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16. Abstract

In this report, Texas Transportation Institute researchers identify key work zone safety and mobility performance measures that the Texas Department of Transportation (TxDOT) should target as part of a work zone monitoring program within a district, region, or across the state. Analysis methodologies and computational procedures are presented that will yield the recommended performance measures. For mobility-based measures, researchers recommend that TxDOT target the collection of queue length and travel time delay data caused by temporary lane closures, as the congestion and delays that result from those activities are the simplest to isolate and attribute to the work activities themselves.

With regard to work zone safety monitoring, researchers developed procedures that aid a district or project engineer in determining which projects are most suitable for safety monitoring via a periodic review of crash statistics occurring before and during the project. Researchers developed graphs that indicate combinations of work zone length (or work zone segment length), average daily traffic, normal crash rate, and work zone phase or project direction that will most likely allow for reasonable inferences to be made regarding the relative level of safety being maintained within the project. Researchers also developed graphs to aid field or district personnel in quickly determining whether accident frequencies being experienced during a project are within, or above, tolerance limits for that type of project on that facility.

17. Key Words
Work Zone, Temporary Traffic Control, Performance Measures, Traffic Impacts

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MONITORING WORK ZONE SAFETY AND MOBILITY IMPACTS IN TEXAS

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DISCLAIMER

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the Federal Highway Administration (FHWA) or the Texas Department of Transportation (TxDOT). This report does not constitute a standard, specification, or regulation. This report is not intended for construction, bidding, or permit purposes. The engineer in charge of the project was Gerald L. Ullman, P.E. #66876.

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INTRODUCTION

STATEMENT OF THE PROBLEM

On September 9, 2004, the Federal Highway Administration (FHWA) amended its regulation (23 CFR Part 630) that governs traffic safety and mobility in highway and street work zones (*1*). The new rule requires state departments of transportation (DOTs) to consider and establish three key components as part of an overall work zone safety and mobility program:

- the required implementation of an overall, state-level work zone safety and mobility policy;
- the development and implementation of standard processes and procedures to support policy implementation, including procedures for work zone impacts assessment, analyzing work zone data, training, and process reviews; and
- the development and implementation of procedures to assess and manage work zone impacts on individual projects.

One of the more challenging provisions in the rule is the requirement for states to collect and analyze both safety and mobility data to support the initiation and enhancement of agency-level processes and procedures addressing work zone impacts. Specifically, states are to develop and implement systematic procedures that assess work zone impacts in project development, and states need to manage safety and mobility during project implementation (*1*). In addition,

> "States *shall* use field observations, available work zone crash data, and operational information to manage work zone impacts for specific projects during implementation. States shall continually pursue improvement of work zone safety and mobility by analyzing work zone crash and operational data from multiple projects to improve state processes and procedures. States should maintain elements of the data and information resources that are necessary to support these activities" (*1*).

This provision in the rule does not require states to necessarily collect new data during project implementation but to make use of whatever data they have available. However, FHWA does suggest that states may need to establish or improve processes to access, collate, and analyze that information to support safety and mobility policy activities (*2*). Furthermore, states are free to enhance whatever data they do collect to improve their evaluation and monitoring procedures. Obviously, the challenge facing TxDOT and other state DOTs is how to best measure and track safety and mobility impacts. Those activities need to support each agency's policy and procedural benchmarking and evaluation in a manner consistent with FHWA requirements.

PROJECT OBJECTIVES

The goal of this project was to identify and investigate methods and procedures that TxDOT could implement to meet the requirements of the FHWA work zone safety and mobility final rule. The specific objectives of this project were as follows:

- determine how available sources of information such as daily project inspector diaries, electronic traffic surveillance systems, and statewide crash records can be used to monitor work zone performance;
- determine what other data sources would be needed to monitor work zone safety and mobility;
- identify the most appropriate performance measures to use in monitoring work zone safety and mobility; and
- develop easy-to-implement procedures on how to compute those performance measures.

BACKGROUND

PREVIOUS EFFORTS TO MONITOR WORK ZONE PERFORMANCE

Overall, the use of performance measures in state DOTs is increasing and is currently being used to gauge agency efforts in the following areas:

- asset preservation,
- mobility and accessibility,
- operations and maintenance,
- safety,
- security,
- economic development,
- environmental,
- social, and
- transportation delivery.

In many instances, agencies monitor measures of **output** (e.g., number of motorist assists by a service patrol, service patrol miles patrolled per month, frequency of repairs to a device, etc.). There are a few examples of **outcome**-based performance measures being used (e.g., changes in pollution levels within a city, average travel times or travel time reliability on various routes in a region, or reductions in the number of hits on a gore area crash cushion). For the most part, output measures are easier to track for an agency and have the benefit of illustrating more directly the efforts of the agency in tackling a particular issue, which may have some public relations benefit. In addition, output measures are usually assumed to be related in some manner to desired outcomes, and so serve as surrogate indicators of outcome measures. The difficulty in this assumption is that actual correlations between agency output and desired outcomes do not always exist. A classic example of this is the correlation between actions to reduce speeds in work zones (such as the use of speed display trailers) and reduced crash likelihood. Although it is generally assumed that such techniques do improve safety through the reduction of crash severity to motorists, research has yet to be performed that verify this assumption. Even more importantly, the correlation of small speed reductions and reduced crash severity with workers have not been established, even though a common reason for selecting reduced speed limits and speed reduction devices is the perception that worker safety is improved.

Although performance measurement in general terms is a key theme within various departments of a transportation agency (such as TxDOT), a review of efforts in other states reveals only a limited number of examples related to the establishment and monitoring of work zone safety and mobility impacts. Most agencies compute delay, queuing, and road user costs at some level as part of their work zone planning and design procedures. However, efforts to actually measure travel and safety impacts during work zones have been extremely limited. Texas Transportation Institute (TTI) researchers contacted personnel in each of the other state DOTs and/or visited their websites to investigate work zone performance measures being used or contemplated.

Table 1 summarizes the measures used by these agencies in making decisions about how work zones are planned, installed, and managed over the course of the project. Essentially all of those agencies who mention a performance measure consider the possible impacts of a work zone via traffic volume-to-work zone capacity comparisons or application of macroscopic or microscopic traffic simulation analyses. If the computations indicate that a significant queue or delay will result, that particular work zone configuration is not considered further in planning or design. Some of the states did indicate that they monitor work zones to make sure the performance threshold (such as a maximum queue length or maximum delay time) does not exceed a pre-established threshold. If conditions do get worse than expected, the agency may terminate the work activity (typically a lane closure) to allow traffic congestion to disperse. However, no agency indicated that it deliberately recorded and tracked the frequency or severity of such events (although it may be possible to manually review project diary entries to locate such events).

Although several states indicate the consideration of mobility and safety measures in their decision-making process for traffic management planning and design, only a handful attempt to record and track data from the field during actual work zone operations. Some states do track such items as a percent of projects on schedule based on construction progress estimates and funding expenditures, such as the example from Florida DOT shown in Figure 1 (*3*). Similarly, the Florida Highway Patrol (FHP) keeps detailed records on its work zone enforcement efforts, tracking stops, citations, and other indicators as shown in Figure 2 (*4*). The data summarized in Figure 2 are output measures of performance reflecting the amount of FHP's efforts expended at work zones. Conversely, the measures in Figure 1 reflect efforts by district personnel and highway contractors to keep projects on schedule and so are outcome measures of performance (e.g., an output measure for this graph might be: amount of overtime work expended to keep a project on time).

Examples of efforts to track travel safety and mobility measures throughout the duration of a project are more difficult to come by. Most states do report monitoring the number of fatalities that occur in their work zones annually. Unfortunately, the agencies acknowledge that without exposure data to normalize these numbers, changes in crash frequencies from year to year are difficult to interpret. One state, Ohio, manually collects police accident reports every two weeks from high-profile projects in its jurisdiction and compares to crashes during construction to the three-year average existing before the project began (*5*). Ohio DOT (ODOT) staff scrutinize those segments where the current work zone crash rate is much higher than the three-year average, believing the higher crash rate is an indicator of potential traffic management. ODOT recently began requiring entrance ramps to be closed whenever acceleration lanes could not be maintained during construction, based in large part on dramatic increases in crash rates observed at reduced-acceleration lane ramps identified through this procedure. Figure 3 illustrates an example of the work zone crash monitoring activities by ODOT.

Table 1. Traffic Performance Measures Considered by State DOTs.

Agency	Measure Considered			
	Time Delay	Queue Length	Traffic Volumes	Crash Rate
Arizona DOT	Yes	Yes		
Arkansas State Highway and Transportation Department	Yes			
California DOT	Yes			
Connecticut DOT				Yes
Florida DOT			Yes	
Georgia DOT				Yes
Indiana DOT	Yes	Yes		
Kentucky Transportation Cabinet		Yes		
Louisiana Department of Transportation and Development	Yes			
Maine DOT	Yes			
Maryland State Highway Administration	Yes	Yes		
Massachusetts DOT	Yes			
Missouri DOT	Yes			
New Hampshire DOT			Yes	
New York State DOT			Yes	
North Carolina DOT		Yes		
North Dakota DOT	Yes			
Ohio DOT			Yes	
Oregon DOT				Yes
Pennsylvania DOT				Yes
South Dakota DOT	Yes			
Tennessee DOT		Yes		Yes
Wisconsin DOT	Yes	Yes		
Wyoming DOT	Yes			

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	Contracts that Reached "PASS" Status Through This Quarter											
District	**Number of Contracts**	**Total Original Contract Amount**	**% Time Increase of Original Days**	**% Contracts < 20% Increase in Time**	**% Cost Increase over Original Amount**	**% Contracts <10% Increase in Cost**	**% Total CEI Cost of Present Amount**	**Total Avoidable Premium Cost**	**Avoidable Cost % of Original Contract Amount**	**Avoidable Time % of Original Days**	**Days from Final Acceptance to Initial Offer**	**Days from Final Acceptance to Project Passed**
Tier 2 Plan Item			T2-CN-7.3		T2-CN-7.2		T2-CN-7.1		T2-CN-6.1	T2-CN-6.1		T2-CN-2.3
1	96	$330,849,236	21.5	74.0	4.0	86.5	8.6	$131,415.38	0.0	1.6	101	351
2	70	$271,513,619	20.7	71.4	9.4	82.9	5.2	$174,742.69	0.1	2.9	60	219
3	24	$127,721,846	26.6	58.3	9.3	75.0	11.9	$308,949.32	0.2	5.6	36	616
4	45	$187,827,161	1.0	77.8	6.0	88.9	13.3	$1,335,460.62	0.7	2.6	44	207
5	62	$147,290,934	12.1	79.0	4.7	83.9	7.1	$435,462.64	0.3	1.6	25	138
6	41	$125,051,816	-3.8	90.2	1.9	92.7	9.8	$28,205.48	0.0	0.4	39	111
7	52	$329,704,750	17.0	61.6	6.5	76.9	9.1	$1,322,946.59	0.4	4.4	43	282
8	4	$15,393,123	7.8	75.0	-9.1	100.0	6.8	$ -	0.0	2.8	31	188
Totals	**394**	**$1,535,352,485**	**13.6**	**73.9**	**5.9**	**84.5**	**8.9**	**$3,737,182.72**	**0.2**	**2.6**	**57**	**258**
Performance Targets			20.0		10.0		12.0		1.0	5.0	30	275

Figure 1. Construction Progress Measures from Florida DOT (recreated from *3*).

FLORIDA HIGHWAY PATROL

HIREBACK TROOP SUMMARY
QUARTERLY REPORT TOTALS

July 2006-September 2006

Troop	Expenditures	Hours	Miles	Written Warnings			Asst Rend	Crash Invest	F/E Notices	Arrests						Total
				HOV	Speed	Other				Seatbelt	Speed	DUI	Other	HOV	TOLL	
A	$57,430.76	2,448.50	22,166	0	270	117	373	91	193	62	399	4	259	0	0	724
B	$9,939.11	300.50	3,461	0	21	7	47	3	5	3	54	1	4	0	0	62
C	$21,218.68	514.50	8,455	0	91	18	67	2	37	57	540	14	212	0	0	823
D	$30,693.48	973.50	13,652	3	82	112	152	11	45	13	104	8	110	0	0	235
E	$35,957.84	1046.00	11,737	78	256	95	68	10	156	150	674	0	605	0	0	1,429
G	$72,216.56	2,210.50	31,513	0	422	587	111	33	411	423	1,781	3	961	0	0	3,168
H	$21,577.72	671.50	14,459	0	120	39	41	4	50	29	150	0	60	0	0	239
K	$148,544.62	4,511.75	55,324	13	220	394	722	35	230	123	873	0	493	4	30	1,523
L	$260,536.97	5,836.50	58,913	387	1,468	788	1,217	71	757	654	2,996	26	3,418	41	0	7,135
Grand Total	**$676,115.74**	**18,513.25**	**219,680**	**481**	**2,950**	**2,157**	**2,798**	**260**	**1,884**	**1,514**	**7,571**	**56**	**6,122**	**45**	**30**	**15,338**

Figure 2. Work Zone Enforcement Efforts by the Florida Highway Patrol (recreated from *4*).

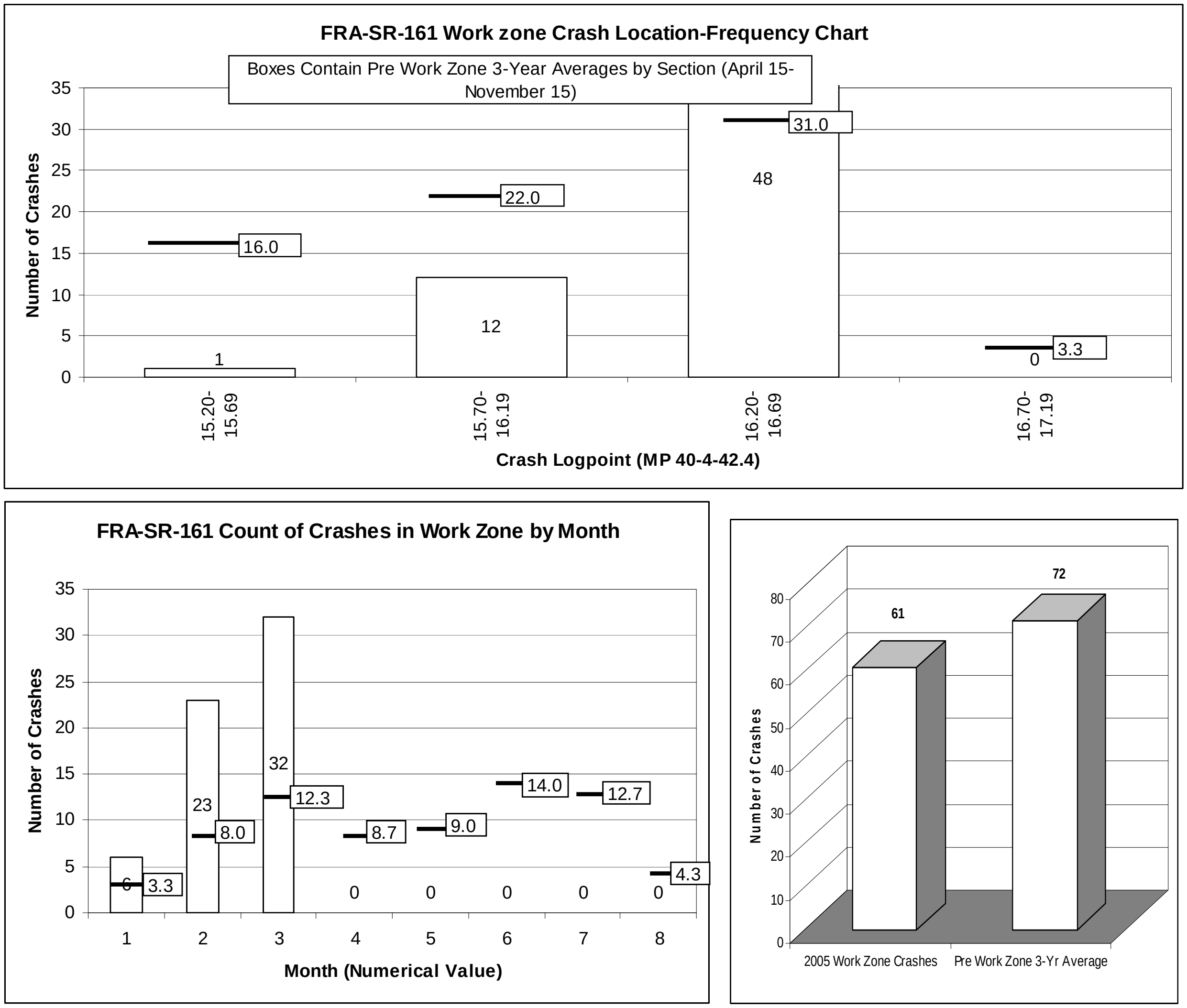


Figure 3. Ohio DOT Work Zone Safety Performance Measures (recreated from 5).

With regards to traffic mobility performance measures, the Missouri DOT (MoDOT) reportedly conducts regular reviews of its work zones statewide and compares the traffic conditions existing at those work zones with their expectations from traffic analyses made earlier in the work zone planning and design process (*6*). Figure 4 shows an example of this performance measure. Preliminary discussions with MoDOT staff indicate that these observations are qualitative rather than quantitative in nature. In addition, the relationship between “meeting expectations” and amounts and durations of delay and congestion are not immediately apparent.

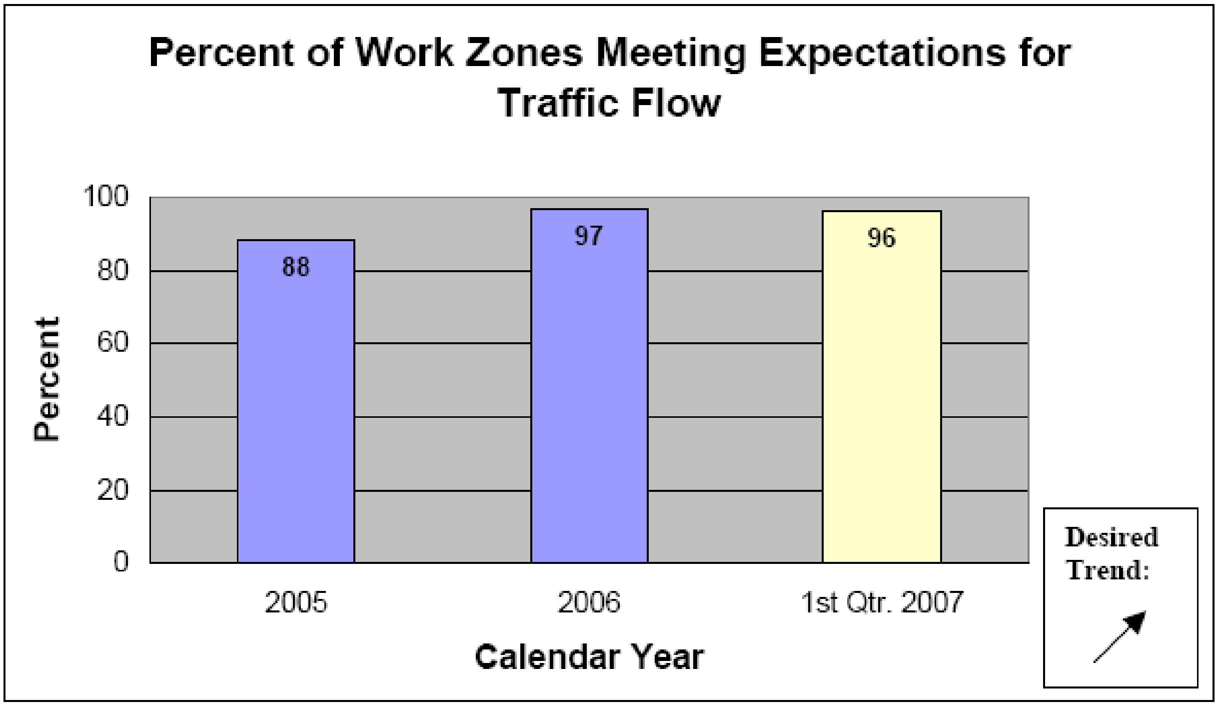


Figure 4. Traffic Mobility Performance Measure Used by Missouri DOT (*6*).

At the federal level, FHWA began tracking state DOT output levels of performance related to work zone safety and mobility in 2003 (*7*). FHWA is conducting annual self-assessment surveys of actions being taken to address work zone safety and mobility concerns in work zones. Six areas of emphasis are targeted, with questions underneath each area designed to explore level of agency commitment to the topic. Emphasis areas and questions used to gauge efforts within those areas are as follows:

- Leadership and policy:
    - Has the agency developed a process to determine whether a project is impact types I, II, or III?
    - Has the agency established strategic goals specifically to reduce congestion and delay in work zones?
    - Has the agency established strategic goals specifically to reduce crashes in work zones?
    - Has the agency established measures (e.g., vehicle throughput, queue length, etc.) to track work zone congestion and delay?
    - Has the agency established measures (e.g., crash rates, etc.) to track work zone crashes?
    - Has the agency established a policy for the development of Transportation Management Plans to reduce congestion and crashes due to work zones?
    - Has the agency established work zone performance guidance that addresses: maximum queue lengths, number of open lanes, maximum traveler delay, etc.?
    - Has the agency established criteria to support the use of project execution strategies (e.g., night work and full closure) to reduce public exposure to work zones and reduce the duration of work zones?

  - Has the agency developed policies to support the use of innovative contracting strategies to reduce contract performance periods?
  - Has the agency established Memoranda of Understanding (MOUs) between utility suppliers that promote the proactive coordination of long range transportation plans with long range utility plans to reduce project delays and minimize the number of work zones on the highway?

- Project programming and planning:

  - Does the agency's planning process actively use analytical traffic modeling programs to determine the impact of future types I and II road construction and maintenance activities on network performance?
  - Does the agency's planning process include developing alternative network options (e.g., frontage roads, increased capacity on parallel arterials, beltways, strategically placed connectors, etc.) to maintain projected traffic volumes due to future road construction and maintenance activities?
  - Does the agency's planning process manage the transportation improvement program to eliminate future network congestion due to poorly prioritized and uncoordinated execution of projects?
  - Does the agency's transportation planning process include a planning cost estimate review for work types I, II, and III that accounts for traffic management costs (e.g., incident management, public information campaigns, positive separation elements, uniformed law enforcement, intelligent transportation systems [ITS], etc.)?
  - Does the agency's transportation planning process include active involvement from the planners during the project design stage to assist in the development of congestion mitigation strategies for types I and II projects?
  - Does the agency's transportation planning process engage the planners as part of a multi-disciplinary/multi-agency team in the development of Transportation Management Plans involving major corridor improvements?

- Project design:

  - During project design, does the agency have a process to estimate and use road user costs to evaluate and select, based on road user costs or project strategies (e.g., full closure, night work traffic management alternatives, detours, etc.) for work types I and II projects?
  - During project design, does the agency develop a Transportation Management Plan that addresses all operational impacts specifically focused on project congestion for work types I and II projects?
  - During project design, does the agency use multi-disciplinary teams consisting of agency staff to develop Transportation Management Plans for types I and II projects?
  - During project design, does the agency perform constructability reviews that include project strategies intended to reduce congestion and traveler delays during construction and maintenance activities for types I and II projects?
  - During project design, does the agency use independent contractors or contractor associations to provide construction process input to expedite project contract time for types I and II projects?
  - During project design, does the agency use time- and performance-based scheduling techniques such as Critical Path Method or parametric models to determine contract performance times for work types I and II projects?

  - During project design, does the agency have a process to evaluate the appropriate use of ITS technologies to minimize congestion in and around work zones for types I, II, and III projects?
  - During project design, does the agency have a process to consider the use of life cycle costing in selecting materials that reduce the frequency and duration of work zones for types I, II, and III projects?
  - Does the agency have a process to assess projects for the use of positive separation devices for types I and II projects?
  - During project design, does the agency anticipate and design projects to mitigate future congestion impacts due to repair and maintenance activities for types I, II, and III projects?
  - In developing the Traffic Control Plan for a project, does the agency use contractor involvement in the development of the Traffic Control Plan for types I and II projects?
  - In developing the Traffic Control Plan for a project, does the agency use computer modeling to assess Traffic Control Plan impacts on traffic flow characteristics (e.g., speed, delay, capacity, etc.) for types I and II projects?

- Project construction and operation:

  - Is the letting schedule altered or optimized to reflect the available resources and capabilities of the construction industry?
  - Is the letting schedule altered or optimized to minimize disruptions to major traffic corridors?
  - In bidding types I and II projects, does the agency include road user costs in establishing incentives or disincentives to minimize road user delay due to work zones (e.g., I/D, A+B, Lane Rental, etc.)?
  - In bidding types I, II, and III contracts, does the agency use performance-based selection to eliminate contractors who consistently demonstrate their inability to complete a quality job within the contract time?
  - In bidding types I and II project contracts, does the agency use incident management services (e.g., wrecker, push vehicles, service patrols, etc.)?
  - In bidding contracts, does the agency use flexible starting provisions after the Notice to Proceed is issued?
  - During project types I, II, and III, does the agency use uniformed law enforcement?
  - Does the agency provide/require training of contractor staff on the proper layout and use of traffic control devices?
  - Does the agency provide training to uniformed law enforcement personnel on work zone devices and layouts?

- Communication and outreach:

  - Does the agency maintain and update a work zone website providing timely and relevant traveler impact information for project types I, II, and III that allows travelers to effectively make travel plans?
  - Does the agency sponsor National Work Zone Awareness week?
  - Does the agency assume a proactive role in work zone educational efforts?
  - During types I, II, and III project construction, does the agency use a public information plan that provides for specific and timely project information to the traveling public through a variety of outreach techniques (e.g., agency website, newsletters, public meetings, radio, and other media outlets)?
  - During types I, II, and III projects, does the agency use ITS technologies to collect and disseminate information to motorists and agency personnel on work zone conditions?

- Program evaluation:
    - Does the agency collect data to track work zone congestion and delay in accord with agency established work zone congestion and delay measures?
    - Does the agency collect data to track work zone safety performance in accord with agency work zone crash measures?
    - Does the agency conduct customer surveys to evaluate work zone traffic management practices and policies on a statewide/area-wide basis?
    - Does agency develop strategies to improve work zone performance based on work zone performance data and customer surveys?

As suggested in Table 2, respondents rate their level of effort from 0 (no efforts or consideration being given to that issue) to 15 (issue is fully considered and addressed as a matter of normal operating procedures within the agency).

Table 2. Work Zone Self-Assessment Scoring Criteria.

Adoption Phase	Scoring Range	Description
Initiation	(0-3)	Agency has acknowledged a need for this item and supports further development of the requirements of this item.
Development	(4-6)	Agency has developed a plan or approach to address requirements of this item.
Execution	(7-9)	Agency has executed an approach to meet requirements of this item.
Assessment	(10-12)	Agency has assessed the performance of this item.
Integration	(13-15)	Agency has integrated the requirements of this item into agency culture and practices.

Figure 5 provides a summary of average ratings across the 50 states and across the various questions for each emphasis area. Specific responses from individual states are not available, to guard against state-by-state comparisons. Again, one of the major challenges with this type of performance measure is getting a comparative response between states. Two states may be doing almost exactly the same types of things under a given emphasis area, but one gives itself a "5" while the other gives itself an "8." Even more problematic is the natural tendency of longitudinal data collection efforts such as this to naturally escalate scores over time regardless of whether actions are improving (or improving by the amount indicated in the higher score). The increasing scores shown in Figure 5, while desirable, may or may not reflect true improvements in state agency efforts or actions when measured on some type of absolute, objective scale.

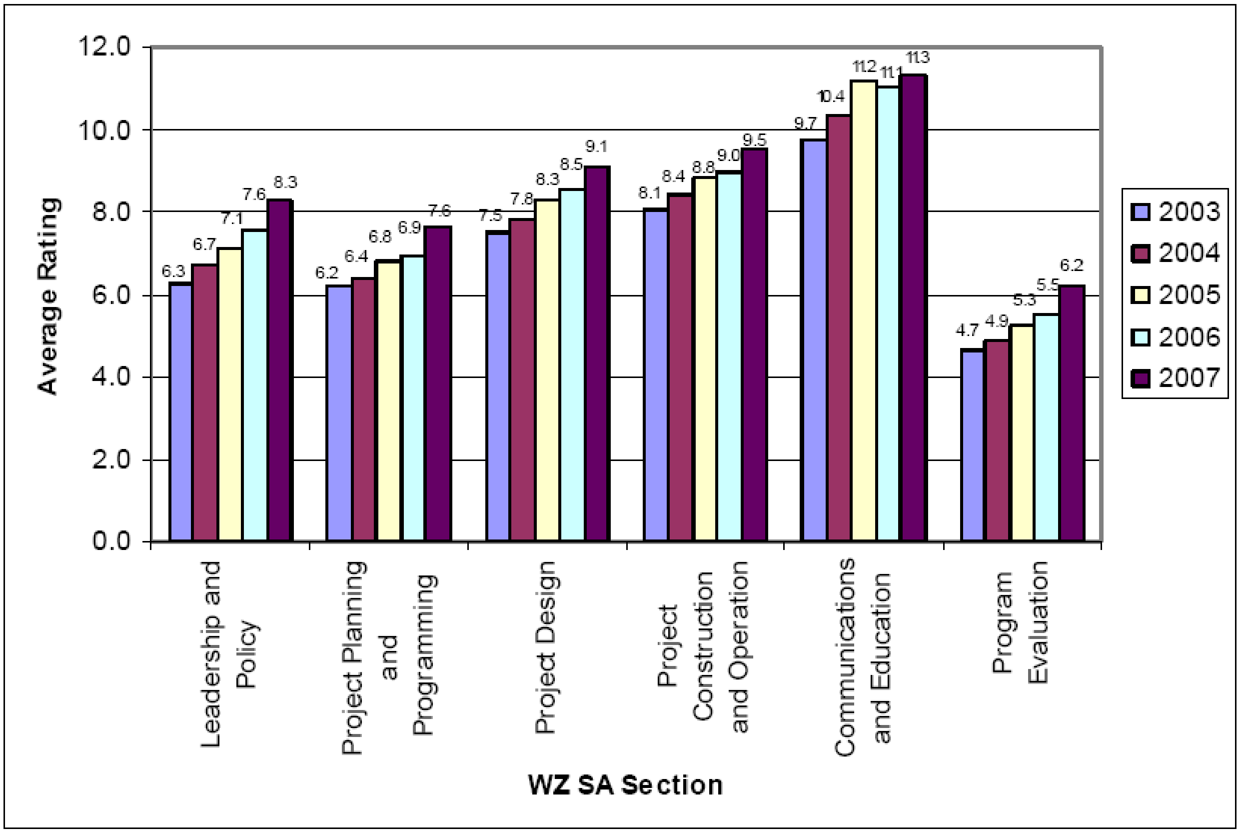


Figure 5. Evaluation Scores across All 50 States for the FHWA Work Zone Self-Assessment (WZ SA) (7).

FHWA is also currently supporting initiatives to monitor traffic performance on major roadways in various regions where real-time traffic information is available (*8*). These efforts are fairly extensive undertakings, based on millions of megabytes of sensor data and other data sources. Recently, individuals and agencies involved with these performance measurement efforts have begun to try and assess how much of the delay and congestion being experienced over the current or most recent time period is attributable to various forms of non-recurrent conditions (e.g., incidents, weather, and work zones).

As part of implementation support of the new work zone safety and mobility rule, FHWA has been looking into appropriate performance measures to suggest to states, both output and outcome-based measures. An initial preliminary list of measures is divided among 13 different categories, as shown below:

- Traffic demand/usage/exposure:
    - Annual Average Daily Traffic AADT
    - Truck percentages
    - Peak period traffic demands (AM, PM)
    - Average and total nighttime traffic volumes

  - Average and total weekend traffic volume
  - Vehicle miles traveled (VMT) through work zone
  - Percent of VMT through work zone when lane(s) closed
  - Percent truck VMT passing through work zones

- Throughput:

  - Maximum hourly throughput volume
  - Total capacity loss in work zone
  - Capacity loss per work zone mile

- Mobility:

  - Total vehicle delay
  - Average vehicle delay during peak periods, daily
  - Vehicle delay due to work zone(s) alone during peak periods, daily
  - Work zone delay per vehicle per peak period and per day
  - Work zone travel time index during peak period and per day
  - Percent of daily traffic experiencing congestion in work zones
  - Percent of day that congestion in work zone is "mild" (and length of congestion)
  - Percent of day that congestion in work zone is "severe" (and length of congestion)
  - Maximum queue length at work zone
  - Duration with queue length greater than some threshold (e.g., 0.5 mile)

- Reliability:

  - 95th percentile travel time index
  - Work zone buffer time index

- Safety:

  - Total fatalities
  - Total injuries
  - Highway workers killed and injured
  - Crash rates per 100 million VMT
  - Crash rates per work zone
  - Increase in rates relative to non-work zone conditions
  - Speed and enforcement surrogates
    - Percent of vehicles exceeding speed limit
    - Speed variability

- Roadway characteristics

- Work zone characteristics:

    - Number of work zones by roadway type, within region
    - Miles of work zone by roadway type in region
    - Lane-miles lost to work zones in region
    - Lane-mile lost rate (lane-miles lost per work zone)
    - Lane-mile hours lost in region
    - Peak period lane-mile hours lost in region
    - Shoulder miles lost in region
    - Matrix of lane miles lost by number of lanes originally on roadway
    - Foot-miles of lane width reductions
    - Average duration by work zone type by number of lanes lost

- Work zone activities:

    - Average and total work zone duration by type of work zone
    - Ratio of inactive to active days (some work performed in 24-hour period)
    - Inactive capacity loss ratio (time of inactive lane closures/total project duration)
    - Night activity to daylight activity ratio
    - Average number of traffic control plan changes per work zone

- Other events in the work zone:

    - Frequency of incidents in work zones
    - Median and total duration of incidents occurring in work zone
    - Median duration of incident blockage time in work zone
    - Lane-hours lost due to incidents

- Customer satisfaction:

    - Percentage of survey respondents rating work zone management as "poor"
    - Percentage of survey respondents who think work zones are much less safe than normal highways
    - Percentage of respondents who have experienced excessive delays in rural work zones
    - Percent of respondents who rate work zones as primary source of travel delay
    - Percent of time respondents were aware of work zones prior to making trips

- Highway durability:

    - Average time between work zone activity on roadway segments in region

- Project construction and planning

- Construction productivity

Ultimately, several of these measurement categories are interrelated. For example, traffic demand, vehicle throughput, roadway characteristics, and work zone characteristics all influence the mobility measures listed. Meanwhile, those same measures combined with work activity information ultimately relate to how work zones influence travel reliability. In many cases, the "measures" are actually data needed to estimate and stratify the mobility impacts that a work zone may create.

IDENTIFYING TXDOT WORK ZONE PERFORMANCE MEASUREMENT GOALS AND OBJECTIVES

TTI researchers created a telephone and email-based survey to gain insight into the current practices used by various TxDOT districts to monitor safety and performance in work zones and opinions regarding measures that TxDOT personnel would like to see or could see using in the future. Researchers targeted 20 traffic, construction, design, and area engineers in nine districts for the survey. Emails and follow-up telephone calls yielded ten surveys from seven of those districts. The following is a summary of the key findings from that survey.

All districts consider potential work zone impacts on mobility and safety during project planning and design.

Generally speaking, traffic control plan designers evaluate traffic-handling approaches for a particular work zone project or phase on the basis of expected traffic demands and expected work zone capacity to determine if the alternative is feasible. Long-term lane closures are generally avoided if the peak-period traffic volumes are expected to be higher than the reduced work zone capacity. Short-duration and short-term lane closures during off-peak periods are then allowed, usually restricted to nighttime hours in high-volume urban areas. For larger projects, designers may calculate road user costs to establish accelerated construction provisions of the contract. However, none of the predictions made during these analyses are verified or refuted once the work zone is put in place. One respondent did note that actually monitoring work zone conditions in the field would be useful in determining how accurate and reasonable their planning and design assessment procedures are and whether those procedures need to be modified in some fashion.

Most district personnel were not familiar with the FHWA work zone safety and mobility final rule.

It was clear through the survey that field personnel were not highly concerned with the intent or the specifics of the rulemaking at the time of the interviews. Some respondents stated that they expected that the ramifications of the rule would be passed down through TxDOT administration in the form of policy memorandums and directives on what exactly they will need to do to be in compliance. It should be noted that TxDOT did issue updated guidance pertaining to this issue in July 2007, four months prior to the implementation date of October 2007 required by FHWA.

Some work zone performance monitoring already occurs but varies significantly from district to district.

Most respondents viewed the Form 599 inspection process as their key performance monitoring data collection activity, even though the form is used to address traffic control device deficiencies such as placement, device condition, lack of reflectivity, etc., and not as a data collection instrument. Districts with ITS infrastructure reported that they monitored traffic conditions on their instrumented roadways and that work zones on those roadways received real-time monitoring as well. However, these data are not currently retained or analyzed explicitly for the purpose of evaluating how the work zone is or was impacting travel on that route. Rather, the monitoring is done to identify other problems, such as crashes or vehicle stalls, that may occur in the work zone and which should be managed through dispatch of motorist assistance patrols and display of messages on upstream dynamic message signs. The emphasis is on real-time impact mitigation. Rural districts did not envision much of a need for monitoring conditions in their work zones due to the lower traffic volumes present on most roadways.

At the district and area office levels, goals and objectives for work zone performance monitoring are to avoid creating any "bad" situations either in terms of significantly higher crash likelihood or excessive motorist delays.

Some of the district personnel indicated a desire to have no crashes in the work zone but recognized that this goal is unlikely to be fully attainable. Other districts, typically those in urban areas, indicated a desire to ensure "high vehicle throughput" and "good progression" through the work zone so as to minimize delays (in addition to minimizing crashes). It was noted that the majority of projects under TxDOT jurisdiction in rural areas do not have the potential to create significant mobility impacts. Similarly, the lower traffic volumes at these types of projects will translate into a relatively small number of additional crashes that may be attributable to the work zone and thus would not raise concerns. All districts reported investigating fatal crashes that occurred in the work zones, regardless of whether it was an urban or rural location and/or a lower-volume or higher-volume facility. Districts typically designate someone to retrieve crash reports from local authorities to be reviewed by appropriate district personnel so that any improvements in traffic control that are needed at a particular project can be identified and corrections made. The reports are also saved for reference in case of future litigation. Typically, however, the crash reports themselves are not collated in a manner for formalized subsequent analysis.

District personnel envision that work zone performance monitoring and measurement will involve the monitoring of a variety of data sources, including crashes, delays, queuing and/or the extent of congestion, speeds, and speed reductions.

One respondent indicated a concern about how performance measures might be misused or improperly interpreted. The example given was the completion of a work activity or project that can be accomplished much quicker with a traffic control approach that causes a higher level of individual delays but over a very short period of time. Another traffic control approach might require a greater number of days to complete but would yield slightly lower delays to individuals passing through the work zone. Although total delay created may be less in the first case, so would the maximum delay that individual drivers would experience. Consequently, it would not be clear which alternative is preferable.

Some (but not all) district personnel see potential benefit to having performance measures that allow comparison of one work zone to the next. However, indiscriminate use of measures (especially those using some type of "hard" score or threshold) would be counterproductive to ensuring good mobility and safety in work zones.

Work zone performance is highly subjective and influenced by a number of factors. What might be an important statistic for one district might not be important for another. Still, respondents did recognize that some sort of standardization of measures would be necessary, as well as stratification of measures of various work zones on such variables as average daily traffic (ADT) or roadway characteristics.

In summary, the general approach taken by TxDOT personnel is to set up work zones based on TxDOT standards, previous successes, and engineering judgment, and assume that it will work because it has worked in the past. The extent of formal monitoring is limited to the 599 forms, traffic control reviews performed periodically, and safety reviews of accidents that occur in work zones. Based on the results of these surveys, performance monitoring in work zones is currently more of a qualitative endeavor, with changes only occurring when there seems to be a problem. One qualitative measure that was repeatedly mentioned by respondents was the number of complaint phone calls an agency or district received. If a number (around three for a rural district was a rough estimate given as an example) of citizens call and complain about a particular work zone, agencies take these complaints as a sign that something is wrong and that the work zone needs to be reevaluated. Decision makers do care about performance measures for work zones in a quantitative sense but are also concerned that efforts to monitor and measure work zone performance not require field personnel to collect a large amount of additional data that will not be useful to them in how they manage day-to-day operations of the work zone.

DEFINING A WORK ZONE SAFETY AND MOBILITY MONITORING PLAN

IDENTIFYING SUITABLE PERFORMANCE MEASURES

Mobility-Based Performance Measures

In general terms, the decision of the fundamental traffic control strategy to be used for a particular project is either between:

- closing one or more travel lanes on a long-term basis while work is completed, or
- requiring the number of travel lanes be maintained in the work zone through temporary or permanent additions to the travel pavement and/or the reduction of lane widths within work areas.

For most high-volume roadway projects, agencies typically follow the latter approach. The phasing and sequencing of work required to complete the project are then matched with traffic control requirements needed to safely guide motorists through the work zone itself. The approach may also entail geometric changes such as long-term lane shifts, shoulder and lane width restrictions, and ramp closures. For the most part, such traffic control features will normally have only minor influences on traffic mobility (travel times, stops, etc.). In fact, the mobility impacts due to these work zone features may be less than the normal day-to-day variability in conditions caused by random traffic demand fluctuations, and changes in capacity resulting from differences in weather, driver mix, etc. The influences of individual work zone design elements (and combinations thereof) upon safety are generally not as well understood, however.

In addition to these long-term work zone influences on traffic conditions, it is usually necessary to occasionally close one or more lanes of traffic on a temporary basis during each project. Such temporary closures may be very sporadic, required only when it is necessary to change traffic control for a project phase change, or a necessity required on a daily or nightly basis to remove, replace, and/or overlay pavement. Other projects may be a hybrid of sporadic closures during some phases of the project, and regular temporary off-peak day or night lane closures during other phases. If the work crew closes travel lanes when the traffic demand is less than the reduced work zone capacity, the mobility impacts are again minimal. However, if the volumes exceed the reduced capacity through the work zone during all or part of the closure, queues and substantial travel delays develop. It is these queues and resulting travel delays that are the main source of frustration to motorists. More importantly, these conditions are those which TxDOT personnel try to minimize and/or manage through decisions about the number of lanes allowed to be closed by the contractor, time periods when such closures are allowed, and efforts to promote driver diversion to other routes so as to reduce traffic demands.

While emphasis is on minimizing the impacts of the work upon travel mobility, the actual project management decisions are made by trying to balance this desire to minimize impacts with the needs of the contractor or maintenance crew to complete the work in a timely and cost-effective manner. For many (if not most) projects, work activities that require lane closures can be limited to periods of lower traffic volume and thereby avoid creating significant mobility impacts. However, in other locations, traffic volumes are so high that there are few (if any) hours when lanes can be closed without creating queues and delays. Further complicating matters is the fact that the work activities that need to be completed often require a minimum lane closure duration in order to be cost-effective for the contractor to initiate efforts.

This trade-off assessment, which occurs continuously throughout the duration of each project, has significant ramifications upon efforts to establish meaningful performance measures that properly reflect the impacts upon travel mobility. Most importantly, this means that project location and the type and extent of work that the contractor must accomplish as part of the project, neither of which are under the control of the project engineer and inspectors providing oversight of the project, may dramatically influence the impacts on mobility in an absolute sense. Two projects on two different facilities may be managed in ways such that the impacts on mobility in one case reflect a number of poor decisions by contractors and inspector personnel, but in the other case, reflect the best decisions possible under the roadway and traffic conditions that exist at that location. Despite these differences between a "good" and a "bad" project (from the perspective of how traffic was managed), both could end up yielding the same amount of traffic delay, queues, and degradation in travel time reliability.

This issue is recognized in the new TxDOT policy and guidelines for traffic safety in work zones, which state that districts are to give special attention to significant projects so as to not create work zone impacts greater than what the district assesses as "tolerable." Consequently, it makes sense that the way in which a district chooses to define "tolerable" should be explicitly captured in at least some of the performance measures used to assess mobility and safety impacts. In other states, common indicators of "tolerable" include maximum individual motorist delays (15-20 minutes is common) as well as queue lengths and/or durations (Ohio DOT uses a combination of queue length and duration).

Taking these points into consideration, Table 3 presents the research team's recommendations of the mobility-related work zone performance measures that would be of most value to practitioners, along with some justifications for the recommendations. The measures address both the breadth and depth of possible impacts. Conceptually, the measures are described at the project level of monitoring. It is expected that the measures themselves can then be collated by roadway type, project type, area, or district as aggregate indicators of work zone safety and mobility performance. Furthermore, a distinction is recommended between total impacts that are generated and those which exceed what is defined as "tolerable" by TxDOT. A few possible thresholds are suggested in Table 3, but these suggestions should be adjusted based on location and characteristics of the project(s) of interest.

Not all of the measures will be equally available or calculable, depending on the location and type of a project. However, researchers believe that the recommended measures will provide decision-makers with the type of information needed to evaluate agency processes and procedures. In addition, the data could be combined in other ways, such as across projects done by a particular highway contractor, to aid tracking of underperforming entities (with regard to traffic impacts generated) and identify those whose scheduling may need to be scrutinized in greater detail.

Table 3. Recommended Work Zone Mobility Measures to Target.

Performance Measure	Justification for Inclusion
Total Delay (vehicle-hours): • Average per hour of daytime lane closures • Average per hour of nighttime lane closures • Average per hour of weekend lane closures • % of total delays occurring when average vehicle delay exceeds 20 minutes per vehicle • % of total delays occurring when lane closure queue lengths exceed 0.5 mile	Delays are generated predominantly by lane closures, and number of closures required varies from project to project. Usually, lane closures can be moved to night/weekends if volumes during the day will cause lane closures to create impacts that are not tolerable. Averages can be multiplied by hours of such closures per project and across projects in a region (if necessary) to estimate aggregate totals. Average vehicle delay and queue lengths are common indicators of tolerable levels of impacts.
Average Delay (per vehicle): • Per hour of daytime lane closures • Per hour of nighttime lane closures • Per hour of weekend lane closures • % of lane closure hours when average delays exceed 20 minutes per vehicle	Similar justification as above.
Queuing Caused by Lane Closures: • Average length per hour of daytime lane closures • Average length per hour of nighttime lane closures • Average length per hour of weekend lane closures • % of daytime lane closure hours creating a queue • % of nighttime lane closure hours creating a queue • % of weekend lane closure hours creating a queue • % of daytime lane closure hours creating a queue > 0.5 mile • % of nighttime lane closure hours creating a queue > 0.5 mile • % of weekend lane closure hours creating a queue > 0.5 mile	Queue lengths are likely to be the main measure that can be reasonably recorded by field personnel when traffic surveillance (portable work zone, permanent regional intelligent transportation system technology) is not available for use to monitor the work zone(s). A queue length greater than 0.5 mile is sometimes used as a threshold of acceptable or tolerable congestion due to work zone lane closures. Excessive queue lengths can disrupt travel patterns on ramps and roadways far upstream of the work zone.
Changes in Buffer Index: • During peak periods • During off-peak periods • During nighttime periods • During weekend periods	Degradation in travel time reliability is a main complaint about work zones by the motoring public. This measure captures both the magnitude of travel time increases over the course of the project and the frequency of these changes.

Values shaded in table above would be changed to reflect local district definition of what constitutes intolerable impacts.

Safety-Based Performance Measures

Table 4 lists a set of recommended safety measures of performance for work zones targeted in this study. One of the biggest challenges to attempting such exploration had been the lack of available crash data because of delays in getting the new TxDOT Crash Records Information System (CRIS) up and running (CRIS has sent been brought online to alleviate this challenge). At a project level, methods for estimating the changes in crash likelihood due to the work zone (and during various periods within the overall duration of the project) are fairly well known, as long as the project is of sufficient length and duration that adequate numbers of crashes are available for analysis. Methods of combining the effects of multiple projects upon crashes by work zone type and work activity (e.g., periods of work activity with and without lane closures required, periods of work inactivity, etc.) are also available. However, it has been noted that field personnel desire to use crash data as a way of assessing the effectiveness and safety of work zone design elements and/or operating strategies. Given that design elements and operating strategies do not exist in isolation, but are interrelated to other design elements and strategies occurring upstream (and possibly downstream) of the element location, the amount of variability in crash effects when attempting to evaluate the elements and strategies can be quite high. The ramification of higher variability is the need for larger sample sizes (number of projects and crashes within the projects) in order to identify statistical significance in any differences found.

Table 4. Recommended Work Zone Safety Measures to Target.

Performance Measure	Justification for Inclusion
Increase in crash rates per MVM or crash likelihood by project type, roadway type, and work period for: • Fatalities, • Injuries, and/or • Property damage only. Identification of projects experiencing crash rate increases greater than those normally expected or tolerable by TxDOT	Crash rates are standard safety measures used in numerous studies in the literature. Crash rates are simpler to use and estimate, but are less precise than approaches using crash frequencies.
Increase in crash rate or likelihood when a specific design element or combination thereof is used in a project	TxDOT personnel envision this type of performance measure has substantial benefit for determining improvements in work zone design features.

The questions of crash data and project data sample size adequacy notwithstanding, there also remains the issue of identifying design or strategy elements that are potential safety concerns. For the most part, analyses of projects will occur post hoc where the combined effect of multiple design elements, some possibly changing over time, along with operational strategies and other influences affecting the overall crash history experienced at the site are estimated. At the present time, no clear mechanism is available to allow subsequent analyses of possible safety concerns of a particular design element or combination of elements. The only place such elements are documented is in the set of construction plans prepared for the project. If agency personnel can identify an element or element combination a priori as a focus of analysis, projects occurring with the element(s) can be flagged, monitored, and the changes in crashes occurring at a collection of projects with the same element can be compared to projects without those elements present. However, analysts performing post-hoc analyses will not usually have specific work zone design feature information available to them, and so be less able to identify which element or elements may be responsible for any crash increases observed.

DEFINING NECESSARY DATA REQUIREMENTS

Table 5 summarizes the relationships between recommended performance measures and required data elements. Table 6 lists unique data requirements needed to execute a work zone performance monitoring program that encompasses all of the mobility and safety-related measures in Table 5. Researchers used both tables to identify and evaluate alternative data collection and analysis strategies. In certain locations, existing traffic data infrastructure (e.g., loop detectors, microwave sensors, automatic vehicle identification [AVI] technologies) is available to collect and estimate some of the required data elements. These technologies are in their widest use in urbanized areas with traffic management centers (TMCs) and are less common and virtually non-existent in smaller urban areas and rural locations. In areas with existing data collection infrastructure, the focus is primarily major commuter routes; other major routes may or may not be covered. In addition, construction activities may interrupt the functionality of spot-sensors and other technologies. Data collection and analysis requirements will vary directly with the amount of existing infrastructure coverage. The differences are primarily relevant to estimating recommended mobility measures (e.g., delay, queuing, and reliability). Therefore, mobility performance monitoring approaches were identified for work zones on roadways with and without existing data collection capabilities (referred to as TMC-supported and non-TMC-supported approaches for the remainder of this project). Researchers also developed general safety monitoring approaches applicable to any location.

Table 5. Required Data Elements for Recommended Work Zone Performance Measures.

Performance Measure	Units	Data Requirements
Total delay, average (by hour) due to work zone during daytime lane closures	Vehicle-Minutes	Segment termini, start and end dates and times of lane closures, free-flow/desired speed, actual speed (by hour) prior to work zone, actual speed (by hour) during lane closure [OR free-flow/desired travel time, actual travel time (by hour) prior to work zone, actual travel time (by hour) during lane closure], volume (by hour) prior to work zone, volume (by hour) during lane closure
Total delay, average (by hour) due to work zone during nighttime lane closures	Vehicle-Minutes	Segment termini, start and end dates and times of lane closures, free-flow/desired speed, actual speed (by hour) prior to work zone, actual speed (by hour) during lane closure [OR free-flow/desired travel time, actual travel time (by hour) prior to work zone, actual travel time (by hour) during lane closure], volume (by hour) prior to work zone, volume (by hour) during lane closure
Total delay, average (by hour) due to work zone during weekend lane closures	Vehicle-Minutes	Segment termini, start and end dates and times of lane closures, free-flow/desired speed, actual speed (by hour) prior to work zone, actual speed (by hour) during lane closure [OR free-flow/desired travel time, actual travel time (by hour) prior to work zone, actual travel time (by hour) during lane closure], volume (by hour) prior to work zone, volume (by hour) during lane closure
Total delay, percent of occurring when average vehicle delay exceeds 20 minutes per vehicle	Percent	Segment termini, start and end dates and times of lane closures, free-flow/desired speed, actual speed (by hour) during lane closure [OR free-flow/desired travel time, actual travel time (by hour) during lane closure], volume (by hour) during lane closure
Total delay, percent of occurring when queue length exceeds 0.5 mile	Percent	Segment termini, start and end dates and times of lane closures, free-flow/desired speed, actual speed (by hour) during lane closure [OR free-flow/desired travel time, actual travel time (by hour) during lane closure], volume (by hour) during lane closure, queue termini (by hour)
Average delay, (by hour) due to work zone during daytime lane closures	Minutes/Vehicle	Segment termini, start and end dates and times of lane closures, free-flow/desired speed, actual speed (by hour) prior to work zone, actual speed (by hour) during lane closure [OR free-flow/desired travel time, actual travel time (by hour) prior to work zone, actual travel time (by hour) during lane closure], volume (by hour) prior to work zone, volume (by hour) during lane closure
Average delay, (by hour) due to work zone during nighttime lane closures	Minutes/Vehicle	Segment termini, start and end dates and times of lane closures, free-flow/desired speed, actual speed (by hour) prior to work zone, actual speed (by hour) during lane closure [OR free-flow/desired travel time, actual travel time (by hour) prior to work zone, actual travel time (by hour) during lane closure], volume (by hour) prior to work zone, volume (by hour) during lane closure

Table 5. Required Data Elements for Recommended Work Zone Performance Measures (continued).

Performance Measure	Units	Data Requirements
Average delay, (by hour) due to work zone during weekend lane closures	Minutes/Vehicle	Segment termini, start and end dates and times of lane closures, free-flow/desired speed, actual speed (by hour) prior to work zone, actual speed (by hour) during lane closure [OR free-flow/desired travel time, actual travel time (by hour) prior to work zone, actual travel time (by hour) during lane closure], volume (by hour) prior to work zone, volume (by hour) during lane closure
Average delay, percent of lane closure hours exceeding 20 minutes per vehicle	Percent	Segment termini, start and end dates and times of lane closures, free-flow/desired speed, actual speed (by hour) during lane closure [OR free-flow/desired travel time, actual travel time (by hour) during lane closure], volume (by hour) during lane closure
Average queue length, (by hour) due to work zone during daytime lane closures	Mile	Segment termini, start and end dates and times of lane closures, queue termini (by hour)
Average queue length, (by hour) due to work zone during nighttime lane closures	Mile	Segment termini, start and end dates and times of lane closures, queue termini (by hour)
Average queue length, (by hour) due to work zone during weekend lane closures	Mile	Segment termini, start and end dates and times of lane closures, queue termini (by hour)
Queue presence, percent of daytime lane closure hours	Percent	Segment termini, start and end dates and times of lane closures, queue presence (by hour)
Queue presence, percent of nighttime lane closure hours	Percent	Segment termini, start and end dates and times of lane closures, queue presence (by hour)
Queue presence, percent of weekend lane closure hours	Percent	Segment termini, start and end dates and times of lane closures, queue presence (by hour)
Queue length, percent of daytime lane closure hours when queue length is greater than 0.5 mile	Percent	Segment termini, start and end dates and times of lane closures, queue termini (by hour)
Queue length, percent of nighttime lane closure hours when queue length is greater than 0.5 mile	Percent	Segment termini, start and end dates and times of lane closures, queue termini (by hour)

Table 5. Required Data Elements for Recommended Work Zone Performance Measures (continued).

Performance Measure	Units	Data Requirements
Queue length, percent of weekend lane closure hours when queue length is greater than 0.5 mile	Percent	Segment termini, start and end dates and times of lane closures, queue termini (by hour)
Buffer time index, change from pre-work zone to work zone during peak periods	Percent	Segment termini, repeated daily observations of actual speed (by hour) prior to work zone, repeated daily observations of actual speed (by hour) during work zone [OR repeated daily observations of actual travel time (by hour) prior to work zone, repeated daily observations of actual travel time (by hour) during work zone]
Buffer time index, change from pre-work zone to work zone during off-peak periods	Percent	Segment termini, repeated daily observations of actual speed (by hour) prior to work zone, repeated daily observations of actual speed (by hour) during work zone [OR repeated daily observations of actual travel time (by hour) prior to work zone, repeated daily observations of actual travel time (by hour) during work zone]
Buffer time index, change from pre-work zone to work zone during nighttime periods	Percent	Segment termini, repeated daily observations of actual speed (by hour) prior to work zone, repeated daily observations of actual speed (by hour) during work zone [OR repeated daily observations of actual travel time (by hour) prior to work zone, repeated daily observations of actual travel time (by hour) during work zone]
Buffer time index, change from pre-work zone to work zone during weekend periods	Percent	Segment termini, repeated daily observations of actual speed (by hour) prior to work zone, repeated daily observations of actual speed (by hour) during work zone [OR repeated daily observations of actual travel time (by hour) prior to work zone, repeated daily observations of actual travel time (by hour) during work zone]
Crash rates (total and by severity), change from pre-work zone to work zone by project type, roadway type, and work period	Crashes per million vehicle miles	Segment termini, start and end date of work zone, crash occurrence and characteristics over analysis period (date, time, location, severity), daily volume prior to work zone, daily volume during work zone, type of work, start and end dates and times of lane closures
Crash rates (total and by severity), change from pre-work zone to work zone when a specific design element or combination of design elements are used	Crashes per million vehicle miles	Segment termini, start and end date of work zone, crash occurrence and characteristics over analysis period (date, time, location, severity), daily volume prior to work zone, daily volume during work zone, type of work, start and end dates and times of lane closures, temporary traffic control plans, as-built highway plans

Table 5. Required Data Elements for Recommended Work Zone Performance Measures (continued).

Performance Measure	Units	Data Requirements
Expected crash frequencies (total and by severity), change from pre-work zone to work zone by project type, roadway type, and work period	% change in crash likelihood	Segment termini, start and end date of work zone, crash occurrence and characteristics over analysis period (date, time, location, severity), daily volume prior to work zone, daily volume during work zone, type of work, start and end dates and times of lane closures
Expected crash frequencies (total and by severity), change from pre-work zone to work zone when a specific design element or combination of design elements are used	% change in crash likelihood	Segment termini, start and end date of work zone, crash occurrence and characteristics over analysis period (date, time, location, severity), daily volume prior to work zone, daily volume during work zone, type of work, start and end dates and times of lane closures, temporary traffic control plans, as-built highway plans

Table 6. Unique Data Elements for Work Zone Performance Monitoring Program.

Location and General Work Zone Characteristics
• Work zone analysis segment limits • Start and end date of work zone • Type of work • Start and end dates and times of lane closures • Temporary traffic control plans (for work zone design element safety analyses) • As-built highway plans
Traffic
• Daily volume prior to work zone • Daily volume during work zone • Hourly volumes (or hourly distributions of the daily volume) prior to work zone • Hourly volume (or distributions) during lane closure
Speed /Travel Time
• Free-flow/desired speed OR free-flow/desired travel time through work zone, • Actual speed (by hour) prior to work zone OR actual travel time (by hour) pror to work zone • Actual speed (by hour) during lane closure OR actual travel time (by hour) during lane closure
Queues
• Beginning and ending limits of the queue (by hour)
Crashes
• crash occurrence and characteristics over analysis period (date, time, location, severity)

WORK ZONE MOBILITY MONITORING: ANALYSIS METHODOLOGIES AND COMPUTATIONAL PROCEDURES

TMC-Supported Mobility Monitoring

Work zones located on facilities with existing traffic surveillance capabilities offer an opportunity to continuously monitor travel conditions and directly measure or compute mobility measures. This approach has several key advantages. Work activities in urbanized areas often involve temporary lane closures that occur sporadically over the project duration. There may be consecutive days or nights when lane closures are required, followed by several weeks to months where 1) work activity occurs outside of the traveled way, 2) the basic number of lanes is maintained, and 3) significant mobility impacts do not occur. Knowing the actual schedule of the lane closure events any more than a few days in advance is difficult in urbanized areas due to constantly evolving contractor schedules and the desire to only close a lane when absolutely necessary. Therefore, tracking lane closures and resulting mobility impacts is much more feasible to accomplish with traffic surveillance in place.

Two basic surveillance approaches exist in Texas; each has advantages and limitations relative to providing the required data needed for mobility-based performance monitoring. The first approach, representative of data collection hardware available in Houston, is to continuously measure travel times through AVI technologies positioned along major roadways. This type of system reads vehicle toll tags at sequential roadside sensor stations and computes the elapsed time between stations (i.e., travel time). Travel times organized by time of day and day of week have been archived over several years and can be used to make direct comparisons between work zone and pre-work zone travel times and to compute several measures of delay and travel time reliability. Predetermined sensor locations control the mile point limits of the analysis segment and its correspondence to the exact beginning and ending location of the work zone.

AVI sensors are less able to accurately detect queue formation and length. The spacing between AVI sensor stations generally ranges from 2 to 5 miles. Depending on the location of a work zone lane closure, a queue may develop entirely within two sensor stations or extend across two or more stations. Consequently, AVI sensors alone will not directly measure the actual length of the queue itself. Rather, an analyst must use basic computational techniques with reasonable assumptions to relate the observed segment travel time increases and known lane closure locations to probable queue length within the segment. The AVI technologies do not have the ability to directly measure hourly or daily traffic volumes.

The second surveillance approach, representative of the system in San Antonio, uses a series of spot sensors (e.g., loop detectors, video detection, microwave radar) spaced at approximately one-half mile to continuously monitor traffic volumes and vehicle speeds. Speeds are aggregated at 20-second intervals or more. Computers calculate the travel times between sensors based on the average speeds of the sensors at each end of the segment. Summing estimated travel times on consecutive segments provides a travel time estimate along a given stretch of roadway. This approach is reasonably accurate when the roadway segments are not congested. Deviations between estimated and actual travel times can result when one or more sensors are located within areas of congestion. More direct estimates of queue characteristics are possible with spot surveillance technologies through comparisons of traffic counts and speeds between adjacent sensors. Large differences in speeds from one sensor to the next indicate a change from a congested to an uncongested traffic state somewhere between the sensor stations.

The ability to monitor lane closure schedules through a traffic management framework is another advantage to a TMC-supported monitoring approach. For example, roadwork and lane closure information in Houston is submitted to the Houston District Public Information Office (PIO) by the construction or maintenance offices or the construction contractor performing the work. The PIO enters the information into the Daily Roadwork Report database. Staff at TranStar, the regional traffic and emergency operations center, use the database to update lane closure information on the TranStar website and may also choose to activate related messages on dynamic message signs. TranStar staff members then monitor significant project locations—typically the lane closures and other high-volume traffic sites—with surveillance cameras to determine if the posted information matches what is actually happening at the site. In some instances, TranStar broadcasts camera images of the construction project on the website to inform the public of progress. Night operations are more difficult to track with the cameras.

Changes or updates to the website and database are normally not made if a lane closure project begins and ends relatively close to the posted times. The website will be updated accordingly and the original Daily Roadwork Report database will be adjusted if the actual lane closure is running slightly late. Therefore, the website and database may not reflect the actual beginning and ending times of the lane closure in cases with small differences between posted times and actual times, especially in cases where the project finishes early. The public will sometimes inform TranStar staff of discrepancies if the actual lane closure times are significantly different than the posted times on the website.

TranStar provides direct lane closure details (e.g., time and location) on instrumented Houston corridors. The information may need to be verified and supplemented with additional data in some cases (such as project diaries). In addition, TranStar data will not include big picture construction project specifics (e.g., contract number, type of project, traffic control elements, switching dates between construction and temporary traffic control phases, work zone design elements, etc.). These details must be obtained directly from project personnel and project documentation.

The process of reporting lane closure information to TransGuide in San Antonio is very similar to the process in Houston with one exception: the lane closure data is reported directly to TransGuide rather than to the PIO as is done in Houston. TransGuide staff members typically do not monitor the status of individual projects. Much of their information related to schedule changes is provided directly by the contractors or public. When TransGuide is notified of a lane closure timing change through these media, the website and accompanying database are updated with correct times if the posted and actual times are significantly different.

Table 7 summarizes the availability of the required data elements needed to compute the recommended work zone performance measures using AVI (e.g., Houston) and spot-sensor (e.g., San Antonio) traffic surveillance technologies. Researchers assigned data element availabilities to one of three categories: 1) data element can be directly measured or estimated using traffic surveillance technology, 2) data element can be measured or estimated using traffic surveillance technology supplemented with additional information and verification, and 3) data element cannot be measured or estimated using traffic surveillance technology. For example, speeds and travel times can be directly measured or estimated by both systems using the processes described above. Lane closure date and time estimates are possible with both systems, but follow-up checks are recommended to confirm actual schedules. Finally, an analyst must obtain the other required project specifics (e.g., type of work, temporary traffic control plans) elsewhere because they are not available from the traffic surveillance systems.

The major difference between AVI and spot-sensor technologies is the ability of the latter to collect daily and hourly traffic volumes. Reliable volume estimates are important for computing accurate delay- and crash rate-related performance measures.

Table 7. Availability of Required Data Elements using Traffic Surveillance Technologies in TMC-Supported Areas.

Data Element	AVI Measurement Capabilities	Spot-Sensor Measurement Capabilities
Work zone segment limits	◘	◘
Start and end date of work zone	□	□
Type of work	□	□
Start and end dates and times of lane closures*	◘	◘
Temporary traffic control plans	□	□
As-built highway plans	□	□
Daily volume prior to work zone	□	■
Daily volume during work zone*	□	■
Volume (by hour) prior to work zone	□	■
Volume (by hour) during lane closure*	□	■
Free-flow/desired speed OR free-flow/desired travel time	◘	◘
Actual speed (by hour) prior to work zone OR actual travel time (by hour) prior to work zone	■	■
Actual speed (by hour) during lane closure OR actual travel time (by hour) during lane closure*	■	■
Queue limits caused by the work zone (by hour)*	◘	◘

■ = data element can be directly measured or estimated using traffic surveillance technology

◘ = data element can be measured or estimated using traffic surveillance technology supplemented with additional information and verification

□ = data element cannot be measured or estimated using traffic surveillance technology

* These data are collected each occurrence during the project

Once the work zone and electronic surveillance data have been obtained, 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 40 miles per hour (mph) are indicative of queue presence at that sensor location. Perform this assessment at each sensor location in sequence upstream until reaching a sensor where speeds do not drop below 40 mph during the hours of the lane closure. The upstream end of the queue is assumed to be midway between that sensor and the next sensor downstream.

Figure 6 illustrates this process. In this example, sensors are located 0.2 mile, 0.8 mile, and1.3 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, which 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 40 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 mile
• 1:00 PM	0.2 + 0.6 + (0.5/2) = 1.05 mile
• 2:00 PM	1.05 miles
• 3:00 PM	1.05 miles
• 3:30 PM	1.05 miles (lane closure ends)
• 4:00 PM	0 (queue ends)

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

The average travel time through the queue can be estimated 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 6, speeds at sensor 1 would be assumed to represent the 0.5 mile in queue immediately upstream of the closure, and sensor 2 would represent the next 0.55 mile upstream. For each hour that a queue exists, these distances are divided by average speeds measured at each sensor to determine the average travel time through each segment, and then summed as shown in Table 8:

Table 8. Travel Time Computations from Sensor Speed in Example.

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

An analysis of speeds at the same time of day without the lane closure (or an assumption of normal travel speeds) would be subtracted from these numbers to determine individual user delay. For the Figure 6 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 and between 2.1 and 2.4 minutes for the next three hours.

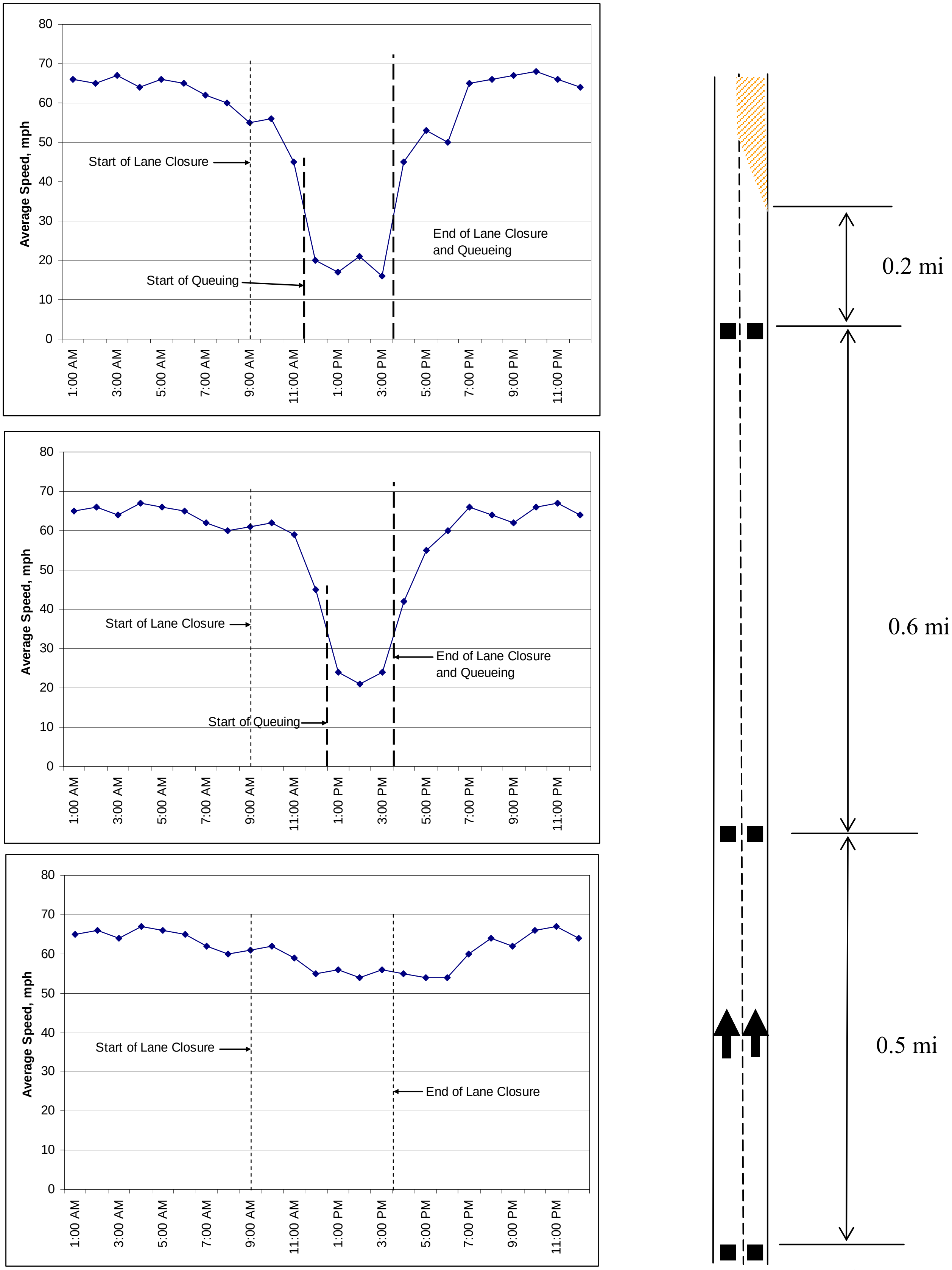


Figure 6. Example of Sensor Speed Analysis to Determine Duration and Length of Queue.

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

Once average vehicle delays have been estimated for each hour that the queue is present, total vehicle-hours of delay can be easily computed by multiplying the normal hourly volume by these average delay values. The analyst uses the normal (historical) volumes rather than those actually measured by the sensors in the queue because the sensors are measuring queue discharge rates rather than approach volumes. More importantly, there is likely considerable real-time diversion naturally occurring at the site that significantly reduces the approach volumes on that facility. Although actual volumes on that roadway are lower, volumes on other routes in the corridor or region experience an increase. One should assume that the alternative route taken by each of those diverting motorists will take longer than normal if they had used that facility as planned. 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.

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 as shown in Table 9.

Table 9. Computations of Delay in Example.

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

Non-TMC-Supported Mobility Monitoring

A large number of work zone locations are likely to be on non-TMC-supported highways. Existing traffic surveillance infrastructure is less common in smaller urban areas and rural locations than in urbanized areas. Urbanized areas with existing data collection infrastructure generally focus surveillance on major commuter routes; other major routes may or may not be covered. In addition, the functionality of spot-sensors and other technologies may be interrupted during construction activities. Alternative ways to collect the 10 of 15 required data elements that would otherwise be fully or partially supported by traffic surveillance technologies are needed. Table 10 provides a preliminary list of options.

The accuracy of work zone monitoring efforts will be maximized by data collection activities that are initiated specifically for this purpose (such as the deployment of work zone ITS at a site).

However, practical limitations on budgets, time, and staffing that can be devoted to these activities make this alternative unrealistic. This will likely remain the case until the benefits of work zone performance monitoring can be demonstrated.

Table 10. Alternative Non-TMC-Supported Data Collection and Estimation Strategies.

Data Element	**Alternative Non-TMC-Supported Data Collection and Estimation Strategies**
Daily volume prior to work zone	• Most recent traffic count on actual or nearby segment • AADT estimate for that roadway segment
Daily volume during work zone	• Most recent traffic count with assumed proportion of diverted traffic • AADT estimate adjusted by proportion of assumed diverted traffic
Volume (by hour) prior to work zone	• Most recent traffic count by hour • Assumed hourly distributions of most recent daily traffic count or AADT estimate
Volume (by hour) during lane closure	• Most recent traffic count by hour with assumed proportions of diverted traffic • Assumed hourly distributions of most recent daily traffic count or AADT estimate with assumed proportions of diverted traffic
Free-flow/desired speed OR free-flow/desired travel time	• Assumed free-flow speed
Actual speed (by hour) prior to work zone OR actual travel time (by hour) prior to work zone	• Speed or travel time study (e.g., spot speeds, floating car, etc.) specific to the work zone monitoring purpose • Estimation with traffic flow theory, traffic analysis tools, and actual or estimated hourly volume counts
Actual speed (by hour) during lane closure OR actual travel time (by hour) during lane closure	• Speed or travel time study (e.g., spot speeds, floating car, etc.) specific to the work zone monitoring purpose • Estimation with traffic flow theory, traffic analysis tools, and actual or estimated hourly volumes[1]
Beginning and ending limits of the queue (by hour)	• Project diaries with more detailed documentation specific to the work zone monitoring purpose • Estimation with traffic analysis tools and actual or estimated hourly volumes

[1] Hourly volumes may be estimated by assuming an hourly distribution of daily work zone traffic or by using a documented queue length and assumed work zone capacity

A more practical alternative involves approximating work zone impacts using estimated hourly work zone volumes and traffic analysis tools (e.g., analytical/deterministic, macroscopic models, microscopic models, etc.). The approach is similar to analyses conducted by some state agencies during work zone planning and impact assessments with the addition of field monitoring, model validation, and model adjustment steps. The proposed approach is demonstrated in Figure 7. The advantage of this approach is that it only requires field collection of one of two data elements (either queue length or speed/travel time). A simple form to be used for documenting queue lengths as part of project inspector note taking for daily diary entries is provided in Table 11.

The level of accuracy of this type of estimation will be directly related to the capabilities of the analysis approach selected (deterministic, macroscopic, or microscopic simulation), the availability of required model inputs, and the thoroughness with which the validation and adjustment steps are conducted.

Without the availability of traffic surveillance data, the queue length estimates collected using the form in Table 11 provide the main source of mobility impact data. Basic traffic flow relationships can be used to estimate the impacts of the temporary work zone lane closures on mobility. 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. The analyst must divide these 24-hour count estimates into hourly directional volumes. Automatic traffic recorder (ATR) stations on similar types of facilities in the vicinity of the project provide hourly distribution values that can be directly applied to the AADT number at a location. The directional split of traffic will also need to be included in the computations. Often, a 50/50 split by direction can be assumed.

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 (*9*):

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

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.

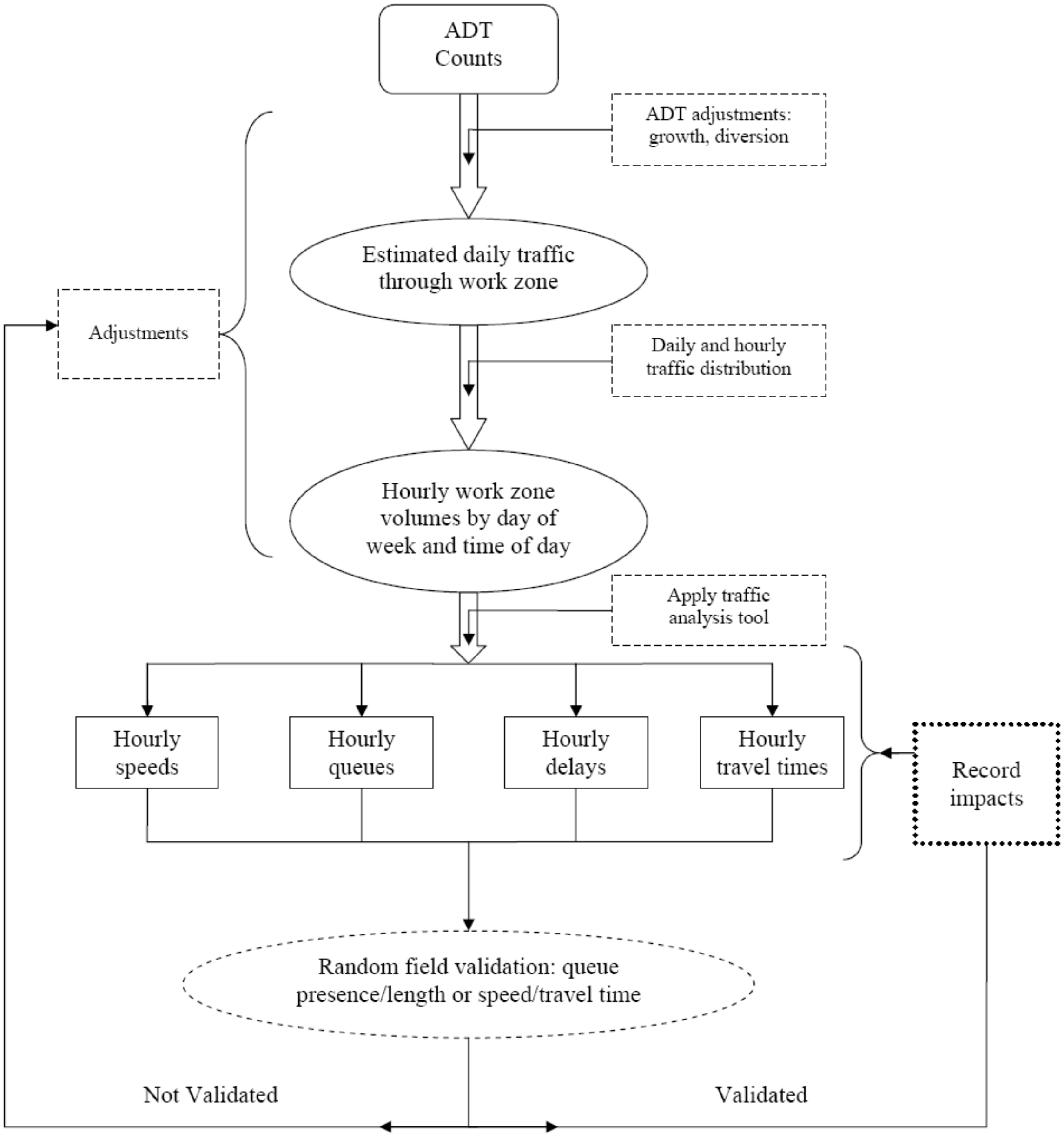


Figure 7. Alternative Work Zone Monitoring Approach for Non-TMC-Supported Highways.

Table 11. 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.

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 being 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, used in the Queue and User cost Evaluation for Work Zones (QUEWZ) program developed in the 1980s by TTI for TxDOT, produces an estimate of the average speed in queue as a function of the normal roadway capacity and the capacity through the work zone (*10*):

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

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

Average Speed in Queue: 70-mph Roadways

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

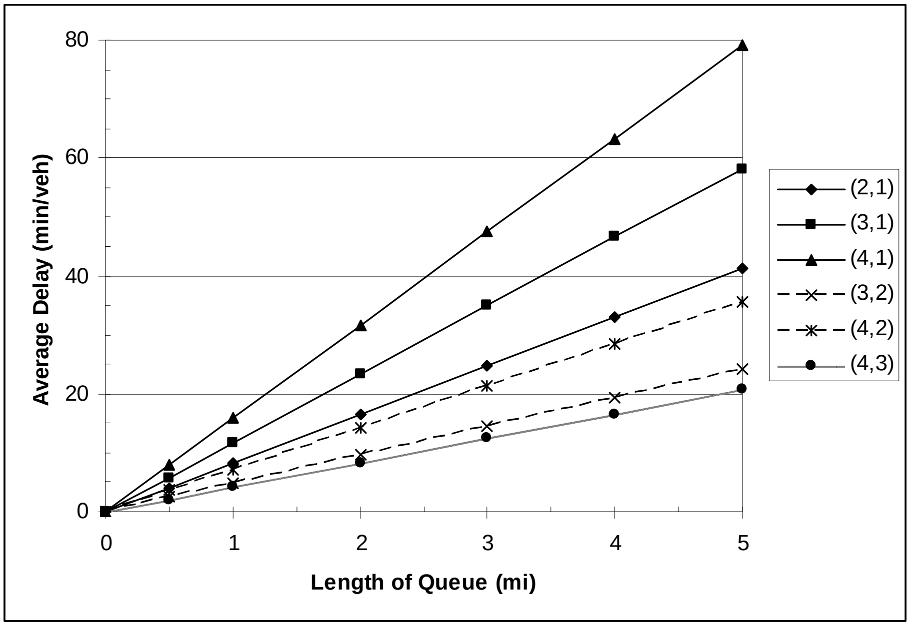
Average Speed in Queue: 65-mph Roadways

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

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, estimates of average delays per vehicle can be computed as a function of the length of queue that was documented. Figure 8 through Figure 10 are provided to simplify the computations.



Note: (x,x) indicates (number of roadway lanes, number lanes open in work zone)
Figure 8. Effect of Queue Length on Average Delay (70-mph Roadways).

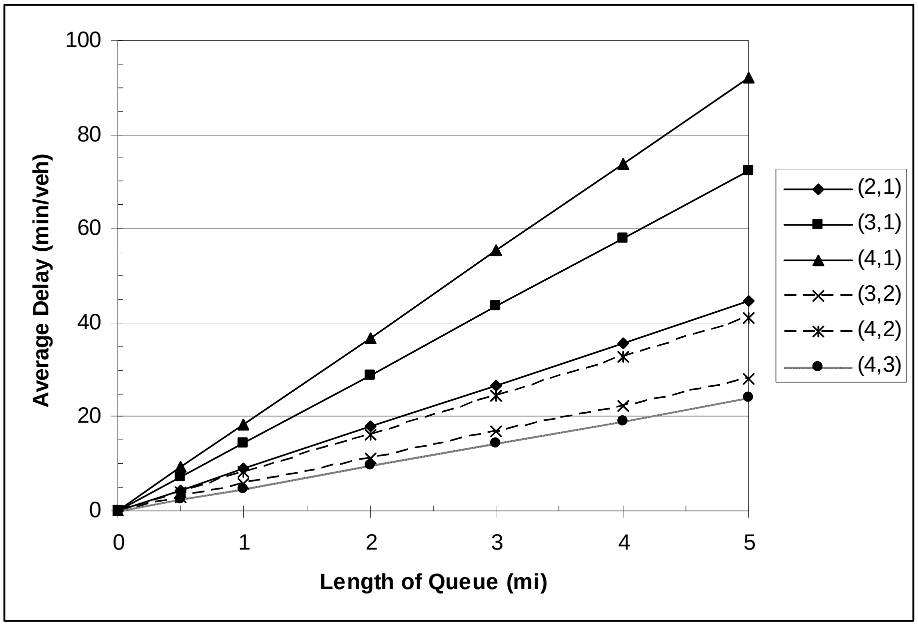


Figure 9. Effect of Queue Length on Average Delay (65-mph Roadways).

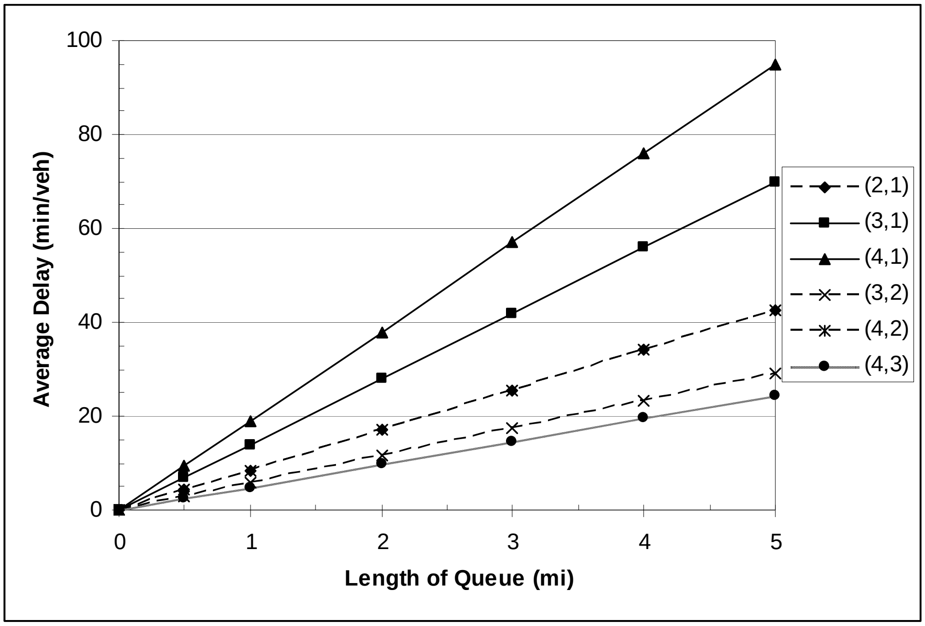


Figure 10. Effect of Queue Length on Delay (60-mph Roadways).

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

Once the average delay per vehicle due to the queue has been estimated, the analyst 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. Of course, this approach does not account for the additional delay caused by vehicles traveling slower through the length of work zone once passing through the queue. 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. For comparative purposes, Figure 11 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. Generally speaking, the estimated additional delay would be less than 1 minute per mile of work zone.

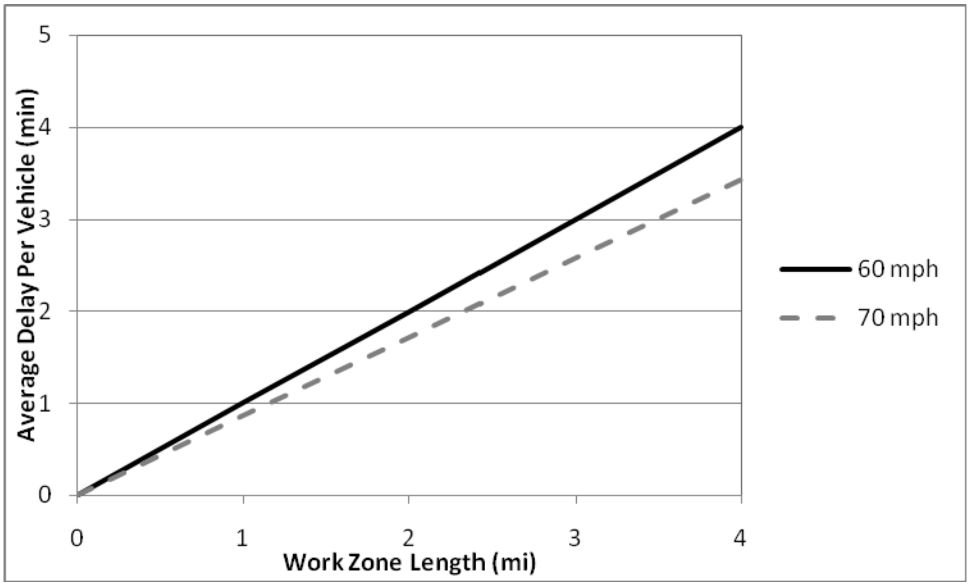


Figure 11. Effect of Work Zone Length on Average Delay.

As a final note, these delays through the queue could be combined with delay that occurs by vehicles traveling through the work zone itself as capacity flow speeds (generally between 28 and 35 mph, depending on normal operating speeds). The delay is calculated simply as the difference between the speed at capacity flow and desired speed through the work zone times the length of the work zone. Many contractors (and some DOTs) prefer slower speeds past the work area, and so may choose to not include this portion of delay in their calculations.

WORK ZONE SAFETY MONITORING: ANALYSIS METHODOLOGIES AND COMPUTATIONAL PROCEDURES

The safety monitoring procedure discussed has two major components:

1. estimating the practicality and frequency of real-time work zone safety monitoring and
2. determining if safety has declined more than expected or more than tolerable on a work zone segment.

Major advances in safety data analysis have occurred over the past decade. Awareness and understanding of the difficulties associated with linking observed accident trends to accident causation have increased. The menu of statistical techniques as well as the host of known caveats associated with conclusions from analysis results have grown. The challenges are particularly prevalent in work zones due to short analysis periods and constantly changing roadway, roadside, and traffic control features and conditions. Safety analysis approaches that have been theoretically dismissed may be the only practical choice for real-time work zone monitoring at this time. Trade-offs are evident. Techniques requiring the smallest amount of data are less likely to directly provide unbiased conclusions; methods aimed at removing or minimizing bias have greater data needs. All such considerations were given thorough treatment.

For purposes of this discussion, safety is defined as the number of accidents, or accident consequences (e.g., accidents by type or severity) *expected* to occur on an entity (e.g., roadway segment, intersection, etc.) during a specified time period. Safety is an underlying property of the entity analogous to a "long-term average" of accident frequency or accident consequences. Safety is not synonymous with *observed* accident counts as there may be a difference between what is expected and what is observed. However, observed accident counts are the key data element used to estimate the safety of an entity.

Figure 12 demonstrates the randomness of observed accident counts. A temporary traffic control plan is implemented and observed for three months (July, August, and September). The lightly-shaded circles represent the observed accident counts for each of these months while the temporary traffic control is in place. The numbers of accidents during each of these same months in the three years prior to the work zone are known and are marked by the hollow squares. The dark, shaded rectangles are the computed mean values (in accidents per month) of the accident counts during the three years prior.

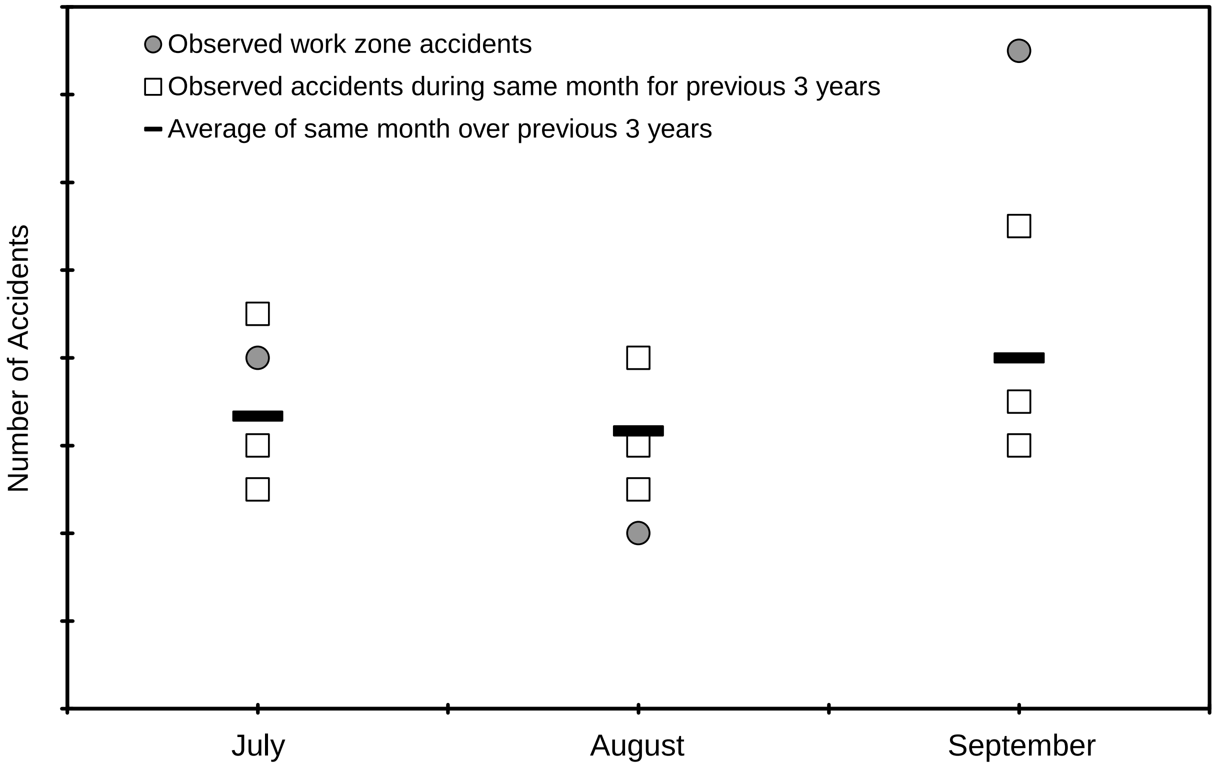


Figure 12. Randomness in Observed Work Zone Accident Counts.

From the data in Figure 12 alone, it is difficult to conclude whether there was a safety reduction on the highway segment. For example, is it reasonable to say that the work zone was less safe than normal conditions in July, safer in August, and less safe in September? What if there were no changes in work phasing or traffic control? Reliably answering these questions is the focus of the remainder of this section.

Estimating the Practicality and Frequency of Real-Time Work Zone Safety Monitoring

Real-time work zone safety monitoring will require manpower investment. The District Safety Review Team or other district staff assigned to safety monitoring responsibilities will need to receive accident information in real-time or near real-time. The data will need to be compiled and analyzed, and researchers may need to conduct follow-up field visits to identify or diagnose possible safety problems implied by data analysis results. These activities will require additional time and agency coordination; it would be useful to know, a priori, the likelihood of success for monitoring a work zone in real-time and the frequency with which the monitoring can reasonably be conducted (e.g., every month, quarterly, semi-annually, or annually).

The graphs in Figure 13 through Figure 18 are designed to address both issues. They provide an estimate of a recommended monitoring period based on the amount of data needed to detect safety reductions from normal operating conditions. The following information is required to use the figures:

- an estimate of the accident rate per million-vehicle-miles (MVM) for the segment where the work zone will be located under normal operating conditions,
- the ADT expected through the work zone, and
- the work zone segment length.

The segment length may be the length of the entire work zone or the length of a specific segment within the work zone boundaries. Analyzing shorter segment lengths with homogenous features in order to account for changes in geometric and traffic control variables throughout the work zone is desirable. Similarly, agencies should monitor work zones frequently (e.g., every month) to capture changes that may occur in work phasing, work intensity, and associated temporary traffic control strategies. Sample size and statistical power become controlling issues in both cases. Work zones where real-time monitoring may not be practical are those where the estimated monitoring period is nearly as long as or longer than the work zone duration.

Several statistical-related assumptions were necessary at intermediate steps of developing the curves in Figure 13 through Figure 18. The first was related to the magnitude and precision of the estimated safety change that can be detected. The two factors are related; less precision is required to conclude that an observed 50 percent crash increase was associated with an actual reduction in safety (and not just a random occurrence) than is needed to conclude that a 5 percent crash increase was associated with a reduction in safety. The curves in the figures are based on the sample size required to estimate a 100 percent safety reduction with standard error of ± 100 percent. This value does not imply that one is only looking to detect changes of 100 percent or greater; rather, it is selected as a way to identify those work zones where there will be sufficient data to detect if safety degrades much more than would be normally expected.

The second assumption was that the ratio of the work zone period of interest to the before period was equal to one-third. This ratio would occur when the observed work zone period is compared to the same time period for the three years prior to the work zone. For example, assume a temporary traffic control plan is implemented in July 2008, and the district chooses to analyze accident data every three months. The number of accidents in the first analysis period, July 2008 through September 2008, will be compared to the average number of accidents from July 2007 through September 2007, July 2006 through September 2006, and July 2005 through September 2005. Using the same months for comparison partially controls for seasonal factors such as fluctuations in traffic, weather, and light conditions.

The following figures are intended to help a district decide, a priori, how frequently (if at all) to compile and analyze accident data for work zones. However, the process of determining if safety has declined more than expected or tolerable following implementation of a temporary traffic control plan (described in the following section) can be executed for any work zone. The figures provide a tool for districts to be proactive in selecting work zones for real-time monitoring and for estimating monitoring frequency; reactive analysis may also be needed after the occurrence of one or more severe crashes or following a large increase in crash frequency.

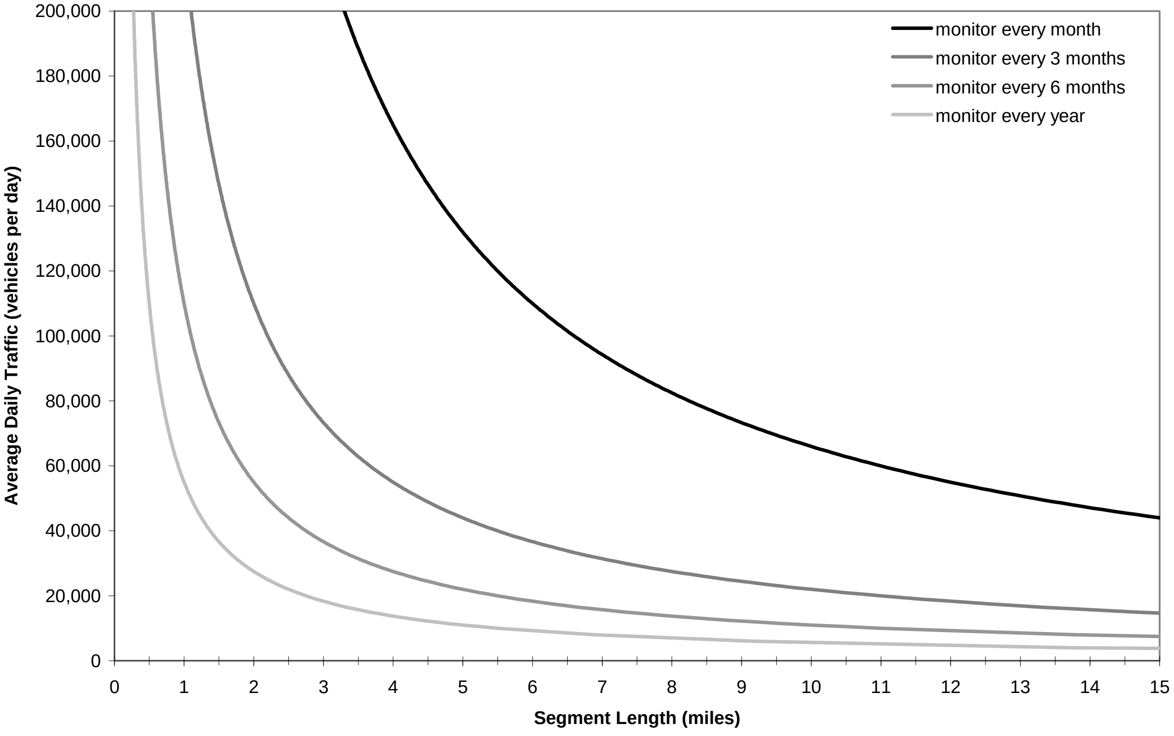


Figure 13. ADT and Project Length Combinations that Allow Detection of Significant Increases in Crashes during the Project (Pre-Work Zone Rate of 0.5 Accidents/MVM).

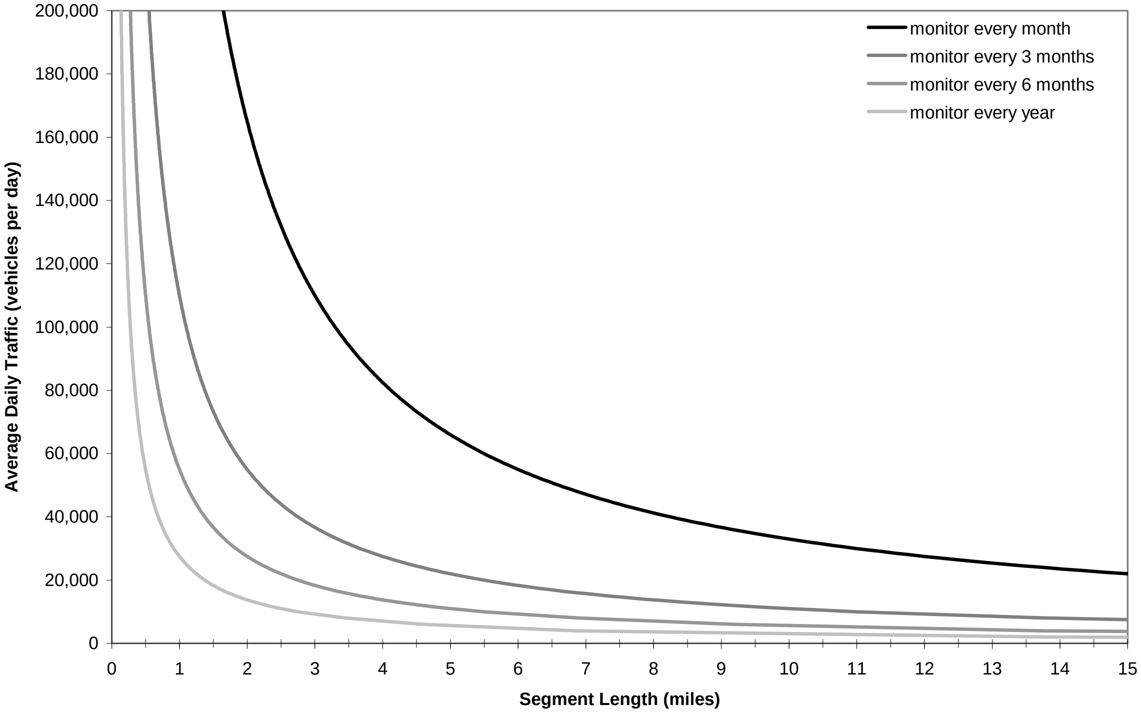


Figure 14. ADT and Project Length Combinations that Allow Detection of Significant Increases in Crashes during the Project (Pre-Work Zone Rate of 1.0 Accidents/MVM).

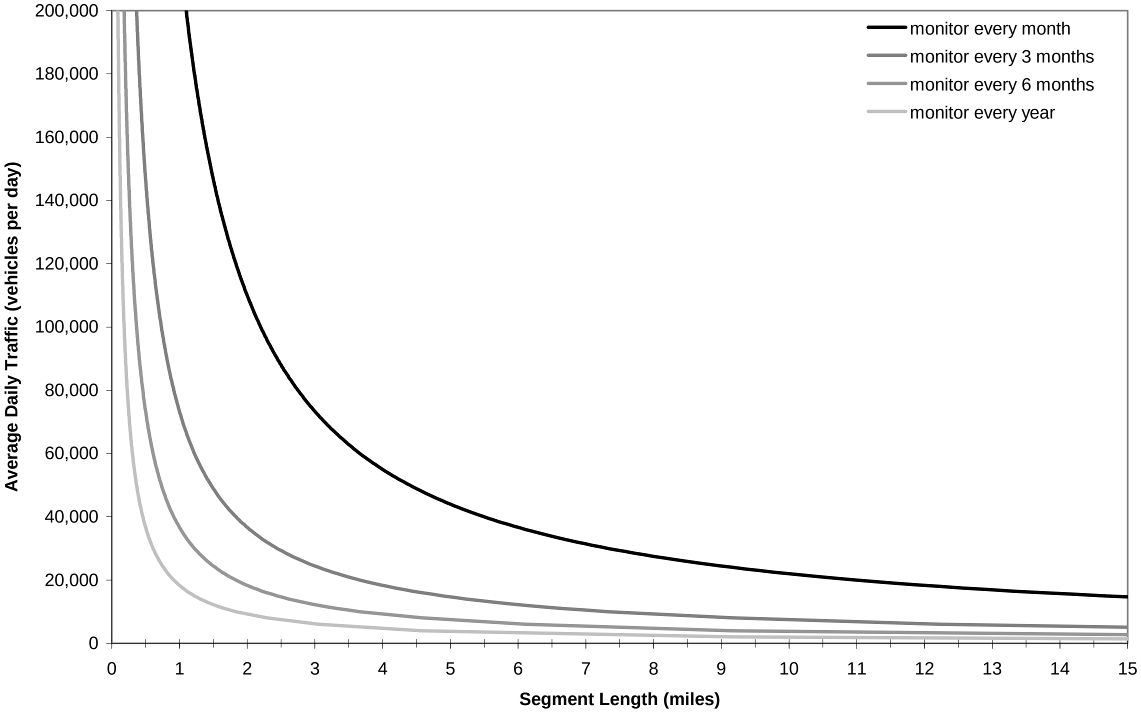


Figure 15. ADT and Project Length Combinations that Allow Detection of Significant Increases in Crashes during the Project (Pre-Work Zone Rate of 1.5 Accidents/MVM).

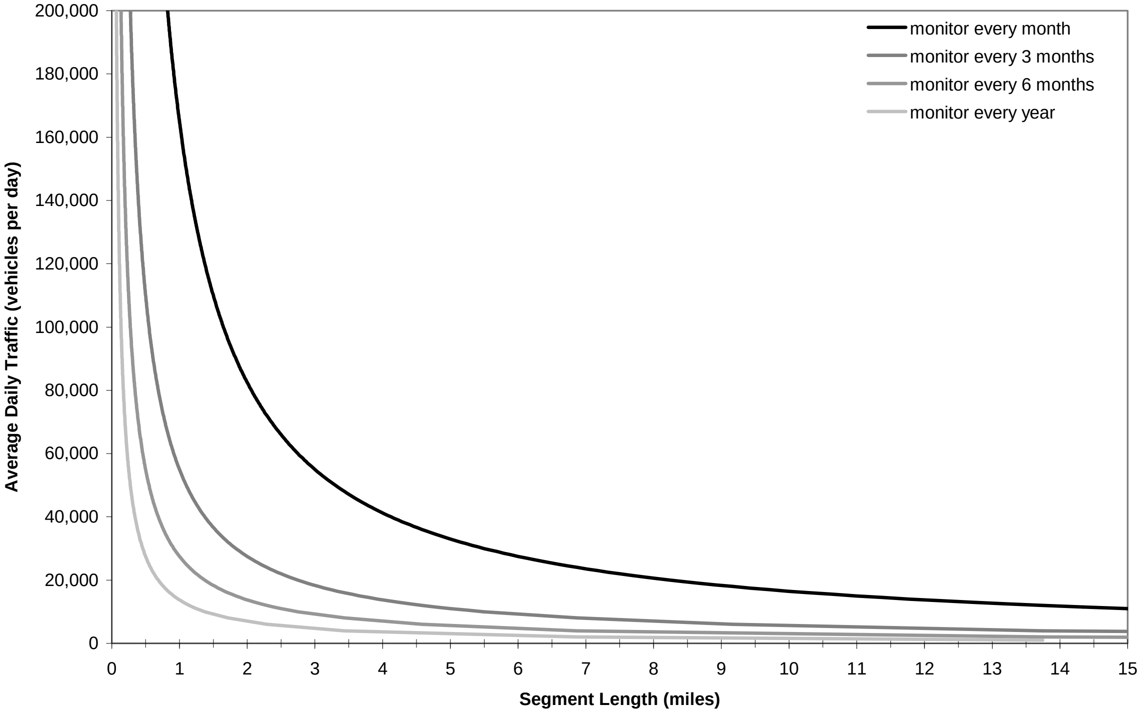


Figure 16. ADT and Project Length Combinations that Allow Detection of Significant Increases in Crashes during the Project (Pre-Work Zone Rate of 2.0 Accidents/MVM).

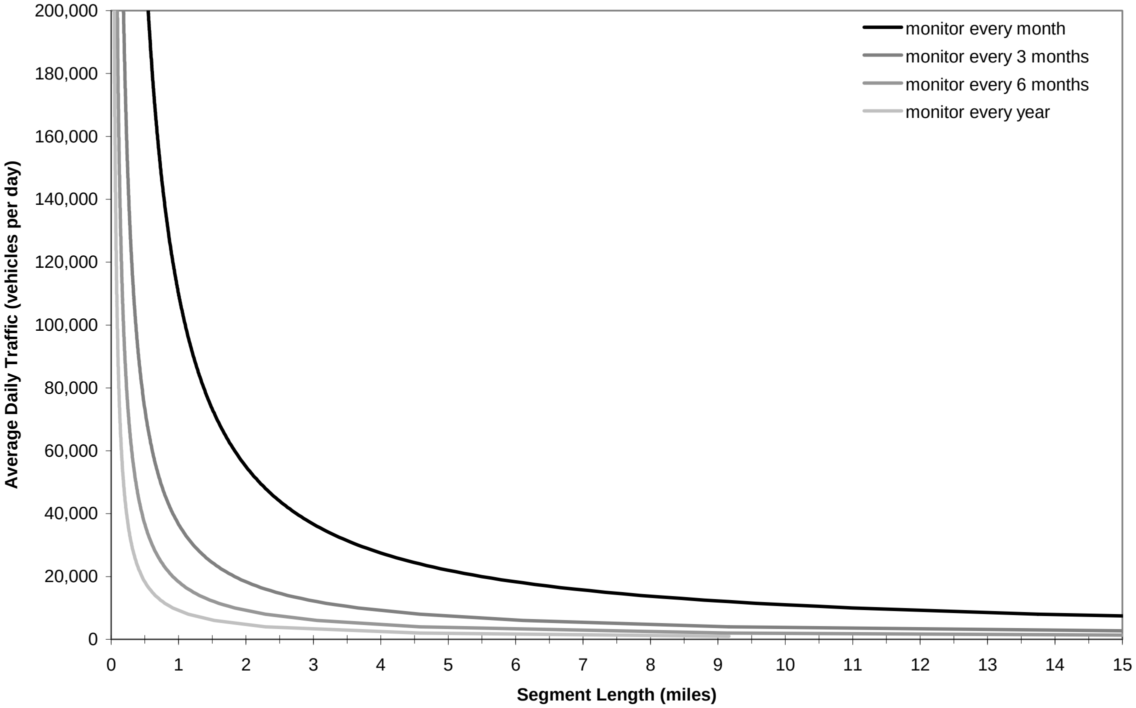


Figure 17. ADT and Project Length Combinations that Allow Detection of Significant Increases in Crashes during the Project (Pre-Work Zone Rate of 3.0 Accidents/MVM).

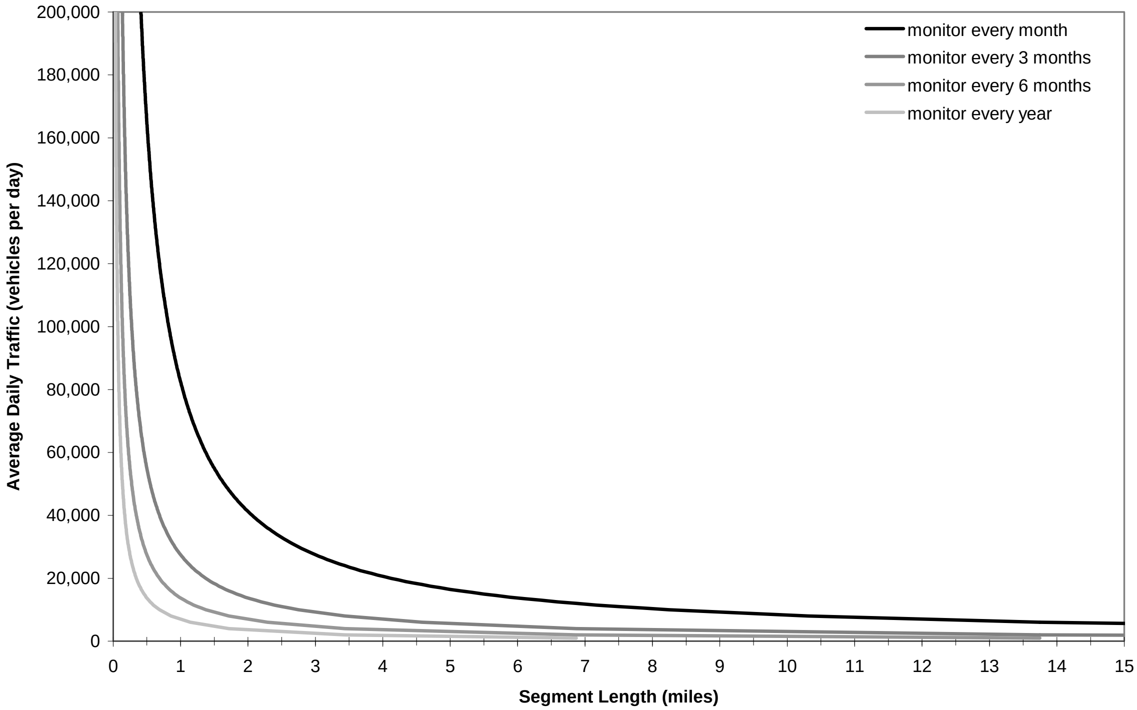


Figure 18. ADT and Project Length Combinations that Allow Detection of Significant Increases in Crashes during the Project (Pre-Work Zone Rate of 4.0 Accidents/MVM).

As an example of the above, assume a 6-mile pavement reconstruction project is scheduled on a four-lane divided freeway with an ADT of 40,000 vehicles per day and a typical accident rate of 1.0 accident per MVM. The entire project will last eight months, with a phase change after four months. Work in both directions of travel will occur simultaneously. What types of monitoring activities can be conducted?

Figure 19 illustrates the trade-off analyses that could be made. As can be seen, one could analyze the entire 6 miles for both directions combined approximately every two months and likely draw meaningful conclusions about whether safety at the work zone is being unduly compromised. Next, one could look at the 6-mile segments separately for each direction of travel (equal to an AADT of 20,000 vpd), but this analysis would require an estimated three-month monitoring period (assuming a 50/50 directional traffic distribution). Similarly, further disaggregation into 3-mile segments in each direction would require an estimated six months of data before meaningful conclusions would likely be possible. Finally, real-time analysis of 2-mile and smaller directional segments would probably not be practical for this work zone (approximately nine months of data needed—longer than the project duration).

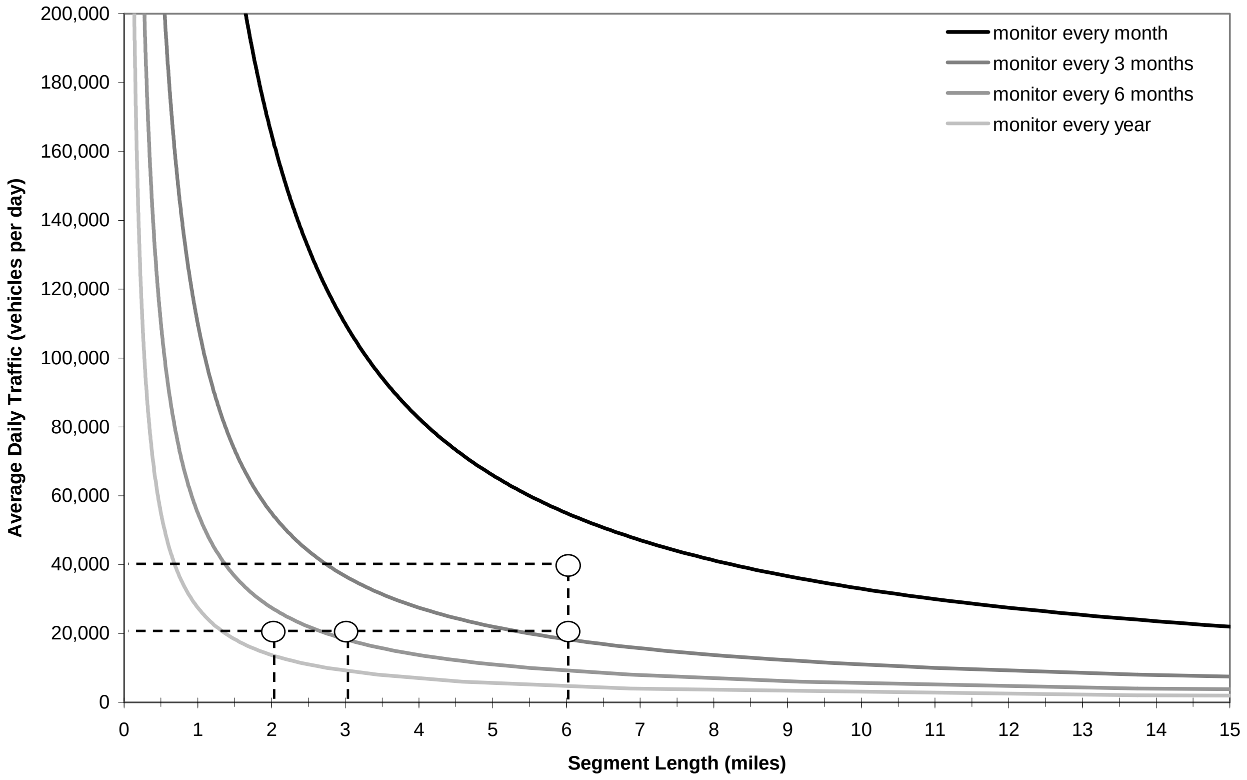


Figure 19. Example of Trade-Off Analysis of Different Segment Lengths and Monitoring Periods (Pre-Work Zone Rate of 1.0 Accidents/MVM).

Determining if Safety Has Declined More than Expected or More than Tolerable on a Work Zone Segment

This section describes a procedure for analyzing work zone segments to determine if safety has declined more than expected or more than the district considers tolerable compared to normal operating conditions. A number of alternative comparisons can be made with respect to defining safety during normal operating conditions. The one presented here is a commonly used comparison that accounts for seasonal fluctuations in extraneous accident 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 the designated before period (K),
- the ratio of the work zone analysis period to the designated before period (r_d),

- 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 ($\hat{r}_{tf}$), and
- the maximum percent safety reduction the district expects or is willing to accept ($\theta\%_{tolerable}$).

The use of "^" above the parameter indicates the value is unknown but is estimated using the best information available. Four computational steps are required:

Step 1: Estimate the safety of the work zone segment during the period of interest ($\hat{\lambda}$) and the variance of that estimate:

$$\hat{\lambda} = L$$

$$V\hat{A}R\{\hat{\lambda}\} = L$$

Step 2: Estimate what would have been the safety of the segment during the same time period had the work zone not been there ($\hat{\pi}$) and that variance of the estimate:

$$\hat{\pi} = r_d \hat{r}_{tf} K$$

$$V\hat{A}R\{\hat{\pi}\} = r_d^2 r_{tf}{}^2 K$$

The value for $\hat{\pi}$ is estimated using a "average" of the accident frequency on the same segment and during the same calendar period while accounting for changes in traffic volumes. A three-year average is recommended, reflecting a balance between the use of recent data and obtaining large enough sample sizes. If traffic has grown and is greater in the work zone than on the same segment for the three years prior, $\hat{r}_{tf}$ 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 $\hat{r}_{tf}$ will be less than 1. If no information on traffic volumes is available, a value of 1.0 should be used for $\hat{r}_{tf}$.

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

$$\hat{\lambda}_{tolerable} = \left(\frac{\theta\%_{tolerable}}{100\%} + 1 \right) * \hat{\pi}$$

$$V\hat{A}R\left\{\hat{\lambda}_{tolerable}\right\} = \left(\frac{\theta\%_{tolerable}}{100\%} + 1\right)^2 * V\hat{A}R\left\{\hat{\pi}\right\}$$

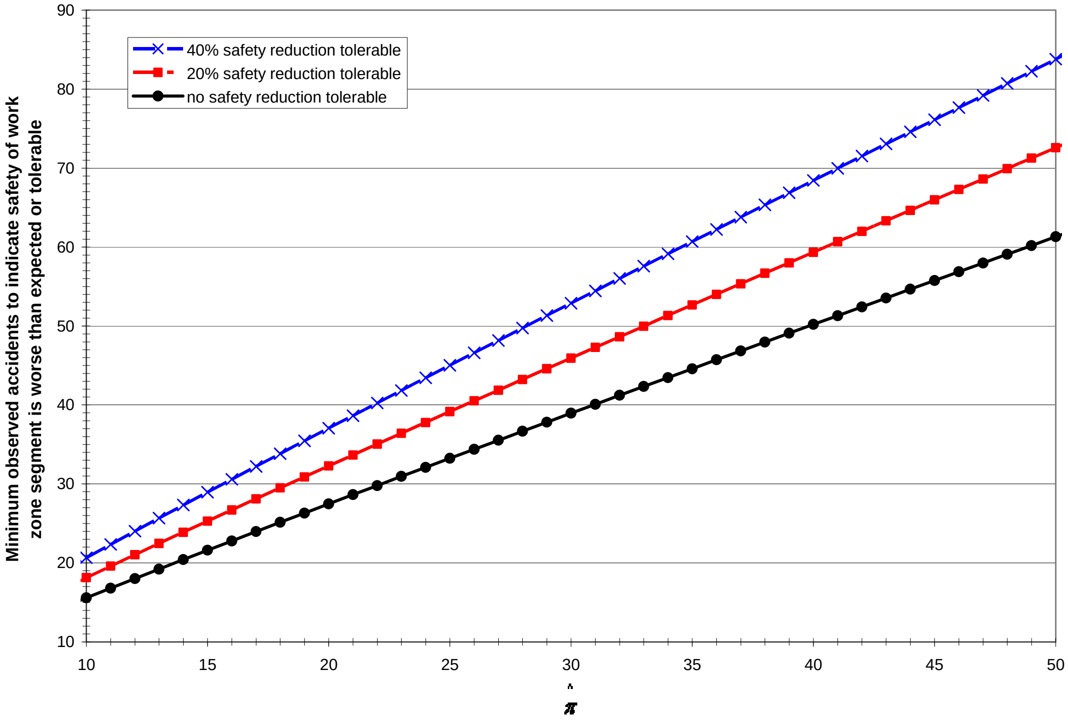
Step 4: Determine if the safety of the work zone segment during the period of interest ($\hat{\lambda}$) is worse than the expected or tolerable work zone safety ($\hat{\lambda}_{tolerable}$):

$\hat{\lambda} > \hat{\lambda}_{tolerable} + 1.282\sqrt{V\hat{A}R\{\hat{\lambda}\} + V\hat{A}R\{\hat{\lambda}_{tolerable}\}}$	Safety of the work zone segment during the period of interest is worse than expected or tolerable.

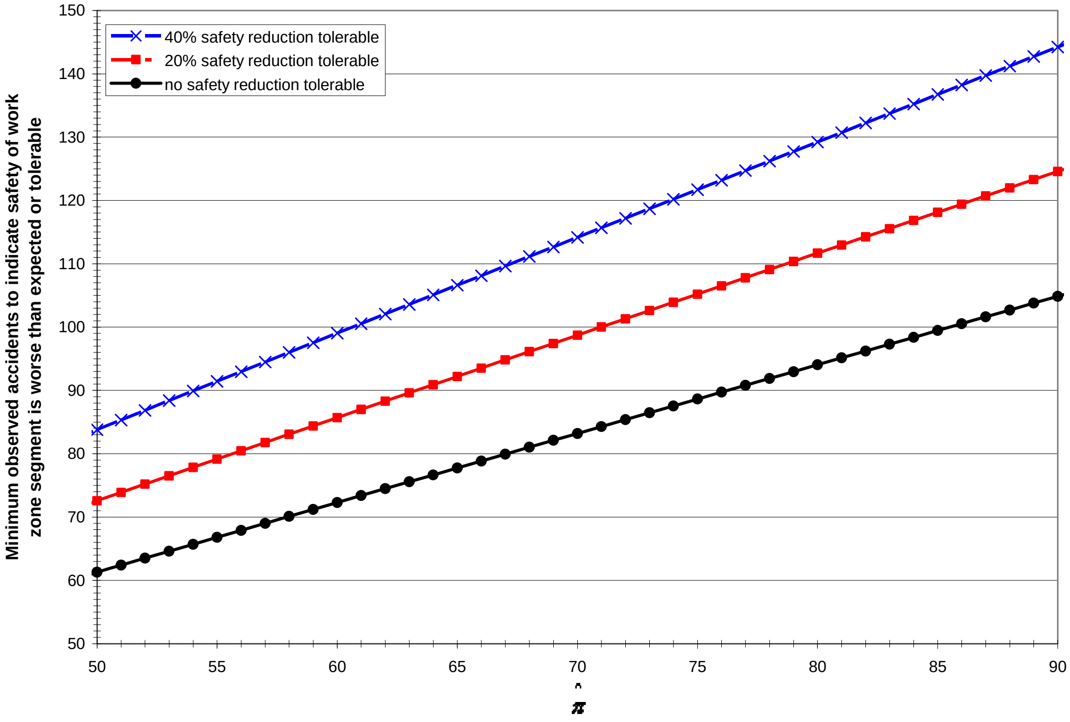
$\hat{\lambda} \leq \hat{\lambda}_{tolerable} + 1.282\sqrt{V\hat{A}R\{\hat{\lambda}\} + V\hat{A}R\{\hat{\lambda}_{tolerable}\}}$	There is not enough evidence to conclude that safety of the work zone segment during the period of interest is worse than expected or tolerable (with caveat explained below).

The use of 1.282 indicates that if we conclude the safety of the work zone segment during the period of interest ($\hat{\lambda}$) is worse than the expected or tolerable work zone safety ($\hat{\lambda}_{tolerable}$), 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. One could reduce the chance of the latter occurrence by decreasing the 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. Assuming work zone safety will also be addressed in each district 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], informal inspections), a 90 percent confidence level is used to try and identify the most extreme safety changes with a high level of confidence.

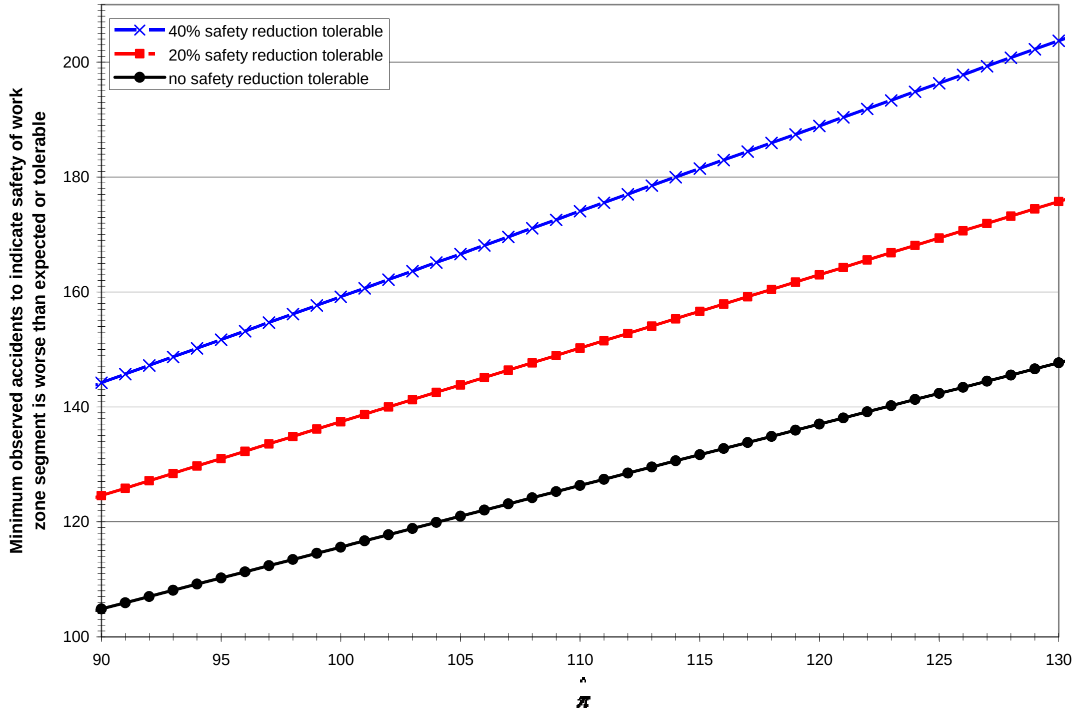
Figure 20 provides a graphical approach to accomplishing steps 3 and 4. The x-axis represents the safety of the segment during the time period of interest when the work zone was not there ($\hat{\pi}$). Values on the y-axis indicate the minimum number of work zone accidents observed during the analysis period ($\hat{\lambda} = L$) that would indicate safety has been reduced greater than expected or tolerable. Relationships are shown for three levels of tolerable safety reductions. The graphs in Figure 20 are intended for use when the ratio of the work zone analysis period to the designated before period is equal to 0.33. This observation holds true when the work zone period is compared to the same time period for three years prior to the work zone. Use of the equations in steps 1 through 4 is recommended for other types of comparisons.



(a) 10 ≤ expected crashes ≤ 50



(b) 50 ≤ expected crashes ≤ 90



(c) 90 ≤ expected crashes ≤ 130

Figure 20. Graphical Representation of Computational Steps 3 and 4.

As an example of these procedures, consider a 3.5-mile pavement rehabilitation project that is located in both directions of on a six-lane divided freeway with an ADT of approximately 120,000 vehicles per day. The project began on August 1, 2007, and the first three months of accident data are available (see Table 12). A district engineer wishes to determine if safety on the segment has been reduced and whether that reduction is greater than what the district expects or considers tolerable (20 percent in this district). The comparison should be made on a monthly and quarterly basis. Traffic volumes have remained fairly constant for the last four years, including daily volumes through the work zone.

August comparison:

$$\hat{\lambda} = L = 25$$

$$\hat{\pi} = r_d \, \hat{r}_{tf} \, K = 0.33 * 1 * (8 + 15 + 15) = 12.5$$

Using Figure 21, the number 22 is the minimum number of observed accidents that would indicate safety has decreased more than expected or tolerable (using the tolerable reduction line of 20 percent shown in the figure). Therefore, safety on this segment was worse than tolerable in August.

September comparison:

$$\hat{\lambda} = L = 17$$

$$\hat{\pi} = r_d \, \hat{r}_{tf} \, K = 0.33 * 1 * (7 + 10 + 23) = 13.2$$

Table 12. Number of Accidents in Work Zone for Both Directions of Travel.

Month	Number of Accidents
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

Again using Figure 21, the number 23 is the minimum number of observed accidents that would indicate safety has decreased more than expected or tolerable (using the tolerable reduction line of 20 percent shown in the figure). Therefore, there is not enough evidence to conclude that safety on this segment was worse than tolerable in September.

October comparison:

$$\hat{\lambda} = L = 21$$

$$\hat{\pi} = r_d \, \hat{r}_{tf} \, K = 0.33 * 1 * (18 + 14 + 25) = 18.8$$

Based on Figure 21, the number 23 is the minimum number of observed accidents that would indicate safety has decreased more than expected or tolerable (using the tolerable reduction line of 20 percent shown in the figure). Therefore, there is not enough evidence to conclude that safety on this segment was worse than tolerable in October.

Quarterly comparison:

$$\hat{\lambda} = L = 21 + 17 + 21 = 59$$

$$\hat{\pi} = r_d \, \hat{r}_{tf} \, K = 0.33 * 1 * (8 + 7 + 18 + 15 + 10 + 14 + 15 + 23 + 25) = 44.6$$

As shown in Figure 21, the number 65 is the minimum number of observed accidents that would indicate safety has decreased more than expected or tolerable (using the tolerable reduction line of 20 percent shown in the figure). Therefore, there is not enough evidence to conclude that safety on this segment was worse than tolerable during the first three months of the work zone. However, one can confidently conclude that there was a safety reduction of at least 5 to 10 percent (59 accidents fall between the black and red lines).

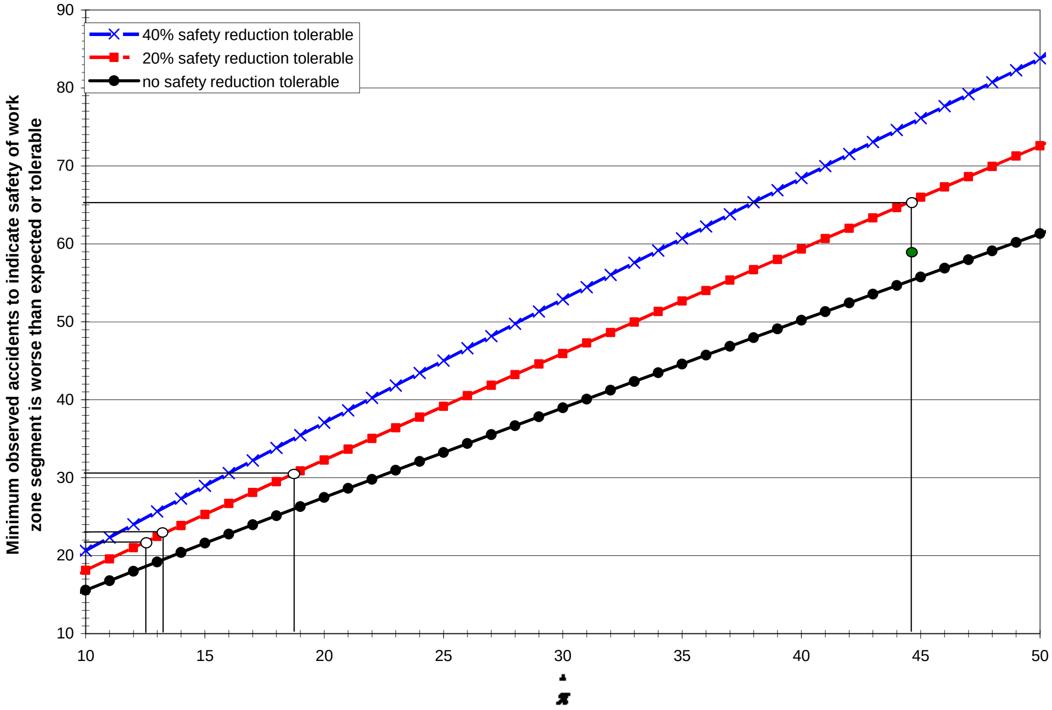


Figure 21. Example of Safety Assessment Procedures.

WORK ZONE MOBILITY MONITORING PILOT TESTING

OVERVIEW

To demonstrate the work zone mobility analysis methodologies and computational procedures described in the previous chapter, researchers contacted several of the urban districts to identify possible work zone pilot test sites. Researchers focused on sites that involved temporary lane closures on multiple days or nights that would generate traffic queuing during all or part of the lane closure period. In addition, researchers targeted sites that existed on routes where traffic surveillance equipment was present (in order to test the TMC-supported mobility monitoring procedures presented previously) and where project personnel were willing to provide queue length estimates for temporary lane closures (in order to test the non-TMC-supported mobility monitoring procedures previously presented). Researchers selected Interstate Highway (IH) 35 near Fort Sam Houston in San Antonio or the pilot test site.

SITE DESCRIPTION

The study section consists of three lanes in each direction. The innermost lane for each direction was closed because of work activity in the center median. Construction work was started in early January 2008 and lasted until May 2008. The pilot test location in the San Antonio area is shown in Figure 22. The lane closure limit for IH 35 northbound started 0.1 mile south of North Walters Street and extended to 0.4 mile north of the IH 410 northbound on-ramp to IH 35 southbound (approximately 3 miles). Similarly, the lane closure limit for IH 35 southbound started 0.4 mile north of the IH 410 northbound on-ramp to IH 35 southbound and terminated 0.6 mile north of North Walters Street (approximately 2.4 miles).

The posted speed limit in this section of freeway is 60 mph. The lane closure activities occurred during weekday off-peak periods between 9:00 AM and 4:00 PM. This site was selected because traffic demands to the on-ramp to IH 410 southbound from IH 35 northbound and the off-ramp from IH 410 northbound to IH 35 southbound often created traffic congestion and queuing at the lane closures.

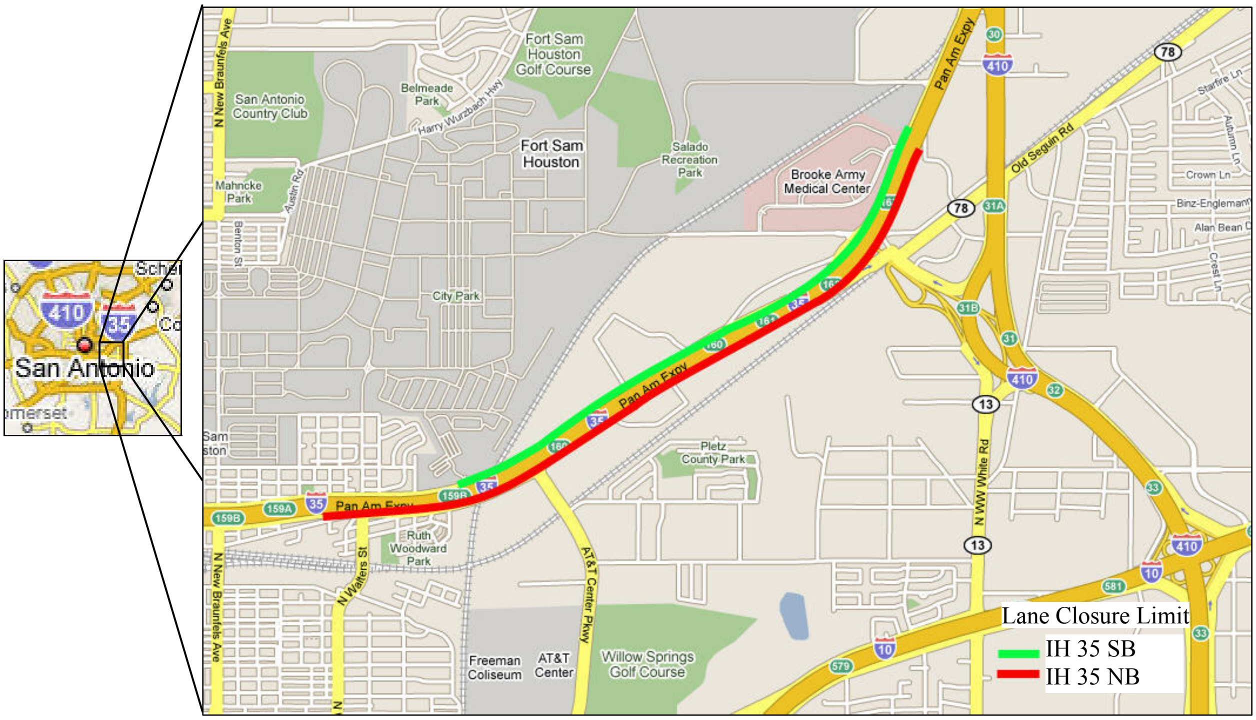


Figure 22. Lane Closure Limits for San Antonio Pilot Test Site (*11*).

DATA COLLECTION

Data were collected in March and April 2008 for use in estimating and comparing traffic mobility impacts resulting from this work activity. These data consisted of TTI researcher-collected travel time runs, spot speeds, and volume data obtained from traffic sensors along IH 35 as part of the TransGuide system in San Antonio, and estimates of queue lengths provided by TxDOT field personnel overseeing work activities at the site.

Travel Time Data

TTI researchers collected travel time data and obtained travel speeds throughout the work zone, the location of work zone features, and queue lengths. Researchers collected these data on March 17, March 20, and March 27, 2008. Researchers used one handheld Global Positioning System (GPS) unit and another GPS unit with the receiver/antenna placed on the roof of the data collection vehicle while conducting a travel time run. Researchers identified the formation of queue if the travel speed fell below 30 mph. Researchers imported these data into a Geographic Information System (GIS) map with street network, and identified the exact location of the beginning and the end of the work zone and the beginning and dissipation of queue length. Queue lengths measured on IH 35 are shown in Table 13 through Table 15 for three days when travel time runs were conducted. The maximum observed queue length was 2.8 miles on March 20, 2008, between 11:30 AM and 11:45 AM.

Table 13. Queue Length Data Collected on 3/17/2008 at IH 35.

Run Number and Direction	Start Time	Queue Length (mile)
Run 1 - IH 35 SB	10:31:59	1.31
Run 1 - IH 35 NB	10:43:28	0.52
Run 2 - IH 35 SB	10:50:28	1.55
Run 2 - IH 35 NB	11:06:06	0.36
Run 3 - IH 35 SB	11:12:06	1.66
Run 3 - IH 35 NB	11:31:28	0.46
Run 4 - IH 35 SB	11:36:24	1.73
Run 4 - IH 35 NB	11:57:31	0.12
Run 5 - IH 35 SB	12:05:10	2.45
Run 5 - IH 35 NB	12:27:35	0.35

Table 14. Queue Length Data Collected on 3/20/2008 at IH 35.

Run Number and Direction	Start Time	Queue Length (mile)
Run 1 - IH 35 SB	10:49:33	1.18
Run 1 - IH 35 NB	11:02:30	0.31
Run 2 - IH 35 SB	11:09:22	2.63
Run 2 - IH 35 NB	11:22:50	0.45
Run 3 - IH 35 SB	11:30:50	2.83
Run 3 - IH 35 NB	11:51:38	0.66
Run 4 - IH 35 SB	12:00:54	1.68
Run 4 - IH 35 NB	12:18:50	0.88

Table 15. Queue Length Data Collected on 3/27/2008 at IH 35.

Run Number and Direction	Start Time	Queue Length (mile)
Run 1 - IH 35 SB	10:23:21	1.80
Run 2 - IH 35 SB	10:42:09	1.56
Run 3 - IH 35 SB	11:58:23	0.83
Run 4 - IH 35 SB	12:12:53	0.81
Run 5 - IH 35 SB	12:28:39	0.72
Run 5 - IH 35 NB	12:36:04	0.93

Data obtained from the travel time runs were used to obtain speed profiles approaching and passing through the work zone. Examples of these profiles (Run 4 as shown in Table 13) are presented in Figure 23 and Figure 24 for the southbound and northbound directions, respectively. In the southbound direction it is important to note that queue speeds decreased continuously within the queue rather than remaining at a constant queue speed. This pattern is consistent with previous research and most likely reflects the real-time behaviors of motorists in the corridor to naturally divert in to other routes in response to the magnitude of queuing that develops (*12*). However, once reaching the lowest speed in queue (at the lane closure taper), vehicle speeds gradually increased through the actual work zone area. This speed profile contrasts slightly with the analysis assumptions presented in the previous chapter, where average speeds were assumed to be at capacity flow (approximately 30 mph for this freeway facility) through the entire length of work zone. Meanwhile, traffic demands in the northbound direction on this particular travel time run were apparently lower, to the point that only a minimal queue was detected.

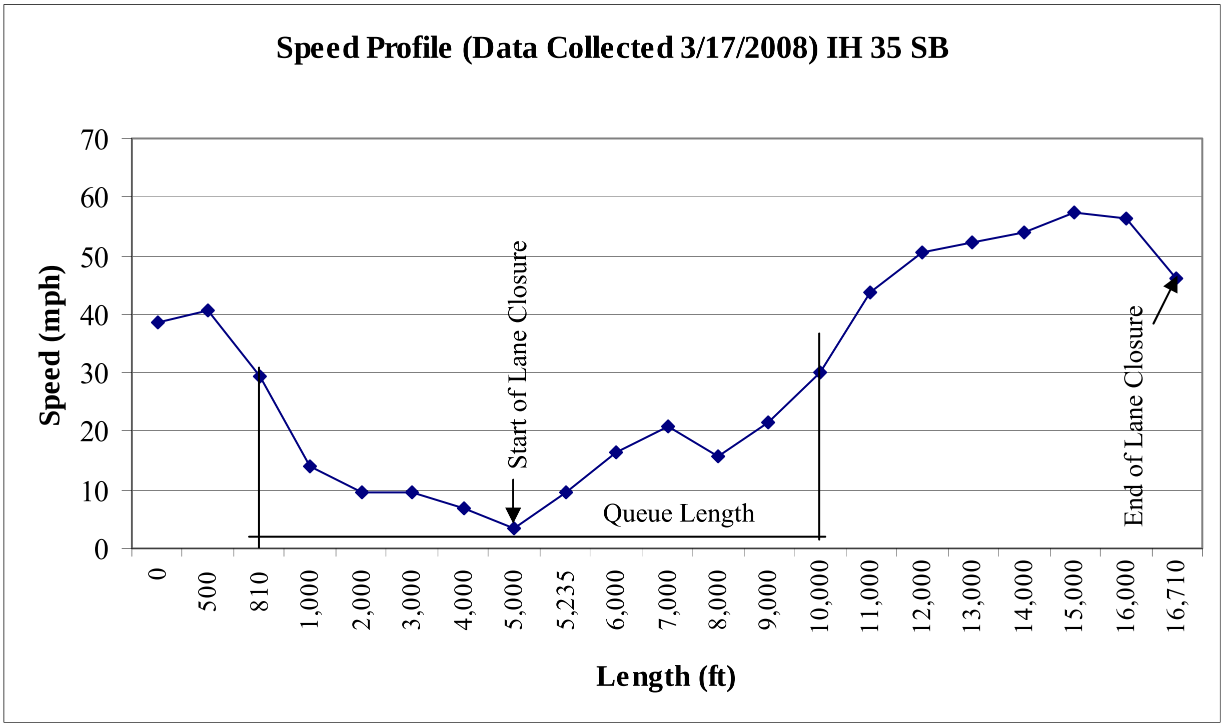


Figure 23. Example of Speed Profile along Work Zone IH 35 Southbound (3/17/2008).

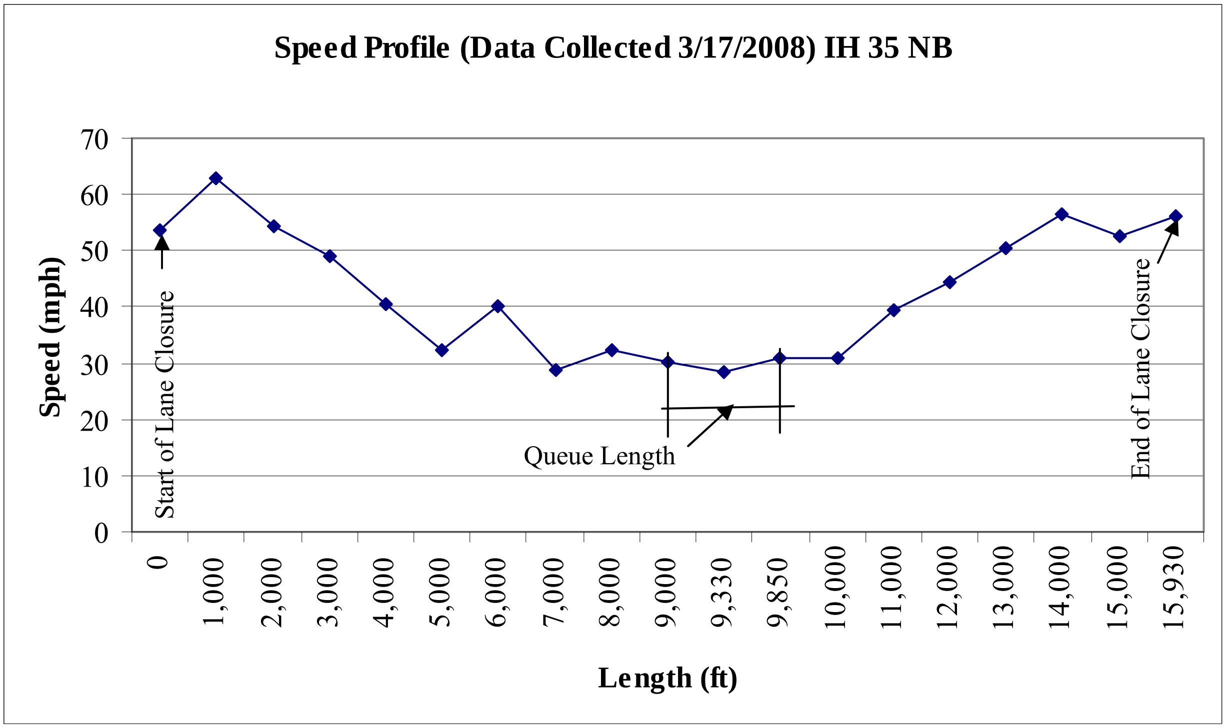


Figure 24. Example of Speed Profile along Work Zone IH 35 Northbound (3/17/2008).

Traffic Sensor Data

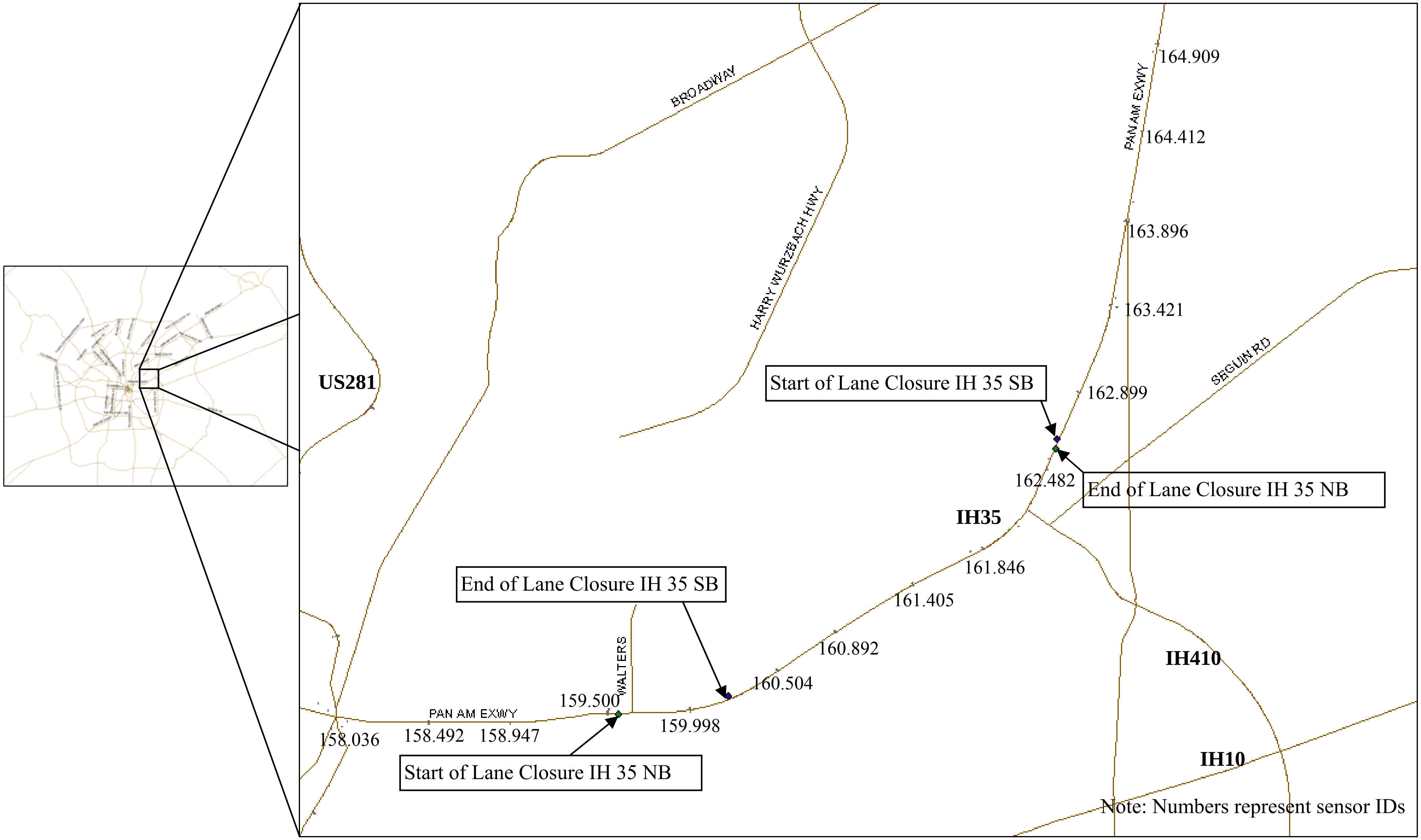
Researchers also obtained electronic traffic sensor data for the pilot test site from TxDOT's TransGuide system in San Antonio. Researchers downloaded data from March 13, 2008, through end of April 2008. These data were downloaded as 20-second interval data, and therefore had to be processed into more useful 15-minute and hourly interval data.

Traffic sensor IDs and length between sensors are shown in Table 16. Graphically, the traffic sensor locations within, upstream, and downstream of the work zone are shown in Figure 25. For reference purposes, the start and endpoints of the lane closure are also shown. The IH 35 southbound lane closure begins 1550 ft downstream of sensor ID 162.899 and ends 1670 ft downstream of sensor ID 160.504. The lane closure for IH 35 northbound starts 350 ft downstream of sensor ID 159.500 and ends 1820 ft downstream of sensor ID 162.482.

Table 16. Location of Sensor IDs at the IH 35 Site.

Sensor ID	IH 35 Northbound Work Zone			IH 35 Southbound Work Zone			Distance Between Sensors (mile)
	Within	Before	After	Within	Before	After	
158.036		X				X	0.00
158.492		X				X	0.46
158.947		X				X	0.46
159.500		X				X	0.55
159.998	X					X	0.46
160.504	X			X			0.54
160.892	X			X			0.39
161.405	X			X			0.51
161.846	X			X			0.44
162.482	X			X			0.64
162.899			X		X		0.41
163.421			X		X		0.52
163.896			X		X		0.48
164.412			X		X		0.52
164.909			X		X		0.50

Queue lengths and corresponding time at a sensor location along IH 35 southbound are shown in the appendix. For some of the days, the queuing caused did continue into the PM peak period after the lane closure had presumably been removed. On these days, the researchers simply quit attributing any of the queuing observed after 4:00 PM to the lane closures. Undoubtedly, though, some of the congestion and delays that were incurred after 4:00 PM on those days could be considered as at least partially induced by the presence of the lane closures earlier in the day.



Note: Numbers represent sensor IDs

Figure 25. Locations of Traffic Sensors and the IH 35 Test Site in San Antonio.

Manual Observation of Congestion by TxDOT Personnel

The research team asked TxDOT field personnel working for this project to prepare a log sheet of approximate queue lengths and corresponding times of occurrence during the lane closures. Field crews provided these data for 10 days during the data collection period. These data reflect a sampling of the queuing behavior observed by field personnel over the six-week study period. The field observation log sheet can be found in Table 17. Field crew personnel documented queue lengths as long as 1.5 miles on some of the days.

Table 17. Queue Information Obtained from TxDOT Field Personnel.

Date	Lane Closure Start Time	Lane Closure End Time	Queue Start Time	Queue End Time	Approximate Queue Length (miles)	Description
3/10/2008	None					Rainy day
3/13/2008	9:00	13:00	11:00	13:00	0.7	
3/13/2008	13:00	15:00	13:00	15:00	0.3	
3/31/2008	9:00	15:00	12:00	13:00	0.9	
4/01/2008	9:00	15:00	12:00	13:00	1.0	Speed down to 40 mph
4/02/2008	9:00	15:00	9:20	10:00	1.4	
4/14/2008	9:00	15:00	12:30	13:30	1.5	
4/16/2008	9:00	15:00	11:00	12:00	1.0	
4/17/2008	9:00	15:00	9:30	10:30	0.9	
4/18/2008	9:00	15:00	10:00	11:00	0.9	
4/28/2008	9:00	15:00	10:30	10:45	0	
4/28/2008	9:00	15:00	11:15	11:45	0	

RESULTS

Table 18 shows a sample of the computations used to estimate average travel time, average delay, and total delay for data collected for the southbound direction on March 13, 2008. Table 19 provides a summary for the other days. Researchers calculated these measures based on average speeds and volumes at the various sensor locations used to detect queue presence during the lane closures.

Table 18. Sample Analysis for Travel Time, Average Delay, and Total Delay for Collected Data on 3/13/2008.

Time	With Lane Closure				Without Lane Closure				Average Delay per Vehicle (min)		Total Vehicle-Hours of Delay		Traffic Volume (VPH)
	Travel Time (min)		Speed (mph)		Travel Time (min)		Speed (mph)						
	Sensor ID 162.482	Sensor ID 162.899	Sensor ID 162.482	Sensor ID 162.899	Sensor ID 162.482	Sensor ID 162.899	Sensor ID 162.482	Sensor ID 162.899	Sensor ID 162.482	Sensor ID 162.899	Sensor ID 162.482	Sensor ID 162.899	
9:00	-	0.54	-	52	-	0.48	59	59	-	0.06	-	0.8	2,918
10:00	1.86	1.34	17	21	0.54	0.48	59	59	1.32	0.86	48.7	31.7	2,208
11:00	1.97	2.16	16	13	0.54	0.48	59	59	1.44	1.68	54.1	63.3	2,256
12:00	1.58	0.88	20	32	0.54	0.48	59	59	1.04	0.40	43.1	16.6	2,479
13:00	1.76	1.08	18	26	0.54	0.48	59	59	1.22	0.60	51.2	25.4	2,519
14:00	1.86	1.87	17	15	0.54	0.48	59	59	1.32	1.40	51.9	54.7	2,352
15:00	1.37	1.34	23	21	0.54	0.48	59	59	0.84	0.86	24.6	25.3	2,353
Average	3.12		22.4		1.02		59		2.10				2,441
Total Delay Due to Lane Closure (Total Vehicle-Hours of Delay)											**491.4**		-

Note: Distance between sensors 162.482 to 162.899 is 0.53 mile. Distance between sensors 62.899 to 163.421 is 0.47 mile. Sensor data obtained from location 162.899 was not consistent for all three lanes; therefore, traffic volume data obtained from location 162.482 was used for both of these locations.

Table 19. Summary of Lane Closure Data along IH 35 Southbound.

Date	Average Speed (mph)		Average Travel Time (minutes)		Average Delay per Vehicle (minutes)	Total Vehicle - Hours of Delay	Length of Queue (miles)	Average Volume during Lane Closure (vph)
	With Lane Closure	Without Lane Closure	With Lane Closure	Without Lane Closure				
3/13/2008	22.4	59.0	1.5	0.5	1.0	491.4	1.0	2,441
3/14/2008	15.8	61.5	2.1	0.5	1.7	687.0	1.0	2,232
3/17/2008	19.6	58.5	2.1	0.5	1.6	589.8	1.0	2,317
3/19/2008	26.8	59.0	1.5	0.6	0.9	142.1	0.5	2,376
3/20/2008	23.0	59.3	3.0	0.9	2.1	822.0	2.5	3,528
3/24/2008	33.5	60.6	1.3	0.6	0.7	283.5	2.9	2,694
3/25/2008	37.0	58.0	0.9	0.5	0.3	16.5	0.5	2,638
3/26/2008	31.3	60.7	1.1	0.5	0.6	57.4	1.0	2,542
3/27/2008	20.1	61.0	1.7	0.5	1.2	451.4	1.0	2,293
3/28/2008	19.2	60.5	1.8	0.5	1.3	566.5	1.0	2,299
3/31/2008	31.7	62.0	1.3	0.5	0.8	69.2	0.5	2,227
4/1/2008	21.5	59.0	1.4	0.5	0.9	53.4	0.5	2,010
4/3/2008	29.8	58.0	1.0	0.5	0.5	56.5	0.5	2,248
4/8/2008	19.6	59.4	1.7	0.5	1.2	242.8	1.5	2,454
4/9/2008	23.3	61.5	1.6	0.5	1.0	726.7	2.0	2,452
4/10/2008	23.0	58.0	1.5	0.5	1.0	259.0	2.0	2,285
4/11/2008	22.7	58.0	1.5	0.5	1.0	337.9	1.0	2,292
4/15/2008	37.0	63.0	0.7	0.4	0.3	3.9	0.5	3,120
4/16/2008	24.0	59.0	2.6	1.0	1.6	239.4	1.9	2,560
4/17/2008	31.1	61.1	2.1	1.0	1.1	293.5	1.9	3,016
4/18/2008	30.2	59.0	2.3	1.1	1.2	309.1	1.9	3,127
4/22/2008	26.0	63.0	1.1	0.4	0.6	34.1	0.5	3,227
4/23/2008	42.0	62.0	0.6	0.4	0.2	8.4	0.5	3,396
4/24/2008	32.4	63.0	1.7	0.8	1.0	359.4	1.5	2,877
4/29/2008	34.5	62.0	1.1	0.5	0.6	47.2	0.5	3,317
Range	15.8-42.0	58.0-63.0	0.6-3.0	0.4-1.1	0.2-2.1	3.9-822.0	0.5-2.9	
50%-tile	26.0	60.5	1.5	0.5	1.0	259.0	1.0	
95%-tile	19.2	58.0	2.6	1.0	1.6	726.7	2.5	

Review of the results in Table 19 indicates that, on average, the impacts of the daily lane closures were not overly excessive at this site. However, one does see that the impact did vary substantially from day to day (as noted by the ranges in values shown at the bottom of the table), even though the lane closure was positioned at the same location and during the same times each day. Researchers further quantified the day-to-day variation in observations by computing both the median (50th percentile) and 95th percentile values of each of the measures, also shown at the bottom of the table. In the case of queue lengths and total vehicular delay per day, the 95th percentile value is nearly three times that of the average value measured. Such variation illustrates the importance of establishing ongoing monitoring programs of work zone impacts, rather than simply relying on predictive models based on average traffic volumes and work zone capacities utilized during the design stage of a project. The variation in both traffic demands and work zone capacity from day to day contribute to much different outcomes in terms of delays, speeds, and traffic queues.

Comparison of queue length for data obtained from the researcher travel time runs and traffic sensor data is shown in Table 20. Queue lengths estimated via the traffic sensor data tended to be slightly shorter than those measured at the same time by the TTI researchers. In the northbound direction, there were several instances where the researchers identified a small queue that was not detected via the traffic surveillance data in or near the work zone. Part of this discrepancy is likely due to the use of a fairly long (15-minute) aggregation period of the sensor data prior to applying the work zone impact measurement procedures. The estimation of queue length via the sensors also tends to be more accurate (relative to the travel time runs) for longer queues than for shorter ones. For both directions of travel, researchers computed the average absolute error (AAE) and the absolute relative error (ARE) of the queue lengths. These terms, used previously to evaluate the accuracy of queue length and other performance measures associated with work zone lane closures, are computed as follows (*13*):

$$AAE = \frac{\sum_{i=1}^{n} \left| O_i - E_i \right|}{n}$$

$$ARE = \frac{\sum_{i=1}^{n} \frac{\left| O_i - E_i \right|}{O_i}}{n} x100\%$$

Table 20. Comparison of Queue Lengths for Data Obtained from Travel Time Runs and Traffic Sensor Data.

Date	Time	Queue Length (mile) IH 35 Southbound		Queue Length (mile) IH 35 Northbound	
		Travel Time Runs	Traffic Sensors	Travel Time Runs	Traffic Sensors
3/17/2008	10:00-11:00	1.4	1.0	0.5	No Queue
	11:00-12:00	1.7	1.0	0.3	No Queue
	12:00-13:00	2.5	1.0	0.4	0.5
3/20/2008	10:00-11:00	1.2	0.5	-	-
	11:00-12:00	2.7	2.5	0.5	0.5
	12:00-13:00	1.7	0.5	0.9	1.5
3/27/2008	10:00-11:00	1.7	1.0	-	-
	11:00-12:00	0.8	1.0	-	-
	12:00-13:00	1.5	1.0	0.9	No Queue
AAE ARE		0.7 mile 49.9%		0.4 mile 43.5%	

As shown in Table 20, the average absolute error in queue length estimation via the traffic sensors was 0.7 mile in the southbound direction and 0.4 mile in the northbound. Expressed as a percentage, the average relative error of the queue length estimates was 49.9 percent in the southbound direction and 43.5 percent in the northbound direction.

Although TxDOT field personnel did not record queue length data on the days that TTI researchers collected travel time and queue length data, it was possible to compare queue lengths obtained from TxDOT field personnel to those estimated from traffic sensor data for a few days during the pilot test period. Table 21 presents the results of that comparison. In a few instances, field personnel reported a queue but the queue was not detected based on traffic sensor data. In the remaining instances, estimates of queue lengths by the two methods vary somewhat, with no clear trend of one method either over- or underestimating queue lengths relative to the other. The disagreement over queue length presence in 4 of the 10 measurements shown in Table 21 led to higher average absolute errors and average relative errors than was computed for Table 20.

Table 21. Comparison of Queue Lengths along IH 35 Southbound for Data Obtained from Traffic Sensors and Data Collected from TxDOT Field Personnel.

Date	Time	Queue Length (mile)	
		TxDOT Field Personnel	Traffic Sensors
3/13/2008	11:00-13:00	0.7	1.0
3/13/2008	13:00-15:00	0.3	1.0
3/31/2008	12:00-13:00	0.9	0.52
4/01/2008	12:00-13:00	1.0	[1]No Queue
4/02/2008	9:20-10:00	1.4	No Queue
4/14/2008	12:30-13:30	1.5	No Queue
4/16/2008	11:00-12:00	1.0	[2]No Queue
4/17/2008	9:30-10:30	0.9	1.93
4/18/2008	10:00-11:00	0.9	0.45
4/28/2008	10:30-10:45	No Queue	No Queue
4/28/2008	11:15-11:45	No Queue	No Queue
	AAE	0.7 mile	
	ARE	83.2%	

[1] Queue initiated at 9:00 and ended at 10:45.

[2] Queue initiated at 12:00 and ended at 14:00.

WORK ZONE SAFETY MONITORING PILOT TESTING

A freeway and frontage road widening project on State Highway (SH) 358 in Corpus Christi was selected as a pilot test site for the recommended safety monitoring procedures. The project consists of four major stages and includes (in addition to widening) installation of high-mast lighting, ramp construction and reconstruction, sign installation, and overlays. Construction activities began on January 9, 2007, and are on-going. The project limits for this analysis are defined by Carroll Lane (control section 0617-01; milepoint [MP] 7.3) and Airline Road (control section 0617-01; milepoint 10.6). Table 22 and Table 23 summarize the available crash and traffic data.

No major traffic diversions from the SH 358 corridor were expected or recorded during construction; traffic numbers identical to 2006 numbers are assumed for 2007 and 2008. Weighting the ADT average by segment length resulted in the following representative daily traffic estimates for the project:

- 2005: 106,380 vehicles per day and
- 2006 – 2008: 101, 330 vehicles per day

The pre-work zone accident rate is estimated by:

$$\frac{\left(\sum_{i=2005,2006} N_i\right) * 1{,}000{,}000}{\sum_{i=2005,2006}\left(ADT_i * L * 365\right)} = \frac{(587+429)*1{,}000{,}000}{106{,}380*3.3*365+101{,}330*3.3*365} \approx 4 \text{ accidents per MVM}$$

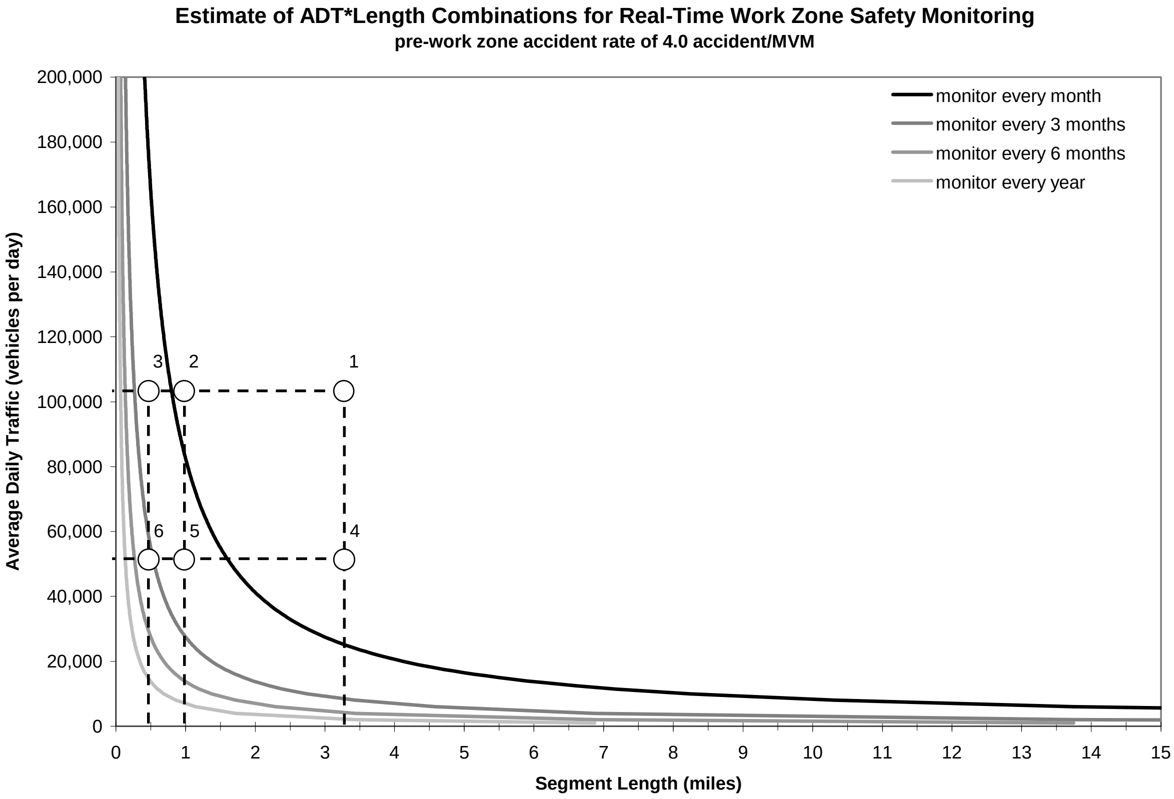
Table 22. Traffic Data for Pilot Test Project.

Highway	Control Section	Beginning Milepoint	Ending Milepoint	ADT 2006	ADT 2005
SH 358	0617-01	6.485	7.518	125,840	135,000
SH 358	0617-01	7.518	7.985	125,840	135,000
SH 358	0617-01	7.985	8.644	103,060	110,300
SH 358	0617-01	8.644	9.983	103,060	110,300
SH 358	0617-01	9.983	11.227	68,540	61,930

Table 23. Accident Data for Pilot Test Project (Control Section 0617-01; Milepoints 7.3 – 10.6).

Month	Year	Number of Accidents
January	2005	50
February	2005	52
March	2005	65
April	2005	46
May	2005	42
June	2005	33
July	2005	47
August	2005	46
September	2005	36
October	2005	43
November	2005	50
December	2005	77
January	2006	41
February	2006	45
March	2006	39
April	2006	29
May	2006	43
June	2006	34
July	2006	24
August	2006	26
September	2006	25
October	2006	33
November	2006	31
December	2006	59
January	2007	45
February	2007	36
March	2007	46
April	2007	36
May	2007	40
June	2007	45
July	2007	64
August	2007	46
September	2007	46
October	2007	48
November	2007	39
December	2007	30
January	2008	36
February	2008	25
March	2008	27
April	2008	24

Figure 26 illustrates the use of Figure 18 to assess monitoring options for the pilot test project. The figure illustrates six levels of possible data aggregation, ranging from monitoring the entire work zone in both directions to monitoring 0.5 mile segments in each direction separately. A monthly or quarterly monitoring frequency is probably practical for all aggregation levels, confirming that this particular multi-year project is a good candidate for real-time safety analyses. The following subsections include safety analyses and results for several different segment lengths (e.g., entire project, 1-mile segments, etc.). The analyses presented for all cases are for both directions of travel. Similar analyses can be conducted for each direction separately (note: the actual monitoring steps are not dependent on daily traffic but an estimate of the ratio of traffic in the work zone to pre-work zone conditions).



[1] Monitoring entire work zone; both directions together

[2] Monitoring one mile segments; both directions together

[3] Monitoring one-half mile segments; both directions together

[4] Monitoring entire work zone; each direction separately

[5] Monitoring one mile segments; each direction separately

[6] Monitoring one-half mile segments; each direction separately

Figure 26. Assessment of Possible Monitoring Levels of the SH 358 Project.

ANALYSIS OF ENTIRE WORK ZONE: BOTH DIRECTIONS TOGETHER

Table 24 and Table 25 summarize the results of a before-during comparison of work zone safety using procedures described elsewhere (*14*). The analyses were of the entire work zone segment in both directions of travel, and the results are used as a basis for comparison to the graphical procedures outlined. The following terminology (in addition to the parameters introduced above) is adapted from (*14*):

- $\hat{\delta}$ = an estimate of the difference in expected work zone accident frequency to the expected accident frequency had the work zone not been in place during the analysis time period ($\hat{\lambda} - \hat{\pi}$),
- $\hat{\sigma}(\hat{\delta})$ = an estimate of the standard deviation of $\hat{\delta}$,
- $\hat{\theta}$ = an estimate of the ratio of expected work zone accidents to the number of expected accidents had the work zone not been in place during the analysis time period ($\left(\hat{\lambda}/\hat{\pi}\right)/\left[1 + V\hat{A}R\{\hat{\pi}\}/\hat{\pi}^2\right]$),
- $\hat{\sigma}\left(\hat{\theta}\right)$ = an estimate of the standard deviation of $\hat{\theta}$,
- $\hat{\theta}\%$ = an estimate of the percent change in expected work zone accidents to the number of expected accidents had the work zone not been in place during the analysis time period ($\hat{\theta} - 1$),
- $\hat{\sigma}\left(\hat{\theta}\%\right)$ = an estimate of the standard deviation of $\hat{\theta}\%$, and
- $\hat{\delta}/\hat{\sigma}\left(\hat{\delta}\right)$ = a test statistic indicating the distance of $\hat{\delta}$ from zero in terms of its standard deviation (e.g., if $\hat{\delta} = 4$ and $\hat{\sigma}\left(\hat{\delta}\right) = 3$, then $\hat{\delta}$ is approximately 1.33 standard deviations away from zero).

Only two years of before data were available for the pilot test. For example, the number of accidents that would have occurred in July 2007 had the work zone not been in place is estimated using data from July 2006 and July 2005. Therefore, the ratio of the work zone analysis period to the designated before period (r_d) is equal to 0.5 in Table 24 and all other subsequent tables that summarize the safety computations. It is recommended that three years of before data be used, and the thresholds graphically represented in Figure 26 are based on this recommendation. The pilot test offers a good opportunity to evaluate how the graphical procedures perform when less than three years of before data are available. The overall project traffic estimates were used to estimate the ratio of traffic in the work zone to traffic on the same segment and during the same calendar period for three years prior ($\hat{r}_{tf}$); the average of 106,380 and 101,330 vehicles per day for the before period and 101,330 vehicles per day for the work zone resulted in a value of 0.98 for $\hat{r}_{tf}$.

The results in Table 24 show a consecutive five-month period (June 2007 through October 2007) with increases in expected accident frequencies ranging from 27 percent ± 23 percent to 81 percent ± 31 percent. Results of the quarterly analyses summarized in Table 25 are consistent with the results in Table 24; however, one disadvantage of longer work zone analysis periods is evident. The quarterly analysis reports a 36 percent increase in expected accident frequency from May 2007 to July 2007. The aggregation into quarters actually masks the observed pattern of no increase in May 2007, but an 81 percent increase in July 2007. This finding could be important, depending on the phasing and work features that were present, or that may have changed, during that particular time period.

Table 26 and Table 27 summarize the results of the graphical analysis approach (e.g., Figure 26). The conclusions reached using the graph are consistent with the conclusions obtained from the more intensive computational approach. There was a significant increase in expected accident frequency for five consecutive months (June 2007 through October 2007). The increase was greater than 20 percent for two of those months (July 2007 and September 2007) and was greater than 40 percent in July 2007. The three-month analysis showed increases greater than 20 percent for two quarters (May 2007 through July 2007 and August 2007 through October 2007). The conclusions regarding these increases in expected accident frequency are made with 90 percent confidence.

Table 24. Results of Computational Safety Analysis: Entire Work Zone; Both Directions Together; One-Month Monitoring.

	L	K	r_d	$\hat{r}_{tf}$	$\hat{\pi}$	$\hat{\lambda}$	$V\hat{A}R\{\hat{\pi}\}$	$V\hat{A}R\{\hat{\lambda}\}$	$\hat{\delta}$	$\hat{\sigma}(\hat{\delta})$	$\hat{\theta}$	$\hat{\sigma}(\hat{\theta})$	$\hat{\theta}\%$	$\hat{\sigma}(\hat{\theta}\%)$
January 2007	45	91	0.50	0.98	44.6	45	21.8	45	0.4	8.2	1.00	0.18	0	18
February 2007	36	97	0.50	0.98	47.5	36	23.3	36	-11.5	7.7	0.75	0.14	-25	14
March 2007	46	104	0.50	0.98	51.0	46	25.0	46	-5.0	8.4	0.89	0.16	-11	16
April 2007	36	75	0.50	0.98	36.8	36	18.0	36	-0.8	7.3	0.97	0.19	-3	19
May 2007	40	85	0.50	0.98	41.7	40	20.4	40	-1.7	7.8	0.95	0.18	-5	18
June 2007	45	67	0.50	0.98	32.8	45	16.1	45	12.2	7.8	1.35	0.26	35	26
July 2007	64	71	0.50	0.98	34.8	64	17.0	64	29.2	9.0	1.81	0.31	81	31
August 2007	46	72	0.50	0.98	35.3	46	17.3	46	10.7	8.0	1.29	0.24	29	24
September 2007	46	61	0.50	0.98	29.9	46	14.6	46	16.1	7.8	1.51	0.29	51	29
October 2007	48	76	0.50	0.98	37.2	48	18.2	48	10.8	8.1	1.27	0.23	27	23
November 2007	39	81	0.50	0.98	39.7	39	19.4	39	-0.7	7.6	0.97	0.19	-3	19
December 2007	30	136	0.50	0.98	66.6	30	32.7	30	-36.6	7.9	0.45	0.09	-55	9
January 2008	36	91	0.50	0.98	44.6	36	21.8	36	-8.6	7.6	0.80	0.16	-20	16
February 2008	25	97	0.50	0.98	47.5	25	23.3	25	-22.5	6.9	0.52	0.12	-48	12
March 2008	27	104	0.50	0.98	51.0	27	25.0	27	-24.0	7.2	0.52	0.11	-48	11
April 2008	24	75	0.50	0.98	36.8	24	18.0	24	-12.8	6.5	0.64	0.15	-36	15

Table 25. Results of Computational Safety Analysis: Entire Work Zone; Both Directions Together; Quarterly Monitoring.

	L	K	r_d	$\hat{r}_{tf}$	$\hat{\pi}$	$\hat{\lambda}$	$V\hat{A}R\{\hat{\pi}\}$	$V\hat{A}R\{\hat{\lambda}\}$	$\hat{\delta}$	$\hat{\sigma}(\hat{\delta})$	$\hat{\theta}$	$\hat{\sigma}(\hat{\theta})$	$\hat{\theta}\%$	$\hat{\sigma}(\hat{\theta}\%)$
February 2007 - April 2007	118	276	0.50	0.98	135.2	118	66.3	118	-17.2	13.6	0.87	0.10	-13	10
May 2007- July 2007	149	223	0.50	0.98	109.3	149	53.5	149	39.7	14.2	1.36	0.14	36	14
August 2007 - October 2007	140	209	0.50	0.98	102.4	140	50.2	140	37.6	13.8	1.36	0.15	36	15
November 2007- January 2008	105	308	0.50	0.98	150.9	105	74.0	105	-45.9	13.4	0.69	0.08	-31	8
February 2008 - April 2008	76	276	0.50	0.98	135.2	76	66.3	76	-59.2	11.9	0.56	0.07	-44	7

Table 26. Results of Graphical Safety Analysis: Entire Work Zone; Both Directions Together; One-Month Monitoring.

	L	K	r_d	$\hat{r}_{tf}$	$\hat{\pi}$	$\hat{\lambda}^1$	Threshold for Increase	Threshold for Greater than 20% Increase	Threshold for Greater than 40% Increase
January 2007	45	91	0.50	0.98	44.6	45	56	▨	▨
February 2007	36	97	0.50	0.98	47.5	36	**	▨	▨
March 2007	46	104	0.50	0.98	51.0	46	▨	▨	▨
April 2007	36	75	0.50	0.98	36.8	36	▨	▨	▨
May 2007	40	85	0.50	0.98	41.7	40	▨	▨	▨
June 2007	45	67	0.50	0.98	32.8	45	42	50	▨
July 2007	64	71	0.50	0.98	34.8	64	45	53	61
August 2007	46	72	0.50	0.98	35.3	46	45	53	▨
September 2007	46	61	0.50	0.98	29.9	46	39	46	53
October 2007	48	76	0.50	0.98	37.2	48	47	55	▨
November 2007	39	81	0.50	0.98	39.7	39	▨	▨	▨
December 2007	30	136	0.50	0.98	66.6	30	▨	▨	▨
January 2008	36	91	0.50	0.98	44.6	36	▨	▨	▨
February 2008	25	97	0.50	0.98	47.5	25	▨	▨	▨
March 2008	27	104	0.50	0.98	51.0	27	▨	▨	▨
April 2008	24	75	0.50	0.98	36.8	24	▨	▨	▨

[1] the number in this column is compared to the accident thresholds

** shaded regions represent cases where there was a reduction in accidents or the number of accidents observed did not pass a previous threshold

Table 27. Results of Graphical Safety Analysis: Entire Work Zone; Both Directions Together; Quarterly Monitoring.

	L	K	r_d	$\hat{r}_{tf}$	$\hat{\pi}$	$\hat{\lambda}$[1]	Threshold for increase	Threshold for greater than 20% increase	Threshold for greater than 40% increase
February 2007 - April 2007	118	276	0.50	0.98	135.2	118	**		
May 2007- July 2007	149	223	0.50	0.98	109.3	149	125	149	173
August 2007 - October 2007	140	209	0.50	0.98	102.4	140	118	140	162
November 2007- January 2008	105	308	0.50	0.98	150.9	105			
February 2008 - April 2008	76	276	0.50	0.98	135.2	76			

[1] the number in this column is compared to the accident thresholds

** shaded regions represent cases where there was a reduction in accidents or the number of accidents observed did not pass a previous threshold

ANALYSIS OF ONE MILE SEGMENTS: BOTH DIRECTIONS TOGETHER

Table 28 through Table 33 summarize the results of a before-during comparison of work zone safety as previously described, but with the work zone divided into 1-mile segments. Results show the advantage of segmenting the work zone into smaller segments, which allows for greater insights into the timing and locations of safety reductions. Reductions in safety are evident at some locations during months other than the five (June 2007 through October 2007) identified above. Results of both the monthly and quarterly analysis are consistent, but with some dilution resulting from data aggregation. For example, the 72 percent increase observed from milepoint 8.5 to 9.5 in April 2007 is balanced by reductions in February 2007 and March 2007. Only a 2 percent ± 20 percent reduction is observed when all three months are combined.

Table 34 through Table 39 summarize the results of the graphical analysis approach (e.g., Figure 26) Again, the conclusions reached using the graphical approach are consistent with the conclusions obtained from the more intensive computation approach. It is important to note that the ability to discern an actual reduction in safety from a random increase in accidents is more difficult as the monitoring period and segment lengths become shorter. For example, a 46 percent increase in accident frequency was observed from milepoint 7.5 – 8.5 during September 2007. However, the graphical approach shows that there was not enough evidence to conclude that this increase was actually due to a safety reduction. Results of the quarterly analysis on this same segment show that there was a detectable safety reduction from August 2007 through October 2007.

Increases in expected accident frequency greater than 20 percent occurred from milepoint 8.5 – 9.5 during April 2007 and September 2007 and during the quarter of May 2007 through July 2007. An increase also occurred during the quarter of August 2007 through October 2007. The results show that conclusions may depend on how consecutive three-month periods are combined into quarters. Ultimately, the analyst must apply judgment along with knowledge of the beginning and ending dates of major construction phases in determining the appropriate time ranges to analyze.

Increases, some relatively large, in expected accident frequency were also observed on the segment bounded by milepoints 9.5 and 10.5. The increases were observed from January 2007 through March 2007, June 2007 through October 2007, and January 2008. Increases were greater than 40 percent for June 2007 through August 2007 and greater than 20 percent in October 2007. Results of the quarterly analysis are also consistent with these conclusions. Again, the conclusions regarding increases in expected accident frequency are made with 90 percent confidence.

Table 28. Results of Computational Safety Analysis: MP 7.5 – 8.5; Both Directions Together; One-Month Monitoring.

	L	K	r_d	$\hat{r}_{tf}$	$\hat{\pi}$	$\hat{\lambda}$	$V\hat{A}R\{\hat{\pi}\}$	$V\hat{A}R\{\hat{\lambda}\}$	$\hat{\delta}$	$\hat{\sigma}(\hat{\delta})$	$\hat{\theta}$	$\hat{\sigma}(\hat{\theta})$	$\hat{\theta}\%$	$\hat{\sigma}(\hat{\theta}\%)$
January 2007	10	32	0.50	0.98	15.7	10	7.7	10	-5.7	4.2	0.62	0.22	-38	22
February 2007	7	33	0.50	0.98	16.2	7	7.9	7	-9.2	3.9	0.42	0.17	-58	17
March 2007	11	42	0.50	0.98	20.6	11	10.1	11	-9.6	4.6	0.52	0.17	-48	17
April 2007	6	27	0.50	0.98	13.2	6	6.5	6	-7.2	3.5	0.44	0.19	-56	19
May 2007	14	27	0.50	0.98	13.2	14	6.5	14	0.8	4.5	1.02	0.32	2	32
June 2007	5	17	0.50	0.98	8.3	5	4.1	5	-3.3	3.0	0.57	0.27	-43	27
July 2007	15	28	0.50	0.98	13.7	15	6.7	15	1.3	4.7	1.06	0.33	6	33
August 2007	11	21	0.50	0.98	10.3	11	5.0	11	0.7	4.0	1.02	0.36	2	36
September 2007	10	13	0.50	0.98	6.4	10	3.1	10	3.6	3.6	1.46	0.57	46	57
October 2007	14	19	0.50	0.98	9.3	14	4.6	14	4.7	4.3	1.43	0.48	43	48
November 2007	6	17	0.50	0.98	8.3	6	4.1	6	-2.3	3.2	0.68	0.31	-32	31
December 2007	14	38	0.50	0.98	18.6	14	9.1	14	-4.6	4.8	0.73	0.22	-27	22
January 2008	13	32	0.50	0.98	15.7	13	7.7	13	-2.7	4.5	0.80	0.26	-20	26
February 2008	7	33	0.50	0.98	16.2	7	7.9	7	-9.2	3.9	0.42	0.17	-58	17
March 2008	6	42	0.50	0.98	20.6	6	10.1	6	-14.6	4.0	0.28	0.12	-72	12
April 2008	7	27	0.50	0.98	13.2	7	6.5	7	-6.2	3.7	0.51	0.21	-49	21

Table 29. Results of Computational Safety Analysis: MP 8.5 – 9.5; Both Directions Together; One-Month Monitoring.

	L	K	r_d	$\hat{r}_{tf}$	$\hat{\pi}$	$\hat{\lambda}$	$V\hat{A}R\{\hat{\pi}\}$	$V\hat{A}R\{\hat{\lambda}\}$	$\hat{\delta}$	$\hat{\sigma}(\hat{\delta})$	$\hat{\theta}$	$\hat{\sigma}(\hat{\theta})$	$\hat{\theta}\%$	$\hat{\sigma}(\hat{\theta}\%)$
January 2007	18	25	0.50	0.98	12.3	18	6.0	18	5.8	4.9	1.41	0.42	41	42
February 2007	13	33	0.50	0.98	16.2	13	7.9	13	-3.2	4.6	0.78	0.25	-22	25
March 2007	11	28	0.50	0.98	13.7	11	6.7	11	-2.7	4.2	0.77	0.27	-23	27
April 2007	16	18	0.50	0.98	8.8	16	4.3	16	7.2	4.5	1.72	0.56	72	56
May 2007	13	18	0.50	0.98	8.8	13	4.3	13	4.2	4.2	1.40	0.48	40	48
June 2007	14	28	0.50	0.98	13.7	14	6.7	14	0.3	4.6	0.99	0.31	-1	31
July 2007	16	12	0.50	0.98	5.9	16	2.9	16	10.1	4.3	2.51	0.89	151	89
August 2007	12	23	0.50	0.98	11.3	12	5.5	12	0.7	4.2	1.02	0.35	2	35
September 2007	19	21	0.50	0.98	10.3	19	5.0	19	8.7	4.9	1.76	0.53	76	53
October 2007	11	23	0.50	0.98	11.3	11	5.5	11	-0.3	4.1	0.94	0.33	-6	33
November 2007	18	30	0.50	0.98	14.7	18	7.2	18	3.3	5.0	1.18	0.34	18	34
December 2007	6	42	0.50	0.98	20.6	6	10.1	6	-14.6	4.0	0.28	0.12	-72	12
January 2008	8	25	0.50	0.98	12.3	8	6.0	8	-4.3	3.7	0.63	0.25	-37	25
February 2008	6	33	0.50	0.98	16.2	6	7.9	6	-10.2	3.7	0.36	0.16	-64	16
March 2008	8	28	0.50	0.98	13.7	8	6.7	8	-5.7	3.8	0.56	0.22	-44	22
April 2008	12	18	0.50	0.98	8.8	12	4.3	12	3.2	4.0	1.29	0.46	29	46

Table 30. Results of Computational Safety Analysis: MP 9.5 – 10.5; Both Directions Together; One-Month Monitoring.

	L	K	r_d	$\hat{r}_{tf}$	$\hat{\pi}$	$\hat{\lambda}$	$V\hat{A}R\{\hat{\pi}\}$	$V\hat{A}R\{\hat{\lambda}\}$	$\hat{\delta}$	$\hat{\sigma}(\hat{\delta})$	$\hat{\theta}$	$\hat{\sigma}(\hat{\theta})$	$\hat{\theta}\%$	$\hat{\sigma}(\hat{\theta}\%)$
January 2007	16	30	0.50	0.98	14.7	16	7.2	16	1.3	4.8	1.05	0.32	5	32
February 2007	15	27	0.50	0.98	13.2	15	6.5	15	1.8	4.6	1.09	0.34	9	34
March 2007	24	30	0.50	0.98	14.7	24	7.2	24	9.3	5.6	1.58	0.42	58	42
April 2007	13	28	0.50	0.98	13.7	13	6.7	13	-0.7	4.4	0.91	0.30	-9	30
May 2007	12	37	0.50	0.98	18.1	12	8.9	12	-6.1	4.6	0.64	0.21	-36	21
June 2007	26	21	0.50	0.98	10.3	26	5.0	26	15.7	5.6	2.41	0.68	141	68
July 2007	31	28	0.50	0.98	13.7	31	6.7	31	17.3	6.1	2.18	0.55	118	55
August 2007	22	26	0.50	0.98	12.7	22	6.2	22	9.3	5.3	1.66	0.46	66	46
September 2007	14	22	0.50	0.98	10.8	14	5.3	14	3.2	4.4	1.24	0.41	24	41
October 2007	22	26	0.50	0.98	12.7	22	6.2	22	9.3	5.3	1.66	0.46	66	46
November 2007	14	30	0.50	0.98	14.7	14	7.2	14	-0.7	4.6	0.92	0.29	-8	29
December 2007	10	50	0.50	0.98	24.5	10	12.0	10	-14.5	4.7	0.40	0.14	-60	14
January 2008	15	30	0.50	0.98	14.7	15	7.2	15	0.3	4.7	0.99	0.30	-1	30
February 2008	11	27	0.50	0.98	13.2	11	6.5	11	-2.2	4.2	0.80	0.28	-20	28
March 2008	12	30	0.50	0.98	14.7	12	7.2	12	-2.7	4.4	0.79	0.26	-21	26
April 2008	3	28	0.50	0.98	13.7	3	6.7	3	-10.7	3.1	0.21	0.12	-79	12

Table 31. Results of Computational Safety Analysis: MP 7.5 – 8.5; Both Directions Together; Quarterly Monitoring.

	L	K	r_d	$\hat{r}_{tf}$	$\hat{\pi}$	$\hat{\lambda}$	$V\hat{A}R\{\hat{\pi}\}$	$V\hat{A}R\{\hat{\lambda}\}$	$\hat{\delta}$	$\hat{\sigma}(\hat{\delta})$	$\hat{\theta}$	$\hat{\sigma}(\hat{\theta})$	$\hat{\theta}\%$	$\hat{\sigma}(\hat{\theta}\%)$
February 2007 - April 2007	24	102	0.50	0.98	50.0	24	24.5	24	-26.0	7.0	0.48	0.11	-52	11
May 2007- July 2007	34	72	0.50	0.98	35.3	34	17.3	34	-1.3	7.2	0.95	0.20	-5	20
August 2007 - October 2007	35	53	0.50	0.98	26.0	35	12.7	35	9.0	6.9	1.32	0.28	32	28
November 2007- January 2008	33	87	0.50	0.98	42.6	33	20.9	33	-9.6	7.3	0.77	0.15	-23	15
February 2008 - April 2008	20	102	0.50	0.98	50.0	20	24.5	20	-30.0	6.7	0.40	0.10	-60	10

Table 32. Results of Computational Safety Analysis: MP 8.5 – 9.5; Both Directions Together; Quarterly Monitoring.

	L	K	r_d	$\hat{r}_{tf}$	$\hat{\pi}$	$\hat{\lambda}$	$V\hat{A}R\{\hat{\pi}\}$	$V\hat{A}R\{\hat{\lambda}\}$	$\hat{\delta}$	$\hat{\sigma}(\hat{\delta})$	$\hat{\theta}$	$\hat{\sigma}(\hat{\theta})$	$\hat{\theta}\%$	$\hat{\sigma}(\hat{\theta}\%)$
February 2007 - April 2007	40	79	0.50	0.98	38.7	40	19.0	40	1.3	7.7	1.02	0.20	2	20
May 2007- July 2007	43	58	0.50	0.98	28.4	43	13.9	43	14.6	7.5	1.49	0.29	49	29
August 2007 - October 2007	42	67	0.50	0.98	32.8	42	16.1	42	9.2	7.6	1.26	0.24	26	24
November 2007- January 2008	32	97	0.50	0.98	47.5	32	23.3	32	-15.5	7.4	0.67	0.13	-33	13
February 2008 - April 2008	26	79	0.50	0.98	38.7	26	19.0	26	-12.7	6.7	0.66	0.15	-34	15

Table 33. Results of Computational Safety Analysis: MP 9.5 – 10.5; Both Directions Together; Quarterly Monitoring.

	L	K	r_d	$\hat{r}_{tf}$	$\hat{\pi}$	$\hat{\lambda}$	$V\hat{A}R\{\hat{\pi}\}$	$V\hat{A}R\{\hat{\lambda}\}$	$\hat{\delta}$	$\hat{\sigma}(\hat{\delta})$	$\hat{\theta}$	$\hat{\sigma}(\hat{\theta})$	$\hat{\theta}\%$	$\hat{\sigma}(\hat{\theta}\%)$
February 2007 - April 2007	52	85	0.50	0.98	41.7	52	20.4	52	10.4	8.5	1.23	0.21	23	21
May 2007- July 2007	69	86	0.50	0.98	42.1	69	20.6	69	26.9	9.5	1.62	0.26	62	26
August 2007 - October 2007	58	74	0.50	0.98	36.3	58	17.8	58	21.7	8.7	1.58	0.27	58	27
November 2007- January 2008	39	110	0.50	0.98	53.9	39	26.4	39	-14.9	8.1	0.72	0.13	-28	13
February 2008 - April 2008	26	85	0.50	0.98	41.7	26	20.4	26	-15.7	6.8	0.62	0.14	-38	14

Table 34. Results of Graphical Safety Analysis: MP 7.5 – 8.5; Both Directions Together; One-Month Monitoring.

	L	K	r_d	$\hat{r}_{tf}$	$\hat{\pi}$	$\hat{\lambda}$[1]	Threshold for increase	Threshold for greater than 20% increase	Threshold for greater than 40% increase
January 2007	10	32	0.50	0.98	15.7	10	**	▨	▨
February 2007	7	33	0.50	0.98	16.2	7	▨	▨	▨
March 2007	11	42	0.50	0.98	20.6	11	▨	▨	▨
April 2007	6	27	0.50	0.98	13.2	6	▨	▨	▨
May 2007	14	27	0.50	0.98	13.2	14	19	▨	▨
June 2007	5	17	0.50	0.98	8.3	5	▨	▨	▨
July 2007	15	28	0.50	0.98	13.7	15	20	▨	▨
August 2007	11	21	0.50	0.98	10.3	11	16	▨	▨
September 2007	10	13	0.50	0.98	6.4	10	11	▨	▨
October 2007	14	19	0.50	0.98	9.3	14	14	17	▨
November 2007	6	17	0.50	0.98	8.3	6	▨	▨	▨
December 2007	14	38	0.50	0.98	18.6	14	▨	▨	▨
January 2008	13	32	0.50	0.98	15.7	13	▨	▨	▨
February 2008	7	33	0.50	0.98	16.2	7	▨	▨	▨
March 2008	6	42	0.50	0.98	20.6	6	▨	▨	▨
April 2008	7	27	0.50	0.98	13.2	7	▨	▨	▨

[1] the number in this column is compared to the accident thresholds

** shaded regions represent cases where there was a reduction in accidents or the number of accidents observed did not pass a previous threshold

Table 35. Results of Graphical Safety Analysis: MP 8.5 – 9.5; Both Directions Together; One-Month Monitoring.

	L	K	r_d	$\hat{r}_{tf}$	$\hat{\pi}$	$\hat{\lambda}$[1]	Threshold for increase	Threshold for greater than 20% increase	Threshold for greater than 40% increase
January 2007	18	25	0.50	0.98	12.3	18	18	21	
February 2007	13	33	0.50	0.98	16.2	13	**		
March 2007	11	28	0.50	0.98	13.7	11			
April 2007	16	18	0.50	0.98	8.8	16	14	16	19
May 2007	13	18	0.50	0.98	8.8	13	14		
June 2007	14	28	0.50	0.98	13.7	14	20		
July 2007	16	12	0.50	0.98	5.9	16	11	12	14
August 2007	12	23	0.50	0.98	11.3	12	17		
September 2007	19	21	0.50	0.98	10.3	19	16	18	21
October 2007	11	23	0.50	0.98	11.3	11			
November 2007	18	30	0.50	0.98	14.7	18	22		
December 2007	6	42	0.50	0.98	20.6	6			
January 2008	8	25	0.50	0.98	12.3	8			
February 2008	6	33	0.50	0.98	16.2	6			
March 2008	8	28	0.50	0.98	13.7	8			
April 2008	12	18	0.50	0.98	8.8	12	14		

[1] the number in this column is compared to the accident thresholds

** shaded regions represent cases where there was a reduction in accidents or the number of accidents observed did not pass a previous threshold

Table 36. Results of Graphical Safety Analysis: MP 9.5 – 10.5; Both Directions Together; One-Month Monitoring.

	L	K	r_d	$\hat{r}_{tf}$	$\hat{\pi}$	$\hat{\lambda}$[1]	Threshold for increase	Threshold for greater than 20% increase	Threshold for greater than 40% increase
January 2007	16	30	0.50	0.98	14.7	16	22		
February 2007	15	27	0.50	0.98	13.2	15	19		
March 2007	24	30	0.50	0.98	14.7	24	22	25	
April 2007	13	28	0.50	0.98	13.7	13	**		
May 2007	12	37	0.50	0.98	18.1	12			
June 2007	26	21	0.50	0.98	10.3	26	16	18	21
July 2007	31	28	0.50	0.98	13.7	31	19	24	27
August 2007	22	26	0.50	0.98	12.7	22	19	22	26
September 2007	14	22	0.50	0.98	10.8	14	17		
October 2007	22	26	0.50	0.98	12.7	22	19	22	26
November 2007	14	30	0.50	0.98	14.7	14			
December 2007	10	50	0.50	0.98	24.5	10			
January 2008	15	30	0.50	0.98	14.7	15	22		
February 2008	11	27	0.50	0.98	13.2	11			
March 2008	12	30	0.50	0.98	14.7	12			
April 2008	3	28	0.50	0.98	13.7	3			

[1] the number in this column is compared to the accident thresholds

** shaded regions represent cases where there was a reduction in accidents or the number of accidents observed did not pass a previous threshold

Table 37. Results of Graphical Safety Analysis: MP 7.5 – 8.5; Both Directions Together; Quarterly Monitoring.

	L	K	r_d	$\hat{r}_{tf}$	$\hat{\pi}$	$\hat{\lambda}$[1]	Threshold for increase	Threshold for greater than 20% increase	Threshold for greater than 40% increase
February 2007 - April 2007	24	102	0.50	0.98	50.0	24	**	▨	▨
May 2007- July 2007	34	72	0.50	0.98	35.3	34	▨	▨	▨
August 2007 - October 2007	35	53	0.50	0.98	26.0	35	34	41	▨
November 2007- January 2008	33	87	0.50	0.98	42.6	33	▨	▨	▨
February 2008 - April 2008	20	102	0.50	0.98	50.0	20	▨	▨	▨

[1] the number in this column is compared to the accident thresholds

** shaded regions represent cases where there was a reduction in accidents or the number of accidents observed did not pass a previous threshold

Table 38. Results of Graphical Safety Analysis: MP 8.5 – 9.5; Both Directions Together; Quarterly Monitoring.

	L	K	r_d	$\hat{r}_{tf}$	$\hat{\pi}$	$\hat{\lambda}$[1]	Threshold for increase	Threshold for greater than 20% increase	Threshold for greater than 40% increase
February 2007 - April 2007	40	79	0.50	0.98	38.7	40	49		
May 2007- July 2007	43	58	0.50	0.98	28.4	43	37	43	50
August 2007 - October 2007	42	67	0.50	0.98	32.8	42	42	50	
November 2007- January 2008	32	97	0.50	0.98	47.5	32	**		
February 2008 - April 2008	26	79	0.50	0.98	38.7	26			

[1] the number in this column is compared to the accident thresholds

** shaded regions represent cases where there was a reduction in accidents or the number of accidents observed did not pass a previous threshold

Table 39. Results of Graphical Safety Analysis: MP 9.5 – 10.5; Both Directions Together; Quarterly Monitoring.

	L	K	r_d	$\hat{r}_{tf}$	$\hat{\pi}$	$\hat{\lambda}^{1}$	Threshold for increase	Threshold for greater than 20% increase	Threshold for greater than 40% increase
February 2007 - April 2007	52	85	0.50	0.98	41.7	52	52	61	
May 2007- July 2007	69	86	0.50	0.98	42.1	69	52	61	72
August 2007 - October 2007	58	74	0.50	0.98	36.3	58	46	51	62
November 2007- January 2008	39	110	0.50	0.98	53.9	39	**		
February 2008 - April 2008	26	85	0.50	0.98	41.7	26			

[1] the number in this column is compared to the accident thresholds

** shaded regions represent cases where there was a reduction in accidents or the number of accidents observed did not pass a previous threshold

SUMMARY

The recommended short-term monitoring technique, a graphical version of a direct comparison of the safety of the work zone segment to what would have been the safety of the same segment had the work zone not been there, provided consistent results to generally accepted computational methods. The graphical methods are practical for TxDOT district personnel to implement on construction projects. Results showed that the ability to discern an actual reduction in safety from a random increase in accidents is more difficult as the monitoring period and segment lengths become shorter. Figure 13 through Figure 18 provide assistance in selecting an appropriate segment length and monitoring period. Results showed that conclusions may also depend on how roadway segments or consecutive months are aggregated. The analyst will need knowledge of the beginning and ending dates of major construction phases in order to make useful data aggregation decisions.

SUMMARY AND RECOMMENDATIONS

The goal of this project was to identify and investigate methods and procedures that TxDOT could implement to meet the requirements of the FHWA work zone safety and mobility final rule. Toward this goal, TTI researchers identified key work zone safety and mobility performance measures that TxDOT should target as part of a work zone monitoring program within a district, region, or across the state. Researchers developed analysis methodologies and computational procedures that yield the recommended performance measures. For mobility-based measures, the methodologies differ depending on the type of data that is available or can be obtained regarding the operating conditions in the field. Initially, researchers recommend that TxDOT target the collection of queue length and travel time delay data caused by temporary lane closures, as the congestion and delays that result from those activities are the simplest to isolate and attribute to the work activities themselves. If the work zone is located within the limits of a functioning electronic traffic surveillance system, data from the traffic sensors of that system are used to develop the targeted measures of work zone performance. If a traffic surveillance system is not available, queue length data documented systematically by TxDOT field crews were shown to be a reasonable method of collecting performance data. In both cases, researchers presented computational procedures to illustrate how the key measures of performance can then be determined from the field data collected.

With regards to work zone safety monitoring, researchers developed procedures that aid a district or project engineer in determining which projects are most suitable for safety monitoring via a periodic review of crash statistics occurring before and during the project. Researchers developed graphs that indicate combinations of work zone length (or work zone segment length), ADT, normal crash rate, and work zone phase or project direction. These graphs will most likely allow for reasonable inferences to be made regarding the relative level of safety being maintained within the project. Researchers also developed graphs to aid field or district personnel in quickly determining whether accident frequencies being experienced during a project are within, or above, tolerance limits for that type of project on that facility.

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APPENDIX: TRANSGUIDE-DETECTED QUEUE PRESENCE DURING IH-35 PILOT TEST

Table 40. Times of Queue Presence between Sensor IDs: IH 35 Southbound (3/13-4/8/2008).

	13-Mar		14-Mar		17-Mar		18-Mar		19-Mar		20-Mar		24-Mar		25-Mar		26-Mar	
Sensor ID	Start	End	Start	End	Start	End	Start	End	Start	End	Start	End	Start	End	Start	End	Start	End
158.036	🟨		🟨		🟨		🟨		🟨		🟨		🟨		🟨		🟨	
158.492	🟦		🟨		🟨		🟨		🟨		🟨		🟦		🟦		16:30	18:30
158.947	🟦		🟦		🟨		🟦		🟨		🟦		🟨		🟨		🟨	
159.500	🟨		🟦		🟦		🟨		🟦		🟦		🟦		🟦		15:45	18:30
159.998	🟨		🟦		🟨		🟨		🟨		🟨		🟦		🟨		🟨	
160.504	🟦		🟨		🟦		🟦		🟦		11:00	12:00	11:15	12:15	🟦		15:45	18:30
160.892	🟦		🟨		🟨		🟨		🟦		11:00	12:00	11:15	12:15	🟨		🟨	
161.405	🟦		🟦		🟨		🟦		🟦		🟨		11:15	12:15	🟦		16:00	18:00
161.846	🟨		🟨		🟨		🟦		🟨		🟨		🟨		🟨		🟨	
162.482	10:00	15:45	9:15	14:45	9:30	14:30	🟦		🟨		9:30	14:00	11:30	13:15	9:45	10:30	13:30	15:00
162.899	9:45	15:45	9:15	14:45	9:30	14:45	🟨		11:00	14:15	🟨		11:30	13:00	🟦		14:45	15:00
163.421	🟨		🟨		🟨		🟨		🟨		🟨		🟨		🟨		🟨	
163.896	🟨		🟨		🟨		🟨		🟨		🟨		🟨		🟨		🟨	
164.412	🟨		🟨		🟨		🟨		🟨		🟨		🟨		🟨		🟨	
164.909	🟨		🟨		🟨		🟨		🟨		🟨		🟨		🟨		🟨	
Queue Length (ft)		1.0		1.0		1.0				0.5		2.5		2.9		0.5		1.0

	27-Mar		28-Mar		31-Mar		1-Apr		2-Apr		3-Apr		4-Apr		5-Apr		6-Apr		7-Apr		8-Apr	
Sensor ID	Start	End	Start	End	Start	End	Start	End	Start	End	Start	End	Start	End	Start	End	Start	End	Start	End	Start	End
158.036	🟨		🟨		🟨		🟨		🟨		🟨		🟨		🟨		🟨		🟨		🟨	
158.492	🟨		🟦		7:15	8:15	🟨		🟨		🟨		🟨		🟦		🟦		🟨		🟨	
158.947	🟨		🟦		🟨		🟨		🟨		🟨		🟦		🟨		🟨		🟦		🟦	
159.500	🟦		🟦		🟦		🟦		🟦		🟦		🟨		🟦		🟨		🟨		🟨	
159.998	🟨		🟨		🟨		🟨		🟨		🟨		🟨		🟨		🟨		🟨		🟨	
160.504	🟦		🟦		🟦		🟨		🟨		🟦		🟦		🟦		🟦		🟨		🟦	
160.892	🟦		🟦		🟨		🟨		🟨		🟨		🟨		🟨		🟨		🟦		🟨	
161.405	🟦		🟦		🟦		🟦		🟦		🟨		🟦		🟦		🟨		🟦		🟦	
161.846	🟨		🟨		🟨		🟨		🟨		🟨		🟨		🟨		🟨		🟨		9:00	11:00
162.482	9:00	15:00	9:30	15:00	11:30	13:15	🟨		🟨		🟨		🟨		🟦		🟦		🟦		9:00	11:00
162.899	9:00	11:30	9:45	15:00	🟦		9:00	10:45	🟦		10:30	13:45	🟦		🟦		🟦		🟦		9:00	10:00
163.421	🟨		🟨		🟨		🟨		🟨		🟨		🟨		🟨		🟨		🟨		🟨	
163.896	🟨		🟨		🟨		🟨		🟨		🟨		🟨		🟨		🟨		🟨		🟨	
164.412	🟨		🟦		🟨		🟦		🟨		🟦		🟦		🟨		🟨		🟦		🟦	
164.909	🟨		🟨		🟨		🟨		🟨		🟨		🟨		🟨		🟨		🟨		🟨	
Queue Length (ft)		1.0		1.0		0.5		0.5				0.5										1.5

Table 41. Times of Queue Presence between Sensor IDs: IH 35 Southbound (4/9-4/30/2008).

	9-Apr		10-Apr		11-Apr		13-Apr		14-Apr		15-Apr		16-Apr		17-Apr		18-Apr	
Sensor ID	Start	End	Start	End	Start	End	Start	End	Start	End	Start	End	Start	End	Start	End	Start	End
158.036	🟨		🟨		🟨		🟨		🟨		🟨		🟨		🟨		🟨	
158.492	🟨		🟨		21:15	0:30	🟦		🟦		🟦		🟦		🟦		🟦	
158.947	🟦		🟦		🟨		🟨		🟨		🟨		🟨		🟨		🟨	
159.500	🟦		🟦		20:45	0:30	🟦		🟦		🟦		12:30	13:45	9:30	11:45	11:00	12:15
159.998	🟨		🟨		🟨		🟨		🟨		🟨		🟨		🟨		🟨	
160.504	🟦		🟦		20:30	0:30	🟨		🟨		🟦		🟨		🟨		🟨	
160.892	🟨		🟨		20:30	0:30	🟨		🟨		10:00	10:15	12:00	14:00	9:15	12:30	9:15	12:45
161.405	9:30	11:45	9:15	9:45	20:45	23:45	🟦		🟦		🟦		🟨		🟨		🟨	
161.846	9:00	14:45	9:15	15:00	🟨		🟨		🟨		🟨		🟨		🟨		🟨	
162.482	9:00	12:00	9:00	15:00	9:15	15:00	🟦		🟦		🟦		16:30	17:30	🟦		🟨	
162.899	9:00	11:00	9:00	11:15	9:15	10:30	🟦		🟦		🟦		🟦		🟦		🟦	
163.421	🟨		🟨		🟨		🟨		🟨		🟨		🟨		🟨		🟨	
163.896	🟨		🟨		🟨		🟨		🟨		🟨		🟨		🟨		🟨	
164.412	🟦		🟦		🟦		🟨		🟨		🟨		🟨		🟨		🟦	
164.909	🟨		🟨		🟨		🟨		🟨		🟨		🟨		🟨		🟨	
Queue Length (ft)		2.0		2.0		1.0						0.5		1.9		1.9		1.9

	20-Apr		21-Apr		22-Apr		23-Apr		24-Apr		25-Apr		26-Apr		27-Apr		28-Apr		29-Apr		30-Apr	
Sensor ID	Start	End	Start	End	Start	End	Start	End	Start	End	Start	End	Start	End	Start	End	Start	End	Start	End	Start	End
158.036	🟨		🟨		🟨		🟨		🟨		🟨		🟨		🟨		🟨		🟨		🟨	
158.492	🟦		🟦		🟦		🟦		🟦		🟦		🟦		🟦		🟦		🟦		🟦	
158.947	🟦		🟨		🟦		🟦		🟦		🟦		🟦		🟦		🟦		🟦		🟦	
159.500	🟦		🟦		🟦		🟦		🟨		🟨		🟨		🟨		🟨		🟨		🟨	
159.998	🟨		🟨		🟨		🟨		🟨		🟨		🟨		🟨		🟨		🟨		🟨	
160.504	🟦		🟦		14:00	15:00	🟦		🟨		🟨		🟨		🟨		🟨		🟨		🟨	
160.892	🟦		🟦		🟨		14:45	15:15	9:15	12:15	🟦		🟦		17:30	18:15	🟦		🟦		🟦	
161.405	🟦		🟦		🟦		🟦		🟨		🟦		🟨		🟦		🟨		🟦		🟦	
161.846	🟦		🟨		🟨		🟨		8:45	11:15	🟦		🟨		🟨		🟨		8:45	10:00	🟨	
162.482	🟦		🟨		🟨		🟦		🟦		🟦		🟦		🟦		🟦		🟦		🟦	
162.899	🟦		🟦		🟦		🟦		🟦		🟦		🟦		🟦		🟦		🟦		🟦	
163.421	🟨		🟨		🟨		🟨		🟨		🟨		🟨		🟨		🟨		🟨		🟨	
163.896	🟨		🟨		🟨		🟨		🟨		🟨		🟨		🟨		🟨		🟨		🟨	
164.412	🟦		🟦		🟦		🟨		🟨		🟦		🟨		🟦		🟨		🟦		🟨	
164.909	🟨		🟨		🟨		🟨		🟨		🟨		🟨		🟨		🟨		🟨		🟨	
Queue Length (ft)						0.5		0.5		1.5						0.5				0.5		

Note: Initiation of queue if speed is lower than 30 mph and queue dissipates if speed is higher than 30 mph. Queue length is calculated between lane closure time 9:00 AM and 16:00 PM as applicable.

🟦 No queue

🟨 Data not available/not collected

Table 42. Times of Queue Presence between Sensor IDs: IH 35 Northbound (3/13-4/8/2008).

	13-Mar		14-Mar		17-Mar		18-Mar		19-Mar		20-Mar		24-Mar		25-Mar		26-Mar		27-Mar	
Sensor ID	Start	End	Start	End	Start	End	Start	End	Start	End	Start	End	Start	End	Start	End	Start	End	Start	End
158.036	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
158.492	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟦	🟦	🟦	🟦	🟦	🟦	🟨	🟨
158.947	🟦	🟦	13:45	16:00	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
159.500	🟨	🟨	11:30	18:30	12:45	13:15	🟨	🟨	🟦	🟦	11:15	15:00	🟨	🟨	14:15	15:00	🟦	🟦	13:30	14:45
159.998	🟨	🟨	12:00	18:00	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
160.504	15:45	18:30	13:30	18:30	🟦	🟦	🟦	🟦	🟦	🟦	12:15	12:45	🟦	🟦	🟦	🟦	14:15	14:30	🟦	🟦
160.892	15:30	18:30	12:45	19:00	🟨	🟨	🟨	🟨	🟦	🟦	14:30	14:45	🟦	🟦	🟨	🟨	🟨	🟨	🟦	🟦
161.405	15:30	18:30	14:00	19:00	🟨	🟨	🟦	🟦	🟦	🟦	10:30	11:00	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
161.846	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
162.482	15:00	18:45	16:00	19:00	17:15	17:30	🟨	🟨	🟨	🟨	16:30	18:00	16:45	17:30	🟦	🟦	16:00	17:45	16:15	17:45
162.899	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
163.421	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
163.896	14:30	18:45	🟨	🟨	🟨	🟨	🟨	🟨	16:45	17:15	16:15	18:15	16:15	17:00	17:30	17:45	🟨	🟨	16:00	18:00
164.412	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
164.909	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟦	🟦	🟨	🟨	🟨	🟨	🟨	🟨	🟦	🟦
Queue Length (ft)		2.0		2.9		0.5						1.5		2.0		0.5		0.5		0.5

	28-Mar		31-Mar		1-Apr		2-Apr		3-Apr		4-Apr		5-Apr		6-Apr		7-Apr		8-Apr	
Sensor ID	Start	End	Start	End	Start	End	Start	End	Start	End	Start	End	Start	End	Start	End	Start	End	Start	End
158.036	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
158.492	🟦	🟦	🟦	🟦	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟦	🟦	🟦	🟦	🟨	🟨	🟨	🟨
158.947	🟦	🟦	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟦	🟦	🟨	🟨	🟨	🟨	🟦	🟦	🟦	🟦
159.500	11:45	14:30	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟨	🟨	🟦	🟦	🟨	🟨	🟨	🟨	🟨	🟨
159.998	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
160.504	12:45	14:30	🟦	🟦	🟨	🟨	🟨	🟨	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟨	🟨	🟦	🟦
160.892	12:45	14:30	🟦	🟦	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟦	🟦	🟨	🟨
161.405	12:45	14:15	🟦	🟦	🟦	🟦	🟦	🟦	🟨	🟨	16:45	17:15	🟦	🟦	🟨	🟨	11:15	11:30	🟦	🟦
161.846	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟦	🟦	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟦	🟦
162.482	16:15	17:45	🟨	🟨	🟦	🟦	16:15	17:30	🟨	🟨	🟨	🟨	🟨	🟨	🟦	🟦	11:00	11:30	16:30	17:00
162.899	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
163.421	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
163.896	15:45	17:45	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
164.412	14:45	18:00	🟨	🟨	🟨	🟨	🟨	🟨	16:45	18:00	15:30	18:30	🟨	🟨	🟨	🟨	15:45	17:45	15:45	16:45
164.909	🟦	🟦	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
Queue Length (ft)		2.4						0.5		0.5		3.5						1.5		0.5

Note: Initiation of queue if speed is lower than 30 mph and queue dissipates if speed is higher than 30 mph. Queue length is calculated between lane closure time 9:00 AM and 16:00 PM as applicable.

🟦 No queue

🟨 Data not available/not collected

Table 43. Times of Queue Presence between Sensor IDs: IH 35 Northbound (4/9-4/30/2008).

	9-Apr		10-Apr		11-Apr		13-Apr		14-Apr		15-Apr		16-Apr		17-Apr		18-Apr		20-Apr	
Sensor ID	Start	End	Start	End	Start	End	Start	End	Start	End	Start	End	Start	End	Start	End	Start	End	Start	End
158.036	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
158.492	🟨	🟨	🟨	🟨	🟦	🟦	🟦	🟦	14:30	14:45	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
158.947	🟦	🟦	🟦	🟦	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟦	🟦
159.500	🟦	🟦	🟨	🟨	12:00	15:15	🟦	🟦	14:00	15:00	14:15	14:30	9:15	9:45	🟦	🟦	13:15	14:45	🟦	🟦
159.998	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
160.504	15:45	16:45	🟦	🟦	14:00	14:15	🟨	🟨	🟨	🟨	16:00	16:15	🟨	🟨	🟨	🟨	🟨	🟨	🟦	🟦
160.892	🟨	🟨	🟨	🟨	12:00	15:00	🟨	🟨	🟨	🟨	15:45	16:45	9:30	9:45	🟦	🟦	🟦	🟦	🟦	🟦
161.405	15:30	17:15	🟦	🟦	20:15	23:45	🟦	🟦	🟨	🟨	🟦	🟦	🟨	🟨	🟨	🟨	🟨	🟨	🟦	🟦
161.846	15:30	16:45	🟦	🟦	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟦	🟦
162.482	15:15	17:00	16:30	17:30	15:45	16:45	🟦	🟦	🟦	🟦	16:45	17:45	🟦	🟦	16:15	18:30	🟨	🟨	🟦	🟦
162.899	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
163.421	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
163.896	11:00	17:00	13:15	15:15	11:00	15:15	🟨	🟨	17:00	17:15	🟨	🟨	15:45	17:15	16:30	18:30	11:00	14:45	🟨	🟨
164.412	10:45	18:00	10:00	15:15	9:45	13:15	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	9:15	17:30	🟦	🟦
164.909	10:15	15:45	🟨	🟨	9:15	13:15	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟦	🟦
Queue Length (ft)		4.7		1.0		1.9				1.5		0.5		1.9		2.0		0.5		

	21-Apr		22-Apr		23-Apr		24-Apr		25-Apr		26-Apr		27-Apr		28-Apr		29-Apr		30-Apr	
Sensor ID	Start	End	Start	End	Start	End	Start	End	Start	End	Start	End	Start	End	Start	End	Start	End	Start	End
158.036	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
158.492	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
158.947	🟨	🟨	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
159.500	🟦	🟦	🟦	🟦	🟦	🟦	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
159.998	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
160.504	🟦	🟦	🟦	🟦	🟦	🟦	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
160.892	16:45	17:30	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	17:15	17:30
161.405	16:45	17:00	🟦	🟦	🟦	🟦	🟨	🟨	🟦	🟦	🟨	🟨	🟦	🟦	🟨	🟨	🟦	🟦	17:15	17:30
161.846	🟨	🟨	🟨	🟨	🟨	🟨	🟦	🟦	🟦	🟦	🟨	🟨	🟨	🟨	🟨	🟨	🟦	🟦	🟨	🟨
162.482	16:15	17:15	17:45	18:30	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	16:30	17:45	16:15	17:00	16:15	17:45
162.899	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
163.421	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
163.896	🟨	🟨	17:15	18:30	🟨	🟨	🟨	🟨	🟦	🟦	🟦	🟦	🟨	🟨	16:15	17:45	🟦	🟦	🟨	🟨
164.412	🟨	🟨	17:15	18:30	🟨	🟨	16:00	17:45	15:30	17:00	🟨	🟨	🟦	🟦	🟨	🟨	15:45	17:15	🟨	🟨
164.909	16:15	16:30	17:15	18:30	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟨	🟨	🟨	🟨	🟦	🟦
Queue Length (ft)		2.8		2.8				0.5		0.5						2.3		0.5		2.0

Note: Initiation of queue if speed is lower than 30 mph and queue dissipates if speed is higher than 30 mph. Queue length is calculated between lane closure time 9:00 AM and 16:00 PM as applicable.

🟦 No queue

🟨 Data not available/not collected