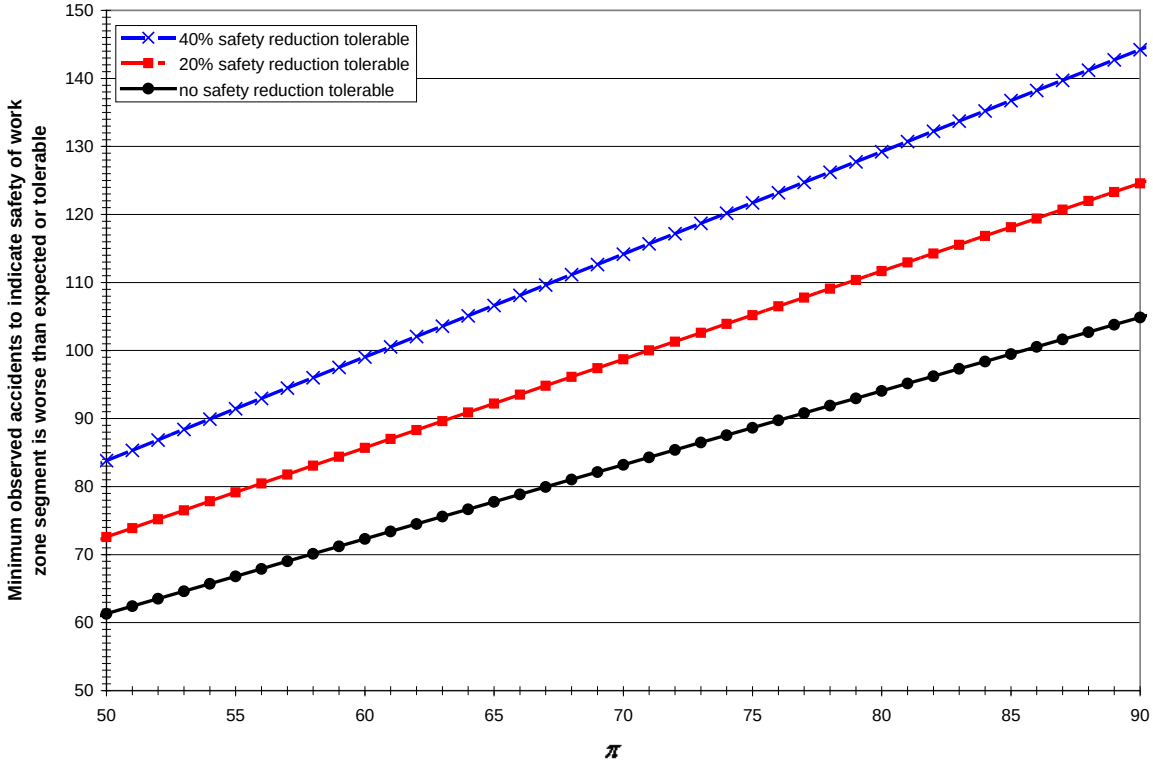


Figure A-1. Graphical Representation of Computational Steps 3 and 4.