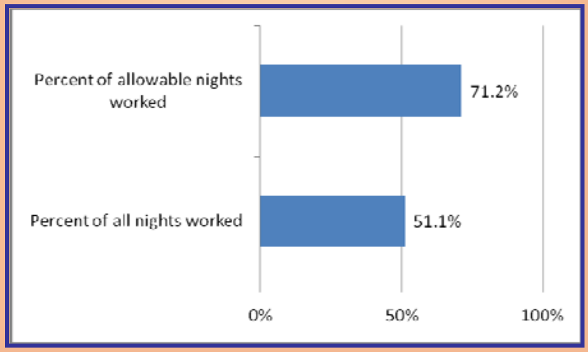
Work Zone Performance Measures Pilot Test

April 2011



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Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA-HOP-11-022		

4. Title and Subtitle	5. Report Date
WORK ZONE PERFORMANCE MEASURES PILOT TEST	April 2011
	6. Performing Organization Code
7. Author(s) Gerald L. Ullman , Timothy J. Lomax , and Fan Ye -TTI Tracy Scriba – FHWA	8. Performing Organization Report No.
9. Performing Organization Name and Address Texas Transportation Institute The Texas A&M University System College Station, Texas 77843-3135	10. Work Unit No. (TRAIS) 11. Contract or Grant No. DTFH61-06-D-00007
12. Sponsoring Agency Name and Address U.S. Department of Transportation Federal Highway Administration Office of Operations 1200 New Jersey Avenue, SE Washington, DC 20590	13. Type of Report and Period Covered 14. Sponsoring Agency Code HOTO

15. Supplementary Notes

Project Leader: Tracy Scriba, FHWA.
Project carried out under contract to Battelle for the FHWA Office of Operations.

16. Abstract

Currently, a well-defined and validated set of metrics to use in monitoring work zone performance do not exist. This pilot test was conducted to assist state DOTs in identifying what work zone performance measures can and should be targeted, what data they will need to collect to compute those measures, and what methods exist to obtain that data. Work zone activity and traffic data from five work zone projects were gathered and analyzed. Multiple data sources and collection methods were examined and utilized to the extent available at each project. These sources were field crew personnel manually documenting queue presence, length, and duration; traffic surveillance data from a transportation management center or from portable work zone ITS; and third-party probe vehicle data (in this test, large truck speed data obtained via the FHWA Office of Freight Management).

The results of the pilot test indicate that manual documentation of queuing by field personnel, and the use of permanent or portable traffic sensor data can be used effectively to measure work zone impacts, given that information as to the time and location of work activities is known. Probe vehicle data is also believed to be a viable source of data, but sample size issues did limit is applicability in this pilot test. Average and maximum queue lengths and duration, duration of queues exceeding pre-determined thresholds, vehicle exposure to queues, and vehicle delays when queues are present were among the several performance measures tested and demonstrated as viable indicators of work zone mobility impacts. A number of lessons learned through this pilot test effort are also included in the report. A primer on how to select and compute work zone performance measures is being developed based on the findings documented in this report.

17. Key Words	18. Distribution Statement
WORK ZONE SAFETY AND MOBILITY, TRAFFIC IMPACTS, PERFORMANCE MEASURES	No restrictions.

19. Security Classif.(of this report)	20. Security Classif.(of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	112	

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

ACKNOWLEDGEMENTS

The authors of this report gratefully acknowledge the contributions by several representatives of the following public agencies during the data collection portion of this project:

- Nevada Department of Transportation
- Regional Transportation Commission of Southern Nevada, Freeway and Arterial System of Transportation (FAST)
- North Carolina Department of Transportation
- Pennsylvania Department of Transportation
- Washington State Department of Transportation.

The authors are also appreciative to staff in the FHWA Office of Freight Management and at the American Trucking Research Institute for their efforts in providing truck transponder speed data from each of the pilot test sites. Finally, the assistance of iCone® staff in an attempt to obtain speed and volume data at the I-95 site near Lumberton, NC is also gratefully acknowledged.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

EXECUTIVE SUMMARY

Transportation professionals are increasingly pressed to demonstrate sound management decisionmaking and resource allocation. Performance management is a method to quantify and improve performance, and engage and communicate with citizens and other stakeholders. One of the challenges facing state Departments of Transportation (DOTs) is to determine how to best measure and track safety and mobility impacts associated with highway work zones. The development and use of work zone safety and mobility performance measures can be valuable to agencies in several ways, including the following:

- They allow agencies to quantify how work zones are impacting motorists, and how actions being taken (management strategies, technologies deployed) to mitigate those impacts are or are not working.
- They assist agencies in making investment decisions, developing and improving policies, and defining program priorities.
- They assist agencies in communicating with elected officials and with the public.

This report describes the results of a pilot test conducted to assist state DOTs in identifying the following:

- What work zone performance measures can and should be targeted?
- What data is needed to compute the measures?
- What methods exist to obtain that data?

In addition, the test was designed to generate practical guidance, lessons learned, useful tips, etc., that state DOTs could use to initiate and/or improve upon a successful work zone performance measurement program.

A series of potential work zone performance measures were developed to address potential state DOT needs under each of the following five priority categories:

- Exposure
- Traffic queuing
- Traveler delay
- Travel time reliability
- Safety

For the pilot tests, emphasis was placed on collecting the needed data and performing the necessary computations for the measures in four of the five categories. Safety performance measures were excluded from the pilot test effort because of the potential for significant lag times in obtaining crash data at the pilot test locations, and because safety performance measures themselves are fairly well-defined and understood. For the remaining categories, the proposed performance measures in each category were pilot tested at five different projects nationally:

- I-95, Lumberton, North Carolina
- I-95, Philadelphia, Pennsylvania
- I-405, Seattle, Washington
- I-15/US95 Design-Build Project, Las Vegas, Nevada
- I-15 Express Lane Project, Las Vegas, Nevada

In addition, two different methods for collecting the data necessary to compute the performance measures were also tested (to the extent possible) at each project:

- Electronic traffic surveillance data of conditions (e.g., speeds) at particular points on the roadway, or of elapsed travel time along a particular roadway segment
- Manual observations of queue durations and lengths by field personnel during work activities.

The performance measures computed with each type of data were compared to each other, and to ground-truth measurements of travel times, delays, and queues made by research staff. Key findings with regard to the computation and use of work zone performance measures were as follows:

- Work activity measures (percent of days worked, average hours per day of work) is useful in tracking and comparing contractor level of effort.
- Capturing lane closure hours (percent of hours involving 1, 2, etc. lanes closed) is relevant only if total lanes remaining open is also captured.
- The percent of time when queues exceed selected threshold values should be useful as a potential performance specification for work zone traffic control and impact mitigation.
- The measure "percent of traffic encountering a traffic queue" provides a direct indication of the breadth of impacts of the work zone to the motoring public.
- The average duration of queues, average queue length, and maximum queue length all have value for assessing both project-level and process-level traffic management decisions pertaining to work zone mobility.
- The average delay per queued vehicle, along with the percent of traffic encountering a queue, appears to be a straightforward way to account for both the intensity and breadth of work zone impacts on motorists.
- The buffer index, as a travel time reliability measure for work zone performance monitoring, appears to offer useful insights into another dimension of user impacts due to the work zone at locations where recurrent traffic congestion already exists prior to the start of the project.

Key lessons were also learned with respect to data collection and analyses of work zone exposure and mobility data, and include the following:

- Estimates of queue lengths need to include a description of the location of the queue relative to the lane closure (upstream, beyond taper and into work zone, partially upstream and partially within the work zone, etc.).
- Field personnel documentation of when and where lane closures were placed and hours of work activity will still be needed to compute mobility performance measures, even if electronic traffic surveillance data is being used to monitor traffic conditions.
- It is important to make sure that the traffic sensors themselves will remain operational when construction begins.
- The level of accuracy in work zone mobility performance measurement achievable with electronic traffic surveillance data depends heavily on the design of the system (particularly traffic sensor spacing).

To assist practitioners in applying the findings and lessons learned from this pilot test effort, a primer on selecting and computing work zone performance measures is being developed to accompany this report.

1. INTRODUCTION

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 updated 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.
- The development and implementation of procedures and transportation management plans (TMPs) 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 operational/mobility data to support the initiation, assessment, and enhancement of agency-level processes and procedures addressing work zone impacts. Specifically, states are encouraged 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 and may need to collect additional data if limited data are currently not available (*2*). States are free to enhance whatever data they do collect to improve their evaluation and monitoring procedures. Obviously, the challenge facing state DOTs is to determine how to best measure and track safety and mobility impacts, and to assess how practices implemented by the DOT affect the level of impacts. Those activities need to support each agency's policy and procedural benchmarking and evaluation in a manner consistent with FHWA requirements.

WHY MONITOR WORK ZONE PERFORMANCE?

Transportation professionals are increasingly pressed to demonstrate sound management decision-making and resource allocation. Performance management is a method to quantify and improve performance, and engage and communicate with citizens and other stakeholders (*3*). Overall, performance measures to gauge agency efforts are currently being used by state DOTs in the following areas:

- Asset preservation
- Mobility and accessibility
- Operations and maintenance
- Safety
- Security
- Economic development
- Environmental
- Social equity (i.e., which user groups are impacted)
- Transportation delivery

Depending on the topic of interest, an agency may use "output" measures of performance that describe how much effort has been made to address a particular issue or concern, or "outcome" measures that reflect the actual effects or results experienced with respect to that issue. In fact, both types of measures are often needed to fully characterize an issue.

From the state DOT perspective, the use of work zone safety and mobility performance measures are valuable for the following reasons:

- ***Work zone performance measures allow agencies to quantify how work zones are impacting motorists, and how actions being taken (management strategies, technologies deployed) to mitigate those impacts are or are not working.*** This relates directly to the intent and the requirements of 23 CFR Part 630.

- ***Work zone performance measures assist agencies in making investment decisions, developing and improving policies, and defining program priorities.*** Information about the effectiveness or ineffectiveness of strategies and technologies is valuable to state DOTs when determining whether or not to include them on upcoming projects. Performance measures can also aid agencies in refining work zone policies and procedures (e.g., Is setting a specific maximum allowable delay per vehicle a useful policy objective? Do the traffic impact analysis tools being used accurately reflect what actually occurs in the field?). Finally, performance measures emphasize accountability by the agency, since what gets measured typically gets done (or is at least considered).

- ***Work zone performance measures assist agencies in communicating with elected officials and with the public.*** State DOTs can use work zone performance measures to "tell their story" and ensure that everyone has the correct information about how safety and mobility is being affected by roadway construction and maintenance efforts under their jurisdiction. The story includes both what is being done and how well what is being done is working. This type of agency transparency facilitates public understanding and can improve acceptance of the impacts that do occur and builds trust that any subsequent funding will be spent wisely.

As the discussion implies, work zone performance measures can be of interest or value to a wide range of audiences. More importantly, these different audiences may need somewhat different performance measures.

WHY CONDUCT A WORK ZONE PERFORMANCE MEASURE PILOT TEST?

Although the importance of having and tracking work zone performance measures is evident, a well-defined and validated set of metrics to use in monitoring work zone performance do not currently exist. This pilot test was conducted to assist state DOTs in identifying the following:

- What work zone performance measures can and should be targeted
- What data they will need to collect to compute those measure
- What methods exist to obtain that data.

In addition, the test was designed to generate practical guidance, lessons learned, useful tips, etc., that state DOTs could use to initiate and/or improve upon a successful work zone performance measurement program.

Although there have been a few efforts to monitor and evaluate the safety and mobility impacts of work zones to date, emphasis on systematic collection and analysis of objective data to develop quantitative measures of work zone performance is still lacking. Therefore, a pilot test effort to develop and utilize quantitative measures at several real-world work zone projects was undertaken.

2. BACKGROUND AND DESCRIPTION OF THE WORK ZONE PERFORMANCE MEASURE PILOT TEST

BACKGROUND

In a recent study (*4*), several state DOTs were queried as to their efforts and interest in work zone safety and mobility performance measures. In general terms, many states compute delay, queuing, and road user costs at some level as part of their work zone planning and design procedures. These are accomplished via simple traffic volume-to-work zone capacity comparisons or application of macroscopic or microscopic traffic simulation analyses. States may use some of these measures or values in establishing incentives and disincentives for contracting purposes. Meanwhile, efforts to actually measure traffic and safety impacts during work zones are extremely limited. A few states did indicate that they monitor work zones in the field to make sure a performance threshold (such as a maximum queue length or maximum delay time) is not exceeded at a project. If conditions do get worse than expected, the agency may terminate the work activity (typically a lane closure) to allow traffic congestion to disperse or assess penalties, although it is also possible that the field crews may not do anything and allow conditions to continue. Traditionally, though, the conditions that lead to these actions and the performance measure values often do not get documented anywhere other than in the daily project diary, and are simply used in follow-up negotiations between the agency and the contractor regarding project payments, time charged, or other features.

Two states (Indiana and Michigan) have recently initiated the reporting of queues back to district or headquarter offices in their agency on a more formal basis (*5*, *6*). The intent of this reporting is to determine why the queues occurred, since both agencies conduct traffic analyses during project design to avoid generating queues. The ultimate goal is to refine and improve the inputs and assumptions being used in the analysis tools, such as the work zone capacity assumed or the expected hourly demand volumes to the work zone. However, some basic metrics may be generated by the agencies for tracking purposes, such as the percent of work zones each year that meet the delay expectations for that particular project. Both agencies noted the challenges that exist in attempting to monitor and analyze queues occurring in urban work zones due to the interdependence between the queues that develop and the diversion to other routes that then occurs.

The Missouri DOT (MoDOT) 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 (*7*). Figure 1 shows an example of this performance measure. These observations are qualitative rather than quantitative in nature. Consequently, the relationship between "meeting expectations" and amount and duration of delay and congestion that occur is not immediately apparent. However, this approach does address a key concern heard from field personnel that performance measures need to be tied to what is considered acceptable (or the "target") for that particular work zone or category of work zones, and not considered independently from the other decisions that go into the successful completion of a particular project. Other mobility/operational measures sometimes considered by state DOTs include vehicle delays measured as part of the inspector drive-through of the project, and user complaints (*8*).

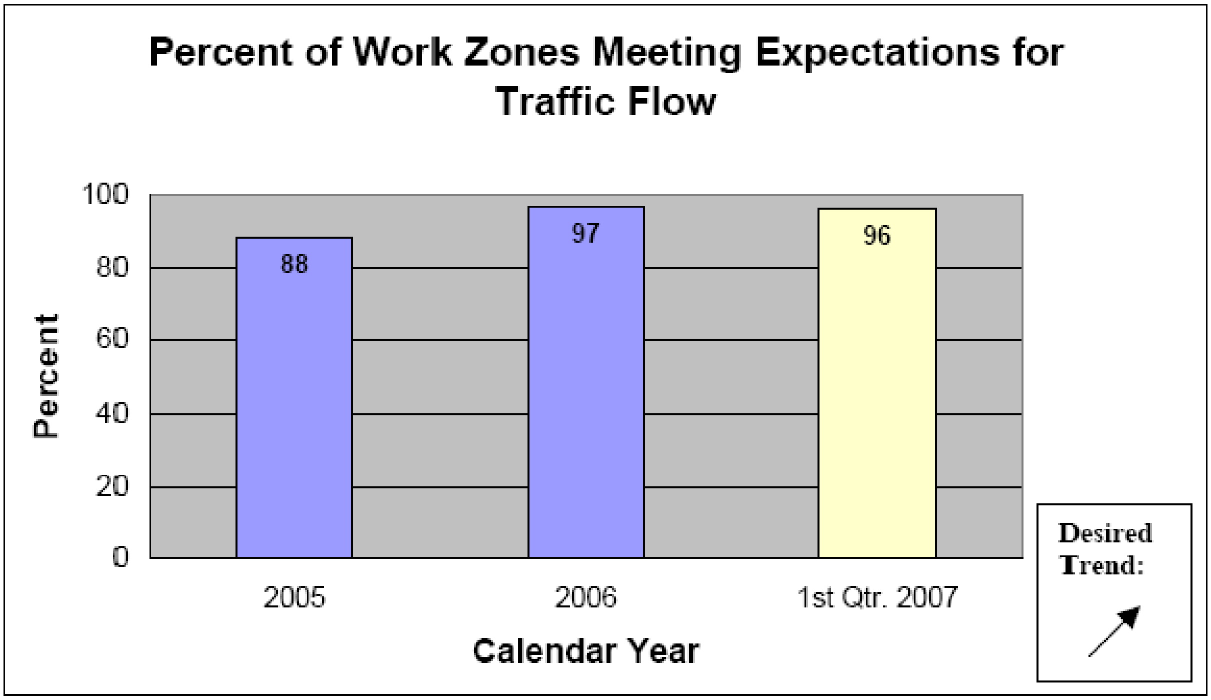


Figure 1. Traffic Mobility Performance Measure Used by Missouri DOT (*7*).

With regard to work zone safety performance monitoring, many states do monitor the number of fatalities that occur in their work zones annually. Unfortunately, agencies acknowledge that without exposure data (e.g., number of work zone hours or work periods, or the traffic volumes traveling through the work zones) to normalize these numbers, changes in crash frequencies from year to year are difficult to interpret. In addition, the relatively small numbers of work zone fatalities that occur in most states often do not yield meaningful insights into problems or possible corrective actions that should be taken (some states do enlarge the database considered by including injury crashes in the analysis). Also, most crash databases do not include much information concerning the work zone characteristics at the time of the crash (e.g., the type of temporary traffic control [TTC] in place, the proximity of workers and equipment to traffic), which limits what can be extracted from the data.

Even if an adequate data sample is available for work zone safety performance monitoring, another key concern that plagues most agencies is the time lag that typically exists in obtaining crash data from individual projects. Interestingly, the Ohio DOT (ODOT) 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 (9). ODOT personnel 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 and control concerns. Figure 2 illustrates an example of the work zone crash monitoring activities by ODOT.

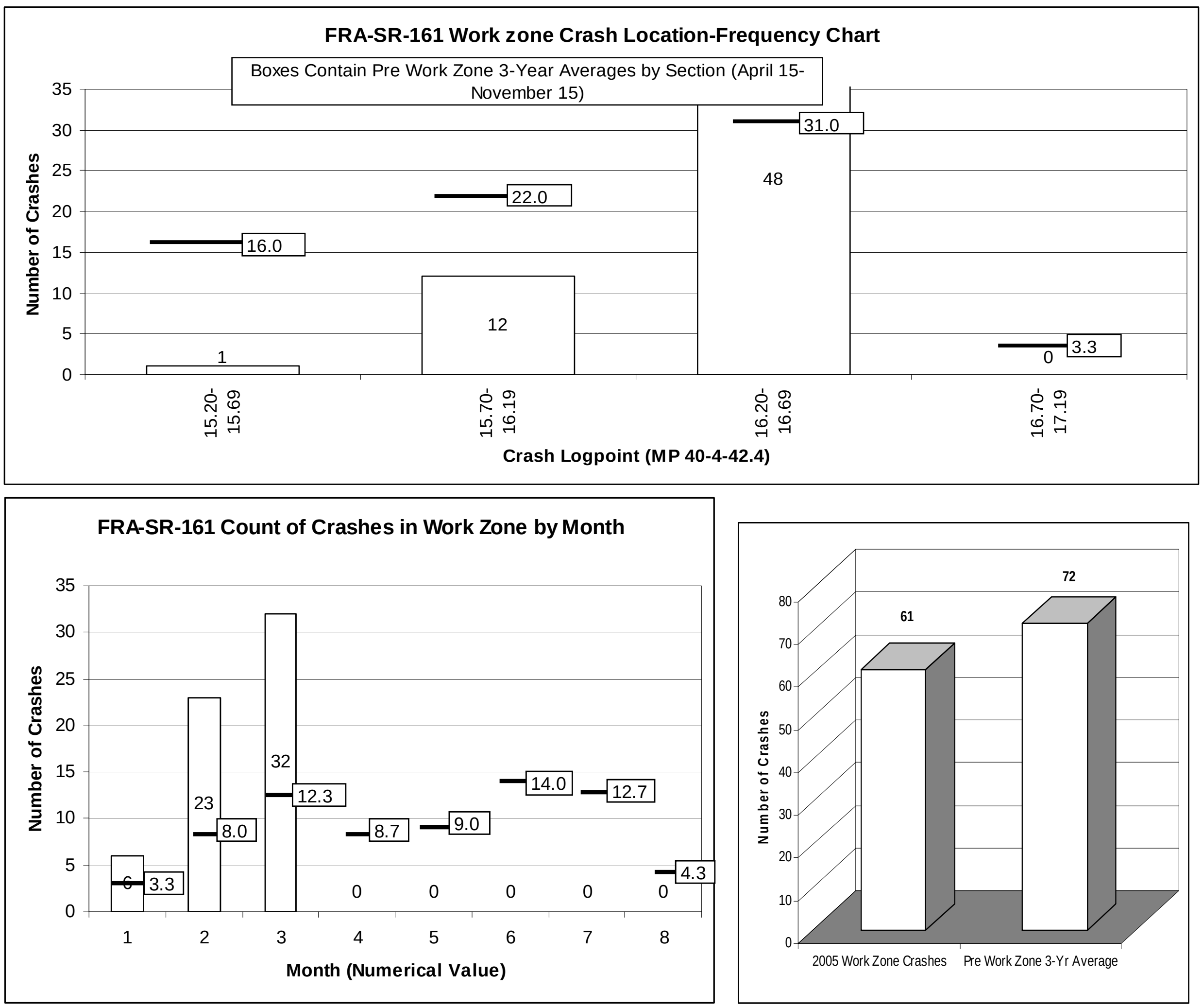


Figure 2. Ohio DOT Work Zone Safety Performance Measures (recreated from 9).

A number of researchers have examined work zone crashes in traditional before-during or work zone versus no-work zone analyses in recent years, attempting to identify and quantify the factors that contribute to crashes and/or to evaluate countermeasures to reduce crash risk (e.g., *10, 11, 12*). Generally speaking, these studies utilize data from multiple work zones in a region or state, and may even include data from multiple states. These types of analyses are fairly complex and not typically attempted by state DOT personnel; rather, universities or consultants are contracted to perform the study. These studies generally suffer from delays in obtaining access to the crash data, although some states have implemented electronic crash report data entry systems which can significantly reduce this delay time. Even if crash data access concerns can be overcome, the design features, operating strategies, and management techniques utilized during each work zone project of interest must be manually extracted from project files, inspector diaries, or other data sources and combined with the crash data before analyses can be performed. This process itself can be extremely time-consuming, and the various combinations of these features/strategies/techniques possible make it difficult to establish a uniform dataset with enough projects to allow meaningful conclusions to be drawn. Given the challenges associated with the use of crash data for performance measurement, some agencies rely on surrogate measures such as TTC quality inspection scores, average speeds or speed variance at a project, or frequency of fire department responder calls (*8*).

DESCRIPTION OF THE WORK ZONE PERFORMANCE MEASURE PILOT TEST

For this pilot test, a set of desirable work zone safety and mobility-related performance measures was first identified. Those measures pertaining to work zone exposure and mobility were then targeted to be computed for each of five work zone projects nationally. Safety performance measures were not computed in this pilot test effort for two main reasons. First, many state DOTs report very lengthy lag times (several months, or even years in some cases) between when crashes occur and when a data set of information about the crashes can be obtained by the agency for analysis purposes. Waiting for such data from every project was not judged to be a worthwhile use of time for this pilot test. The second, and perhaps more important, reason for not including work zone safety performance measures in the test is that such measures are already fairly well-defined and understood by practitioners. Although it may be challenging for some agencies to obtain the data and to find the time to compute crash rates and other work zone safety performance measures, the measures once computed are recognized as useful. In contrast, it is less clear what types of exposure and mobility-related work zone performance measures can be computed with data sources that are typically available to agencies, and how best to interpret those measures once they are computed.

Consequently, the goals of the pilot test project were to identify and compute various types of work zone exposure and mobility-related performance measures, and to do this with different data collection methodologies that could be used for work zone mobility performance measurement. Specifically, the pilot test targeted a proposed manual method of data collection that relies on field crew personnel to document queues that develop during work activities, and the use of electronic traffic surveillance technology that may be available at certain work zone projects. Within the electronic category are project locations where transportation management centers (TMCs) already in place have point measurement devices (traffic sensors) that can measure traffic volumes, speeds, and detector occupancy values; locations where a portable work zone intelligent transportation system (ITS) has been deployed for incident detection and response, driver advisories, or other purposes; and point-to-point travel time measurement technologies that are becoming more and more affordable and prevalent. Given that neither type of data has been sufficiently evaluated as a potential source for work zone performance measurement data, the pilot tests were designed to have both types of data available at the same time so that direct comparisons of the measures estimated from each could be made. Ground-truth data collection by research staff was also obtained to assess how well each data source can represent actual conditions at a particular work zone.

These alternative methods of obtaining and computing the mobility-related performance measures were tested at the following five work zone project locations across the country:

- I-95, Lumberton, North Carolina
- I-95, Philadelphia, Pennsylvania
- I-405, Seattle, Washington
- I-15/US95 Design-Build Project, Las Vegas, Nevada
- I-15 Express Lane Project, Las Vegas, Nevada

This report describes the results of those pilot test efforts, and highlights the lessons learned and factors to consider when developing these types of work zone performance measures.

3. IDENTIFYING THE WORK ZONE PERFORMANCE MEASURES OF INTEREST

The first step of the pilot test process was to identify a desired set of performance measures to target. Input was solicited from members of the AASHTO Subcommittee on Traffic Engineering (SCOTE) and the Subcommittee on Systems Operations and Management (SSOM) work zone technical teams. Field personnel comments obtained through the recent Texas DOT work zone performance monitoring study were also reviewed (*4*). These efforts identified three key points with regards to work zone safety and mobility performance measure identification:

- ***The measures selected must relate to the safety and mobility goals and objectives that the agency has established for itself.*** Examples of such goals and objectives established by agency policy or procedures include maximum tolerable queue lengths and duration, maximum motorist delays, target reductions in work zone crash rates, and minimum customer satisfaction ratings.
- ***The measures must adequately capture both the breadth and depth of motorist impacts so that the trade-offs between accommodating motorists' needs and other requirements of a project (time, access, cost, etc.) can be adequately balanced.*** The effect that a project has upon motorists can vary dramatically from one project to the next. One project may result in a few work periods of intense motorist congestion and delays with several other work periods of no impacts to motorists, whereas another project may have a fairly small but consistent impact upon motorists throughout the duration of the project. When examining across all motorists passing through the work zone during the project, the average vehicle delay for those two projects may be quite similar. However, they would likely be perceived quite differently by the public. Focusing on measures that only examine one aspect of those impacts (e.g., maximum individual motorist delay) may not accurately reflect the overall picture of what happened, and lead to erroneous decisions as to how to best complete the work, or the mitigation strategies that may be needed. Rather, several measures are often needed.
- ***The measures must be sensitive to the alternative strategies available to agencies for accommodating traffic.*** Over the course of a project, certain tasks or phases may generate some impacts while others have little or no impact. When considering how to best accommodate travel during a work zone project, agencies have the option of choosing when work should occur, how much of the roadway to allocate to the work and how much to leave for traffic to use, and what (if any) techniques or strategies that may be used to enhance roadway capacity, improve safety and/or traffic flow, etc. Measures should be selected to allow agencies to assess whether such decisions did or did not work. It may be desirable to compute measures separately by project phase; by work activity condition (during work activity when lane closures are present, during work activity without lane closures, during periods of no work when lane closures are present, during

periods of no work activity and no lane closures are present); and by various time periods during the day or night (peak-period, daytime off-peak, nighttime, weekend, etc.).

- ***Different audiences may need or desire different performance measures***. For instance, measures useful to DOTs for work zone mobility impacts (e.g., percent of work zones meeting the agency queue threshold) may be different than those used to describe impacts to the public, local residents, or nearby businesses (e.g., average work zone delay).

Together, these issues indicate the importance of having a suite of performance measures that can be tailored as desired to the needs of a particular agency. The measures need to reflect project level as well as individual traveler level impacts, and the strategies used to accommodate travel. Methods of stratifying these impacts within project phases, periods of work activity, or when specific traffic-handling strategies are in effect are also needed. Ultimately, these measures may be aggregated across multiple projects for regional and statewide assessments. With these requirements in mind, measures were developed to address these needs under each of the following five priority categories:

- Exposure
- Traffic queuing
- Traveler delay
- Travel time reliability
- Safety

EXPOSURE MEASURES OF INTEREST

Exposure measures describe the amount of time, roadway space, and/or vehicle travel that a work zone (or a collection of work zones) affects or requires. Both output and outcome exposure measures of performance can be useful. For example, output measures of exposure are needed for tracking contractor activity and efficiency. The contractor typically has considerable leeway in determining when and how specific tasks are performed. Exposure measures that capture how much effort (work activity) is being expended, and when such work is being accomplished, relative to the total time available for doing the work, is a key indicator of the level of importance the contractor is giving to the project. Another dimension of exposure that relies on output-based measures is the roadway capacity restrictions required. The number of lanes closed (relative to the number of lanes normally open), the hours when the lane closures occur, and the lane-mile-hours of closure are additional ways to capture highway agency and contractor decisions on when and how work was accomplished. Whereas some work zone design features (crossovers, lane shifts) may decrease capacity slightly through the work zone, the magnitude of decrease will typically be much less than that experienced by a full lane closure. Table 1 presents a list of proposed performance measures pertaining to work zone exposure. Both output- and outcome-level measures are described, as is the rationale for including each one in the table.

Table 1. Exposure Measures of Interest

Measure	Measure Type	Definition	Use
% Calendar Days (or Nights) with Work Activity	Output	$\frac{\sum \text{Days of Work}}{\sum \text{Days in Evaluation Period}}$	Some projects are issued based on a total calendar day bid; for such projects, comparison of work effort to available calendar days is appropriate.
% Available Working Days (or Nights) with Activity	Output	$\frac{\sum \text{Days of Work}}{\sum \text{AllowableWork Days in Evaluation Period}}$	Other projects are issued with restrictions on which days or nights work can occur; therefore, comparison of work effort should be based on when work is allowed.
Average hours of work per day (or night)	Output	$\frac{\sum \text{Hours Worked}}{\sum \text{Days of Work}}$	The amount of time typically used by the contractor per shift can then be used to extrapolate total work hours over an entire project, or across similar projects.
%Work Activity Hours with: 1 lane closed, 2 lanes closed, 3 lanes closed, etc.	Output	$\frac{\sum \text{Hours Worked with 1, 2,3, etc. lane closed}}{\sum \text{Hours Worked}}$	The amount of time multiple lanes are closed can be compared against the amount of delay and queuing generated to evaluate the adequacy of lane closure policies.
Average Lane Closure Length	Output	$\frac{\sum \text{Lane Closure Length each work period}}{\sum \text{work periods with a lane closure}}$	Average lane closure length can be used to extrapolate across and projects not being monitored as closely.
Lane-mile-hours of closures	Output	$\sum_{i=1}^{n} \text{Hours worked with i lanes closed} \times \text{miles of i lanes closed}$	Lane-mile-hours of closures can be useful for assessing contractor and work crew productivity.
Vehicles passing through the work zone in evaluation period during: -Work activities -Lane closures -Inactive times	Outcome	∑vehicles entering work zone during periods of (activity, lane closures, inactivity, etc.)	Vehicle exposure during various time periods is needed to estimate delays on a per-vehicle basis; in some instances, it may be desirable to assess safety impacts on a per-vehicle basis as well.
Vehicle-miles-of travel in evaluation period during: -Work activities -Lane closures -Inactive times	Outcome	∑vehicles entering work zone during periods of (activity, lane closures, inactivity, etc.) × length of (work zone, activity area, lane closure, etc.)	Vehicle-miles-traveled is a traditional denominator used to establish vehicle crash rates.

Indicators of vehicular travel that passes through the work zone (both the number of vehicles and the corresponding vehicle-miles traveled) are outcome-level exposure measures. These measures allow mobility and safety impacts to be normalized on a per-vehicle or per-vehicle-mile basis, and can be further stratified by other output-level exposure measures listed above (i.e., vehicle-miles-traveled (VMT) during hours of work activity). These statistics are outcome measures (as opposed to output measures) because the creation of significant congestion and delays due to roadwork can significantly alter driver route choice diversion decisions, which affects the amount of traffic traveling through the work zone.

One of the challenges of utilizing VMT as an exposure term is in defining what length or limits should be used in the computations. For major roadway rehabilitation and reconstruction projects, temporary geometric changes over the limits of the project suggest the use of the project limits as the basis for estimating VMT exposure. For these types of projects, essentially all traffic and VMT would be considered affected by the work zone (travel and shoulder lane width restrictions and other geometric constraints would be present even when no work is occurring). However, for other projects, vehicle exposure during the times when temporary lane closures are occurring (during hours of a hot-mix asphalt overlay job, for example) may be the only exposure of interest. Here, the limits of the project may not be as relevant as the length of actual lane closures each day or night. Monitoring and computation of VMT exposure to this activity is straightforward; relating this value to the total VMT in the section of roadway would be less so. For these projects, estimating exposure in terms of the percentage of average daily traffic on the facility (or in terms of the total amount of traffic on the roadway during the project) would likely be more relevant in determining the percentage of the driving public that likely traveled through the work zone.

QUEUE MEASURES OF INTEREST

Both queuing and traffic delays reflect the effect of work zones on traveler mobility, and are obviously correlated with each other. However, safety considerations relative to the formulation of queues (i.e., increased risk of rear-end crashes, ensuring that sufficient advance warning signing is located upstream of the start of queuing, etc.) make direct monitoring of their length and duration important as well. Also, the fluctuations in traffic demands and other factors will affect queuing patterns that develop during each work shift, and across work shifts over the duration of a project. Measures that can assess how frequently specific levels of queuing are being exceeded (and by how much) are important indicators of these fluctuations. Table 2 presents a suite of queue measures of performance identified for this pilot test effort. As noted in the table, these measures can be defined relative to specific agency thresholds, such as the frequency of queues at a project that exceed a given length for a given duration.

Table 2. Queuing Measures of Interest

Measure	Measure Type	Definition	Use
% of work activity periods when queuing occurred	Outcome	$\frac{\sum \text{Work Periods with a Queue}}{\sum \text{Work Periods in Evaluation Period}}$	This measure can also be defined relative to a minimum threshold (i.e., the percent of work activity periods when queues exceeded a given length or duration).
Average duration when a queue was present	Outcome	$\frac{\sum \text{Queue duration each work period with queue}}{\sum \text{Work periods with queue in evaluation period}}$	The average duration of queues can be useful to agencies in deciding how far upstream from the work zone to begin warning motorists about possible delays.
Average length when a queue was present	Outcome	$\frac{\sum \text{Average queue length per work period}}{\sum \text{Work periods with queue in evaluation period}}$	The average length of queues can be used to estimate average vehicle delays if travel time data are not being collected to directly measure delays.
Maximum length of queue during evaluation period	Outcome	Max (queue length measurements during evaluation period)	Maximum queue lengths are tracked to assess whether advance warning signing is being placed far enough upstream of the lane closure to adequately warn approaching motorists.
% of work activity when queue > 1 mile	Outcome	$\frac{\sum \text{time when queue length} > 1 \text{ mile}}{\sum \text{Hours of work activity in evaluation period}}$	The threshold distance (1 mile) can be changed to reflect agency policy objectives. Also, multiple measures using multiple thresholds (i.e., 1 mile, 2 miles, etc.) could be computed to give a more complete picture of queuing patterns occurring at a site.
Amount (or %) of traffic that encounters a queue	Outcome	$\sum$ traffic when a queue is present during time period of interest	Assessing the number of vehicles or percent of daily traffic that encounter a queue is useful for evaluating appropriate beginning and ending times of temporary lane closure periods.

These measures are defined relative to a no-queue condition during the periods of work activity; that is, the assumption is that any queues that develop are the direct result of the work activity and temporary lane closures required. If queues were occurring during the same times before the project began, these measures would need to be defined in terms of changes from their pre-work zone levels in order to isolate the effects of the work zone from these normal congestion impacts. Most agencies strive to avoid closing lanes when congestion already exists at a location, reducing the need to factor in existing queues.

DELAY MEASURES OF INTEREST

From an agency perspective, delays are directly relevant in estimating road user costs caused by work activities, which in turn drive decisions regarding bidding approaches and contracting strategies employed, incentives and/or disincentive provisions of the contract, etc. From this perspective, total delays summed across all users are of most interest. Conversely, from a user satisfaction perspective, delays experienced by individual motorists encountering the work zone are better indicators of mobility impacts. Recognizing that individual delays can vary significantly over the course of a project or even hours of a particular work shift, multiple indicators may be needed to capture both the extreme and "typical" impacts are of interest. Another measure, percent of work activity time when motorist delays are exceeding some threshold will be useful to agencies that have identified a maximum tolerable level of motorist work zone delay. Table 3 presents the delay measures of performance targeted in this pilot test.

TRAVEL TIME RELIABILITY MEASURES OF INTEREST

Another dimension of assessing travel quality pertains to the reliability of trip travel times on a given roadway or route. Drivers want dependable travel times so that they can better plan their departure and arrive at a destination near a desired time (*13*). A given roadway may have an average travel time associated with it, but frequently have incidents or other events occur that temporarily increase the travel time. Roadways with highly variable travel times require that motorists "buffer" in more time in their departure time decision to ensure that they are likely to arrive on time, even though there is a chance that they will arrive much earlier than necessary if travel conditions are favorable. The prevailing approach to measuring travel time reliability is to compare the average travel time for roadway segment in a particular time period (i.e., peak period) to the 95th percentile travel time in that time period; the greater the difference between the average and the 95th percentile travel time, the more unreliable travel conditions on that roadway are considered to be. This difference is usually divided by the average travel time to normalize it as a percentage, and is then referred to as the buffer index:

$$Buffer\ Index = \frac{95^{th} percentile\ TT - Average\ TT}{Average\ TT}$$

Table 3. Delay Measures of Interest

Measure	Measure Type	Definition	Use
Total delay during entire evaluation period	Outcome	$\sum$Vehicle-hours delay in evaluation period	This measure can be multiplied by the value of time to estimate additional road user costs being caused by the project.
Total delay per work period	Outcome	$\frac{\sum \text{Vehicle} - \text{hours delay in evaluatiom period}}{\sum \text{Work Periods in evaluation period}}$	This measure is useful (when multiplied by the value of time) for estimating the user benefits achieved by accelerated construction techniques.
Total delay per work period when queues are present	Outcome	$\frac{\sum \text{Vehicle} - \text{hours delay in evaluation period}}{\sum \text{Work periods with queuing in evaluation period}}$	This measure can be useful when compared to the total delay per work period to determine the variability in work zone mobility impacts that are occurring from work period to work period.
Average delay during work activities per entering vehicle	Outcome	$\frac{\sum \text{Vehicle} - \text{hours delay during work activity}}{\sum \text{Vehicles arriving during work activity}}$	This measure can be useful when queues occur fairly frequently at a work zone, and can be compared fairly easily across projects.
Average delay during work activities per queued vehicle	Outcome	$\frac{\sum \text{Vehicle} - \text{hours delay during work activity}}{\sum \text{Vehicles arriving when queues are present during work activity}}$	This measure can be useful when queues only occur sporadically during a project, targeting the subset of vehicles that actually encounter a queue.
Maximum individual delay during evaluation period	Outcome	Max (individual delay per vehicle during evaluation period)	The upper bound on maximum individual delay experienced during the project can be helpful in responding to public complaints about perceived level of work zone mobility impacts.
% of vehicles experiencing delays greater than 10 minutes	Outcome	$\frac{\sum \text{Vehicles experiencing} > 10 \text{ minutes delay during work activity}}{\sum \text{Vehicles arriving during work activity}}$	This measure indicates the percentage of drivers experiencing greater than tolerable delays (10 minutes should be changed to reflect the agency's acceptable delay threshold).

The use of the 95th percentile travel time as the upper limit implies that someone who allows that amount of time for their trip would arrive late no more than once every 20 days (but would typically be early). Other upper limits could be used as well and interpreted similarly. For example, use of the 80th percentile travel time in the above computation would correspond to arriving late no more than once every five days (i.e., once in a typical work week).

Work zones can also temporarily reduce the capacity of the roadway, and influence the reliability of travel times on a roadway. This measure is of most interest where there is already some degree of travel time unreliability on the roadway segment, and a question exists as to whether (and how much) a work zone further affected reliability. In locations where work occurs on roadway segments and during times that are normally congestion-free, the relevance of a change in travel time reliability is less since the impacts of the work zone are fully characterized through the frequency and extent of delays and queues that develop. Consequently, a travel time reliability measure was only examined at two pilot test locations where traffic congestion and queuing was already occurring on a regular basis prior to the start of the construction project.

SAFETY MEASURES OF INTEREST

Safety measures of performance are needed to assess changes in crash risk relative to pre-work zone levels for both the individual motorist and for the driving public in total. Crash-based performance measures will not be very useful for work zones that are short in length or duration, or occur on lower-volume roadways, as the numbers of crashes themselves will be too small to draw solid conclusions. Although some agencies may propose to monitor operational indicators such as speeds or changes in speed in lieu of actual crash data, there does not yet exist credible research that correlates work zone speeds (or other operational measures) to safety impacts. Table 4 presents two proposed traffic safety measures of work zone performance. These changes could be stratified by time-of-day and/or work activity type if desired. Individual crash rates, expressed in terms of crashes per million-vehicle-miles traveled (MVMT) or changes in that crash rate when a work zone is present, capture the effect that the work zone had upon individual motorist risk. Conversely, the change in crash costs of a particular project or project phase represents the effect upon the driving public in total. A project done primarily at night may have a higher crash rate increase per MVMT, but may result in far fewer crashes in total than if the project had been done during daytime hours, due to the much lower traffic volumes present at night. Similarly, construction strategies implemented to reduce project or project phase duration could result in a higher crash rate per MVMT, but again lead to fewer total crashes if the project duration (and thus the amount of traffic passing through the work zone in total) was reduced significantly.

Table 4. Safety Measures of Interest

Measure	Measure Type	Definition	Use
% change in crash rate during work zone -total -severe (injury + fatal)	Outcome	$\frac{\left(\frac{\text{\# crashes in wz}}{\text{\# vehicles in wz}} - \frac{\text{\# crashes normally expected}}{\text{\# vehicles normally expected}}\right)}{\left(\frac{\text{\# crashes normally expected}}{\text{\# vehicles normally expected}}\right)}$	Changes in crash rates per million-vehicle-miles-travelled reflect the additional risk per mile experienced by a motorist traveling through the work zone.
Change in crash costs from expected no-work zone crash costs	Outcome	$\sum (\Delta\text{crash severity type } i_{wz} \times \$ \text{ per crash type } i$	Differences in total crash costs combine both changes in frequency and severity due to the work zone together in one measure.

Δ crash severity type i_{wz} = change in number of crashes of a given severity in the work zone from what would have been expected over the same time period at that location if the work zone were not present

In addition to a convenient way to characterize the total effects of a project (or group of projects) on safety, the use of crash costs best captures the trade-offs that may exist in establishing policy decisions or safety mitigation procedures that influence crash severities more so than total crashes (certain strategies may increase certain types of less-severe crashes but decrease the more severe crashes that could occur). This approach was used in a recent comparison of nighttime and daytime work zone safety (*14*). If used, a decision must also be made as to how crash costs themselves will be estimated. Recent FHWA guidelines could be used as a starting point (*15*).

4. DATA COLLECTION METHODS

The development of work zone performance measures requires data about the project, work activities, crashes, and traffic operations. Project data will come primarily from the project plans or files, and daily inspector diaries. Crash data will most likely come from each state's crash database, although an agency may choose to gather crash reports directly from law enforcement offices for key projects (such as is done by the Ohio DOT) and may have its field personnel collect additional data for some crashes that occur. Finally, to measure mobility impacts, some type of traffic operations data must be obtained. Two basic types of such data exist:

1. Electronic traffic surveillance data of conditions (e.g., speeds) at particular points on the roadway, or of elapsed travel time along a particular roadway segment; or
2. Manual observations of queue durations and lengths by field personnel during work activities.

A summary of the main options for collecting mobility-related data at a work zone is provided in Table 5. These options are described in greater detail in the sections that follow.

Table 5. Overview of Data Collection Methods for Work Zone Mobility Data

Method	Permanent or Temporary Devices?	Electronic or Manual Data Collection?	Point Measures or Segment Measures?
Existing Transportation Management Center Speed Sensors	Permanent	Electronic	Point
Work Zone Intelligent Transportation Systems	Temporary	Electronic	Point
Automatic Vehicle Location (AVL) data	Temporary	Electronic	Can be either, depending on use
Automatic Vehicle Identification (AVI) data	Permanent[a]	Electronic	Segment
License Plate Recognition data	Permanent or temporary	Electronic	Segment
Cellular Telephone/Bluetooth Tracking data	Permanent or temporary	Electronic	Segment
Field Personnel Queue Documentation	Temporary	Manual	Segment

[a] Portable AVI readers could be developed for temporary applications, if desired.

ELECTRONIC TRAFFIC MONITORING

Conditions at a Particular Point on the Roadway

Traffic surveillance data obtained at a point location generally relies on spot sensors. These types of sensors can provide the following:

- Volume counts
- Speeds
- Detector occupancies

Sensors can be permanently installed or temporary, and may be fixed or portable. The sensors may be inductive loops cut into the pavement, video detection cameras[1], or microwave radar detectors located next to or over the roadway. For work zone performance monitoring, it is generally desirable to have such sensors located at periodic intervals along the roadway segment where a work zone exists, including the length upstream where queues due to the work zone may extend. Examining the data from several sensors along the roadway allows estimates of such things as queue lengths and travel times (computational procedures for doing this are described in the next chapter). The quality of these estimates depends on the spacing between sensors and other factors.

In many urban areas, spot sensor data can be easily obtained via existing transportation management systems that have already been installed for general roadway monitoring purposes. Unfortunately, some work zone activities will interfere with the normal operation of these systems because of the need to move communication lines, turn off power to the sensors from time to time, pave over sensors, etc. If such activities are planned for the project or if the project is located where permanent sensors are not available, it is necessary to rely on alternative data sources. For example, a deployment of a portable work zone ITS can be used to gather and store traffic sensor data for work zone performance measurement, even if the system is installed primarily for other purposes such as incident detection and response or driver advisories (*16*). Also, portable traffic surveillance devices have recently been developed that allow traffic sensor data to be easily collected for use in work zone performance measurement. One such device is illustrated in Figure 3. The device consists of a rechargeable power supply, wireless communication capabilities, radar, and a global positioning system (GPS) antenna, all self-contained within a standard traffic drum. The vendors of this device gather the data from each device, process it, and post it to an Internet site for access by the highway agency personnel or whoever else has been authorized to access. A smaller subset of that data can also be made available for viewing on a public website as well.

[1] Cameras used for visual monitoring of traffic conditions do not gather traffic data

Figure 3. Illustration of a Portable Traffic Sensor Data Collection Device.

For both permanent and portable systems that rely on point measurements, the choice of sensor spacing will ultimately affect the accuracy of the analysis. A sensor spacing of one mile would yield an average queue length error of 0.5 mile, sensors spaced at 0.5-mile intervals would have an average queue length error of 0.25 mile, etc. Since queue lengths and delays are related, sensor spacing also affects the accuracy of estimated delays due to the work zone. The increased accuracy of closer sensor spacing must be balanced against the additional costs for more sensors and staff time to monitor and process the data. Also, it is more important to have sensor data over the entire length of congestion at a longer spacing than to have only a portion of the congestion that develops be monitored at a closer sensor spacing. Once a traffic queue extends upstream beyond the last sensor, it becomes impossible to estimate (even with a greater average error) the length of the queue or the delay that is generated.

Another unique data source that was examined as part of this pilot test effort was truck speed data obtained via transponders located within the trucks themselves. The database is used by private-sector companies to track freight movement. This is an example of automatic vehicle location (AVL) technology, which other types of private-sector fleet systems also use to monitor their fleet vehicle speeds and position. Transponders periodically upload vehicle position, direction of travel, and current speed via satellite to a database. The FHWA Office of Freight Management and Operations is sponsoring ongoing research on the use these data for freight performance measurement initiatives (*17*). For the work zone pilot test effort, available truck speed readings corresponding to the dates, times, and locations of work zone activity at the pilot tests were extracted from the overall database and "binned" in one-mile intervals along the roadway. Conceptually, this approach is similar to that of obtaining data at a point location and then assuming it represents conditions over some length (based on the distance between successive sensors). However, the selection of the roadway "bin" length must take into consideration the amount of truck traffic with transponders utilizing the roadway to allow for a large enough sample size that traffic conditions can be reasonably monitored. A drawback to the use of truck transponder data (as well as the segment-based travel measures discussed in the section below) is that it does not provide a way to obtain the traffic volume data necessary for estimating system-level impacts such as total vehicle-hours of delay and similar measures.

Travel Time Data along a Roadway Segment

Another traffic surveillance approach that can be used to monitor work zone mobility is the collection of vehicle probe data in the traffic stream to obtain speed and travel time information. A wide range of approaches exist on how such data can be obtained. These include:

- Automatic vehicle identification (AVI) technology
- License-plate recognition technology
- Cellular telephone tracking technology
- Blue-tooth tracking technology

It should be noted that, in addition to tracking current position and speeds at a point, AVL technology can also track instrumented vehicles continuously as they traverse a route and obtain elapsed travel times over a given roadway segment. Unfortunately, a very small portion of vehicles in a traffic stream will be outfitted with this type of technology. Furthermore, gaining access to that data from the fleet owners can be quite time-consuming, if access can be obtained at all.

Different than AVL technology, automatic vehicle identification (AVI) technology relies on antennae mounted at specific locations that can detect a uniquely-numbered sensor in a vehicle at each antennae location, and compute elapsed travel times between antennae locations. Electronic toll tag technology is perhaps the most common type of AVI system in use for this purpose. The real-time traffic map in Houston (see http://traffic.houstontranstar.org/layers/) relies on toll tags to estimate average freeway speeds throughout the region. The sensitivity of these data to changes in traffic conditions at specific locations along a route (such as at a work zone lane closure) depends on the spacing of the antennae used to track the vehicle probes, and the market penetration of the devices being monitored within the traffic stream. In some situations, it may be worthwhile to deploy portable antennae at strategic locations within and upstream of the work zone to capture AVI data and allow for a travel time measurement at a finer level of detail than would be possible by using travel time data over the longer segment length that is constantly being monitored. To be successful, this type of temporary supplemental deployment would need to occur prior to the start of the work zone so that comparable data was obtained before the start of construction.

Other technologies can also accomplish point-to-point travel time estimates, such as electronic license-plate recognition systems with plate number matching software. A license-plate recognition and matching system was successfully used for real-time travel time monitoring at a work zone in Arizona (*18*).

Most recently, researchers have been experimenting with the tracking of cellular telephone signals and/or devices that emit a Bluetooth signal as a way to obtain elapsed travel times (*19, 20*). These types of technologies are appealing to agencies because they do not require large investments in equipment to deploy. As with AVI and AVL systems, their effectiveness is dependent upon the level of market penetration and volume levels on the roadway segment. In addition, the accuracy with which the technology can pinpoint vehicle location influences the accuracy of the data that can be obtained. It should also be noted that, in some locations nationally, travel time data based on probe vehicles and other sources of travel-time data can be purchased from private-sector providers.

Regardless of the technology used, though, one primary drawback to using these types of probe systems is that they do not gather traffic volume data in any way. Consequently, traffic flows must either be estimated based on historical data or other information in order to estimate system-level impacts such as total vehicle-hours of delay.

MANUAL WORK ZONE MOBILITY MONITORING

Although there are various electronic traffic surveillance mechanisms available for use in monitoring work zone mobility impacts, a large number of work zone locations occur on roadways without such traffic surveillance capabilities. Furthermore, the functionality of spot-sensors and other technologies may actually be interrupted during construction activities due to the loss or relocation of power or communication lines, loss of structures to attach the sensors or antennae to, etc. Another approach to monitoring mobility impacts in work zones is to have personnel in the field document the duration and length of traffic queues that develop at the work zone. As stated earlier, the existence of a queue should be a key performance measure for work zones, as it pertains both to mobility concerns (queues create traffic delays) and safety concerns (the presence of queues is associated with increased rear-end crash potential). Direct monitoring and documentation of queues as a performance measure makes most sense at locations that normally have no congestion and queuing present. In this way, the queues that are documented can be attributed solely to the presence of the work zone. If queues and traffic congestion are normally present, some amount of "before" data will be required to factor out the pre-work zone impacts from what is observed during the work zone itself.

A simple form that can be used for documenting queue lengths by field personnel for this pilot test is provided in Table 6. The more detail that is gathered during each work zone activity that creates a traffic queue (generally, this will be periods when travel lanes are temporarily closed), the more accurate the estimates of the impacts upon work zone mobility. For the pilot test, field personnel were asked to measure or estimate queue lengths hourly as well as to document the times when queues began and ended for each work activity period. The personnel were asked to complete the form each work shift, regardless of whether queues developed, as a way to extract the other work zone exposure data of interest (hours of work activity and length of lane closures) and to verify that queues were monitored but just were not present during that particular shift. Although some field staff will faithfully document lane closure information during each work shift, previous studies suggest that the success of this practice varies widely from worker to worker (*4*).

Although the manual approach appears fairly simple, several questions remain unanswered as to its effectiveness for work zone performance measurement. First and foremost of these is whether field personnel can reasonably document queue conditions with enough accuracy and precision to be useful to agencies. Intuitively, the answer to this question likely depends on the level of importance given to the queue documentation task by field crew supervisors and managers, the workload of the person assigned to perform the documentation, and the extent of queuing itself.

SAFETY MONITORING DATA

The safety-related work zone performance measures listed in Table 4 imply the need for traffic volume data, project data, and actual crash data. Certainly, traffic volume data being collected through one of the electronic traffic monitoring methods for work zone mobility monitoring would be appropriate for work zone safety monitoring as well. If traffic volume data were not collected during the project, historical traffic counts or planning estimates of traffic volumes on the facility could be used as long as an assumption that traffic volume patterns on the facility were not changed by the work zone is reasonable. Project data would likewise be the same as is needed for work zone mobility monitoring.

The challenge exists with respect to work zone crash data. All states do have electronic crash databases that can be accessed to obtain crashes occurring in and around the limits of work zone limits over the duration of the project. Once that data is obtained, traditional crash rate computations can easily be made. However, timely access to crash data hampers many state DOTs for work zone safety performance measurement purposes. Many states have a six-month to one-year lag time in obtaining crash data. Such lag times limits analysis of work zone safety-related performance measures to post-project before-during comparisons performed months or years after a project has been completed. Given that the issue is one of safety data timeliness and not necessarily the data gathering techniques or computational procedures that challenge agencies, this pilot test effort focused exclusively on mobility-related work zone data acquisition, performance measurement computation, and interpretation.

Table 6. Data Collection Form for Manual Documentation of Queue Lengths and Duration

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 Clo-sure	# Lns Clsd	Time Q Starts	Time Q Ends	Q Lngth Hr 1	Q Lngth Hr 2	Q Lngth Hr 3	Q Lngth Hr 4	Q Lngth Hr 5	Q Lngth 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.

5. PERFORMANCE MEASURE COMPUTATIONAL PROCEDURES

In this chapter, various procedures used to compute the work zone performance measures of interest are described. Some basic computations must be made once the necessary data is obtained to translate that data into the performance measures of interest. For example, data from point measures of an electronic traffic surveillance system will have actual speeds at several locations, but these must be extrapolated across multiple locations in sequence to estimate travel times and delays. Those speeds must also be compared between point measure locations to determine the estimated length of queue that exists during each time interval of interest. If a travel time-based surveillance system is being used, travel times and delays are being measured directly, but queue lengths must somehow be approximated based on those data. If queue lengths are being collected directly by field inspectors using the manual documentation technique, computations are needed to estimate how travel times may be affected by the length and duration of the queues that are documented. The following sections describe these computational procedures in detail.

POINT MEASUREMENT ELECTRONIC TRAFFIC SURVEILLANCE DATA COMPUTATIONS

It is generally assumed that traffic flow characteristics obtained at a particular point measurement location represent conditions for some distance upstream and downstream of that measurement location. Therefore, a roadway section is divided into a series segments, with conditions in each segment assumed to be represented by its corresponding spot sensor data, as illustrated in Figure 4. The travel time at any point in time j across a region i (TT_{ij}) is simply the length of that region (L_i) divided by the speed at that point in time obtained from the sensor. Summing the individual travel times for each region together provides a total travel time over the length of roadway of interest at that point in time.

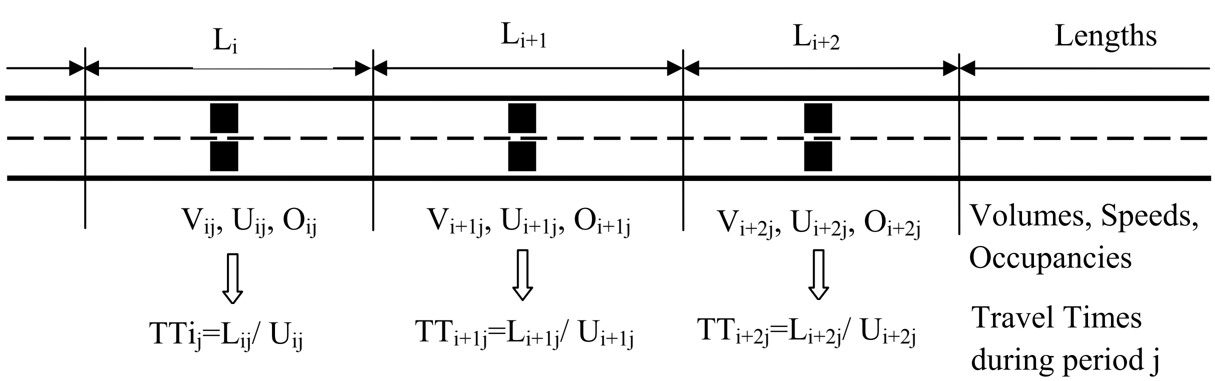


Figure 4. Illustration of Traffic Surveillance Estimates using Spot Sensor Data.

To estimate work zone delays, the travel times estimated in a pre-work zone condition can be directly compared to those estimated from the speeds measured during the work zone over the same summed length of interest, and the difference between the two considered the individual motorist delay being created by the work zone. As an alternative, a desired speed through the work zone can be defined and travel times based on that desired speed used as a baseline to compare against actual work zone travel times. Such an approach might be used if the agency has posted a reduced speed limit through the work zone, and does not want delays measured against the normal, non-work zone speed limit and operating speeds. With individual motorist delays identified, the number of motorists encountering these delays can be multiplied by this individual delay and summed over the duration of the work activity (and eventually, the project) to estimate total delay.

Next, to approximate queue lengths from point measurements, the speeds at each measurement location are examined in sequence and over time to identify regions in which speeds drop below a selected threshold (for 70 mile-per-hour [mph] roadways, a 35 mph speed would be recommended as the threshold denoting queued conditions). The time period when speeds are below the threshold represent the duration of the queue in each point measurement segment. To estimate the length of queue over time, speeds at successive point measurement locations are examined together, and the length L_i for each segment denoted as being below the threshold is added together for each time interval of interest.

Figure 5 helps illustrate this process. In this example, point measurements are located 0.2 mile, 0.8 mile, and 1.3 miles upstream of the temporary lane closure. Project diary information indicates that a 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 30 mph at that location during the hours of work activity. Therefore, the queue length each hour would be estimated as shown in Table 7.

Table 7. Queue Length Computations Based on Point Measurement Data

Time	Estimated Location of Upstream End of Queue	Estimated Queue Length
11:00 am	None	0
12:00 pm	Between Sensors #1 and #2	0.2 + (0.6/2) = 0.5 mile
1:00 pm	Between Sensors #2 and #3	0.2 + 0.6 + (0.5/2) = 1.05 mile
2:00 pm	“	1.05 mile
3:00 pm	“	1.05 mile
4:00 pm	None	0

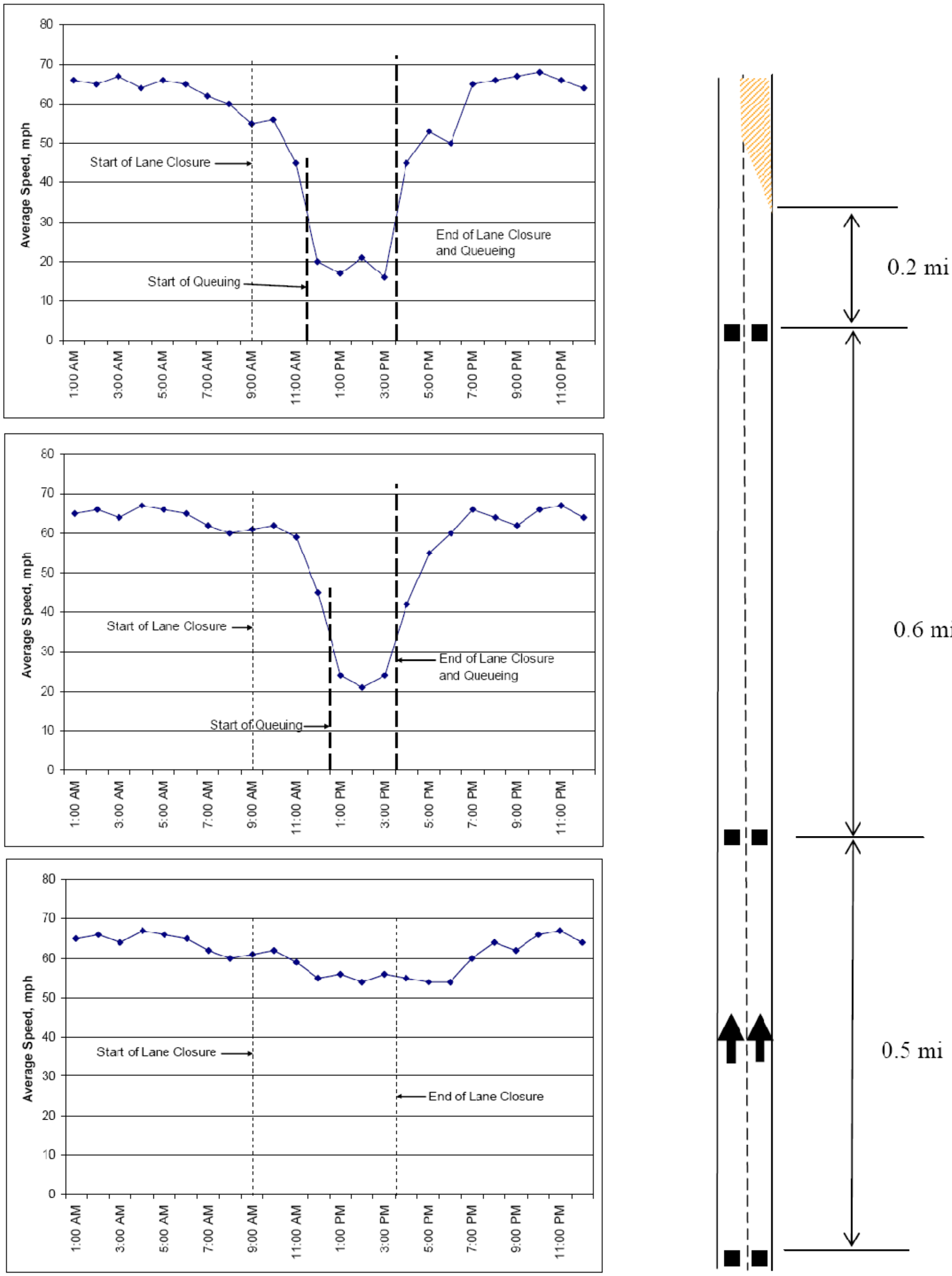


Figure 5. Example of Sensor Speed Analysis to Determine Duration and Length of Queue.

TRAVEL-TIME BASED ELECTRONIC SURVEILLANCE DATA COMPUTATIONS

If travel time information is obtained directly from an electronic surveillance system, the estimation of individual motorist delay over the roadway segment of interest is straightforward. The difference in travel times between normal, non-work zone conditions (at the same time-of-day) and those measured when the work zone is present is the individual motorist delay that exists at that particular time period. Multiplying the individual delays in a given time interval by the number of vehicles passing through the work zone, and accumulated over the days and time periods of interest, yields the total delay (in vehicle-hours) caused by the work zone.

Unfortunately, travel-time based electronic surveillance methods themselves do not also count traffic data. Consequently, volumes occurring through the day (and night) on the roadway segment must be measured by other means (such as temporary traffic counters) or approximated based on historical volumes developed for planning and programming purposes. In many states, only total daily traffic volumes are estimated for most roadway segments. If this is the case, a method of dissecting that 24-hour count into estimated hourly counts by direction will be required. Fortunately, most state agencies have directional and hourly distribution factors developed for various roadway classes that can be used for this purpose. In other locations, nearby automated traffic recording (ATR) stations may be used to generate directional and hourly volume distribution values.

Travel-time based electronic surveillance data is also more limited with respect to estimating queue lengths and durations. If antennae are located close enough together, conditions within each segment may be similar enough to allow for a segment-by-segment comparison as described above for spot sensor data. However, as the length between successive antennae increases, the possibility for missing any queuing that occurs increases. This is because while speeds may drop dramatically in the region where congestion and queuing exists, its effects are diluted with the other portions of the segment that may be operating at higher speeds, either normal (non-work zone) speeds prior to reaching the start of the queue, and/or at speeds near capacity flow conditions through the work zone itself. While it would be mathematically possible to define equations to relate the lengths of the non-work zone, queued, and work zone subsections with a given roadway segment based on assumed or estimated speeds of each subsection, the level of effort required and potential magnitude of errors possible suggest that it would be preferable to simply rely on such data for travel time delays, and to have field personnel manually document queue lengths and durations as described in the next section.

MANUAL QUEUE LENGTH DATA COMPUTATIONS

For locations in which field crew documentation of queue lengths present during a work shift is the primary traffic flow data available, historical estimates of traffic volumes must be obtained as discussed above for travel-time based electronic traffic surveillance systems. In addition, computational methods are needed to estimate how travel times are affected by the presence of the queue.

The manual queue documentation approach will work best if applied at locations when and where, in the absence of the work zone, congested traffic flow conditions would not exist. If this is the case, then the queues as well as the travel times that result because of the queues will be attributable to the work activity in the work zone. Of course, it is possible that an incident or adverse weather conditions in or immediately upstream of the work zone could also contribute to the queue and delays of a work zone. If such incidents occur, it would be important for field personnel to make a special note about it on the data collection form so that the queue and delay numbers can be appropriately interpreted.

To estimate how the documented queues result in travel time delays, it is assumed that both the queue itself and the work zone result in slower speeds for some travel distance. This is depicted in Figure 6. If a queue has formed upstream of the work zone (at the lane closure bottleneck), it is realistic to assume that the flow rate through the work zone is at or near capacity, such that the speed at capacity flow can be assumed to govern through the work zone. For simplicity purposes, an assumption of a linear relationship between speeds and density would suggest that the capacity flow speed would be one-half of the free-flow speed on the facility. Upstream of the work zone, the queue that develops would be flowing at a speed less than the capacity flow speed. Again using a simple linear speed-density relationship, the following equation produces an estimate of the average speed in queue as a function of the normal roadway capacity and the capacity through the work zone (*21*):

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

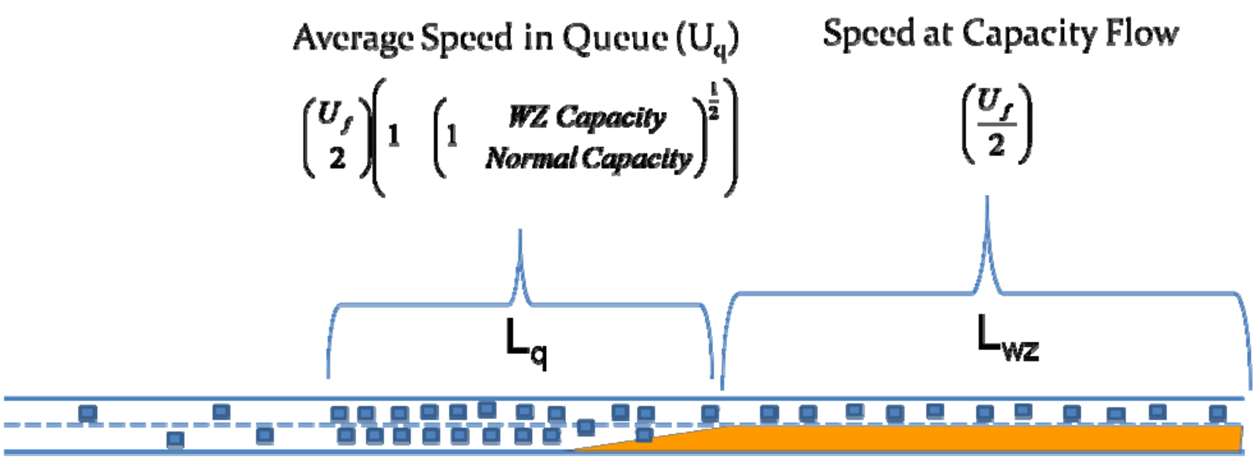


Figure 6. Components of Work Zone Delay.

The capacity of the work zone can be estimated using procedures in the *Highway Capacity Manual* (HCM) (*22*). The HCM also provides procedures to estimate the normal traffic-carrying capacity of the roadway segment. 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

Assuming that these speeds are maintained, on average, through the entire length of the queue and work zone documented, estimates of average delays per vehicle through the queue can be computed as a function of the length of queue. Some threshold (most likely the desired speed or the posted work zone speed limit [U_{WZSL}]) would serve as the basis against which the longer travel times through the queue would be computed. This queue delay would then be added to the delay that would be generated as vehicles pass through the remainder of the work zone at capacity flow speeds (30-35 mph):

$$\frac{Delay}{Vehicle} = L_q\left(\frac{1}{u_q} - \frac{1}{U_{WZSL}}\right) + L_{wz}\left(\frac{1}{\frac{u_f}{2}} - \frac{1}{U_{WZSL}}\right) \qquad (2)$$

Once the average delay per vehicle is estimated for each time interval that a queue is noted on the documentation form, the total vehicle-hours of delay is computed simply 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.

The use of historical volumes for these computations implies that any diversion that occurs because of the work zone will result in delays for diverted motorists that are approximately equal to those being experienced by motorists remaining on the roadway and passing through the queue and the work zone. Such an approximation is likely to be fairly reasonable given the approximate level of accuracy anticipated in the queue length and duration estimation process. If actual traffic counts during the work activity are available, it may still be more appropriate to utilize historical volumes on the facility so that the mobility effects of traffic diversion are taken into consideration to some degree. In general, diversion concerns will only exist in urban areas where there are frequent access and egress points to a roadway, and multiple alternative paths to use as diversion routes. In rural areas, the options are much more limited, and most traffic will have to pass through the queue and work zone.

6. PILOT TEST LOCATION #1: I-95, LUMBERTON, NC

DESCRIPTION

The first work zone location where the proposed work zone performance data were gathered and measures computed was on Interstate 95 in southern North Carolina, near the town of Lumberton. A 10-mile section of the roadway (milepoint 0 to milepoint 10) was undergoing resurfacing of travel lanes, improvements to the shoulder and other roadside appurtenance improvements in both directions of travel. When work was occurring, one of the two lanes in a given direction of travel was closed to traffic. The length of the lane closure varied each work period, depending on the anticipated work tasks to be completed.

The posted speed limit on this roadway segment is 65 mph. As of 2007, this section of I-95 reportedly serviced approximately 47,000 vpd, a significant portion of them large trucks. The North Carolina Department of Transportation (NCDOT) decided to allow the contractor to perform the work at their discretion anytime between Monday and Friday morning in the northbound direction, and between 10 am and 5 pm Monday through Thursday in the southbound direction; weekend lane closures were not allowed. Although the NCDOT analysis indicated that queues would not be a problem, contract documents also specified that the contractor was not to allow traffic queues due to a lane closure to grow beyond three miles in length.

DATA SOURCES

This section of I-95 is a fairly rural portion of North Carolina, and thus was not within the limits of an existing transportation management center (and its associated data collection devices). Consequently, the primary source of data for this pilot test was manual documentation of queues by field personnel on site each day of work activity. The manual documentation was done using the data collection form previously shown in Table 6. Work zone activities were recorded by project field crews between the dates of August 4 and November 25, 2008. A total of 66 days of work activity occurred during that time period. The summer of 2008 turned out to be extremely wet for southern North Carolina. As a result, the contractor was rained out on many of the potential weekdays that work could have occurred.

At this location, an attempt was also made to utilize the portable traffic surveillance devices previously described (see Figure 7). For this pilot test, the plan was to deploy six of these devices approximately 1-mile apart from each other, three of them upstream of the temporary lane closure taper, and three within the work zone itself.

Figure 7. Portable Traffic Data Collection Device at Pilot Test Location.

Initially, the device did experience some data communications problems. These problems were subsequently corrected. Unfortunately, the end result of the efforts to get these devices to the field was that they were used occasionally over the study period, but not each and every work shift. In addition, the days that the devices were deployed happened to occur when no queues or congestion developed at the site. Consequently, the data that was available from these devices could not be applied to this particular pilot test.

A second source of traffic operational data gathered for this site was truck transponder information from the FHWA Office of Freight Management data collection effort (also previously described). For this work zone monitoring effort, a request was made to query the database on dates of queuing reported by the field crews, and to provide that data in one-mile increments within and upstream of the work zone each of those days. As shown in Table 8, the query yielded five days of truck transponder data. Unfortunately, the sample size at this site was very low, averaging fewer than one truck speed per hour per mile of roadway investigated. There were a few instances where multiple observations were obtained during the same hour in the same mile segment, but those were the exception rather than the rule (and so were not identified specifically in the table).

Table 8. Truck Transponder Sample Size, I-95, Lumberton

Date	Hours of Closure Examined	Length of Section Examined	Truck Transponder Observations	Observations per Mile per Hour
August 4, 2008	6 hr	9 mi	55	1.0
August 28, 2008	10 hr	9 mi	63	0.7
November 3, 2008	6 hr	9 mi	31	0.6
November 20, 2008	10 hr	9 mi	72	0.8
November 24, 2008	10 hr	9 mi	47	0.5
5-Day Average	8.4 hr	9 mi	53.6	0.7

RESULTS

Exposure Measures

Based on the work day restrictions set forth in the contract documents, a total of 66 days were allowed for the contractor to work during the four-month evaluation period of this pilot test. Of these, the field crew documentation tables indicated that work actually occurred on 31 of those days. As shown in Figure 8, this represents less than 50 percent of the days allowable in the contract. If this effort is compared to all days in the entire four-month period, work actually occurred slightly more than one out of every four days.

Intuitively, such numbers seem fairly small, and would normally be cause for an agency to investigate more closely and/or potentially look into its current methods of estimating work duration and contracting language. However, the rainy weather alluded to previously certainly had much to do with this low level of activity. Because this pilot test is for illustrative purposes only, rain days were not extracted from the total allowable days in the analysis. For actual monitoring purposes, such exclusions might be appropriate in the final calculations by an agency.

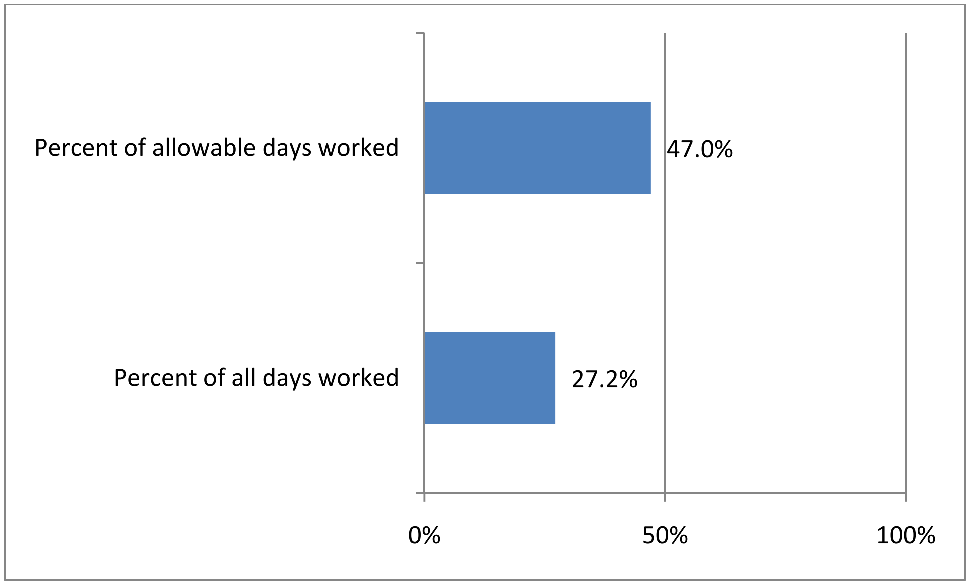


Figure 8. Work Exposure Measures, I-95 Lumberton.

Table 9 summarizes the hours of work activity reported on the field crew data collection forms. Over the 31 days of activity, the contractor performed 290 hours of work, averaging approximately 9.3 hours per work shift. Based on these data, it does appear that the contractor was making full use of available work windows when they did mobilize and initiate a work shift on this project.

Table 9. Hours of Work Activity, I-95 Lumberton

Work Exposure Measure	Value
Total hours of work activity during evaluation period	290
Average number of hours of work per day	9.3

The next facet of exposure data gathered and computed for the North Carolina project were the roadway capacity losses. These are provided in Table 10. At this project, all work activity that occurred involved the closure of one lane of travel in either the northbound or southbound direction. Furthermore, when work crews were not on site, all lane closures were removed from the site. One does see that over the 31 days of work in the evaluation period, a total of 558 lane-mile-hours of roadway capacity loss were required for the project, or an average 1.9-mile lane closure each day of work activity.

Table 10. Roadway Capacity Loss Measures, I-95 Lumberton

Capacity Loss Exposure Measure	Value
Percent of work hours involving 1of 2 lanes closed in a given direction	100%
Percent of inactive hours involving lane closures	0%
Lane-Mile-Hours of closures in evaluation period	558 ln-mi-hr
Average lane closure length per work activity period	1.9 miles

The relatively infrequent work activity of this project during the evaluation did have the positive consequence of limiting motorist exposure to the work activity and lane closures. As shown in Table 11, approximately 348,000 vehicles passed through active work zone lane closures during the evaluation period of this project. Overall, this corresponds to less than 7 percent of the total amount of traffic that utilized this section of I-95 during the evaluation period. A total of 661,200 vehicle-miles of travel occurred through the work zone during the evaluation period.

Table 11. Vehicle Exposure Measures, I-95 Lumberton

Capacity Loss Exposure Measure	Value
Number of vehicles passing through active lane closures in evaluation period	348,000
Percent of total traffic in evaluation period encountering work activity and lane closures	6.5%
Total vehicle-miles-traveled past active work zone lane closures in evaluation period	661,200 veh-mi

Queuing Measures

Table 12 and Figure 9 both summarize queue measure characteristics at this site. Although this section of I-95 serves a significant amount of traffic during the typical daytime period, the temporary closure of a travel lane did not always result in the creation of queues and congestion at the site. According to field crew documentation, queues developed only about one out of every four days of work activity at the site. On average, queues that did develop on certain days lasted 1.3 hours before dissipating, and were approximately 0.6 miles long. The maximum queue length documented by the field crews during the evaluation period was 2.0 miles, significantly below the 3-mile threshold established by NCDOT. These measures highlight the value of monitoring, gathering, and evaluating work zone mobility-related data on an ongoing basis. In the absence of such numbers, it would be difficult for NCDOT to decide, based on this project, whether to continue to allow daytime lane closures on this section of I-95 on future projects.

Table 12. Comparison of Queue Measures, I-95 Lumberton

Queue Measure	Based on Field Crew Data	Based on Electronic Truck Transponder Data
Days of work activity when queuing occurred	25.8%	5.6%
Amount of work activity time when queue > 1 mi	1.4%	2.5%
Amount of work activity time when queue > 3 mi	0.0%	0.7%
Amount of traffic volume through active work zone that encounters a queue	4.8%	3.6%

For comparison purposes, Table 12 and Figure 9 also provide the same queue measures estimated from the available truck transponder data at this location during the evaluation period. It should be noted that the sample size for these estimates was very small, as only one or two truck speed samples were typically available in any given hour in any mile interval within the study segment. In many cases, no data were available when and where queues were documented by the field personnel. Consequently, fewer instances of queuing could actually be identified with the truck transponder data. As Table 12 illustrates, the field crews indicated queuing approximately once every four days of work activity, while the truck transponder data indicated the presence of queues on about once every 20 days of work. Similarly, the queues had to be somewhat larger and longer in duration in order to be detected through the truck transponder data because of the one-mile interval that was used to group the truck transponder speeds. Estimates of average and maximum queue lengths and queue duration via the truck transponder data were somewhat higher than those reported by the field crews, and the truck transponder data did yield a small amount of time (but more than was reported by the field crews) when the queues exceeded the contract-stated threshold of 3 miles.

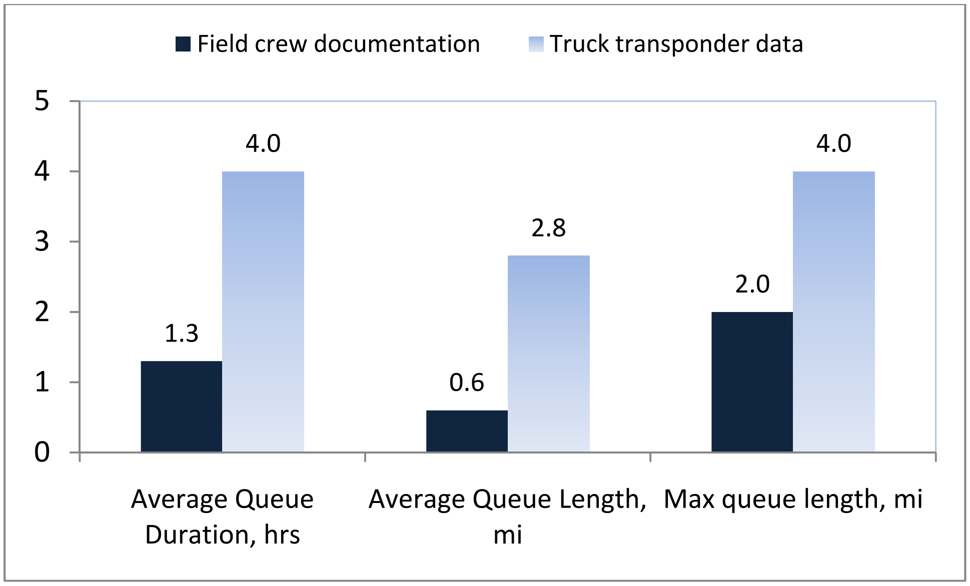


Figure 9. Comparison of Queue Length Measures, I-95 Lumberton.

In addition to the field crew and truck transponder data sources obtained for this pilot test location, a limited amount of "ground truth" travel time and queue length data were gathered during one week in October 2008. Comparison of these data to the field crew documentation indicates reasonable, but not excellent, agreement and accuracy by field personnel in estimating queue conditions at the site. During that week, the field crews reported queues on two of the four days of travel time studies. Unfortunately, truck transponder data were not available to determine how well that data source compared to actual queue lengths at this site. Table 13 summarizes the comparison between field crew and ground-truth measures of queue duration and length on three of the days of travel time data collection. Travel time studies on October 13th supported field crew documentation that no queues developed during work activities on that day. Overall, field crew documentation and travel time studies correlated well on two of the three days in terms of queue duration and maximum queue lengths. However, travel time studies did show some queuing on October 15 that was not documented in the field crew data collection forms.

Table 13. Comparison of Queue Conditions During Travel Time Studies, I-95 Lumberton

	October 14, 2008		October 15, 2008		October 16 2008	
	Based on Field Crew Data	Measured via TT Studies	Based on Field Crew Data	Measured via TT Studies	Based on Field Crew Data	Measured via TT Studies
Queue Duration (Hrs)	0.5	0.8	0.0	1.8	2.0	1.5
Maximum Queue Length (Mi)	1.0	1.0	1.0	0.6	1.5	2.1

TT= travel time

Delay Measures

Computations of delays from the queue length data at this site uncovered a major source of variability that was not anticipated or considered in the pilot test design. Specifically, it became clear that simply noting the existing of a queue and its approximate length over time was not sufficient to reasonably approximate delays being experienced by motorists who are passing through the work zone. This is because delays are highly dependent upon the average speed assumed to exist within the length of queue. In the computational procedures previously described, it was assumed that a queue would develop at the point of a lane closure bottleneck and grow upstream of that point across all approach lanes, leading to very slow speeds in queue. In reality, bottleneck locations often developed farther into the work zone lane closure, and grew upstream from that point in the remaining open lane. The ramifications of this is that the average speed within a queue that forms within the work zone would be expected to be flowing at speeds closer to the capacity flow of traffic than at the previously-defined average speed in queue. If the queue were to grow to a point where it extended beyond the lane closure taper, the section upstream of that taper would then be expected to begin operating at a much slower average speed as vehicles fill in both lanes and begin to take turns moving into the open lane and through the work zone.

The ramifications of the location of the queue (and thus whether it is assumed to be operating at a capacity flow speed or an upstream traffic queue speed) upon delay estimates is dramatic. As noted in Table 14, estimates of the average delay per vehicle caused by the work zone traffic queues that developed vary by a factor of almost 10, depending on the assumptions as to where the queues were located (within or upstream of the lane closure taper). Comparing the truck transponder data, one sees that the delay estimates tended towards the upper end of the range of values computed from the field personnel queue length documentation. It should be remembered, though, that the delays estimated from the truck transponder data correspond to queue lengths that were much longer than those documented by the field personnel.

Consequently, the correlation between the two data sources is smaller than it actually appears in the table.

Table 14. Comparison of Delay Measures, I-95 Lumberton

Delay Measure	Based on Field Crew Data Data[a]	Based on Truck Transponder Data[b]
Average delay per entering vehicle during work	0.0-0.4 min/veh	0.3 min/veh
Average delay per queued vehicle during work	0.9-8.9 min/veh	9.7 min/veh
Maximum delay per queued vehicle during work	2.0-17.5 min/veh	13.7 min/veh
Total delay during work over entire evaluation period	246-2485 veh-hrs	944 veh-hrs
Total delay per day of work	8-80 veh-hrs	63 veh-hrs
Total delay per day of work when queues occur	31-311 veh-hrs	944 veh-hrs

[a] The lower end of the range shown was computed assuming the queue was located within the work zone and moving at capacity flow speeds; the upper end was computed assuming the queue was located upstream from the lane closure taper and moving at the computed reduced speed in queue from equation 1.

[b] This dataset represents fewer days of queuing, and captures only the longer duration and lengthier queues.

The travel time data collected during October 2008 was also compared to these delay estimates and the assumptions regarding the average speed in queue. The results, presented in Table 15, indicate that the speed in queue on October 14 matched more closely to the capacity flow speed (i.e., the queue was located within the work zone). On October 16, the average speed in queue measured through the travel time studies was something between a capacity flow speed and a speed in queue when located upstream of the lane closure taper. This would imply that part of the queue was located within the limits of the work zone, and part extended upstream of the lane closure taper. In fact, notes taken during the travel time studies on that date indicate that the queue was indeed located partially beyond, and partially upstream, of the work zone lane closure taper.

Table 15. Comparison of Speed and Delay During Travel Time Studies, I-95 Lumberton

	October 14, 2008		October 15, 2008		October 16 2008	
	Based on Field Crew Data [a]	Measured via TT Studies	Based on Field Crew Data	Measured via TT Studies	Based on Field Crew Data[a]	Measured via TT Studies
Average Speed in Queue (Mph)	6.3-30	27	n/a	25	6.3-30	17
Average Delay per Vehicle (Min)	0.4-8.5	0.4	0.0	0.6	0.9-10.0	3.0

[a] The lower end of the range shown was computed assuming the queue was located within the work zone and moving at capacity flow speeds; the upper end was computed assuming the queue was located upstream from the lane closure taper and moving at the computed reduced speed in queue from equation 1.

TT= travel time, n/a=data not available

KEY FINDINGS FROM I-95 LUMBERTON PILOT TEST

Based on the data obtained and measures computed with this pilot test, it does appear that field personnel were able to document queues fairly accurately when such documentation occurred. It does appear that there may have been a work shift or two in which queue documentation was not performed (as suggested in Table 12 and Table 13). Given that field personnel have multiple job duties and responsibilities at most project sites, an occasional miss of queues was not unexpected.

Overall, the exposure, queue, and delay measures as defined earlier in this report were able to be computed using the data gathered by the field personnel, and yielded results which, for the most part, appeared reasonable and potentially useful for agency work zone policy and procedure assessments in the future. However, a key limitation in the proposed data collection and analysis procedures was identified relative to the use of field personnel documentation of queue durations and lengths at project sites. Specifically, it will be necessary for field crews to not only document the lengths and durations of any queues that develop, but also to assess whether the queue is located upstream of the work zone lane closure, or within the lane closure in the work activity area. Speeds in queue vary by a factor of 5 to 10 depending where it is located relative to the lane closure taper, and so the location of the queue will dramatically alter the delays that would be computed based on a given length and duration of queue.

7. PILOT TEST LOCATION #2: I-405, SEATTLE, WASHINGTON

DESCRIPTION

The next performance measure pilot test was located on Interstate 405 in Bellevue, WA (a suburb of Seattle) between SE 8th street on the north and 112th Avenue SE to the south (2.6 miles). This project was a multi-year reconstruction and widening project to add a travel lane in each direction, widen or reconstruct several bridges in the section to accommodate the additional capacity, and remove the Wilburton tunnel. As of 2007, the most heavily traveled section of I-405 was near SE 8th Street in downtown Bellevue, with an average of 200,000 vpd. Within this section, there are generally three to four travel lanes per direction, some of which are auxiliary lanes between adjacent ramps. The leftmost lane in each direction is designated as an HOV lane that is operational between 5 am and 7 pm (that is, it can be used as a regular travel lane at night). The posted speed limit on this roadway segment is 65mph.

The overall project began in July 2007 and was scheduled to be completed in late 2009. Many of the project tasks involved work activities away from travel lanes behind concrete barriers, on cross-streets to the freeway, etc. For purposes of this pilot test, work activities involving temporary lane closures and potential traffic queuing were targeted. The pilot test duration lasted between July 9 and October 9, 2008 (92 days). During this study period, work activities required the closure of one or more travel lanes at night. A single lane of travel in each direction was allowed to be closed beginning at 8 pm, a second lane could be closed at 10 pm (if necessary), and a third lane could be closed at 11 pm. Over this time period, a total of 43 nights of work activity occurred in the southbound direction of travel, and 39 nights of work activity in the northbound direction. The contractor was not allowed to close lanes on Friday or Saturday nights.

DATA SOURCES

At this location, project field personnel were again asked to fill out a field data collection form to obtain nights and hours work activity, lane closure information (location, duration, number of lanes closed and open), and approximate hourly queue length data on those nights when queues formed. These lane closure and queue length data were then used to estimate work zone exposure measures, as well as average individual vehicle delay and total vehicle-hours of delay during congestion.

In addition to the manual queue length documentation by field personnel, electronic traffic sensor data was available from the regional TMC that has been operational in the Seattle region for a number of years. Along the I-405 segment of interest, a series of inductive loop and non-intrusive traffic sensors have been installed which measure volumes, speeds (at some locations), and sensor occupancies (which are correlated to traffic density). Two types of sensor stations exist in this system;

- Single loop sensors which collect vehicle count data only in the travel lane
- Dual-loop sensor stations that can measure speeds and collect vehicle count data in the travel lane

Non-functional sensors at some sensor locations meant that only one or two lanes of traffic were being recorded. Table 16 and Table 17 provide a summary of the location and types of sensors in this roadway segment. Although the mixture of single and dual loop sensors may serve the TMC functions adequately, they do present a bit of a challenge from the standpoint of monitoring work zone performance. Recall that speed data provide the primary indicator of queuing and is critical to the estimation of travel times (and changes thereof) upstream and through the work zone. Thus, although sensor stations were located at approximately 0.33 to 0.5-mile intervals in this roadway segment, speed sensors were available at about every other or every third set (i.e., at about 1 mile intervals). Further complicating the situation was the fact that individual sensor stations in the vicinity of the lane closures were sometimes non-functional at night when work was occurring, or only provided vehicle count data instead of both vehicle counts and speeds. It is not known whether temporary power disruptions required by work activities were responsible for this loss of data, or whether the quality control algorithms used by the TMC detected perceived "anomalies" in the data and simply discarded them from the database. Either way, the end result was a lack of data on certain nights at critical locations upstream and within the lane closure section.

Table 16. Spot Sensor Location Northbound, I-405 Seattle

Sensor Location	Milepoint	Sensor Type
NE 37th	7.00	V only
NE 44th	7.45	V only
SE 70th	8.03	V & S
SE 64th	8.40	V & S
SE 59th	8.90	V & S
112th Ave SE	9.21	V only
SE 47th	9.75	V only
Coal Crk Pkwy	10.13	V only
SE 40th	10.55	V & S
SE 39th	10.79	V only
I-90	11.21	V only
SE 30th	11.47	V only
SE 20th	12.05	V only
SE 4th	13.06	V & S
NE 4th	13.60	V only

V = volume, S = speed

Table 17. Spot Sensor Location Southbound I-405 Seattle

Sensor Location	Milepoint	Sensor Type
SR 520	14.63	V & S
NE 14th	14.27	V & S
NE 4th/8th	13.33	V only
SE 4th	13.06	V only
SE 20th	12.05	V & S
SE 30th	11.47	V only
I-90	11.21	V & S
SE 40th	10.55	V & S
Coal Crk Pkwy	10.13	V only
SE 47th	9.75	V & S
112th Ave SE	9.21	V only
SE 59th	8.90	V & S
SE 64th	8.40	V & S
SE 70th	8.03	V only
NE 44th	7.40	V only
NE 37th	7.00	V only

V = volume, S = speed

For this study, manual field personnel documentation of queue duration and length, and TMC speed and volume data were all collected each night of work activity in order to allow comparisons of the results. In addition, actual travel time studies were conducted during the week of September 1, 2008 to assess how each type of data compared to these "ground truth" delay and queue length measurements. Finally, a small sample of truck transponder data were obtained for three nights of work activity (September 15-17, 2008) over a 7-mile segment of roadway (in each direction). A comparison set of truck data were also provided for that roadway segment from March 2009. Unfortunately, as was the case for the I-95 Lumberton project in North Carolina, the sample size obtained at this site was extremely small (see Table 18). Many mile segments had no observations in many hour intervals (93 percent of the mile-segment-hours had no speed observations). In only one instance was there more than two speed observations in a given mile segment in a given hour of work activity.

Table 18. Truck Transponder Sample Size, I-405, Seattle

Date	Hours of Closure Examined	Length of Section Examined[a]	Truck Transponder Observations	Observations per Mile per Hour	
				Average	Maximum
Sep. 15, 2008	9 hr	14 mi	18	0.1	6
Sep. 16, 2008	9 hr	14 mi	10	0.1	2
Sep. 17, 2008	9 hr	14 mi	15	0.1	2
3-Day Average	9 hr	14 mi	14.3	0.1	6

[a] 7 miles in each direction

RESULTS

Exposure Measures

As shown in Figure 10, the field crew documentation tables indicated that work actually occurred on slightly more than one-half of all of the nights during the evaluation period. Considering only Sunday through Thursday nights when the contractor was actually allowed to be on I-405 and close lanes, work activity occurred on slightly more than 70 percent of the allowable nights.

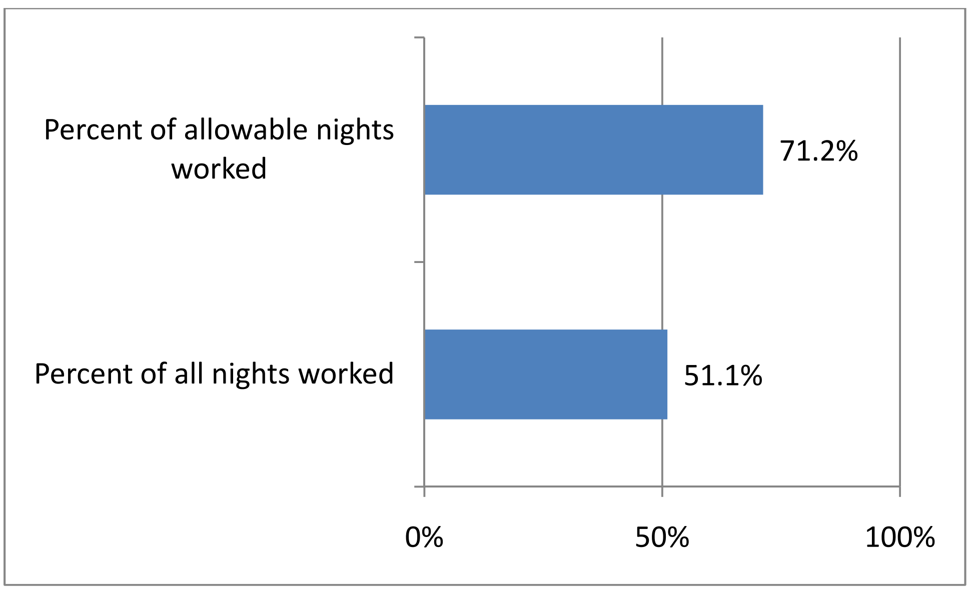


Figure 10. Work Exposure Measures, I-405 Seattle.

Table 19 summarizes the hours of work activity reported on the field crew data collection forms. Over the 47 nights of activity in the pilot test evaluation period, the contractor performed 407 hours of work, averaging approximately 8.7 hours per work shift. Overall, it was apparent that the contractor was making full use of available work windows at night when they did mobilize and initiate a work shift on this project.

Table 19. Hours of Work Activity, I-405 Seattle

Work Exposure Measure	Value
Total hours of work activity during project	407
Average number of hours of work per day	8.7

The next facet of exposure data gathered and computed for the Washington project were the roadway capacity losses. These are provided in Table 20. Tracking and consolidating lane closure data for this project proved to be a fairly significant task, given the acceptable times of lane closures allowed at night in the contract. In addition, there were a few nights when work crews were in both directions of travel. Overall, one sees in Table 20 that over one-half of the lane closure time involved the closure of three out of four available lanes. The maximum number of lanes present within the limits of the work zone each night was used as the baseline, rather than attempting to characterize each auxiliary lane or lane drop segment separately. Also, there are a very few number of hours included in Table 20 where the entire roadway section was closed for a few minutes while overhead beams were moved into place or other tasks occurred which required full closure of the roadway.

Table 20. Roadway Capacity Loss Measures, I-405 Seattle

Capacity Loss Exposure Measure	Value
Percent of work hours involving:	
1 of 4 lanes closed in a given direction	13.8%
2 of 4 lanes closed in a given direction	27.4%
3 of 4 lanes closed in a given direction	57.1%
4 of four lanes closed in a given direction	0.2%
Percent of inactive hours involving lane closures	0%
Lane-Mile-Hours of closures in evaluation period	5,456
Average lane closure length per work activity period	5.5 miles

Over the 47 nights of work in the evaluation period, a total of 5,456 lane-mile-hours of roadway capacity loss were required for the project. This equates to an average of 5.5 miles of lane closure each night of work activity. Often, this length of lane closure was split between both directions of travel.

The decision to work at night did minimize the extent to which Seattle drivers were exposed to the nightly lane closures on this roadway segment. Still, the absolute exposure numbers were quite significant. As shown in Table 21, approximately more than 1.3 million vehicles passed through active work zone lane closures during the evaluation period of this project. Overall, this corresponds to less than 10 percent of the total amount of traffic that utilized this section of I-405 during the evaluation period. Meanwhile, nearly 5 million vehicle miles of travel occurred through the temporary lane closures over the duration of the evaluation period of this project.

Table 21. Vehicle Exposure Measures, I-405 Seattle

Vehicle Exposure Measure	Value
Number of vehicles passing through active lane closures in evaluation period	1,385,500
Percent of total traffic in evaluation period encountering work activity and lane closures	9.3%
Total vehicle-miles-traveled past active work zone lane closures in evaluation period	4,846,400 veh-mi

Queuing Measures

Table 22 and Figure 11 both summarize queue measure characteristics at this site as documented by field personnel on the data collection form, and through analysis of available traffic sensor data from the regional TMC. Because work activity typically occurred simultaneously in both directions of travel each night, separate analyses were performed for each direction. The restriction of temporary lane closures to nighttime hours no doubt did reduce the frequency and severity of queues and congestion that might have otherwise developed. However, as noted in Table 22, field personnel still reported the creation of queues on 80 percent of the nights when a lane closure was implemented in either direction. The traffic sensor data at this site was not as sensitive to detecting queue presence, as analyses found evidence of queuing on only 35 to 59 percent of the nights of work activity. This result was expected given the limited number of sensor locations that had functional volume and speed data available. Looking back at Table 16 and Table 17, the effective spacing between traffic sensors with both volume and speed was nearly 1 mile in either direction. Furthermore, there are several segments where the distance between useful sensors is several miles (i.e., between mile points 10.55 and 13.06 in the southbound direction, between mile points 14.27 and 12.05 in the northbound direction). The large spacing of sensors severely limited the accuracy of the estimates of queue length and duration that could be made.

Table 22. Comparison of Queue Measures, I-405 Seattle

Queue Measure	Southbound		Northbound	
	Based on Field Crew Data	Based on Traffic Sensor Data	Based on Field Crew Data	Based on Traffic Sensor Data
Days of work activity when queuing occurred	81.4%	34.9%	82.9%	59.0%
Amount of work activity time when queue > 1 mi	17.1%	1.2%	21.3%	4.7%
Amount of work activity time when queue > 2 mi	11.8%	0.0%	12.6%	1.9%
Amount of traffic volume through active work zone that encounters a queue	19.0%	4.3%	13.6%	9.2%

The effect of the longer distances between usable speed sensors is evident in the other measures as well. Figure 11 illustrates that both queue durations and maximum queue lengths in both directions were shorter based on available traffic sensor data than what the field personnel documented on their data collection forms. Similarly, the percentage of work activity time when queues reportedly exceeded the 1-mile and 2-mile thresholds was much lower for the traffic sensor data than what the field crews reported, as was the amount of traffic estimated to have encountered a queue when traveling through the nightly work zones during the evaluation period.

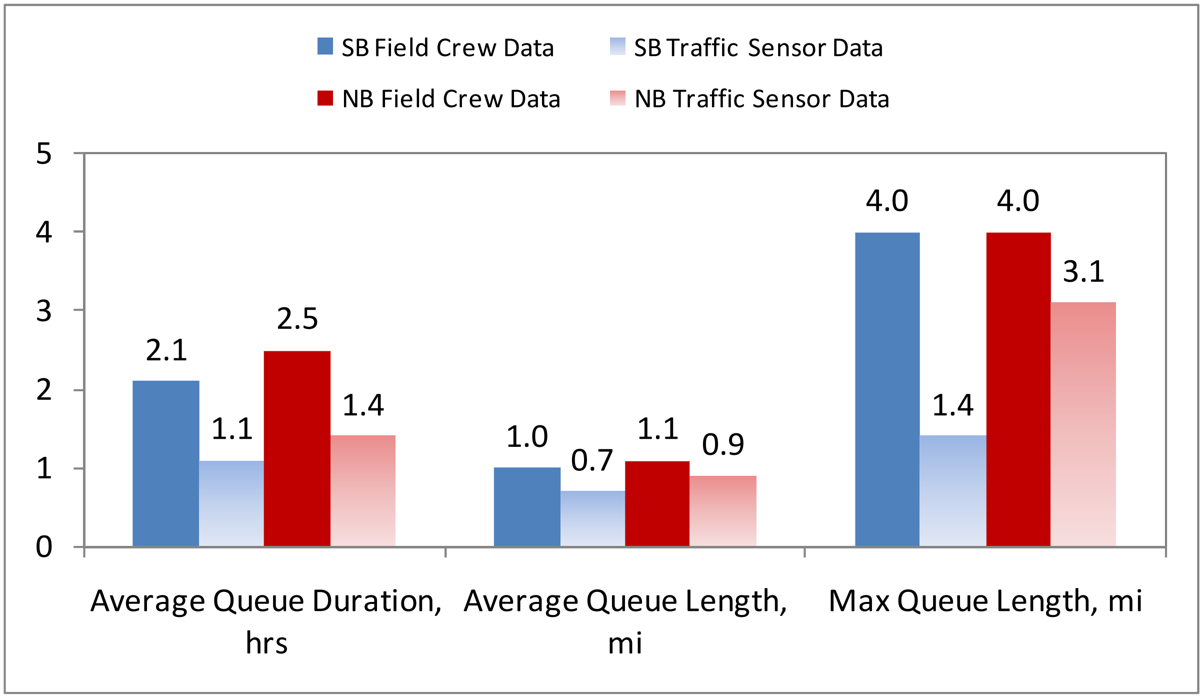


Figure 11. Comparison of Queue Length Measures, I-405 Seattle.

Floating-vehicle travel time studies were performed during September 2-4, 2008 in order to provide a means of comparing the two data collection approaches to a "ground-truth" measure of queues and delays. During that week, the field crews reported small queues on September 2nd and 3rd in the southbound direction, and on all three nights in the northbound direction. Using the available traffic sensor data, however, queues were detected only on September 2nd in both the southbound and northbound directions. Table 23 summarizes the comparison between field crew, traffic sensor and ground-truth queue measures. Overall, the field crews were better able at identifying when queuing conditions developed each night (as would be expected). In terms of queue lengths and duration, the two data sources appeared to be equally accurate compared to the ground-truth travel time data. Although field personnel were not interviewed as part of this testing process, it is likely that there was some degree of approximation occurring in terms of queue lengths, which could explain some of the deviations from the ground-truth values.

Table 23. Comparison of Queue Conditions During Travel Time Studies, I-405 Seattle

	September 2, 2008			September 3, 2008			September 4, 2008		
	Based on Field Crew Data	Based on Traffic Sensor Data	Measured via TT Studies	Based on Field Crew Data	Based on Traffic Sensor Data	Measured via TT Studies	Based on Field Crew Data	Based on Traffic Sensor Data	Measured via TT Studies
Southbound:									
Queue Duration (Hrs)	1.0	0.3	0.5	1.0	0.0	0.5	1.0	0.0	1.0
Max. Queue Length (Mi)	0.3	0.5	1.1	0.5	0.0	0.9	0.3	0.0	1.5
Northbound:									
Queue Duration (Hrs)	1.0	0.3	0.5	1.0	0.0	0.0	0.0	0.0	0.0
Max. Queue Length (Mi)	0.3	0.4	0.5	0.5	0.0	0.0	0.0	0.0	0.0

TT= travel time

The very limited amount of truck transponder data that could be obtained for this site did not allow for a comprehensive comparison to either field-reported or traffic sensor data estimates of queues. Field personnel did report small queues developing each of the four nights (in both directions) for which transponder data were available, but the transponder data was such that slower speeds (15 mph) were detected on only two of the nights, and there was only a single speed observation during each night. These single observations occurred in the northbound direction, and were actually several miles away from the reported location of the work activity. Furthermore, it is not certain that the field personnel and truck transponder frames of reference used the same mile marker system. Ultimately, it would not have been possible to estimate traffic impacts of the work activity based on the limited transponder data.

Delay Measures

The limitations of the effectiveness and accuracy of the traffic sensor data subsequently extended from queue duration and length estimates into delay computations. Table 24 provides a comparison of the delays computed using the field personnel estimates of queuing and the computational procedures for estimating delays based on queue lengths to delay estimates computed from the available traffic sensor data. In general, the total vehicle-hours of delay computed using the project field crew measurements are more than twice those estimated using the available traffic sensor data, even if it was assumed that the queues reported by the field personnel occurred within the work zone rather than upstream (i.e., a speed in queue of 30 mph was used rather than a much lower speed in queue that would have been computed using equation 1). Considering the queues as existing upstream of the lane closure points would have pushed the delay estimates to the upper values shown in the table.

Since field personnel were not asked to note where relative to the temporary lane closures the queues occurred each night, a wide range of potential delay impacts could have occurred at this site during the evaluation period. In Table 24, average delays through a queue may have been as small as 6 minutes per vehicle or as high as 22 minutes per vehicle, depending on the speeds that existed within the reported queues. Table 25 summaries the travel time "ground truth" speed and delay study results from the September 2008 data collection trip, and compares them to the estimates of speed and delays computed for those same days via field personnel documentation and the traffic sensor data.

Table 24. Comparison of Delay Measures, I-405 Seattle

Delay Measure	Southbound		Northbound	
	Based on Field Crew Data[a]	Based on Traffic Sensor Data	Based on Field Crew Data[a]	Based on Traffic Sensor Data
Total delay during work activities	2,905-11,368 veh-hr	450 veh-hr	3,653-14,258 veh-hr	1,197 veh-hr
Delay per night of work	68-266 veh-hr	10 veh-hr	94-367 veh-hr	31 veh-hr
Delay per night of work when queues developed	83-325 veh-hrs	30 veh-hr	101-394 veh-hr	52 veh-hr
Average delay per entering vehicle during work\ activities	0.3-1.3 min/veh	0.1 min/veh	0.5-1.8 min/veh	0.2 min/veh
Average delay per queued vehicle during work activities	1.6-5.7 min/veh	1.0 min/veh	1.7-6.3 min/veh	1.3 min/veh
Maximum delay per queued vehicle during work activities	5.9-21.0 min/veh	2.1 min/veh	5.9-21.9 min/veh	4.6 min/veh

[a] The lower end of the range shown was computed assuming the queue was located within the work zone and moving at capacity flow speeds; the upper end was computed assuming the queue was located upstream from the lane closure taper and moving at the computed reduced speed in queue from equation 1.

Table 25. Comparison of Delays During Travel Time Studies, I-405 Seattle

	September 2, 2008			September 3, 2008			September 4, 2008		
	Based on Field Crew Data[a]	Based on Traffic Sensor Data	Measured via TT Studies	Based on Field Crew Data[a]	Based on Traffic Sensor Data	Measured via TT Studies	Based on Field Crew Data[a]	Estimated from Traffic Sensors	Measured via TT Studies
Southbound:									
Ave. Speed in Queue (Mph)	5.7-30	30	33	5.7-30	---	12	5.7-30	---	17
Ave. Delay per Vehicle (Min)	0.3	0.5	1.0	0.5	---	3.6	0.3	---	3.8
Northbound:									
Ave. Speed in Queue (Mph)	5.7-30	30	30	5.7-30	---	---	---	---	---
Ave. Delay per Vehicle (Min)	0.4	0.4	0.5	0.6	---	---	---	---	---

--- data not indicating presence of queue delay

[a] The lower end of the range shown was computed assuming the queue was located within the work zone and moving at capacity flow speeds; the upper end was computed assuming the queue was located upstream from the lane closure taper and moving at the computed reduced speed in queue from equation 1.

It is interesting to note the range of speeds in queue that was measured by the travel time studies. On September 2nd, the traffic queue was located almost entirely within the limits of the lane closure, and speeds in queue were very close to those expected to exist when traffic is operating at near capacity flow conditions (i.e., 30-35 mph). However, on the other two nights, the queues tended to develop near the lane closure taper and extend upstream, which led to average speeds in queue of between 12 and 17 mph. Once again, knowing whether any queue that develops is located within or upstream of the work zone lane closure can significantly improve the ability of an analyst in estimating the average speed in queue, and in turn the actual delays being experienced by the traveling public.

KEY FINDINGS FROM I-405 SEATTLE PILOT TEST

The feasibility of having field personnel document daily (nightly) work activity and queue durations and lengths that occur was again validated through this pilot test effort. It appears that the field personnel were quite accurate and meticulous in their documentation efforts; all instances of queues identified during the ground truth travel time studies were noted as queued conditions on the data collection forms.

A key limitation in the proposed data collection and analysis procedures was again identified relative to the use of field personnel documentation of queues. Specifically, it will be necessary for field crews to not only document the lengths and durations of any queues that develop, but also to assess whether the queue is located upstream of the work zone lane closure, or beyond it in the work activity area.

With regard to the use of electronic traffic sensor data for work zone mobility monitoring and performance measure development, a significant amount of effort was required in this pilot test to extract and use data files, only to find out that the files themselves were incomplete or provided only volume counts. The effectiveness of a spot sensor system to reasonably estimate both queues as well as delays due to work zone activity hinges on the availability of speed data at each sensor location. System configurations that provide only occasional sensors with speed data collection capabilities will provide less accurate estimates of work zone mobility impacts. The lack of speed data may be a design constraint, in which case the agency is somewhat limited in its options. However, the lack of data may also be a result of construction activities themselves, which the agency may be able to mitigate to some degree. There were several nights in the evaluation period where certain sensors appeared to "quit functioning" for a period of time in the vicinity where the field personnel documented some work activity occurring. It is likely that the work activities themselves may have disrupted power or communications to and from the sensor to render it unusable during the work activity. Developing and implementing methods of counteracting these type of temporary data losses due to work activities would significantly improve the potential for using traffic sensor data in computing work zone performance measures.

It was hoped that the review of truck transponder data would have provided additional insights into the potential use of this data for work zone traffic mobility monitoring efforts. Unfortunately, even though I-405 is a very high-volume facility, the amount of truck traffic that uses the facility (and is equipped with transponder technology) appears to be fairly small. This is most likely especially true at night once regular commuting traffic has decreased to the point where uncongested speeds (i.e., 55 mph or more) can be maintained on the main north-south freeway through Seattle (I-5). Once again, the usefulness of truck transponder data depends upon having an adequate sample size available, which was not the case here for the I-405 project.

8. PILOT TEST #3: I-95, PHILADELPHIA, PA

DESCRIPTION

A third pilot test location selected for study was an approximate 8-mile segment of I-95 in southern Philadelphia, PA, extending from Broad Street on the south to East Allegheny Avenue on the north. This section of I-95 consists of three to four lanes per direction, with occasional lane additions and drops around the major interchanges with I-676 and I-76. Traffic volumes on this section of roadway in 2008 ranged from 90,000 to 150,000 vpd. The posted speed limit is between 55 and 60 mph.

Between August 18 and October 31, 2008, a highway contractor performed the following roadway repairs at various locations within this segment:

- Concrete deck repairs on selected bridges
- Asphalt milling
- Asphalt overlay paving
- Pavement patching and sealing
- Construction of an expansion dam at one of the bridges

Work activities were limited to between the hours of 9 pm and 5 am Monday through Friday. Over this time period, a total of 13 nights of work activity occurred in the northbound direction of travel, and 28 nights of activity in the southbound direction. On each night, the contractor usually closed two travel lanes at a location. There were instances, however, when three or more lanes were closed and traffic was narrowed down to a single lane of travel in that particular direction. On two nights, the contractor closed lanes in both directions of travel. The remaining nights involved lane closures in either one direction or the other.

DATA SOURCES

The Pennsylvania Department of Transportation (PennDOT) Philadelphia district office agreed to have its field personnel provide data collection support over the duration of the pilot test. The data collection form that requests work activity, lane closure information (location, duration, number of lanes closed and open), and approximate hourly queue length data were filled out by these personnel on most nights that work activity occurred. These lane closure and queue length data were then used to estimate work zone exposure measures, as well as average individual vehicle delay and total vehicle-hours of delay during congestion (using the previously described manual computation procedures and hourly traffic volumes).

In addition to the field personnel manual data collection efforts, data from a series of roadside-mounted non-intrusive traffic sensors located throughout the corridor were accessed to provide spot sensor data for analysis purposes. At some locations, sensors counted traffic in both travel directions; at other locations, only one direction of travel was being collected. In addition, there were some issues with some of the sensors on certain nights of work activity. As a result, data were not always available at all sensor locations on all nights of interest in the evaluation period.

Table 26 and Table 27 provide a summary of the location of sensors in this roadway segment in each travel direction. The effective spacing between successive sensors during this pilot test ranged from about 0.3 miles to 2.8 miles. Unfortunately, several nights of work activity occurred where sensor spacing was fairly large, which limited the sensitivity of the sensor data to detect and assess work zone impacts upon travel mobility. Although each sensor, when operational, could provide lane-by-lane volumes and speeds, these lane data were summed and averaged to yield overall sensor station measures for use in this pilot test analysis.

Floating vehicle travel time studies were conducted on three nights in early September 2008 to provide a ground-truth comparison of the field personnel and traffic sensor data sources. In addition, truck transponder data was obtained for those nights when work activity was occurring. Researchers were able to obtain truck data over 20 miles (10 miles per direction) on four consecutive nights in August 2008 when work activity and temporary lane closures were in place. Table 28 summarizes the amount of truck speed data that were obtained. Overall, the sample is very low, averaging 0.2 speed measurements per mile per hour. No observations were recorded in most mile segments during most hours of the work periods (82 percent of the mile-segment-hours had no observations). The maximum amount of data that was obtained for any mile segment during any hour of analysis was 5 observations.

Table 26. Spot Sensor Locations Northbound, I-95 Philadelphia

Sensor Location	Milepoint	Distance from Upstream Sensor
Island Ave	12.7	---
Enterprise Ave	14.5	1.8
Broad St	16.6	2.1
between S. Darren and S. 11th	17.9	1.3
Walt Whitman Bridge	18.5	0.6
S of I-676/I-95	20.8	2.3
between Frankford and Girard	22.8	2.0
S of Betsy Ross Bridge	25.4	2.6
Lefevre St	26.3	0.9

Table 27. Spot Sensor Locations Southbound, I-95 Philadelphia

Sensor Location	Milepoint	Distance from Upstream Sensor
Lefevre St	26.3	---
S of Betsy Ross Bridge	25.4	0.9
between Frankford and Girard	22.8	2.6
N of I-676/I-95	21.3	1.5
Walt Whitman Bridge	18.5	2.8
Pattison Ave	17.9	0.6
between S. Darren and S. 11th	17.6	0.3
Broad St	16.7	0.9
Enterprise Ave.	14.5	2.3
Island Ave	13.3	1.2

Table 28. Truck Transponder Sample Size, I-95, Philadelphia

Date	Hours of Closure Examined	Length of Section Examined[a]	Truck Transponder Observations	Observations per Mile per Hour	
				Average	Maximum
Aug. 18, 2008	9 hr	20 mi	28	0.2	2
Aug. 19, 2008	9 hr	20 mi	47	0.3	5
Aug. 20, 2008	9 hr	20 mi	41	0.2	2
Aug. 21, 2008	9 hr	20 mi	46	0.3	3
4-Day Average	9 hr	20 mi	40.5	0.2	5

[a] 10 miles in each direction

RESULTS

Exposure Measures

As shown in Figure 12, the field crew documentation tables indicated that work actually occurred on slightly more than 40 percent of the nights during the evaluation period. Considering only Sunday through Thursday nights when the contractor was actually allowed to be on I-95 and close lanes, work activity occurred on slightly more than 55 percent of the allowable nights. Inclement weather did likely cause the contractor not to work on some of the nights; these were not identified as part of pilot test (but would need to be if an agency were relying on such a measure to gauge the actual level of contractor effort on a project). In addition, the Philadelphia Phillies major league baseball team participated in post-season play in the fall of 2008. It is possible that the contractor was restricted from working on nights when the team was in town at the nearby ballpark.

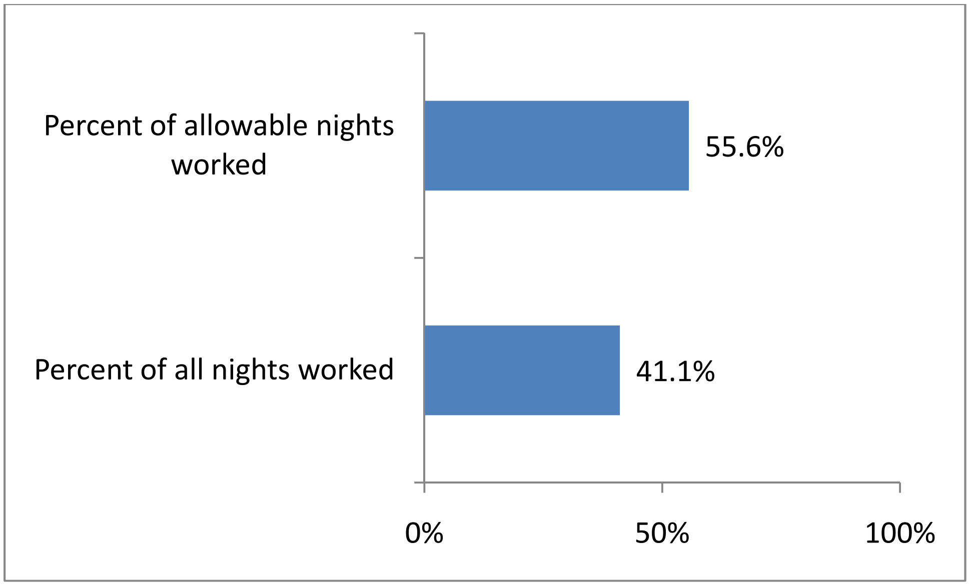


Figure 12. Work Exposure Measures, I-95 Philadelphia.

Table 29 summarizes the hours of work activity reported on the field crew data collection forms. Over a total of 30 nights of activity in the pilot test evaluation period, the contractor performed 252 hours of work, averaging approximately 8.4 hours per work shift.

Table 29. Hours of Work Activity, I-95 Philadelphia

Work Exposure Measure	Value
Total hours of work activity during project	252
Average # hours of work per day	8.4

The next facet of exposure data gathered and computed for the Pennsylvania project were the roadway capacity losses. These are provided in Table 30. Overall, the majority of lane closure time involved the closure of two out of four available lanes. The maximum number of lanes present within the limits of the work zone each night was used as the baseline, rather than attempting to characterize each auxiliary lane or lane drop segment separately. Over the 30 nights of work in the evaluation period, a total of 1,980 lane-mile-hours of roadway capacity loss were required for the project. This equates to an average of 2.9 miles of lane closure each night of work activity.

Table 30. Roadway Capacity Loss Measures, I-95 Philadelphia

Capacity Loss Exposure Measure	Value
Percent of work hours involving:	
1 of 4 lanes closed in a given direction	2.6%
2 of 4 lanes closed in a given direction	93.8%
3 of 4 lanes closed in a given direction	3.6%
Percent of inactive hours involving lane closures	0%
Lane-Mile-Hours of closures in evaluation period	1,980
Average lane closure length per work activity period	2.9 miles

The vehicular exposure to the work zone lane closures during the evaluation period are provided in Table 31. Slightly less than 500,000 vehicles passed through the nighttime temporary lane closures during the evaluation period. Overall, this corresponds to about 6 percent of the total amount of traffic that utilized this section of I-95 during the evaluation period. Meanwhile, nearly 1.5 million vehicle miles of travel occurred through the temporary lane closures over the duration of the evaluation period of this project.

Table 31. Vehicle Exposure Measures, I-95 Philadelphia

Capacity Loss Exposure Measure	Value
Number of vehicles passing through active lane closures in evaluation period	493,000
Percent of total traffic in evaluation period encountering work activity and lane closures	6.2%
Total vehicle-miles-traveled past active work zone lane closures in evaluation period	1,430,000 veh-mi

Queuing Measures

Figure 13 and Table 32 both summarize queue measure characteristics at this site as documented by field personnel on the data collection form, and through analysis of available traffic sensor data from the regional TMC. Because work activity typically occurred simultaneously in both directions of travel each night, separate analyses were performed for each direction. The restriction of temporary lane closures to nighttime hours no doubt did reduce the frequency and severity of queues and congestion that might have otherwise developed. As noted in Table 32, field crews still reported the creation of queues on 77 percent of the nights when a lane closure was implemented in the northbound direction, and on 100 percent of the nights with a lane closure in the southbound direction. For this pilot test location, the traffic sensor data at this site tracked fairly closely to the field crew data for these particular performance measures.

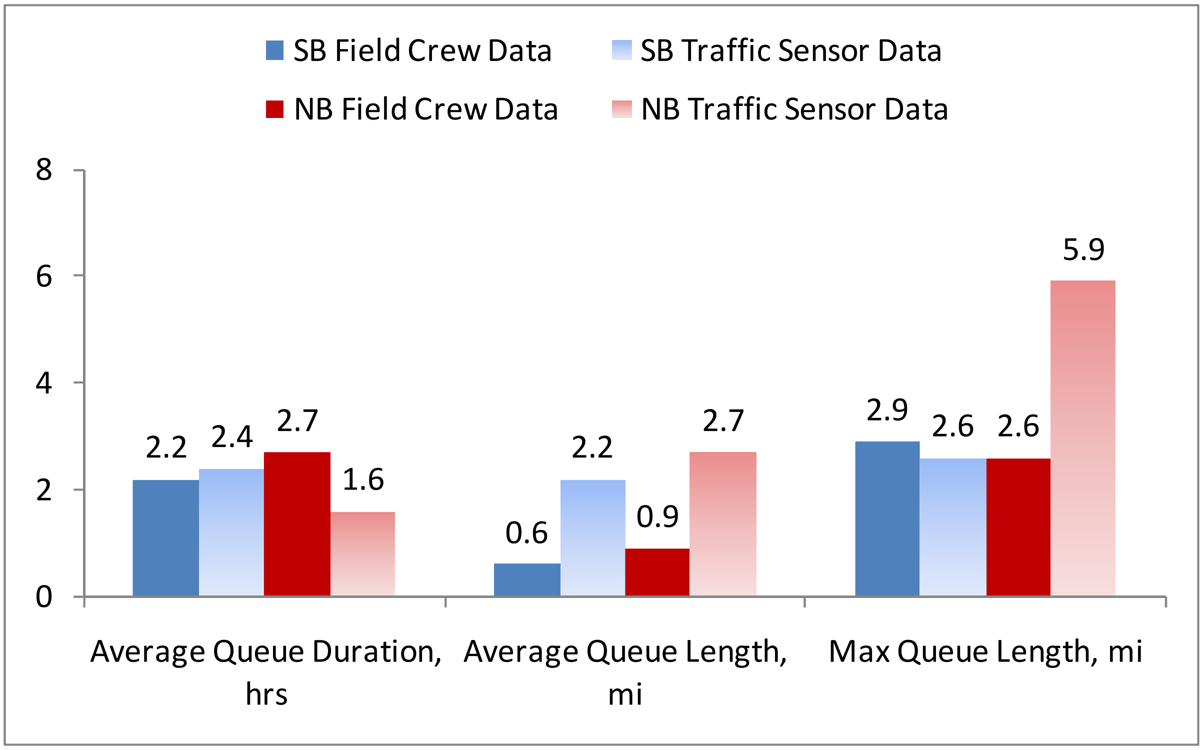


Figure 13. Comparison of Queue Length Measures, I-95 Philadelphia.

As Table 32 also illustrates, analyses of the traffic sensor data from this site found evidence of queuing on 78 percent of the nights of work activity and lane closures in the northbound direction, and 73 percent of the nights in the southbound direction. Even though the distance between sensors was quite large in some locations in the study section, the sensors happened to be in good locations on most nights to detect the development and duration of queues. The traffic sensor data did not align quite as well with the field crew data when it came to queue lengths (as shown in Figure 13), or the amount of time that the queues exceeded the 1-mile and 2-mile thresholds.

Table 32. Comparison of Queue Measures, I-95 Philadelphia

Queue Measure	Southbound		Northbound	
	Based on Field Crew Data	Based on Traffic Sensor Data	Based on Field Crew Data	Based on Traffic Sensor Data
Days of work activity when queuing occurred	100.0%	72.7%	76.9%	77.8%
Amount of work activity time when queue > 1 mi	5.5%	14.5%	14.7%	20.0%
Amount of work activity time when queue > 2 mi	0.2%	14.8%	3.2%	20.0%
Amount of traffic volume through active work zone that encounters a queue	53.8%	35.2%	52.6%	51.6%

Floating-vehicle travel time studies were performed during September 8-12, 2008 in order to provide a means of comparing the two data collection approaches to a "ground-truth" measure of queues and delays. No slowdowns or queues were detected on one night of data collection and the contractor was rained out on two other nights, so only two nights of work activity could be compared. For some reason, the lane closures that week were actually not documented in the field data collection forms, even though there were nights in which the lane closures apparently resulted in small queues at the sites. Therefore, Table 33 summarizes the comparison between traffic sensor and ground-truth queue measures from the travel time studies. The traffic sensor data was relatively accurate in identifying the duration of queuing that occurred on both nights, but tended to estimated longer maximum queues.

Table 33. Comparison of Queue Conditions During Travel Time Studies, I-95 Philadelphia

	September 8, 2008 Southbound		September 10, 2008 Southbound	
	Based on Traffic Sensor Data	Measured via TT Studies	Based on Traffic Sensor Data	Measured via TT Studies
Queue Duration (Hrs)	2.3	2.0	1.5	1.5
Maximum Queue Length (Mi)	2.1	0.4	2.1	0.9

TT= travel time

Once again, the small sample size of truck transponder data did not allow for a comprehensive comparison to field personnel or traffic sensor data. A lack of speeds in successive mile segments during the same or successive hours of work activity limited the analysis to simply identifying individual speeds that were below what was considered to be uncongested. Those speeds were then assumed to be indicative of the presence of a traffic queue in the mile segment in which they occurred during that one-hour period. Unfortunately, even that simplistic assumption did not appear to correlate well with the other data sources. For example, Table 34 identifies those mile point segments and hours each night where truck transponder speeds were below 35 mph, and compares those hours and mile points to queues reported by the field personnel on the data collection forms. On two nights, lower truck speeds did correspond to periods of work activity when field personnel reported queuing occurring in the vicinity of the lane closure. On the remaining nights, field personnel did not report any queues, even though a few very slow truck speeds were recorded. Therefore, it is difficult to know with any certainty whether the truck speeds were indicative of work zone impacts, or the result of other behaviors by the truck drivers such as pulling off the roadway to refuel or to get some sleep.

Table 34. Truck Transponder Queue Indicators, I-95, Philadelphia

Date and Direction	Time	Location	Speed, mph (# in sample)	Queue Documented by Field Crew?
August 19 (Southbound)	3 am	MP 13	22 (1)	No
August 20 (Southbound)	11 pm	MP 4	3 (1)	Yes
August 21 (Northbound)	9 pm	MP 9	12.7 (3)	Yes
August 21 (Southbound)	9 pm	MP 7	5 (1)	No[a]
August 22 (Northbound)	12 am 1 am 2 am	MP 8 MP 10 MP 9	2 (1) 4 (1) 8 (1)	No[b]
August 22 (Southbound)	1 am 2 am	MP 7,8 MP 7,8	3.5 (2) 21.5 (2)	No[b]

[a] Queue was reported, but not beginning until 10:30 pm

[b] Queue reportedly dissipated by midnight

Delay Measures

Table 35 presents a comparison of the delays computed using the field personnel estimates of queuing and the computational procedures for estimating delays based on queue lengths, to delay estimates computed from the available traffic sensor data. On one hand, the total vehicle-hours of delay computed using the project field crew measurements bracket the estimates derived from the traffic sensor data. On the other hand, this result is due mainly to the extremely large range of values documented in Table 35 for the delay computations based on the field crew estimates. As has been the case in each of the pilot tests discussed, a lack of information existed on whether the queue documented in the data collection form was located within the limits of the work zone (and thus operating at speeds closer to the speed of capacity flow on the facility) or was located at the lane closure taper and thus operating at a much lower stop-and-go speed over the length of the queue. The wide range in assumed operating speeds within the queue in turn led to highly different estimates of the individual motorist delay that is experienced, and thus much different computational results with respect to the total delays generated by the work activity during the evaluation period. Depending on which assumption is more correct, motorists who encounter a queue at the work zone may be delayed less than a minute, or as much as 30 minutes.

Table 35. Comparison of Delay Measures, I-95 Philadelphia

Delay Measure	Southbound		Northbound	
	Based on Field Crew Data[a]	Based on Traffic Sensor Data	Based on Field Crew Data[a]	Based on Traffic Sensor Data
Total delay during work activities	2,020-23,313 veh-hr	5,152 veh-hr	509-5,586 veh-hr	1,594 veh-hr
Delay per night of work	72-831 veh-hr	184 veh-hr	94-367 veh-hr	123 veh-hr
Delay per night of work when queues developed	72-831veh-hrs	253 veh-hr	101-394 veh-hr	158 veh-hr
Average delay per entering vehicle during work\ activities	0.3-3.8 min/veh	0.8 min/veh	0.2-2.6 min/veh	0.7 min/veh
Average delay per queued vehicle during work activities	0.6-7.1 min/veh	2.3 min/veh	0.4-4.9 min/veh	1.4 min/veh
Maximum delay per queued vehicle during work activities	2.9-29.8 min/veh	8.5 min/veh	2.7-26.3 min/veh	6.8 min/veh

[a] The lower end of the range shown was computed assuming the queue was located within the work zone and moving at capacity flow speeds; the upper end was computed assuming the queue was located upstream from the lane closure taper and moving at the computed reduced speed in queue from equation 1.

If these values are compared to those obtained from the traffic sensor data, one would conclude that the queues tended to be located within the work zone and operating at speeds approaching capacity flow speeds, and not the extremely low stop-and-go speeds that characterize queues located at the beginning of lane closure tapers. However, examination of speeds determined through the ground truth travel time studies suggests that the traffic sensors yielded speeds that were higher than those actually occurring in the queues at this site, and so tended to underestimate the delays being created for motorists encountering a queue (Table 36). As noted previously, the limited amount of truck transponder data did not allow for an assessment of delay that could be compared to these other sources of data.

Table 36. Comparison of Delay Conditions During Travel Time Studies, I-95 Philadelphia

	September 8, 2008 Southbound		September 10, 2008 Southbound	
	Based on Traffic Sensor Data	Measured via TT Studies	Based on Traffic Sensor Data	Measured via TT Studies
Average Speed in Queue (Mph)	20	7	27	12
Average Delay per Vehicle (Min)	4.1	5.2	2.3	4.1

KEY FINDINGS FROM I-95 PHILADELPHIAPILOT TEST

Overall, the experiences from this pilot test mimic those of the other two pilot tests already described. Field personnel did appear to do a reasonably accurate job of documenting work activity and queue data, when such data were recorded. Unfortunately, it is less clear from this pilot test the degree to which queues were indeed recorded over the evaluation period. The fact that multiple nights of lane closure activity and queuing occurred when data collection personnel were at the site to collect ground truth queue and travel time data but were not recorded on the field crew data collection forms does raise questions about how many other nights were missed.

9. PILOT TESTS #4 AND #5: I-15, LAS VEGAS, NV

DESCRIPTION

The fourth and fifth pilot test locations were located on Interstate 15 in Las Vegas, NV. The southern project (5.7 miles long) extended from I-215 on the south to Sahara Avenue on the north (Figure 14). The northern project extended from the I-15/US-93/US-95 interchange (the "Spaghetti Bowl" [SB] interchange) north to Craig Road (Figure 15). South of the SB interchange, the freeway was four lanes wide per direction, which dropped to three lanes per direction north of the interchange. Continued growth in the corridor and to the north created recurrent congestion in both project sections. South of the SB interchange, recurrent congestion northbound occurred in afternoon and early evening hours between Tropicana Avenue and Sahara Avenue (Figure 14), and occasionally in the SB interchange northward. Congestion also developed southbound in the morning approaching the SB interchange from the north, and occasionally approaching Flamingo Road. Traffic volumes throughout this section of I-15 were approximately 170,000 vpd. The posted speed limit in the work zones is 55 mph, reduced from the normal 65 mph speed limit on the facility.

In the south project, the Nevada DOT (NDOT) is constructing an express lane in both directions within the existing highway median as a way to mitigate the recurrent congestion problem in this section. The project began on September 15, 2008 and was targeted for completion in September 2009. In the initial phases of the project, it was necessary to close the right lane of traffic in several sections to accommodate construction activities. Table 37 summarizes the dates and locations of these closures. Unlike the other pilot test locations, these were long-term lane closures that remained in place at all times until the work was completed. Acceleration and deceleration lanes for entrance and exit ramps within the section had to be closed as well (i.e., ramp traffic was funneled directly into mainline traffic). According to NDOT officials, this traffic control created difficulties for motorists at the merge points and was believed to have increased the duration and extent of congestion and queues that occurred. In early December 2008, the contractor switched the long-term lane closures to the median of I-15. Although the total number of lanes remained the same through the section (3 per direction) as in the earlier phase, the elimination of merge point conflicts with entering traffic significantly reduced traffic crashes occurring regularly in that section (according to NDOT officials). It also appeared that this modification allowed traffic to flow more smoothly into and through the work zone, and may have reduced to some degree the length and duration of queues that developed.

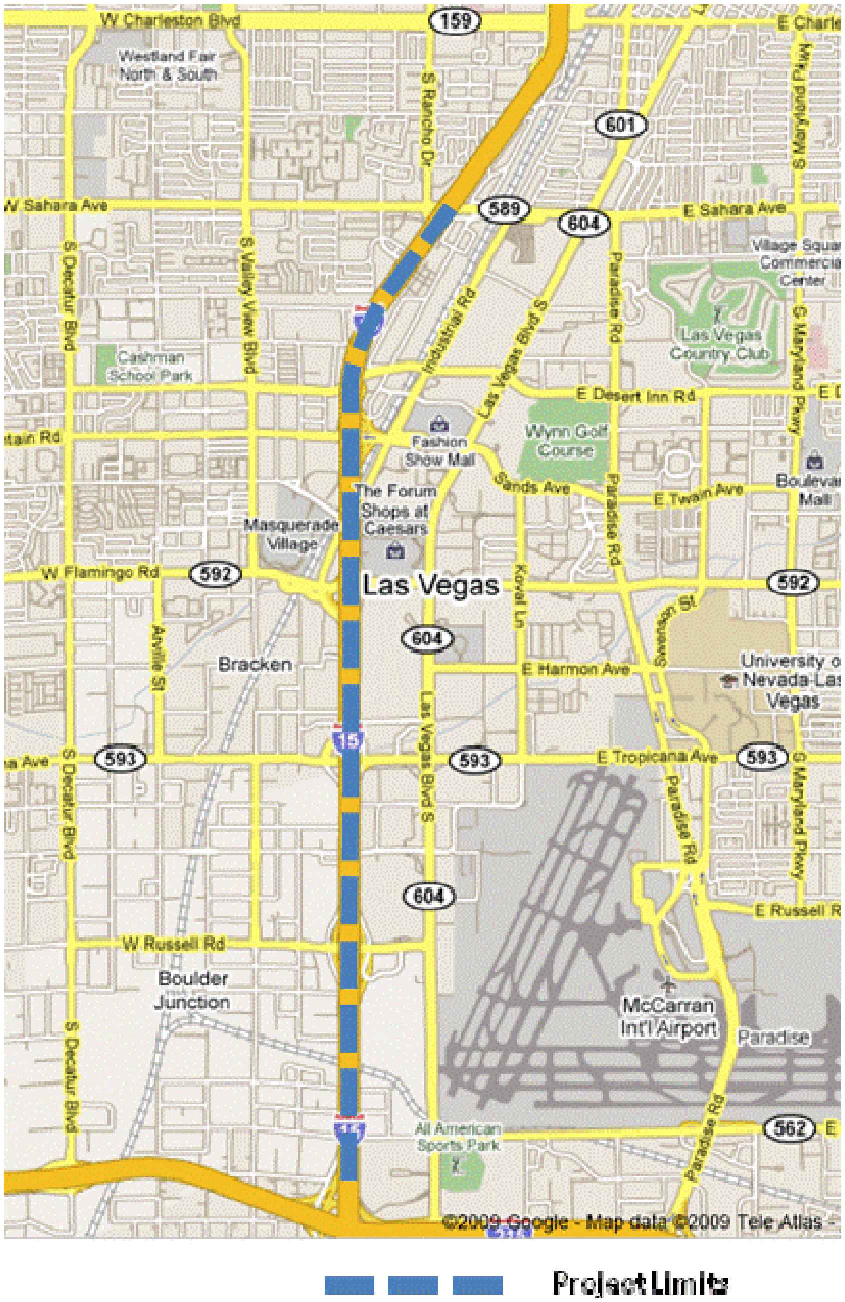


Figure 14. I-15 Express Lanes Widening (South) Project.

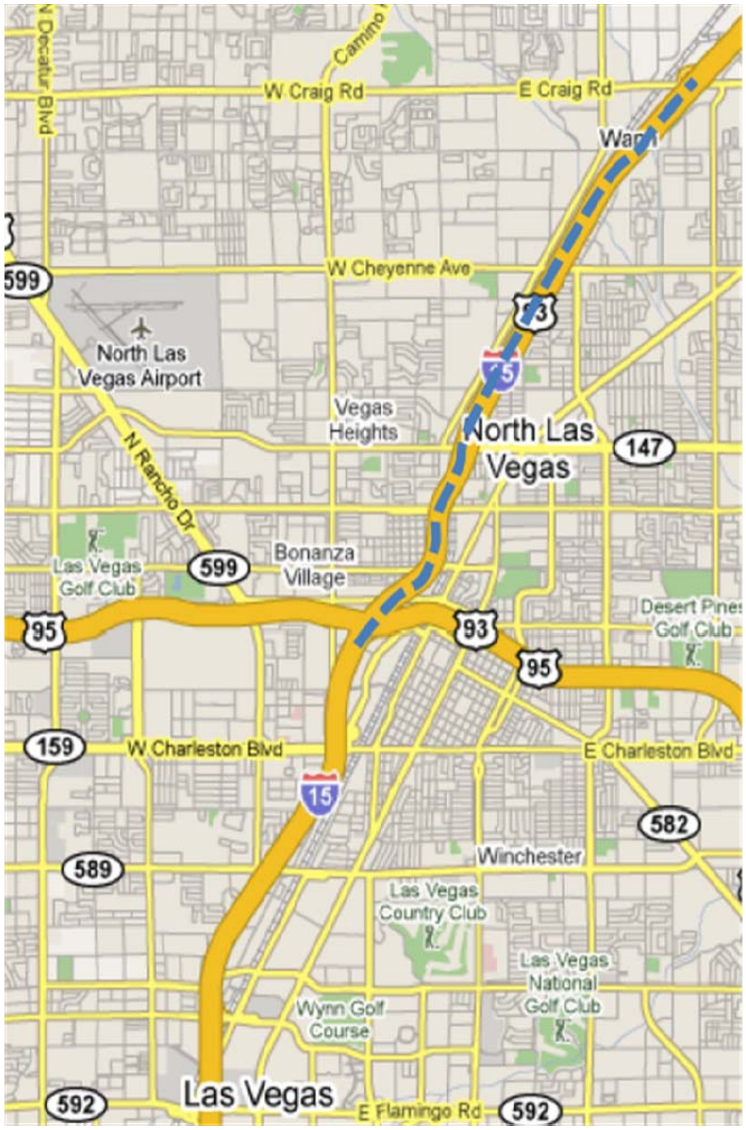


Figure 15. I-15 Interchange and Freeway Widening (North) Project.

Table 37. Location and Dates of Long-Term Lane Closures in South Project Limits

Location of Long-Term Lane Closures	Dates
Northbound Right Lane:	
Russell	September 15 – November 11, 2008
Tropicana	September 22 – November 14, 2008
Flamingo	September 23 – November 18, 2008
Northbound Median Lane:	
Russell to Sahara	December 1, 2008 – February 29, 2009[a]
Southbound Right Lane:	
Flamingo	October 6, 2008 – January 22, 2009
Tropicana	October 20, 2008 – December 4, 2009
Russell	November 13, 2008 – January 23. 2009
Southbound Median Lane:	
Russell to Sahara	December 1, 2008 – February 29, 2009[a]

[a] End of pilot test evaluation period; lane closure extended beyond this date.

The north project was a much larger design-build effort that will ultimately widen the freeway to five lanes per direction. This project began in September 2007 with a target completion date of Fall 2010. Because it was a design-build effort, much of the early effort on the project was design work, and so the actual work zone did not begin until January 2008. During the early portion of the project, no traffic lane restrictions (other than temporary nighttime lane closures) were used. However, in late spring 2008, the contractor requested that one lane in each direction be allowed to be closed long-term between the SB interchange and Lake Mead Boulevard in order to accelerate the rate of construction. The request was approved, and the lanes were closed on July 14, 2008. This meant that, for a distance north of the SB interchange, I-15 consisted of two lanes per direction.

DATA SOURCES AND ANALYSES

The fact that these pilot test sites involved long-term lane closures in a roadway section that was regularly experiencing recurrent congestion complicated the computation of work zone mobility-related performance measures. Specifically, the presence of delays and queues on a particular day during the evaluation period could not be assumed to be solely the result of the work zones (an assumption that could be made in the previous three pilot test locations already discussed). Instead, it was necessary to compare conditions prior to construction to those occurring during construction, with the differences then assumed to be due to the projects. Obviously, this requires that traffic data be available prior to the start of construction of a project. Fortunately, the Las Vegas Freeway and Arterial System of Transportation (FAST) regional TMC had traffic sensors installed since 2007 on a portion of I-15 between I-215 on the south and the SB interchange on the north. On average, traffic sensors are located at approximate 0.3 mile intervals in both directions of travel on I-15 in this area. Although data were not available north of the SB interchange within the actual limits of the north project, its effect upon northbound traffic approaching the interchange could be measured using the FAST data.

Another factor complicating the analyses was the proximity of the two projects themselves. Approximately 2.3 miles separated the north end of the south project (Sahara Avenue) and the south end of the north project (the SB interchange). Prior to the implementation of the long-term lane closures, the pockets of congestion that developed on this facility were separate (between Flamingo Road and Sahara Avenue, and from the SB interchange north along I-15). However, once the closures were installed, queue spillback northbound from the north project occasionally extended upstream beyond Sahara Avenue.

Speed and volume data from the FAST center were obtained for the summer months of 2007 (May-August), and from September and October 2008. Meanwhile, travel times between I-215 and the SB interchange were obtained for the same summer months in 2007 and from September 2008 through February 2009. Although the volumes, speeds, and travel times all come from the same basic sensor data, FAST personnel indicate that the software and database structure makes extraction of the speed and volume data fairly labor-intensive, whereas the travel time data can be directly extracted from information posted on the dynamic message signs (DMS) mounted at strategic locations along the freeway. Consequently, it was much easier to access the travel time data, and so a larger time frame could be examined with those data.

Unfortunately, although detailed traffic sensor data were available before and during the projects, field-collected data regarding work activity and queuing patterns were not. The research team became aware of the projects after they had been initiated, and discussions with NDOT and regional FHWA officials indicated that it would not be feasible to get field personnel to complete the daily data collection forms as had been used in the previous pilot tests, and obtaining access to project diaries would be problematic as well. Project personnel did indicate that the contractors were at the projects "most" days, and could work on both weekdays and weekends. Given that the lane closures remained in place throughout the duration of the evaluation period and were the primary reasons for the increased congestion that developed, the lack of detailed work activity data was less important than at other pilot test locations. Work crews operated behind temporary concrete barrier at both projects, and so influences of work activity upon traffic flows were generally minimal, according to project personnel.

Truck transponder data were requested for the segment of I-15 between Blue Diamond Road to the south and East Craig Road to the north, a distance of approximately 15 miles, including five miles north of the US 93 interchange for which FAST traffic sensor data were not available. A five-day dataset were provided for this segment between January 12 and January 16, 2009. Speed data entries from the database were aggregated hour by hour across each one-mile segment in both directions of travel. Unlike the other pilot test locations, researchers requested data for all hours of the day, since these two pilot test locations both included long-term lane closures that could affect traffic operations throughout the day. As a result, a much larger sample was obtained (1600 + observations). Still, the data were random with pockets of multiple observations occurring within a given mile segment over several hours of the day, but with no observations in other mile segments. In fact, most mile segments did not have any observations in most hours of the day (92 percent of the mile-segment-hours had no observations available). Table 38 summarizes the characteristics of the available truck transponder dataset. Overall, the sporadic nature of these data did not allow for any type of comparison to the other data sources at these sites.

Finally, to assess the accuracy of the FAST data and the truck transponder data, researchers traveled to the project sites to collect travel time data during the week of February 9-13, 2009. Data were collected continuously in both directions of travel daily between 6 am and 7 pm.

RESULTS

Exposure Measures

As previously noted, specific data regarding actual days and hours of work activity were not available for these projects. However, some data were obtained from the south project regarding nights when temporary lane closures installed by the contractor to park a construction vehicle next to the work zone to load and unload materials. During those hours, there were then two lanes closed to traffic (the long-term lane closure plus the nighttime temporary lane closure). Functionally, these temporary lane closures were quite similar to the nighttime temporary lane closures in other pilot test locations previously discussed. Therefore, for comparison purposes, the percentage of calendar nights that involved these types of temporary lane closures was computed for this project, and is presented in Figure 16. One sees that an additional lane was closed on one-third of the nights in the evaluation period. Unfortunately, similar data were not available for the north project.

Table 39 presents the exposure measures pertaining to the loss of roadway lane capacity during the evaluation period at the two projects. For the south project, these values include the single lane closed long term in each direction at each location (each assumed to be approximately 1.5 miles for the various right lane closures and 4.0 miles when the median lane was closed), and an additional 1.5-mile (estimated) lane closure on those nights when a lane was temporarily closed. Assuming that the temporary nighttime lane closures typically lasted 9 hours per work shift as was the case in the previous pilot test locations, a second lane was temporarily closed 3.3 percent of the time during the evaluation period. For the north project, a single lane in each direction was closed for 1.8 of the 5.6 miles of the project during the entire evaluation period. One could argue that the nighttime lane closures at the south project could also be represented in terms of 1 of 3 lanes closed, since there was already a long-term lane closure in place. However, it is shown as the second of four lanes closed in the table.

Table 38. Truck Transponder Speed Sample Size, I-15, Las Vegas

Date	Northbound			Southbound		
	Truck Transponder Observations	Observations per Mile per Hour		Truck Transponder Observations	Observations per Mile per Hour	
		Average	Maximum		Average	Maximum
Jan. 12, 2009	175	0.5	26	123	0.3	19
Jan. 13, 2009	185	0.5	23	176	0.5	25
Jan. 14, 2009	244	0.7	28	168	0.5	25
Jan. 15, 2009	149	0.4	21	203	0.6	23
Jan. 16, 2009	129	0.3	17	134	0.4	14

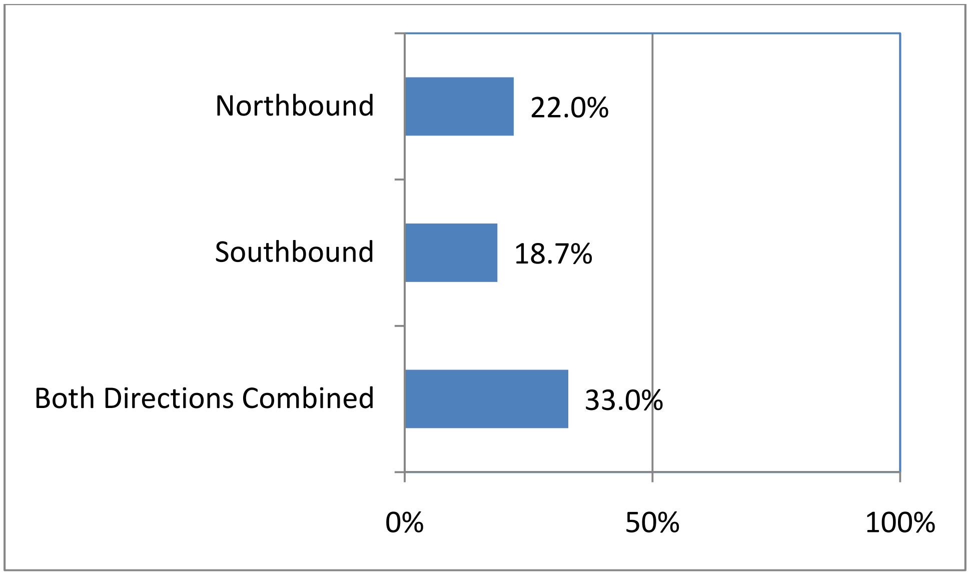


Figure 16. Percentage of Calendar Nights Involving Temporary Lane Closures at the South Project, I-15 Las Vegas.

Table 39. Roadway Capacity Loss Measures, I-15, Las Vegas

Capacity Loss Exposure Measure	South Project	North Project
Percent of evaluation period involving:		
1 of 4 lanes closed in a given direction	96.7%	
2 of 4 lanes closed in a given direction	3.3%	
1 of 3 lanes closed in a given direction		100%
Percent of inactive hours involving lane closures	100%	100%
Average lane-mile-hours of closures per month of evaluation	5,907	1,296
Average lane closure length during evaluation period	2.2 mi	1.8 mi

Since a lane was closed long term in each direction at both projects, all of the inactivity hours during the evaluation period involved a lane closure. In terms of amount of roadway space and time, the project resulted in slightly more than 5,900 lane-mile-hours of losses per month during the evaluation period at the south project, and 1,296 lane-mile-hours of losses per month at the north project. The multiple segments of long-term and nighttime temporary lane closures at the south project resulted in approximately 70 percent of the VMT through the project limits being exposed to lane closures (Table 40). In contrast, 32.1 percent of the VMT passing through the north project was adjacent to long-term lane closures.

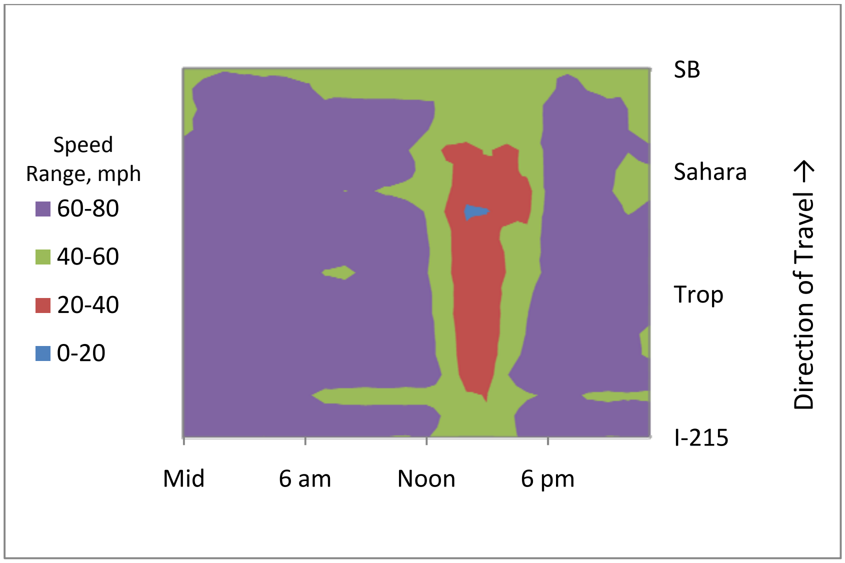
Table 40. Vehicle Exposure Measures, I-15, Las Vegas

Vehicle Exposure Measure	South Project	North Project
Number of vehicles encountering long-term lane closures per day during evaluation period	145,000	185,000[a]
Percent of vehicles in evaluation period encountering nighttime work activity and short-term lane closures	4.5%.	n/a
Total vehicle-miles-traveled through project limits per day	940,500	924,000
Percent of project VMT past long-term lane closures during evaluation period	70.3%	32.1%
Percent of project VMT past short-term nighttime lane closures during evaluation period	0.6%	n/a

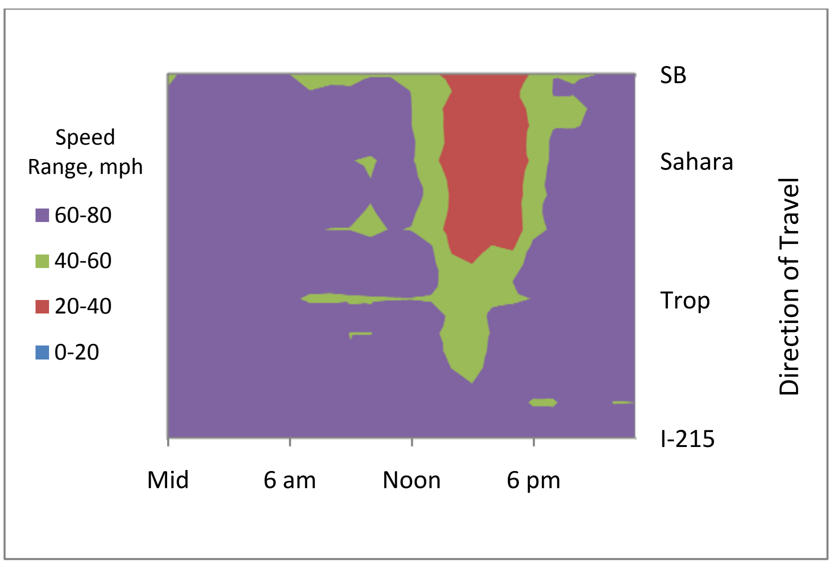
[a] Traffic volumes just south of the SB interchange. Volumes north of the interchange are unknown, but likely are significantly lower than this value.
n/a = data not available

Queuing Measures

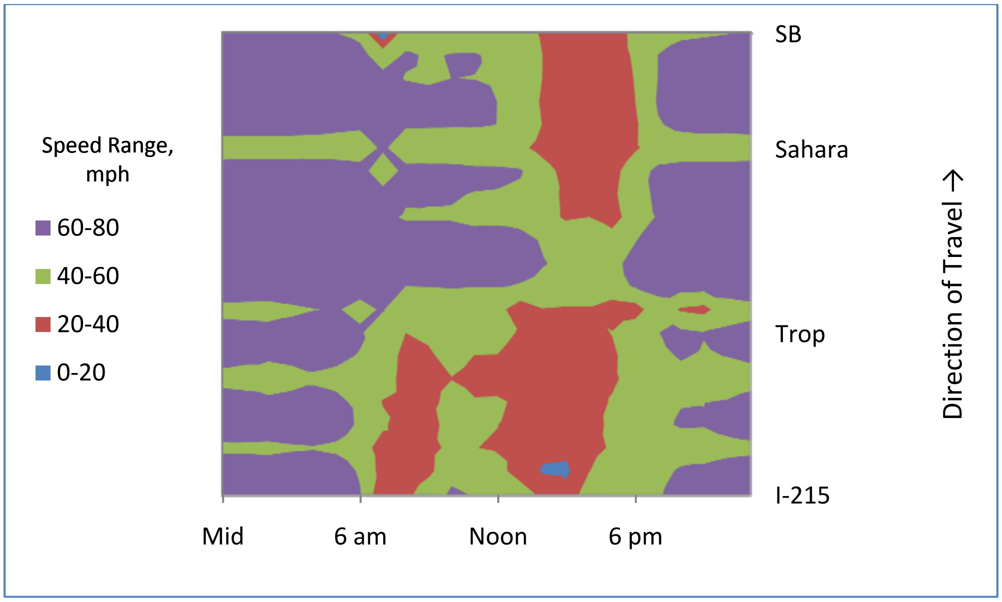
As noted previously, computation of queuing performance measures was more difficult for these projects than for the previous pilot test locations. Specifically, existing congestion patterns and the proximity of the two projects hampered efforts to isolate the effects of each project upon traffic mobility. This can be demonstrated visually through a series of contour plots of speeds over time along the I-15 corridor, as shown in Figure 17 for the northbound direction of travel. Average conditions in the summer of 2007 (when no long term lane closures were present at either project) are provided in part (a) of Figure 17. In part (b), the speeds on I-15 northbound in early September are shown, when the north project had its permanent lane closures in place but before the south project had begun. Finally, in part (c) of the figure, average speeds during the last part of September and all of October are presented, when both the north and the south projects had long-term lane closures in place. In the before condition, a clear congestion pattern is evident from about Sahara Avenue extending upstream, initiating slightly after noon each day until approximately 5 pm or so. Around 3 pm or so each day, this region of slower speeds extended from just north of the I-215 interchange (approximately Russell Boulevard) to Sahara Avenue. Farther north of Sahara, speeds were slightly lower (40 to 60 mph) than free-flow, but not congested.



(a) Speed contour map summer 2007 (before north and south project lane closures)



(b) Speed contour map in early September 2008 (north project lane closures only)

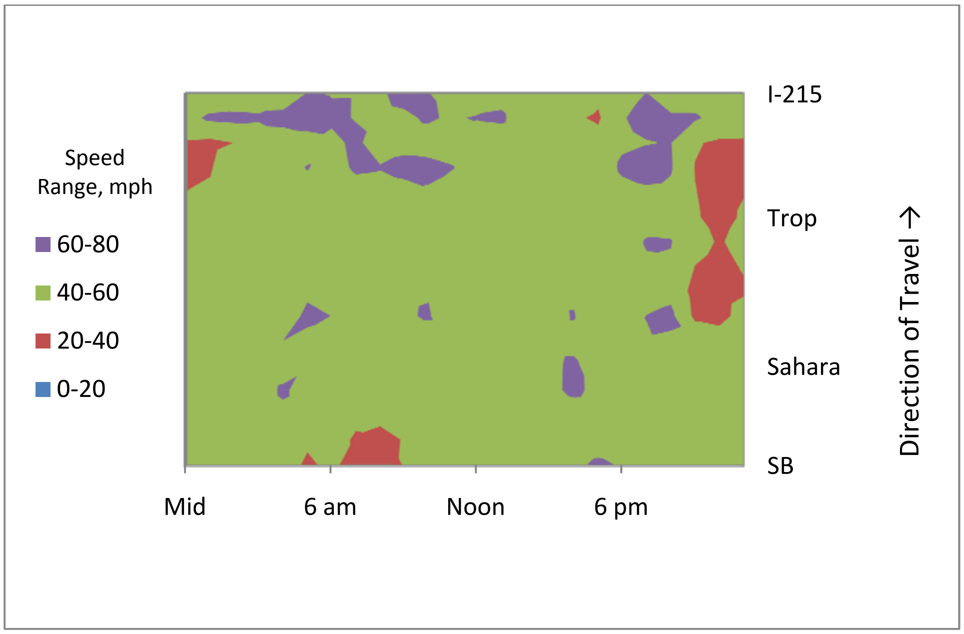


(c) Speed contour map in late September and October 2008 (north and south project lane closures)

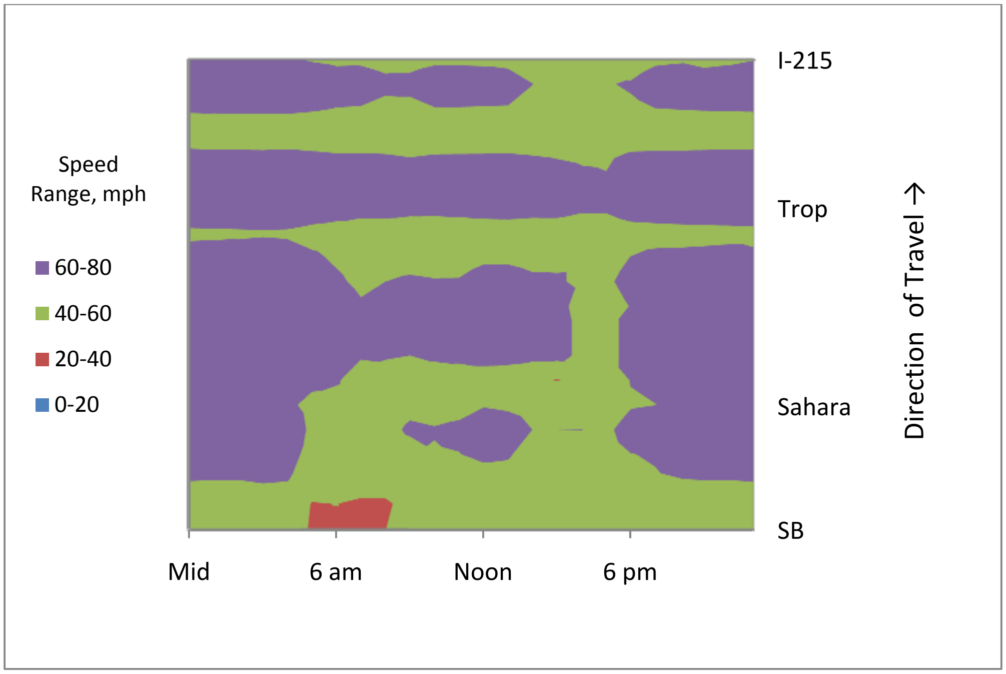
Figure 17. Changes in Average Speeds Northbound Before and During Evaluation Period, I-15 Las Vegas.

In contrast, the speed contour plot in early September demonstrates a clear development of congestion and queuing from the SB interchange. More importantly, this congestion extends beyond Sahara Avenue, which is the northern limit of the south project and is where congestion ended northbound back in 2007. Once the south project began in mid-September, one then sees a second region of slower speeds develop around Tropicana Avenue. The new region of queuing began in the AM peak and generally extended upstream into the I-215 interchange during the AM peak and again in the early afternoon hours. Unfortunately, sensors were not available farther upstream on I-15 to assess how much beyond the I-215 interchange congestion actually extended.

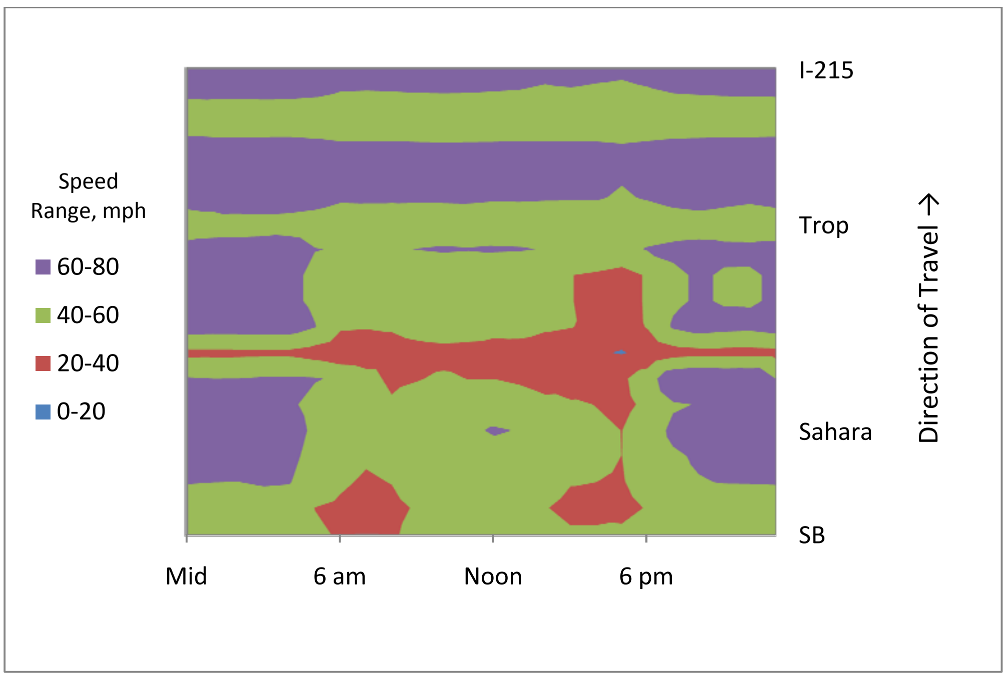
The interdependence between projects is less obvious for the southbound direction, since FAST data were only available south of the north project. Still, one sees different congestion patterns in each of the three conditions (before, north project lane closures only, both south and north project lane closures). In the before condition (Figure 18 (a)), a few hours of congestion are evident just downstream of the SB interchange in the AM peak, and in the late evening/early morning hours from around Flamingo Road to near the I-215 interchange. However, in September 2008 when only the north project lane closures are in place, the late evening congestion at Flamingo Road is no longer evident. Whether this change is due to the north project lane closures acting as a mainlane "meter," due to some diversion away from I-15 to local routes, or a general reduction in travel volumes as part of the economic recession that began in late 2007 cannot be determined strictly with these speed contour plots (although some additional insights can be gained by examining the traffic volume data as is done later in this chapter). However, in October 2008, the introduction of long-term lane closures southbound in the south project at Flamingo Road (Figure 18(c)) appears to result in a significant slowdown most of the daytime hours (instead of occurring at night as in the before condition). Also, this daytime congestion appears to merge with a slowdown past the SB interchange around 5 pm each weekday.



(a) Speed contour map before



(b) Speed countour map in early September 2008 (north project lane closures only)

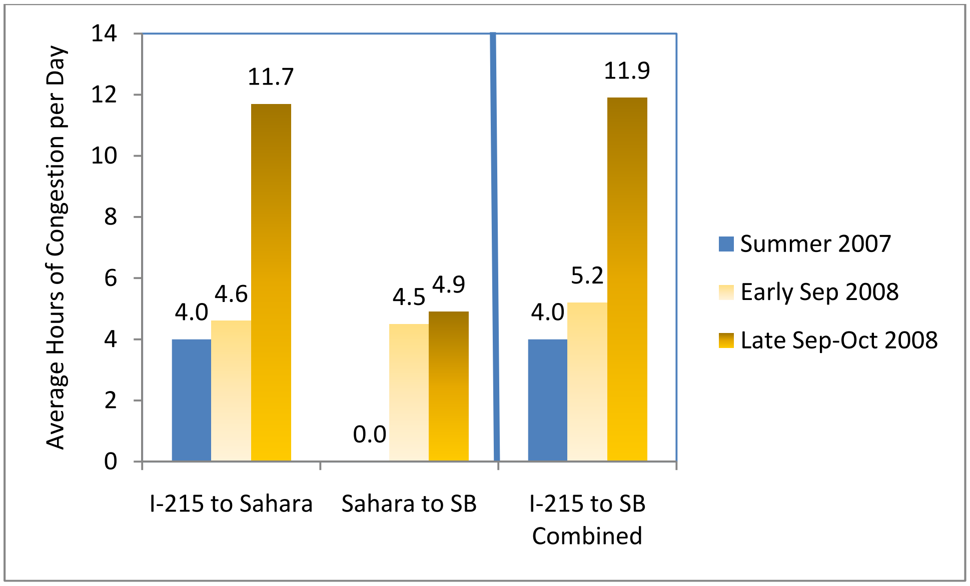


(c) Speed contour map in late September and October 2008 (north and south project lane closures)

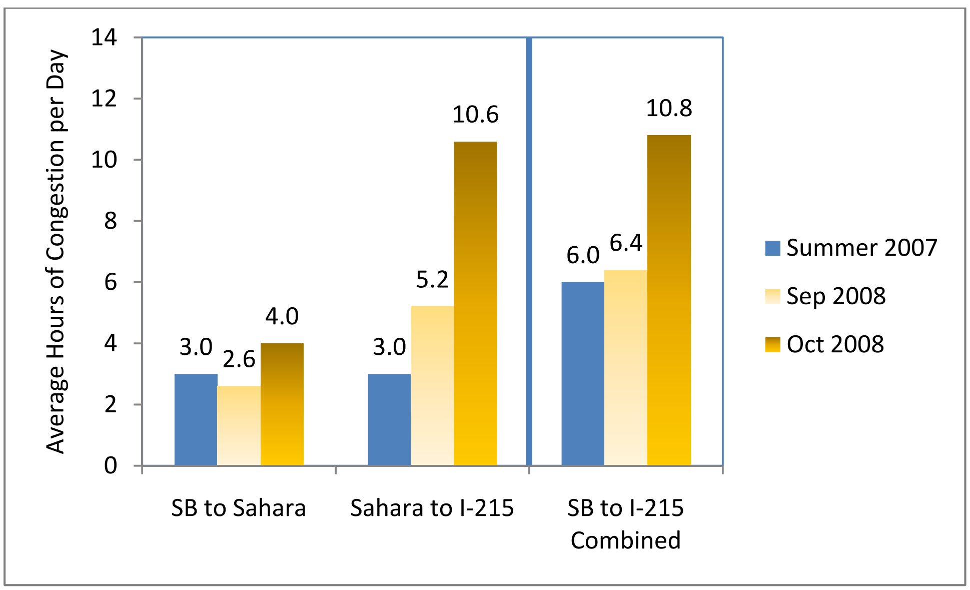
Figure 18. Changes in Average Speeds Southbound Before and During Evaluation Period, I-15 Las Vegas.

Overall, then, it is evident that the two projects did result in mobility impacts along I-15. However, exactly how these impacts should be calculated, and then assigned to each project, is not clear. One could decide that the two distinct congestion regions shown for the northbound direction in Figure 17 (c) could be allocated separately to the two projects (i.e., the congestion from before Sahara Avenue to the SB interchange allocated to the north project; the congestion from I-215 to about Tropicana Avenue allocated to the south project). However, this would mean that a portion of the congestion that existed within the limits of the south project in the before condition would be compared against the north project impacts, rather than those from the south project. In addition, this would entail the division of queues on those days when the queue lengths were longer than average and extended farther down in the south section (for northbound traffic). One could also consider all of the congestion that exists south of Sahara Avenue as part of the south project in both the before and during conditions, and just associate the congestion that developed north of Sahara Avenue as part of the north project impacts. In this approach, the length of queuing and delays for the north project northbound would again be truncated, this time to the Sahara Avenue/SB interchange segment. These two approaches would also require the analyst to decide whether to use the summer 2007 congestion patterns, or those in early September 2008 for comparison against the conditions during the south project. As a final option, the entire length of I-15 between I-215 and the SB interchange could be considered as a single segment, and the impacts discussed as the combination of effects of the two projects.

For illustrative purposes, queuing measures for a separate analysis of each project (with the limits of impacts for each project separated at Sahara Avenue) and for a combined analysis of the entire I-15 segment were computed and are compared in Figure 19 through Figure 21. Queues were defined as when and where speeds dropped to below 35 mph. In Figure 19, the average number of hours of congestion per day is shown for summer 2007 before either project began, in early September 2008 when only the north project lane closures were present, and in late September-October 2008 when both the north and the south projects had long-term lane closures in place. Considered in isolation, one sees that the north project lane closures present in early September 2008 had little effect on northbound congestion in the I-215 to Sahara Avenue subsection, but did in the Sahara Avenue to SB interchange subsection. Once the south project lane closures were in place northbound in late September and October 2008, the duration of congestion increased significantly in the south project subsection, but the subsection between Sahara Avenue and the SB interchange remained fairly consistent in terms of the hours of congestion experienced each day.



(a) Northbound



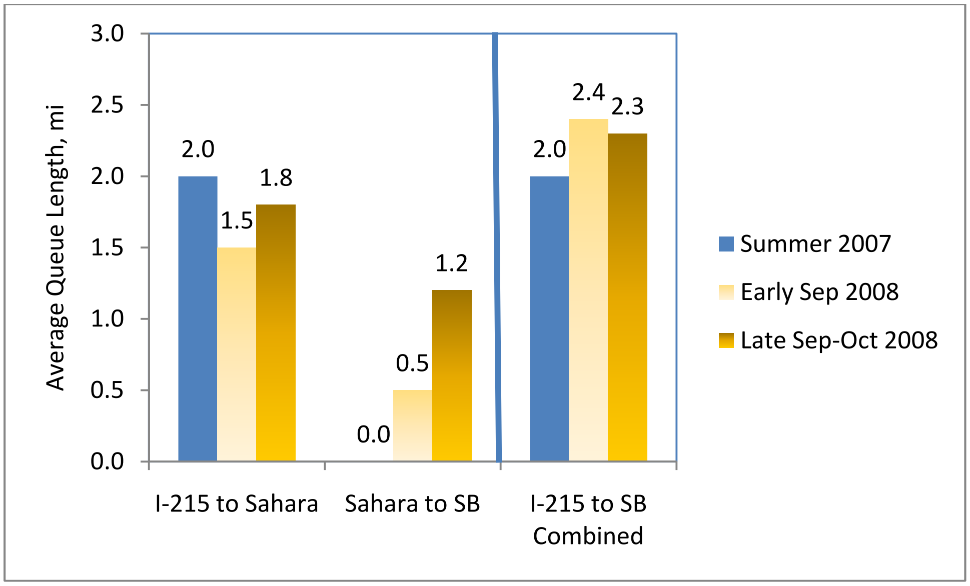
(b) Southbound

Figure 19. Effects of the Pilot Test Projects on Hours of Congestion, I-15 Las Vegas.

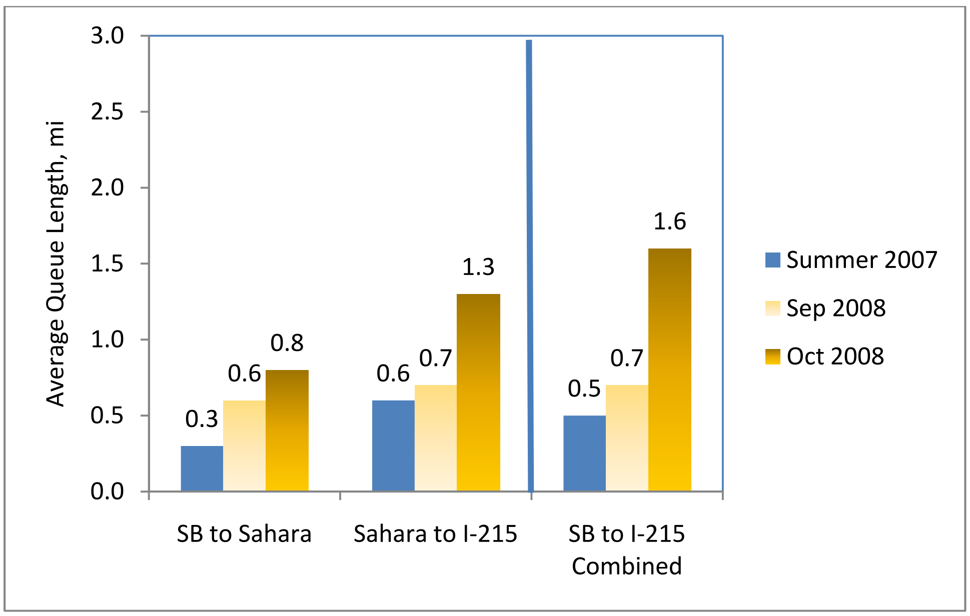
In the southbound direction, the introduction of a lane closure within the north project would not be expected to have a dramatic affect on congestion downstream of the project (i.e., south of the SB interchange). However, one does see a two-hour increase (from 3.0 hours to 5.2 hours) in congestion duration in the section from Sahara Avenue to I-215 in September 2008 when the north project lane closures were in place but not the south project lane closures. The reasons for the longer duration of congestion in that subsection could not be determined from the available data and documentation. Interestingly, though, the entire I-15 section from the SB interchange to I-215 did not experience much of a difference initially in the duration of congestion in the southbound direction when the north project lane closure is in place. Rather, the summer 2007 and September 2008 average hours of congestion are almost identical (6 versus 6.4 hours per day). It is only when the south project lane closures were installed southbound in October 2008 that the duration of congestion increased to more than 10 hours per day.

The interaction between projects is even more evident when one considers their impacts upon queue lengths. Figure 20 presents the average queue lengths each day (when queues were present) for the three time periods of interest in each direction. Northbound, one sees that average queue length in the I-215 to Sahara Avenue section actually declined slightly in both the early September 2008 and the late September-October 2008 periods, but increased in each of the periods in the Sahara Avenue to SB interchange section (by 0.5 miles in the early September 2008 period, by an additional 0.7 miles in the late September-October 2008 period). Looking at the section in its entirety, average queue lengths increased by 0.4 miles in early September 2008, and essentially remained that way into late September-October 2008.

Southbound, the effects of the projects on average queue lengths is more consistent with expectations in each subsection, and overall. Relative to summer 2007, average queue lengths southbound were 0.3 miles longer in the Sahara Avenue to I-215 subsection, and only 0.1 miles longer in the SB interchange to Sahara Avenue subsection. The slightly longer queues in the south subsection could again be due to possible rubbernecking of northbound lane closure conditions by southbound traffic. It is also important to note that while both subsections experienced small queue length increases in this particular period, the effect upon the total SB interchange to I-215 section was only 0.2 miles (from 0.5 to 0.7 miles), less than the sum of the increases of the two subsections. Once the southbound lane closures in the south project were in place (October 2008), average queue lengths grew by an additional 0.2 miles in the southern subsection, but by 0.6 miles (from 0.5 to 1.1 miles) in the SB interchange to Sahara Avenue section. Overall, traffic traveling the entire SB interchange to I-215 section experienced an average 0.9 mile increase in queue lengths (from 0.7 to 1.6 miles) when the south project lane closures were put in place, an amount that is actually greater than the sum of the increases in the two subsections.



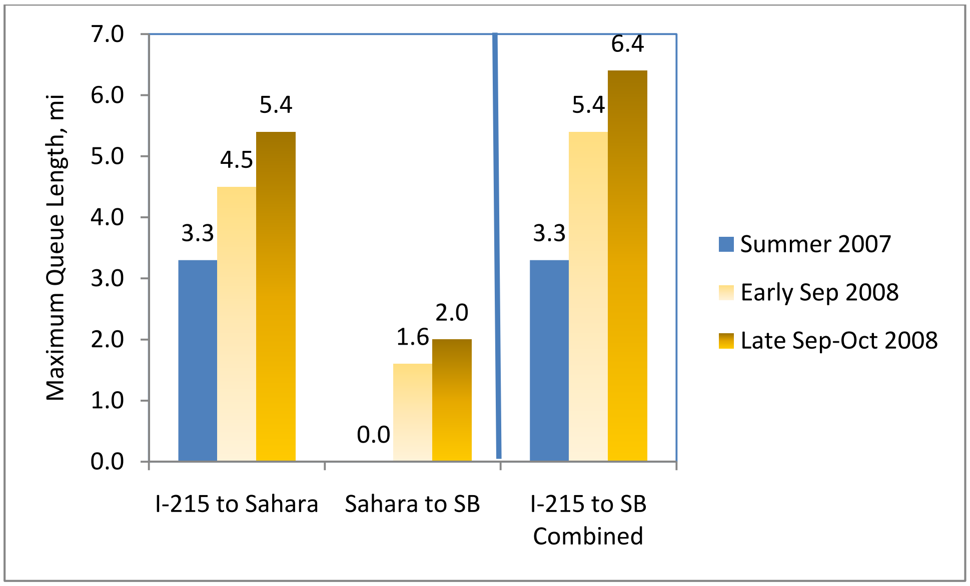
(a) Northbound



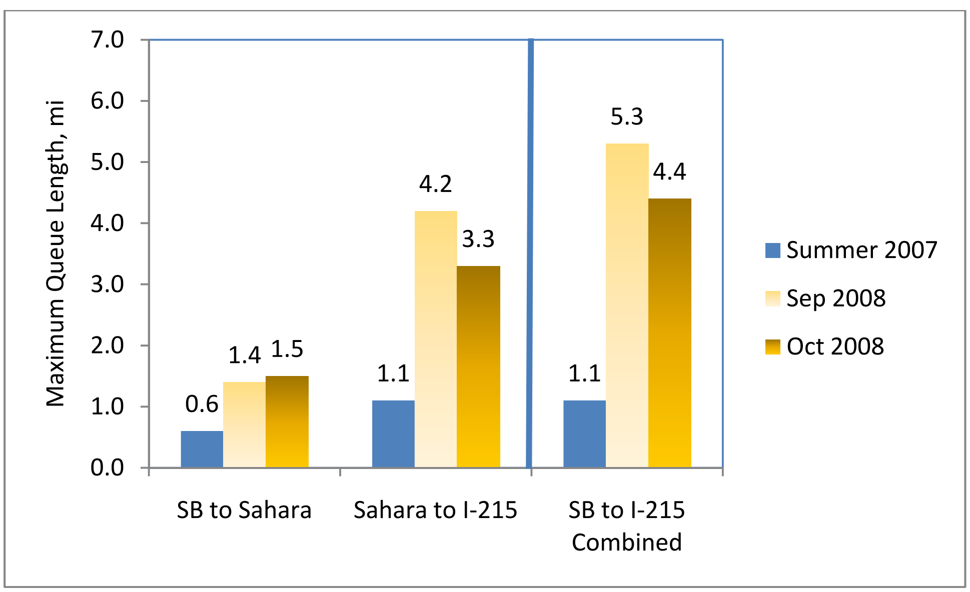
(b) Southbound

Figure 20. Effect of the Pilot Test Projects on Average Queue Length, I-15 Las Vegas.

Figure 21 presents the maximum daily queue lengths estimated during each analysis period. The summer 2007 values are actually a maximum length based on speeds averaged over one summer month (daily values were not available from that time period), whereas those for September and October 2008 are the actual daily maximum lengths. Consequently, the summer 2007 values would be expected to be substantially lower than the September and October 2008 values (which they are). Although direct comparisons to the summer 2007 values are not appropriate, the relative trends are clear and consistent. Northbound, one sees higher maximum queue lengths in both the early September 2008 and the late September-October 2008 periods, with those in the September-October 2008 the highest for both subsections and for the entire I-215 to SB interchange section.



(a) Northbound



(b) Southbound

Figure 21. Effects of Pilot Test Projects on Maximum Queue Lengths, I-15 Las Vegas.

Southbound, the effects of the projects on maximum queue lengths are less clear. In fact, the value in the September 2008 period was higher than that observed in the October 2008 period for the SB interchange to Sahara Avenue subsection, and for the entire SB interchange to I-215 section.

Table 41 provides a summary of the changes in each of the queue performance measures in each of the subsections and the entire freeway segment when the north project lane closures were installed, and then when the south project lane closures were added.

Table 41. Summary of Queue Measures, I-15 Las Vegas

Queue Measure of Interest	Northbound		
	I-215 to Sahara	Sahara to SB Interchange	I-215 to SB Interchange
Effect of North Project on:			
Duration of Queues per Day	0.6 hr ↑	4.5 hr ↑	1.2 hr ↑
Average Queue Length per Day	0.5 mi ↓	0.5 mi ↑	0.4 mi ↑
Maximum Queue Length per Day	1.2 mi ↑	1.6 mi ↑	2.1 mi ↑
Effect of South Project on:			
Duration of Queues per Day	7.1 hr ↑	0.4 hr ↑	6.7 hr ↑
Average Queue Length per Day	0.3 mi ↑	0.7 mi ↑	0.1 mi ↓
Maximum Queue Length per Day	0.9 mi ↑	0.4 mi ↑	1.0 mi ↑
	Southbound		
	SB Interchange to Sahara	**Sahara to I-215**	**SB Interchange to I-215**
Effect of North Project on:			
Duration of Queues per Day	0.3 hr ↓	2.2 hr ↑	0.4 hr ↑
Average Queue Length per Day	0.3 mi ↑	0.1 mi ↑	0.2 mi ↑
Maximum Queue Length per Day	0.8 mi ↑	3.1 mi ↑	4.2 mi ↑
Effect of South Project on:			
Duration of Queues per Day	1.4 hr ↑	5.4 hr ↑	4.4 hr ↑
Average Queue Length per Day	0.2 mi ↑	0.6 mi ↑	0.9 mi ↑
Maximum Queue Length per Day	0.1 mi ↑	0.9 mi ↓	0.9 mi ↓

Next, in Table 42, the amount of time that queues exceeded specified threshold lengths (1, 2, and 3 miles) are presented for each of the three time periods. These measures again show the difficulties of attempting to examine the impacts of the two projects separately, given that the queues extend across the two subsections.

Table 42. Comparison of Queue Threshold Measures, I-15 Las Vegas

Queue Measure	Amount of Time Each Day when Queues Exceeded:		
	1 mile	2 miles	3 miles
Northbound:			
I-215 to Sahara Avenue			
Summer 2007	14.6%	10.4%	6.3%
Early Sep 2008	14.6%	5.0%	0.8%
Late Sep-Oct 2008	37.2%	22.5%	7.6%
Sahara Avenue to SB Interchange[a]			
Summer 2007	0.0%	0.0%	0.0%
Early Sep 2008	13.8%	0.0%	0.0%
Late Sep-Oct 2008	13.6%	0.2%	0.0%
I-215 to SB Interchange			
Summer 2007	14.6%	10.4%	6.3%
Early Sep 2008	17.1%	14.2%	11.3%
Late Sep-Oct 2008	38.6%	26.4%	16.3%
Southbound:			
SB Interchange to Sahara Avenue[a]			
Summer 2007	0.0%	0.0%	0.0%
Sep 2008	1.6%	0.0%	0.0%
Oct 2008	6.0%	0.0%	0.0%
Sahara Avenue to I-215			
Summer 2007	2.1%	0.0%	0.0%
Sep 2008	2.5%	0.9%	0.4%
Oct 2008	23.9%	12.3%	5.3%
SB Interchange to I-215			
Summer 2007	2.1%	0.0%	0.0%
Sep 2008	4.4%	1.1%	0.4%
Oct 2008	25.9%	13.8%	10.5%

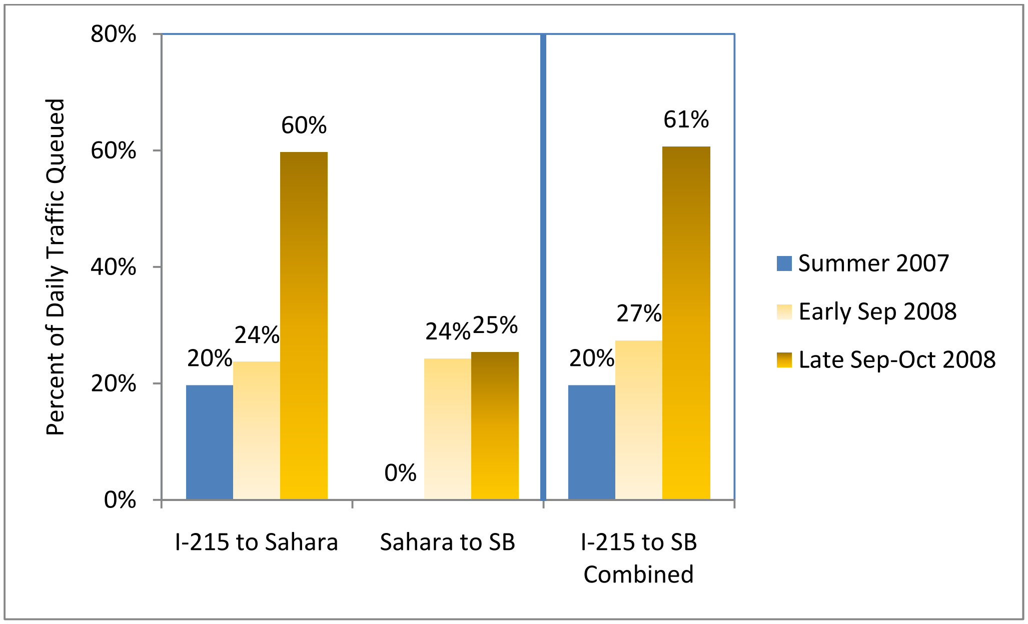
[a] This subsection is less than 3 miles long

Northbound, the I-215 to Sahara Avenue subsection appears to have seen a drop between summer 2007 and early September 2008 in the percentage of time when long (greater than 2 miles) queues were present. This is then followed by a large increase once the lane closures in this subsection were installed in late September-October 2008. For the Sahara Avenue to SB interchange subsection, the amount of time that queues were between 1 and 2 miles increased both in the early September 2008 and the late September-October time periods, relative to the summer 2007 period. Overall, the north project lane closures appears to have increased the percentage of time of 2 and 3 mile queues in early September, and these percentages again increased with the installation of additional south project lane closures in late September-October 2008.

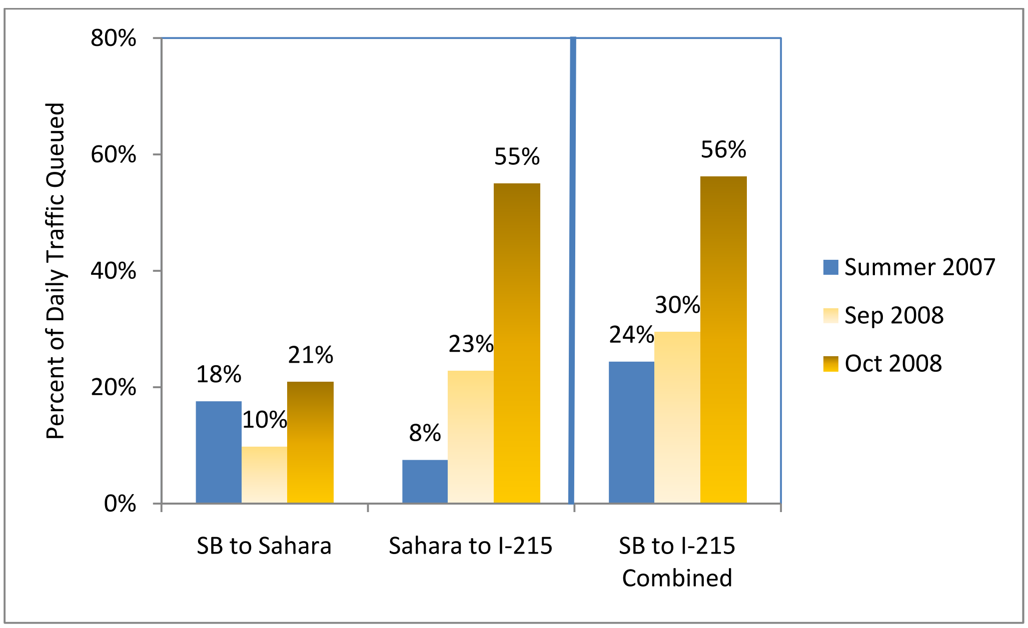
Southbound, the effects are more consistent with expectations, since there is less interaction of impacts between the north and the south project within the limits of available traffic surveillance data from the SB interchange to I-215. A clear trend towards higher percentage of times each day with longer queues are evident in both subsections, and in the entire SB Interchange to I-215 segment.

Finally, the extent to which daily traffic is impacted by the presence of queues is presented in Figure 22. Northbound, the interaction of the two projects upon mobility impacts is again evident. The I-215 to Sahara subsection showed just a small (4 percent) increase in the amount of daily traffic that experienced congestion between summer 2007 and early September 2008, indicating that the north project lane closures had little effect upon this measure. Then, once the south project lane closures were put in place, the amount of traffic experiencing congestion more than doubled (from 24 percent of daily traffic in early September to nearly 60 percent in late September-October 2008). For the northern subsection (Sahara Avenue to the SB interchange), the north project lane closure effects are very evident. Between summer 2007 and early September 2008, this subsection of I-15 changed from having no congestion effects (zero percent of daily traffic experiencing congestion) to more than 24 percent of traffic experiencing queuing in the early September 2008 period. This percentage continued even after the south project lane closures were installed in late September-October 2008, which should have had some amount of metering effect upon northbound traffic approaching from I-215.

Southbound, the measures in Figure 22 (b) again mostly reflect the effects of the south project lane closures. The north subsection (SB interchange to Sahara Avenue) actually saw the percent of daily traffic encountering congestion decrease slightly from 17.6 percent to 9.8 percent between summer 2007 and September 2008, and return to slightly higher levels (20.9 percent) once the southbound lane closures in the south project were installed. In the southern subsection, the percent of daily traffic experiencing congestion increased both in the September 2008 and again in the October 2008 time period. As previously discussed, it is hypothesized that rubbernecking of northbound lane closures and congestion in that subsection is responsible for the increase in September 2008, and the southbound lane closures in October 2008 then resulting in the additional amount of traffic exposure to queues. Looking at the entire I-215 to SB interchange section as a whole, one sees the effects of both the north and south projects in the northbound direction, and two levels of effects of the south project (one due to driver rubbernecking and the other due to actual lane closures).



(a) Northbound



(b) Southbound

Figure 22. Percent of Daily Traffic That Encounters Queuing, I-15 Las Vegas.

Delay Measures

Separate analyses of the two subsections examined with the queuing measures could not performed for delays because the DMS sign travel times from the FAST system used for the analysis were available only for the full section length. These data were available through February 2009, whereas the individual sensor data (speeds, volumes) were only available through October 2008. Use of the DMS travel time data allowed for the analysis of the differences between the right lane and median lane closures (the median lane closures were installed in December 2008).

Delay measures for both northbound and southbound are provided in Table 43. For purposes of this analysis, average speeds less than 55 mph were taken to represent delay. Northbound, recurrent congestion in summer 2007 (before either project began) totaled 1,030 vehicle-hours of delay per day. This equated to an average of less than 1 minute per vehicle using the facility each day, and only an average of 1.2 minutes per vehicle that encountered congestion each day. These values were somewhat higher in early September 2008 when the north project lane closure was in place, but the south project lane closures had not yet began. In this time period, a total of 2,411 vehicle-hours of delay were incurred each day in this section of freeway. On a per vehicle basis, these equated to 1.6 minutes per entering vehicle and 5.9 minutes per vehicle encountering congestion, on average. Depending on the day, however, brief occurrences of delays reached as much as 16.2 minutes during this period.

Table 43. Comparison of Delay Measures, I-15 Las Vegas

Time Period	Minutes of Delay			Veh-Hrs per Day
	Average per Entering Vehicle	Average per Queued Vehicle	Maximum per Queued Vehicle	
Northbound				
Summer 2007	0.8	1.2	n/a	1,030
Early Sep 2008	1.6	5.9	16.2	2,411
Late Sep -Nov 2008	2.3	5.0	21.2	3,417
Dec 2008-Feb 2009	3.4	6.7	30.9	5,019
Southbound				
Summer 2007	0.4	0.4	n/a	536
Sep 2008	0.2	0.5	11.8	313
Oct-Nov 2008	5.4	8.1	24.2	8,621
Dec 2008-Feb 2009	5.1	7.4	29.1	7,951

The late September through November 2008 time period involved both the north project lane closure and the south project lane closures in the right lane and shoulder. The addition of the south project lane closures further increased congestion, such that 3,417 vehicle-hours of delay per day were experienced by motorists during this period. On a per-vehicle basis, this equated to 2.3 minutes per entering vehicle and 5.0 minutes per vehicle encountering congestion. The restriction of roadway capacity at various points in the south project also caused higher spikes in delay during the period, as the maximum delay per vehicle increased to 21.2 minutes.

Delays northbound increased still more once the right lane and shoulder closures in the south project were replaced with a median lane closure in December 2008. For the December 2008 to February 2009 period, 5,019 vehicle-hours of delay were experienced per day by motorists, nearly five times that of the summer 2007 period before the work zones were in place. This delay equated to 3.4 minutes of delay per entering vehicle, and 6.7 minutes per vehicle encountering congestion on this freeway section. During this period, delays reached as much as 30.9 minutes per vehicle on certain days and times. This was somewhat surprising, given that NDOT officials had commented that they believed that traffic flow had improved when the right lane and shoulder closures were replaced with median lane closures in the project. It is possible that the somewhat contrary results northbound were due to spillback effects from the north project that masked any benefits that the lane closure switch in the south project had upon traffic flow.

As shown in Table 43, delays in the southbound direction also increased significantly as a result of construction activities and lane closures in the south project. Whereas delay in summer 2007 and September 2008 averaged between 313 and 536 vehicle-hours per day, it grew to 8,621 vehicle-hours per day in October-November 2008, more than a 15-fold increase. Average delays per entering vehicle also increased significantly from less than a minute to more than 5 minutes per vehicle, and the average delay per queued vehicle grew to 8 minutes per vehicle. Maximum delays also doubled once the lane closures were installed, from 11.8 minutes per queued vehicle in September 2008 to 29.1 minutes in the December 2008 to February 2009 time period.

It is important to note that delays during the south project lane closures actually did decrease slightly (by about 8 percent) in the December 2008-February 2009 time frame when the median lane was closed as compared to the October-November 2008 time frame when the right lane and shoulder was closed. Although such an improvement was not evident in the northbound delay data, delays southbound did suggest that conditions were improved slightly by the lane closure switch to the median. These results further suggest that the effects of the two projects on northbound traffic are intertwined, making it difficult to isolate the effects of one project or the other upon overall traffic conditions.

Finally, as an accuracy check, the travel times extracted from the DMS FAST database were compared to field-collected travel times gathered during the second week of February 2009. Table 44 summarizes the results of that comparison. Overall, the travel times estimated from the FAST system replicated those obtained in the field fairly well. On average, the FAST travel times averaged about 1 to 2 minutes (10 to 13 percent) longer over the 7-mile section than the field measured values. Meanwhile, Pearson Correlation Coefficients were very high, ranging between 0.790 and 0.913.

Table 44. Travel Time Data Comparison, I-15, Las Vegas

	Northbound	Southbound
Average Travel Time from FAST	14.2 min	12.1 min
Average Travel Time from Field Studies	12.3 min	11.0 min
Difference	1.9 min	1.1 min
Z-Statistic	6.49	4.75
Pearson Correlation Coefficient	0.913	0.790

Travel Time Reliability Measure

The final performance measure examined for these two pilot test projects was the effect of the work zones upon travel time reliability along this section of I-15. Reliability was not a measure examined at the previous pilot test project locations, as travel times in the absence of the work zone lane closures were very steady (there was enough excess roadway capacity available to maintain very stable traffic speeds on the facility). Hence, the total effect of the work zones upon reliability is represented by the additional delays created on those days and nights when lanes were closed and congestion developed due to the capacity restrictions. For the two I-15 projects, however, some degree of travel time unreliability already existed during a portion of the day prior to the start of the projects. Consequently, it was necessary to measure how reliability was changed relative to the before condition, similar to the need to compare queues and delays during the projects to those that existed before the project began.

The term "buffer index" was selected as the main reliability measure evaluated. This index represents the percentage increase in average travel times that a person must allocate to their trip in order to be sure they will arrive on time most of the time. Traditionally, "most" has been defined as arriving early or on time 19 out of 20 trips (i.e., 95 percent of the time). Other definitions are possible, however. For example, a buffer index based on the 80th-percentile trip time would mean that drivers arrive early or on time four out of every five trips (i.e., they would typically be late once every five days).

Table 45 and Table 46 present buffer indices computed for both the 95th and 80th percentile travel time thresholds. Individual travel times by time period each day were not available for the summer 2007 time period; however, overall travel times each hour were obtained for July 2008. Given that the lane closures in the north project were initiated in mid-July, it was possible to estimate the buffer index in early July 2008 as the "before" condition. The other periods reflect the north project effects, the combined effects of the north and south projects with right lane and shoulder closures, or the combined effects of the north and south projects with a median lane closure in place, respectively.

From Table 45, the north project lane closures are seen as increasing the buffer index in both the northbound and southbound directions of travel between I-215 and the SB interchange. The buffer index was already rather large during midday hours northbound, and this was further exacerbated by the introduction of the north project lane closures. Interestingly, the additional lane closures installed in the south project in late September only resulted in a slight incremental increase in the buffer index during this period (from 70.5 to 77.3 percent, and then to 80.3 percent when the median lane closures were installed in December 2008). Meanwhile, the effects of the south project lane closures was more substantial in both the peak periods, rising from a buffer index of 9 percent to 37.3 percent and then to 61.9 percent in the morning peak, and from 46.6 percent to 49.2 percent and then 63.9 percent in the evening peak. In the southbound direction, the north project lane closures have very little influence on travel time reliability. In fact, the buffer index from late July through September 2008 is actually less than in early July 2008 during the midday hours. Once lane closures are installed in the south project, significant increases in the buffer index are seen in all time periods. Interestingly, the buffer index is slightly higher in the midday and evening peak hours when the median lane was closed in the south project as compared to the right lane and shoulder closures, even though NDOT and FHWA reported that traffic flow was smoother in the median lane closure condition (the index did decrease in the morning peak period, however).

Table 45. 95th Percentile Buffer Indices, I-15, Las Vegas

Time Period	AM Peak (6-9 am)	Midday (9 am – 3 pm)	PM Peak (3-6 pm)
Northbound			
Early Jul 2008	5.5%	55.0%	22.2%
Late Jul-Early Sep 2008	9.0%	70.5%	46.6%
Late Sep -Nov 2008	37.3%	77.3%	49.2%
Dec 2008-Feb 2009	61.9%	80.5%	63.9%
Southbound			
Early Jul 2008	5.6%	24.7%	22.3%
Late Jul-Sep 2008	17.0%	17.1%	34.9%
Oct-Nov 2008	56.3%	62.5%	60.6%
Dec 2008-Feb 2009	35.4%	77.2%	70.1%

The trends are slightly different if the 80th percentile travel time is used as the basis for computing the buffer index. As depicted in Table 46, the lane closures installed on the north project had very little effect on the buffer indices northbound. The only significant change was during the evening peak when the index increased from 11.5 to 22.6 percent. Even more surprising is the fact that the introduction of lane closures in the south project significantly increased the northbound buffer index in the morning peak (from 1.4 percent to 20.5 percent), but had little effect on the midday or evening peak indices. In fact, the midday buffer index actually decreased in the late September to November period, and was only slightly higher (relative to the late July-early September period) once the lane closures were moved to the median lane in December 2008. Southbound, the north project lane closures had no effect whatsoever on the buffer index. Only when the south project lane closures were installed in October 2008 does the buffer index increase substantially in all time periods.

Table 46. 80th Percentile Buffer Indices, I-15, Las Vegas

Time Period	AM Peak (6-9 am)	Midday (9 am – 3 pm)	PM Peak (3-6 pm)
Northbound			
Early Jul 2008	1.7%	28.9%	11.5%
Late Jul-Early Sep 2008	1.4%	34.4%	22.6%
Late Sep -Nov 2008	20.5%	32.7%	25.1%
Dec 2008-Feb 2009	31.9%	39.0%	33.1%
Southbound			
Early Jul 2008	2.9%	5.3%	5.5%
Late Jul-Sep 2008	3.2%	2.0%	4.3%
Oct-Nov 2008	24.2%	31.2%	37.2%
Dec 2008-Feb 2009	15.0%	26.9%	30.0%

KEY FINDINGS FROM THE I-15 PILOT TESTS

The analysis of impacts from the two pilot test locations on I-15 in Las Vegas, NV proved to be a much more involved process, due to the fact that lane closures which significantly impact capacity were installed on a long-term basis in both projects. Projects which limit lane closure activity to off-peak hours when traffic congestion is not normally present on the roadway allow a reasonable assumption to be made that any impacts are due solely to the work zone lane closure. When long-term lane closures occur in locations where recurrent congestion is already present, such a simplifying assumption cannot be made. Rather, the effects of the lane closures at these I-15 projects were combined with the recurrent congestion already being experienced on this facility before the projects began. Therefore, information about travel conditions before the projects began was required so that incremental changes in performance measures could be estimated during each project. The analysis was also complicated by the fact that both projects were located close enough to each other that their impacts on travel were intertwined. Overall, however, it is apparent that the long-term lane closures at these two projects did have a significant effect on travel conditions within the corridor.

Several useful insights regarding work zone performance measurement were obtained from this analysis. Many of them were similar to those reported for the other pilot test locations as well. However, one unique finding from these two projects is that a travel time reliability measure (buffer index) can be another way of assessing the mobility impacts of work zones in regions already experiencing some degree of congestion on the facility prior to initiating work activity on the project. The roadway capacity reductions caused by long-term work zone lane closures make travel times more susceptible to fluctuations in daily demand, as well as to incidents. Since the available capacity through the roadway segment is constrained, incidents that occur will have a greater affect on travel because they create an incrementally larger reduction in the available capacity than when all lanes were open. The end result is that the predictability of travel times through the work zone may become more unreliable. A travel time reliability measure can be used to track this variability and enable better work zone management and public information.

The results from the I-15 sites also illustrate the value of having a functional TMC available for evaluating work zone mobility impacts in a more complex urban environment. The additional analysis that can be performed with the larger data set is evident by the range of tables and charts in this chapter that were not prepared for the other sites. The availability of TMC data also allows the work zone analyst to compute vehicle exposure much more accurately than would otherwise be possible. Furthermore, when recurrent congestion already occurs on a roadway segment prior to the initiation of the work zone, detailed traffic data that can be obtained from a TMC allow analysts to evaluate both spatial and temporal changes in those congestion patterns. In addition, the effect of work zone capacity reductions upon non-recurrent congestion effects, measured in terms of travel time reliability, can also be evaluated when TMC data are available.

The results of the I-15 pilot tests illustrate the importance of selecting performance measures that are appropriate to the various types of projects and project conditions. For example, for projects like the I-15 ones where there are long-term lane closures, the value of certain exposure measures such as the percent of time when work activities involve lane closures has little meaning. Agencies should consider stratifying projects on the basis of lane closure strategy employed when examining overall trends across projects in a district or region over time.

10. FINDINGS AND LESSONS LEARNED

This report has presented the results of an effort to pilot test the feasibility of several mobility-based work zone performance measures. The measures encompassed various dimensions of:

- Work zone exposure
- Traffic queuing
- Motorist delays
- Travel time reliability

A discussion of useful safety-related measures was also presented. However, because of anticipated lag times in obtaining crash data from the various pilot test locations (and the straightforward nature with which safety-related performance measures are typically developed), exposure and mobility-related performance measures only were targeted at each of the pilot test locations.

The pilot test also incorporated different methods of data collection to support performance measurement computations. The first method was to rely on field personnel at the project to manually document the occurrence of traffic queues that develop because of temporary lane closures or other work activities that constrain roadway capacity. Use of this method assumes that traffic conditions in the absence of the work zone would have been uncongested, such that any queuing or congestion that observed could be attributed solely to the work zone. The second method was to use electronic traffic surveillance data to monitor traffic conditions and compute desired performance measures. This data may come from a regional TMC already in place, or from sensors specifically deployed as part of a portable work zone ITS. The third method relied on truck speed data collected by third-party vendors willing to provide limited access for transportation monitoring purposes. A screening process was undertaken to access available speed observations at each project on specific times and dates when traffic impacts were expected to exist. Organizing these data by location and time of day was expected to provide another method of tracking the effect of work zones on traffic mobility on a facility.

In the following section, a synopsis of the key lessons learned with respect to data collection and analyses of work zone exposure and mobility data are presented. Next, the various performance measures are compared across projects to discuss how they might be used to assess for critiquing project-level decisions and actions, as well as agency policies and processes.

DATA COLLECTION AND ANALYSIS FINDINGS AND LESSONS LEARNED

Manual Documentation of Queues by Field Personnel

Overall, the results of the pilot test suggest that it is possible to obtain fairly good quality queue data from field personnel upon which to base work zone mobility performance measure computations. The impact of data collection demands on field personnel workload was a potential concern initially in this pilot test, but workload-related problems did not appear to materialize. Comparisons of the queue length and duration data to data from traffic surveillance sensors and ground-truth measurements (when available) suggest that reasonable estimates can be obtained. Very few instances were identified where field personnel failed to document either the work and lane closure activity (this type of information is normally needed for project diary entries anyway) or the development of queues. The fact that this was a special request as part of a research project may be part of the reason the effort was so successful. It is likely that regular reminders (possibly as a special note in the project diaries) would be beneficial to agencies striving to adopt this process as part of their monitoring efforts. It is also likely that an indication of the importance of this documentation effort by upper management in an agency would further ensure personnel consistency in reporting.

These successes notwithstanding, a few key lessons were also learned through this pilot test effort.

- ***It will be important for agencies to establish simple operational definitions for field personnel as to what exactly constitutes a traffic queue*** – In most cases, agencies will want to use a reasonable and consistent indicator, such as when vehicle speeds drop below 35 mph. Other agencies may choose to use a much lower value to define what constitutes a queue (some agencies use values as low as 10 mph to define queuing). Unfortunately, it may not be possible for field personnel to accurately gauge vehicle speeds and make distinctions as to whether a backup truly meets the agency definition of a queue. All that an agency may be able to expect is for field crews to be able to define when and how far upstream traffic has "backed up." Estimates of what the speed in queue likely was at that work zone may then need to be computed after the fact using traffic flow relationships.
- ***Estimates of queue lengths need to include a description of the location of the queue relative to the lane closure (upstream, beyond taper and into work zone, partially upstream and partially within the work zone, etc.)*** – Related to the previous bullet, the comparison of queues documented by field personnel and the electronic traffic surveillance sensor data at several sites indicated that some queues occurred at the point of the lane closure transition, whereas others occurred within the work zone next to the location of work activity or other disturbance. When queues occur within the work zone where the number of lanes available remains constant, traffic flow relationships suggest that speeds in those queues will be much higher than in queues at and upstream of a lane closure transition. Equation 1 identified the queue speed estimated for the lane closure transition queues. For queues within the work zone, the speed at capacity flow (approximately one-half of the free-flow speed) is a more realistic value to use.

- ***Manual methods will be less effective in capturing short (less than one hour) disturbances that result in queues*** – Realistically, neither manual methods or electronic surveillance data are likely to be all that effective in capturing short-duration queues that may form because of small fluctuations in traffic flow behavior, a temporary disruption in flow by work vehicles entering or exiting the work area, or other disturbance. Given the workload that field personnel typically carry during work zone activities, only the more significant long-lasting queues that develop are likely to be documented.

Use of Electronic Traffic Surveillance Data

The results of this pilot test also indicate that electronic traffic surveillance data, when available, can be utilized to measure work zone exposure and to compute the effects of work zones on traffic mobility. However, some challenges do exist in obtaining and applying these types of data to work zone exposure and mobility-related performance measurement. The major lessons learned relative to the use of electronic surveillance data are as follows:

- ***Field personnel documentation of when and where lane closures were placed and hours of work activity will still be needed to compute mobility performance measures using electronic traffic surveillance data*** – Although it may be desirable to be able to rely on electronic traffic surveillance data alone to determine when lanes were closed, which lanes were closed, when the lane closures were removed, etc. (and thereby eliminate the need to extract these data from field personnel), the realities of electronic surveillance data is that it is often not easy to distinguish between changes in conditions that are due to the work zone actions listed, those which are due to incidents, and those due to normal "noise" in the traffic stream.
- ***It is important to make sure that the traffic sensors themselves will remain operational when work begins*** – At some of the pilot test sites, it appears that power was disrupted temporarily to the traffic sensors when work was occurring. As a result, data were not available during the exact times they would be needed for monitoring and performance measurement computation purposes. If temporary power disruptions in the vicinity are anticipated, it will be necessary to take steps to fill in gaps in coverage (by manual documentation of conditions by field personnel or by deploying portable traffic sensors that can provide the data during the power outage).
- ***The level of accuracy in work zone mobility performance measurement achievable with electronic traffic surveillance data depends heavily on the design of the system (particularly traffic sensor spacing)*** – Some of the key factors that will affect the extent to which accurate performance measures can be recorded and computed include 1) the availability of speed data from each sensor (critical to the estimation of delays and queue lengths), 2) the spacing between sensors (closer sensor spacing allow for finer resolution of queue lengths and queue length growth/dissipation over time), and 3) the limits of

surveillance relative to the length of impacts that develop (if queues grow beyond the limits of surveillance, the measures computed from that data may be counterintuitive to what is actually occurring at the site).

- ***Aggregation of traffic sensor data to hourly averages is a reasonable compromise between accuracy and practicality for monitoring work zone mobility impacts*** – Data at this level of detail appears to be still sensitive enough to detect the onset and dissipation of congestion, but not so detailed so as to overburden the analyst.

Truck Probe Spot Speed Data

At each of the pilot test locations, analysis and comparison of truck probe speed data for work zone mobility performance monitoring was fairly limited because of a lack of adequate sample size across time and space. In some cases, work activity occurred during nighttime hours when traffic volumes are lower, and this contributed to the low sample size. However, even at the Las Vegas pilot test locations, the amount of truck transponder data obtained was not enough to allow a full comparison to other data sources. There were instances at the three nighttime project pilot test sites in which the knowledge that a work zone was present and that congestion had developed (via other data sources) could be correlated with a reduced speed measurement obtained from the truck transponder data. Unfortunately, there were more instances in which truck speed data were not available at the location and time that work zone queuing was known to have developed. Consequently, its value as a primary data source for mobility monitoring and performance measurement is currently rather limited.

The limitations of this current pilot test notwithstanding, the potential use of vehicle probe speed data for work zone performance measurement is still attractive to highway agencies. As private sector vendors of speed and travel time data continue to evolve, an adequate supply of this type of data may someday become available. Although there were few actual lessons learned through the review of truck transponder speed data in this pilot test effort, the following are three issues to be considered in future efforts to use this type of data:

- ***The choice of segment length must balance the trade-offs between amount of data that is available and level of accuracy of queue and delay estimates*** – For this pilot test, the decision was made to use one-mile segments and one-hour time periods in the analysis. It was found that the amount of data available was insufficient to support the analysis at this level of detail. Unfortunately, even a longer segment length would not have proven beneficial for the pilot test (researchers did examine the possibility of combining mile segments each hour, without much improvement in coverage). For other vehicle probe data sources, the goal should be to dissect the affected roadway segment into intervals that allow for multiple readings (at least three would be preferable in order to establish the degree of variability of each segment estimate) in each segment in each hour. If a reasonable speed estimate can be established in each segment each hour, the computational procedures for determining queue lengths and delays from spot sensor data could be applied.

- ***A common reference system must be used to define the segment endpoints and work zone location* –** In many work zones, the location of work activity and temporary lane closures will change from work period to work period. Documentation of where the work zone is located each period is essential to matching the vehicle probe speed data in each segment to that location so that queue lengths can be approximated.
- ***The potential reaction of the vehicle fleet to the presence of a work zone and resulting congestion should be considered when analyzing the data* –** In the case of truck transponder data, communication between drivers of the presence of severe congestion at a work zone could lead to many drivers leaving the roadway to take a break and wait for congestion to dissipate. Although it was not possible in this pilot test to verify or refute whether this occurred at any of the sites, the potential does exist for such behavior to occur.
- ***It is important to remember that speeds within each road segment are not true "spot" speeds* –** The aggregation of speeds obtained from vehicle probes will either be a compilation of speeds all along the length of the roadway segment, or an estimate of speeds using elapsed travel time on that segment or portion thereof. Significant changes in roadway characteristics within the segment length can cause much different speeds at different locations within the segment. This increased variability makes it more difficult to assess the impacts of a work zone, and implies that a greater sample size will be needed.

Comparison across Possible Data Collection Methods

Table 47 compares and contrasts the various data collection methods currently available for monitoring work zone impacts and assessing performance. The table includes point-to-point travel time measurement systems mentioned previously, but which were not available for inclusion in the pilot test effort.

Table 47. Comparison of Data Collection Methods for Work Zone Monitoring and Performance Measurement

Data Source	Advantages	Disadvantages	Other Considerations
Manual Measurement of Queue by Field Personnel	- Direct control of data by agency - Easy to implement - Minimal additional cost to agency	- Increases work load of field personnel (inspector, TTC supervisor, etc.) - Limited to locations where recurrent congestion not present	- Important to note location of start and end of queue relative to work zone lane closure each work period
Electronic Spot Speed Data:			
Existing TMC already in place	- Minimal additional cost to agency - Availability of "before" data (allows assessment of incremental effects of work zone)	- Location of devices may not be optimum for work zone assessment purposes - Can require significant effort to extract and process desired data from entire system	- Important to ensure that sensors will remain operational during work activities
Portable ITS devices (sensors on trailers, portable sensors in channelizing devices, etc.)	- Allows for optimum placement of sensors for work zone monitoring purposes	- Work zone ITS can be costly to the project	- Portable devices must be placed consistently each work period (or documented if changed each day) - Sensors must extend beyond the limits of anticipated congestion
Vehicle probe data (i.e. truck transponders)	- Does not require agency to purchase technology to deploy - Does not require technology to be moved or maintained	- Sample size is an issue for truck transponder data - May require purchasing from third-party vendors	- Important to remember that speeds are not true "spot" speeds, but are distributed across the segment in which they are included
Electronic Point-to-Point Travel Time Data:			
AVL systems	- Very accurate tracking of speed profiles possible	- Vehicle fleets to draw data from are usually very limited - Will require agreements with agencies or vendors who collect these data	-The potential exists for obtaining data at a finer level of detail than is needed, which could create data management and analysis challenges

Data Source	Advantages	Disadvantages	Other Considerations
AVI toll tags	- Available sample size can be fairly high	- Queues difficult to measure without multiple, very closely spaced sensors - May require agreement with toll agency to gather data - Deployment of additional transponder readers can be costly	- Generally limited to regions where a significant proportion of the driving population has toll tags in their vehicle
License plate recognition systems	- Available sample size can be fairly high	- Costly to implement - Sample size availability depends on ability of system to match license plates - Queues difficult to measure without multiple, very closely spaced sensors	- May create concerns about privacy with local citizens
From bluetooth readers	- Data can be obtained unobtrusively from roadside devices	- Requires purchase and deployment of Bluetooth readers - Queues difficult to measure without multiple, very closely spaced sensors	- Dependent on the volume of traffic present
Cell phone tracking	- Large potential sample size within traffic stream	- Requires agreements with 3rd party vendors to obtain data	- Dependent on the volume of traffic present

FINDINGS AND LESSONS LEARNED REGARDING PERFORMANCE MEASURE COMPUTATION AND INTERPRETATION

The proposed measures themselves offer insights into their potential usefulness to highway agencies for both current and future project-level decision-making, and for process-level reviews.

Exposure Measures

The importance of vehicle-based measures of exposure (volumes through the work zone, vehicle-miles-traveled through the work zone) for computing and normalizing queue, delay, and crash-based performance measures was discussed earlier in this report. The importance and lessons learned regarding some of the additional exposure measures proposed are discussed below.

- ***Work activity measures (percent of days worked, average hours per day of work) will be useful in tracking and comparing contractor level of effort*** – However, many factors affect contractor ability to work on a given project. Consequently, these data are likely to be most useful when averaged across multiple projects, or in some form of compliance assessment to a threshold target (e.g., percent of projects with less than 40 percent of work days with activity). These values would also be useful for monitoring efforts of individual contractors (again, either in terms of averages or as a percentage of projects with work activity percentages below a preset threshold). Finally, these measures could also be extrapolated across all projects in a region as a way to quantify total exposure for use by public information offices or other needs.
- ***Capturing lane closure hours (percent of hours involving 1, 2, etc. lanes closed) is relevant only if total lanes remaining open is also captured*** – Agencies will need to capture and categorize these data based on lanes open/lanes closed configurations. One lane closed on a five-lane section is much different than on a two-lane section. Given how the number of lanes available for traffic can vary from location to location along a section of multi-lane roadway, establishing field documentation procedures for lane closures that require the number of lanes closed, number of lanes open, and location of the lane closure(s) will be important. Proper documentation of lane closure parameters will also facilitate collection and analysis of delay and queue measures (especially when relying on electronic traffic surveillance sensor data).
- ***It will be important to stratify projects based on the type of lane closure being utilized when examining trends or evaluating compliance to thresholds*** – For example, projects involving short-term lane closures each day or night should be examined differently than those involving long-term lane closures. Information regarding percent of lane closure hours with inactivity will be much more valuable for the short-term lane closure projects than for long-term lane closure projects, since the traffic control designer should already

have acknowledged that there will be many inactive hours with lane closures for a long-term lane closure traffic control option. While it still may be worthwhile to quantify this information, mixing the results with short-term lane closure projects will tend to skew the values and make it difficult to assess agency decisions and policies for either type of lane closure being used.

- ***Computation of the total lane-mile-hours of lane closures during the project can provide another way to normalize delay measures*** – Depending on the number of lanes available in a given direction of travel, contractors have options in term of how many lanes are closed for a given work shift. However, the number of lanes closed at a time also affects how many work shifts are needed to complete a task. Normalizing vehicle-hours of delay on a per-lane-mile-hour of closure basis can help connect traffic impacts to both lane closure and work productivity measures, if measured across the total duration of the work task being completed.

Queue Measures

The argument was made earlier in this report that queuing measures themselves were valuable for work zone mobility monitoring and impact assessment. Furthermore, an approach was proposed for estimating delay impacts from queue length and duration documentation by field personnel during work zone activities. The pilot test results did indicate the need to include additional details during queue length documentation to improve delay estimates. Additional insights and lessons learned regarding queue measures are provided below.

- ***The percent of time when queues exceed selected threshold values should be useful as a potential performance specification for work zone traffic control and impact mitigation*** – The results of the pilot tests illustrate that unexpected queues can occur from time to time due to fluctuations in traffic flows and small, temporary disturbances to that flow near areas of work activity. These can occur even if analysis during traffic control plan design indicates that traffic demands do not exceed the expected traffic capacity through the work zone (although the likelihood increases the closer demand is to expected capacity value). It appears that many of these queues are fairly short in duration and length. This performance measure provides a simple way to distinguish between those occasional short-duration queues that are out of the control of the contractor/highway agency, and those that are systemic in exceeding agency threshold targets.
- ***The measure "percent of traffic encountering a traffic queue" provides a direct indication of the breadth of impacts of the work zone to the motoring public*** – However, it may be challenging for agencies to use this measure where recurrent congestion is present prior to the start of the project, and where long-term lane closures have been deployed. For these situations, it will be necessary to first compute this

measure for the before-project condition, and then measure the change in the measure once the work zone has been installed.

- ***The average duration of queue per work shift or day provides valuable information at projects where recurrent congestion was already present prior to the start of the work zone, or where electronic surveillance may not cover the entire length of work zone impacts on a roadway*** – The measure also provides useful insights about scheduling decisions for short-term lane closures each work period.
- ***The average queue length and maximum queue length measures have value for assessing both project-level and process-level traffic management decisions*** – As stated earlier in this report, the maximum queue length is a useful measure for evaluating how well planning and impact analysis tools and procedures worked for the project, and to assess whether advance warning signs and other traffic control provided adequate warning for the project. In addition, it is expected that tracking these measures across multiple projects in a region (appropriately categorized by roadway type) to determine whether policies and procedures should be modified in terms of capacity values assumed, analysis tools and procedures allowed, impact mitigation strategy emphases, etc.

Delay Measures

Vehicle-hours of delay are generally the most significant contributor to the additional road user costs created by work zone activities, and so can have significant implications in terms of contracting strategies used and penalties and incentives incorporated into contract language. Relating these total costs in terms of impacts to individual motorists is also important from a customer service perspective that many agencies emphasize. Since queues and delays are correlated, similar trends and insights can be gained through examination of both types of measures. The delay measures pilot tested in this effort do appear to provide information that could be valuable to a highway agency or a contractor, except for the average delay per entering vehicle measure. Initially, this measure was proposed as a way to account for the fact that a work zone can affect some motorists very significantly during those times when congestion and queues are present (and be perceived somewhat negatively by those motorists), but have no effect and so be perceived much more positively by motorists during other times of the work activity when queues have not developed. In reality, attempting to average the impacts across all vehicles only appears to mute the overall effect of the project and give a somewhat unrealistic perception that the impacts to motorists were not all that significant. The average delay per queued vehicle, along with the percent of traffic encountering a queue, appears to be a more straightforward way to account for both the intensity and breadth of work zone impacts on motorists.

Travel Time Reliability Measure

The use of the buffer index as a travel time reliability measure for work zone performance monitoring was demonstrated for one of the pilot test project locations. For projects where recurrent congestion already exists and where reliability is already affected, computation of buffer indices and comparison to the pre-work zone condition appears to offer useful insights into another dimension of user impacts due to the work zone. Two different reliability thresholds were computed (95^{th} percentile and 80^{th} percentile travel times) for the pilot test, and both indicated impacts due to the work zone. However, the magnitude of the impacts differed. Given that travel time reliability measurement research in general has not provided recommendations about appropriate thresholds to use, it would seem appropriate to compute and monitor both as part of work zone mobility performance measurement at the present time.

Safety Measures

Although data were not available to allow computation of safety performance measures for the pilot test locations, the process by which such measures are computed is fairly straightforward. Traditionally, agencies do (eventually) have access to crash data through their statewide crash records system. What is usually missing is the exposure data that is needed to convert the crash data to meaningful rates that can be compared to pre-work zone conditions or across projects, regions, or the state. In addition, the crash data can also be combined with work activity exposure data to assess the impacts of the project or project task upon overall crash numbers or crash costs.

It is also important to utilize and interpret the safety measures (as well as the exposure and mobility-related measures) relative to the goals of a particular project when making decisions regarding the effectiveness of a particular approach used to complete the work. For example, performing a particular task using only nighttime lane closures may result in a higher crash rate (or increase in crash rate) on per vehicle-mile-traveled basis than doing the work doing the day. However, because of the much lower traffic volumes present at night, the total impact upon traffic crashes over the duration of completing that work task might still have been much lower than if it had occurred during the day. Ensuring that the appropriate measure was computed (total crash costs for the project, in this example) will allow agencies to continue to improve their overall processes and procedures for delivering a functional, safe, and high-quality transportation product to the public.

NEXT STEPS

To assist practitioners in applying the findings and lessons learned from this pilot test effort, a primer on selecting and computing work zone performance measures is being developed to accompany this report.

11. REFERENCES

1. Work Zone Safety and Mobility. Code of Federal Regulations, Chapter 23, Part 630—Preconstruction Procedures, Subpart J. U.S. Government Printing Office, Washington, DC, September 9, 2004.
2. Scriba, T., P. Sankar, and K. Jeannotte. *Implementing the Rule on Work Zone Safety and Mobility*. Report No. FHWA-HOP-05-065. FHWA, U.S. Department of Transportation, Washington, DC, September 2005.
3. Tarnoff, P.J., S.E. Young, J. Crunkleton, and N. Nezamuddin. *Guide to Benchmarking Operation Performance Measures: Appendix B, Implementation Guide*. Draft final report for NCHRP 20-7. Available at ttp://www.catt.umd.edu/documents/appendix_b_implementation_guide%20v6.pdf. Accessed May 28, 2009.
4. Ullman, G.L., R.J. Porter, and G.J. Karkee. *Monitoring Work Zone Safety and Mobility Impacts in Texas*. Report No. FHWA/TX-09/0-5771-1. Texas Transportation Institute, College Station, TX. May 2009.
5. Personal communication with Pat McCarty, Indiana Department of Transportation. November 11, 2008.
6. Personal communication with Dave Van Stensel, Michigan Department of Transportation. February 15, 2009.
7. MoDOT Tracker Measures of Performance. Missouri Department of Transportation, Jefferson City, MO. http://www.modot.org/about/general_info/Tracker.htm**.**
8. *Best Practices in Work Zone Assessment, Data Collection, and Performance Evaluation.* Scan Team Report, NCHRP Project 20-68A, Scan 08-04. TRB, National Research Council, Washington, DC. October 2010. Accessible at http://onlinepubs.trb.org/onlinepubs/nchrp/docs/NCHRP20-68A_08-04.pdf.
9. Holstein, D. Work zone Safety and Mobility. Presented at the Montana Regional Work Zone Rule Workshop, April 2006.
10. Khattak, A.J. and F. Targa. Injury Severity and Total Harm in Truck-Involved Work Zone Crashes. In *Transportation Research Record 1877*. TRB, National Research Council, Washington, DC, 2004, pp. 106-116.
11. Garber, N.J. and M. Zhao. Distribution and Characteristics of Crashes at Different Work Zone Locations in Virginia. In *Transportation Research Record 1794*. TRB, National Research Council, Washington, DC, 2002, pp. 19-25.
12. Bryden, J.E., L.B. Andrews, and J.S. Fortuniewics. Intrusion Accidents on Highway Construction Projects. In *Transportation Research Record 1715*. TRB, National Research Council, Washington, DC, 2000, pp. 30-35.
13. *Travel Time Reliability: Making it There on Time, All the Time*. Report No. FHWA-HOP-06-070. FHWA Office of Operations, Washington, DC. Accessible at http://ops.fhwa.dot.gov/publications/tt_reliability/brochure/.
14. Ullman, G.L., M.D. Finley, J.E. Bryden, R. Srinivasan, and F.M. Council. *Traffic Safety Evaluation of Nighttime and Daytime Work Zones*. National Cooperative Highway Research Program (NCHRP) Report 627. TRB, National Research Council, Washington, DC, 2008.
15. Council, F., E. Saloshnja, T. Miller, and B. Persaud. *Crash Cost Estimates by Maximum Police-Reported Injury Severity within Selected Crash Geometries*. Report No. FHWA-HRT-05-051. FHWA, U.S. Department of Transportation, Washington, DC, October 2005.

16. *Intelligent Transportation Systems in Work Zones: A Cross-Cutting Study*. Report No. FHWA-OP-02-025. FHWA, U.S. Department of Transportation, Washington, DC, November 2002.
17. *Measuring Travel Time in Freight-Significant Corridors*. FHWA, U.S. Department of Transportation, Washington, DC. Accessible at http://ops.fhwa.dot.gov/freight/time.htm. Accessed November 1, 2009.
18. *Work Zone Travel Time System. Intelligent Transportation Systems in Work Zones: A Case Study*. Report No. FHWA-HOP-04-032. FHWA, U.S. Department of Transportation, Washington, DC, October 2004.
19. Fontaine, N.D., and B.L. Smith. Prob-Based Traffic Monitoring Systems with Wireless Location Technology: An Investigation of the Relationship between System Design and Effectiveness. In *Transportation Research Record 1925*. TRB, National Research Council, Washington, DC. 2005. Pp. 3-11.
20. Haseman, R.J., J.S. Wasson, and D.E. Bullock. Real Time Measurement of Work Zone Travel Time Delay and Evaluation Metrics Using Bluetooth Probe Tracking. *CD-ROM Compendium*, 89th Annual Meeting of the Transportation Research Board, Washington, DC, January 10-14, 2010.
21. Memmott, J.L. and C.L. Dudek. *A Model to Calculate the Road User Costs at Work Zones*. Report No. FHWA/TX-83/20+292-1. Texas Transportation Institute, College Station, TX, September 1982.
22. *Highway Capacity Manual 2000*. Transportation Research Board, National Research Council, Washington, DC. 2000.

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April 2011

FHWA-HOP-11-022