

SHRP 2 Reliability Project L17

**Gap Filling Project 4:
A Guidebook for
Standard Reporting and
Evaluation Procedures
for TSM&O Strategies**

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Evaluation Procedures for TSM&O
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TRANSPORTATION RESEARCH BOARD

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SHRP 2 Project L17 – A Framework for Improving Travel Time Reliability

**Gap Filling Project 4:
A Guidebook for Standard Reporting and Evaluation
Procedures for TSM&O Strategies**

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Chapter 1. Purpose of the Guidebook

Overview

Operators are increasingly being asked, “What benefits have we gotten from our Transportation Systems Management and Operations (TSM&O) activities?” Ongoing performance monitoring systems are just now being deployed that can help answer that and other questions. But many questions remain. There is no standard way of developing performance measures and collecting and managing data from different sources. Without standardized guidance, agency staff in different geographical areas are likely to develop their own particular approaches, which in turn can pose problems in uniformity, consistency, and data reliability. Also, because area-wide reporting of performance masks the positive effect of TSM&O strategies, it is important to focus on the strategy’s area of influence. Evaluation of deployed TSM&O strategies is being promoted as a major part of ongoing performance monitoring programs. However, lack of guidance on how to conduct these evaluations has limited their usefulness, often leading to a credibility problem.

With the passage of the Moving Ahead for Progress in the 21st Century Act (MAP-21) legislation—and its emphasis on *performance management* of the highway programs—guidance on conducting evaluations is valuable to practitioners. Project evaluations will be a key component of a performance management system and are a valuable adjunct to systemwide trend monitoring. Specifically, Section 1113 (Congestion Mitigation and Air Quality Improvement Program) states

(A) IN GENERAL.—The Secretary, in consultation with the Administrator of the Environmental Protection Agency, shall evaluate projects on a periodic basis and develop a table or other similar medium that illustrates the cost-effectiveness of a range of project types eligible for funding under this section as to how the projects mitigate congestion and improve air quality.

In a performance management environment, evaluations can provide

- Lessons learned about what worked, what didn’t, and why.
- Highlights of the benefits that can be achieved with TSM&O strategies.

Thus, this guidebook has been developed to provide guidance on how to conduct field evaluations and to use the results both internally and externally. The results of evaluations can be used as a way to promote TSM&O. Procedures are presented for conducting empirical evaluations of system operations and management (TSM&O) strategies using an observational study design.

Generally, observational studies can be classified into two groups:

- Before-and-after studies measure the roadway performance before and after certain TSM&O improvements have been implemented on a test site or a group of test sites.
- Cross-sectional studies compare the roadway performances of the improvement sites with the sites without the improvements at one point in time.

Cross-sectional studies are best applied when general relationships between conditions and performance need to be established. Cross-sectional studies require less data than observational before-and-after studies. For example, if a new operational strategy (e.g., incident management or ramp metering) that includes a roadway data collection system is deployed where no data collection previously existed, no data will exist to establish the base (before) condition.

In these cases, a cross-sectional study is more suitable. A cross-sectional study is similar to a before-and-after study with control sites with the exception that the performance measures prior to the improvement are not required. The assumption is that the test sites and control sites would have similar characteristics in the absence of the improvement. However, since there are no before data, this assumption is not verified in a cross-sectional study.

Because they offer a more direct comparison of the effect of operational treatments, observational before-and-after studies are the preferred method for isolating the effect of TSM&O treatments. **Therefore, the remainder of this guidance focuses on the observational before-and-after study design.**

There are few existing guidelines on TSM&O evaluations on congestion and reliability. However, FHWA and other organizations have published various safety guidebooks, including *Highway Safety Evaluation Procedural Guide* (FHWA 1981), *Before-and-After Study Technical Brief* (ITE 2009), and *A Guide to Developing Quality Crash Modification Factors* (FHWA 2010). Some of the guidelines from safety guidebooks have been adopted in this TSM&O evaluation guidebook.

Congestion mitigation is the typical objective of many TSM&O strategies. Traditionally, the evaluation of such strategies has focused on an average congestion condition such as vehicle miles traveled (VMT) and travel times. However, with the recent insights into travel reliability, more recent studies have been using the measures from travel time distributions as the indicators for travel reliability. Besides congestion and travel reliability, another typical objective of TSM&O strategies is safety.

Observational studies usually make use of experimental controls to account for the effect of variation in the measurement of interest and for the effect of endogenous factors. In classic observational before-and-after studies, controls are sites that have not received the improvement (treatment), but have underlying characteristics similar to the test sites before the improvement.

This guidance introduces another method of establishing experimental controls. Because the primary impact of interest is congestion, this method is based on examining the underlying causal factors to congestion in the before and after periods. These underlying factors are

incidents, inclement weather, presence of work zones, and demand. If the underlying factors are similar, then direct observation of the changes in congestion can be made. If one or more of these factors is substantially different, then the guidance recommends that detailed modeling take place. The key aspect of the modeling is to hold the underlying congestion factors constant in the before and after periods.

Although this guidebook focuses on congestion and safety related measures, it should be noted that TSM&O strategies cover a much wider array of areas, such as agency business operations, economic impacts, freight, transit, traveler satisfaction, and environment.

How to Use This Guidebook

This guidebook provides step-by-step procedures for designing and conducting empirically based (i.e., observational) before-and-after studies for operations strategies. While the focus is on operational strategies, the same procedures may be applied to any highway congestion mitigation strategies, including capacity expansion and demand management. Because the method is empirically based, the user must have a variety of data compiled and must be familiar with their structure and limitations. Because travel time reliability is a key component of the guidebook's analysis procedure, continuously collected travel time data is a fundamental component. Continuously collected travel time data are quite voluminous and require that the user have the proper software and basic analysis skills to process.

Appendix D provides an example application of the methodology.

Chapter 2. Methodology for Conducting a Before-and-After Evaluation

There are eight steps that are used in conducting a before-and-after evaluation. These steps are shown in Figure 1. Details for some of these steps are provided in the appendices and are referenced in the text at the appropriate points.

Step 1: Define the Geographic Scope of the Analysis

1.1 Treatment Sections

The geographic scope is driven by the target of the project. For example, if an analysis is performed in order to pinpoint the safety benefits from the implementation of an incident management strategy over a stretch of a freeway, then the scope would be limited to that stretch. On the other hand, if the objective is to quantify safety improvements for an entire downtown area, then the scope would cover all arterials and roads in the downtown area.

In TSM&O evaluations, a test location typically means a roadway section that has implemented certain TSM&O strategies or has seen the impacts of such strategies. For analysis, roadway sections are typically 5 to 10 miles in length. If a larger area is covered, it is advisable to break it up into multiple sections. Study sections should be relatively homogenous in terms of traffic patterns, roadway geometry, and operating characteristics.

To maintain homogeneity, the beginning and end points of analysis sections are typically selected to coincide with major interchanges, intersections, or other locations where traffic conditions change because of traffic or roadway characteristics. Roadway sections should represent typical commute travel patterns so that measurements, such as travel times, collected from these sections represent typical travelers' experiences. Note that data availability, especially travel time data, may also influence the section boundaries.

1.2 Control Sections

In addition to test sections, TSM&O evaluations must include control sections if the control comparison method is used. (See Step 4 for a discussion on establishing the control method.) Ideally, control sections should have similar traffic and roadway characteristics as the test sections and should follow the same selection criteria as test sections, with the exception being that the TSM&O strategies applied on the test sections would have no impacts on control sections. (See the later discussion on establishing controls.)

1.3 “Influenced” Sections

Because improvements may change travel patterns, it is recommended that additional highways that could possibly be influenced by demand changes also be included in the analysis. For example, a freeway improvement that leads to decreased congestion and improved reliability may attract traffic from nearby or parallel routes. It is recognized that the same amount and quality of data may not be available on these nearby routes, but an attempt should be made to include them in the analysis. If they are excluded, the analysis must specifically state so, and should also provide a qualitative assessment of the possible effect.

Exhibit 1 Overview of Before/After Evaluation Methodology

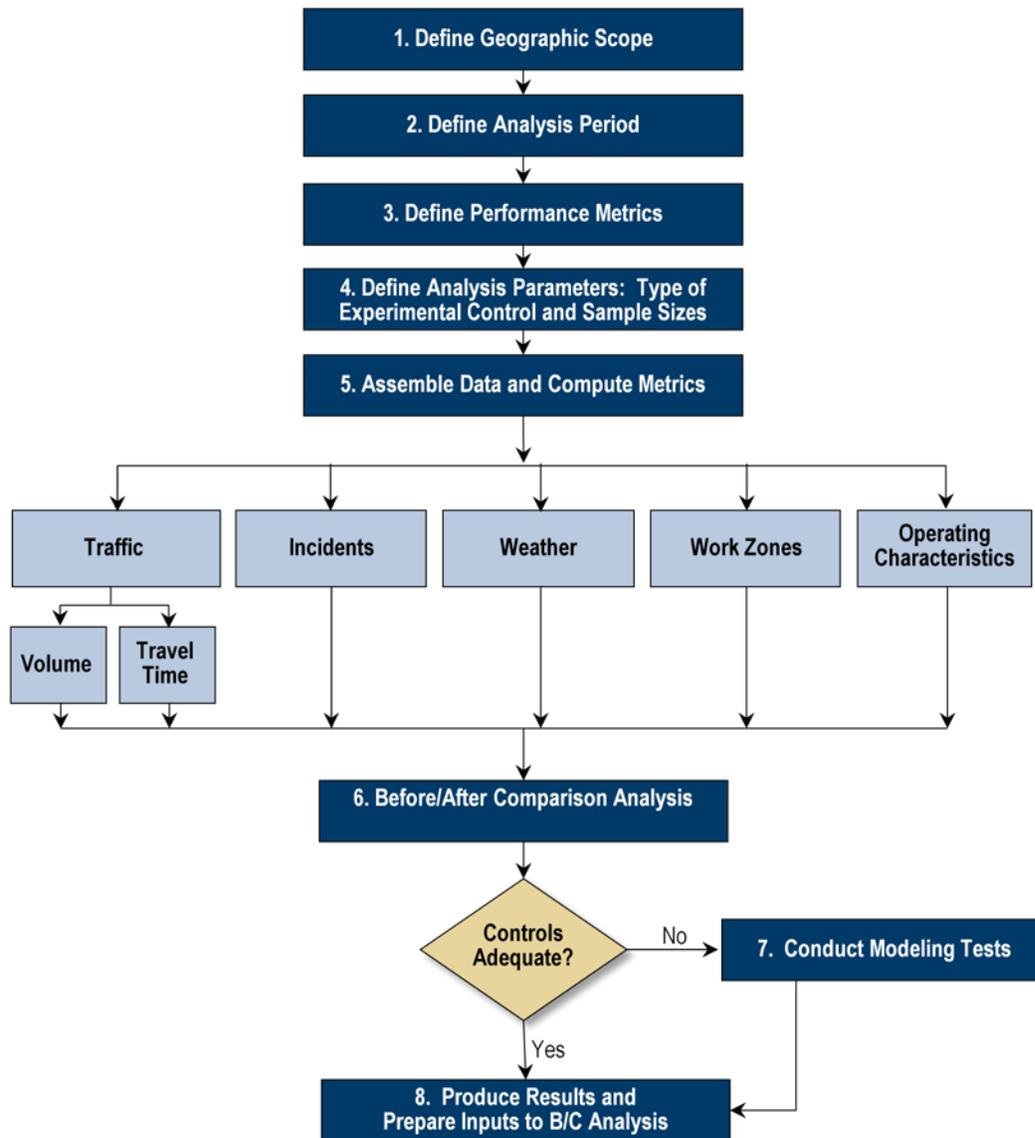


Figure 1. Overview of before-and-after evaluation methodology.

Step 2: Define the Analysis Period

The temporal aspects that should be considered in TSM&O evaluations are

- Time Period
 - Because of the need to compute reliability, a year's worth of data in each of the before and after periods is preferred. Six months is an absolute minimum, but it is likely that seasonal effects will come into play unless the same months of different years are used.
 - For safety analysis, the typical requirement is a minimum of three years of crash data in each of the before-and-after periods. The reason for this is that the number and severity of crashes can vary dramatically from year to year, especially on low-volume highways. If the facility under study is a relatively high-volume facility (e.g., AADT > 100,000), a year's worth of data in each of the before-and-after study periods can be used, with caution. Procedures for adjusting the number of crashes, such as the empirical Bayesian approach presented in the *Highway Safety Manual*, should be investigated when high annual fluctuations in crashes are suspected. In no case should less than a year's worth of data in each period be used.
- The time periods should include user-defined peak periods (a.m. and p.m.), midday, and off-peak periods. The peak periods should be defined for weekday nonholidays. At a minimum, the peak periods should be analyzed; other periods may be added at the analyst's discretion. Note that in some cases, the time period of interest may be different from those mentioned; for example, weekends in rural recreational areas may be the focus of an operational treatment.

Step 3: Establish Performance Measures

3.1 Outcome-Related Performance Measures

The recommendations for performance measures are based on several criteria. First, the measures should be appropriate for evaluations at the project level. The literature identifies many measures that are useful at regional or systemwide scales, but this guidebook is concerned with the performance of individual projects. Second, the measures should be easily understandable by both technical and nontechnical audiences. Third, the measures should be capable of being used in economic analyses. Analysts are free to include additional metrics beyond those recommended here, which are meant to serve as the core set of measures that all evaluations should report.

Congestion: Typical (Average) Conditions

- Travel time (minutes): because the project length or coverage is usually the same in the before and after periods, straight travel time may be used as a performance measure.
- Travel time index (TTI; unit-less): the ratio of actual travel time to the ideal or free-flow travel time. For evaluating an individual project, the ideal or free-flow travel time¹ should be the same in the before and after periods. Although straight travel time is recommended also, the TTI is useful because it is normalized and the project may be compared with others with different project lengths.
- Delay (vehicle-hours and person-hours): the actual vehicle- or person-hours of travel (VHT and PHT) that occur minus those that occur under free flow or ideal conditions. Delay is a useful measure because economic analyses have a long history of applying monetary value to delay.

Congestion: Reliability

Travel time reliability relates to how travel times for a given trip and time period perform over time. There are two widely held ways that reliability is defined. Each is valid and leads to a set of reliability performance measures that capture the nature of travel time reliability. Reliability can be defined as

1. The *variability* in travel times that occur on a facility or a trip over the course of time; and
2. The number of times (trips) that either *fail* or *succeed* in accordance with a pre-determined performance standard.

In both cases, unreliability is caused by the interaction of factors that influence travel times: fluctuations in demand (which may be due to daily or seasonal variation, or special events), traffic control devices, traffic incidents, inclement weather, work zones, and physical capacity (based on prevailing geometrics and traffic patterns). These factors produce travel times that vary from day to day for the same trip.

From a measurement perspective, reliability is quantified from the distribution of travel times, for a given facility or trip and time period (e.g., weekday peak period), that occurs over a significant span of time. One year is generally long enough to capture nearly all of the variability caused by the interactions of factors that influence travel time (see Figure 2). A variety of different metrics can be computed once the travel time distribution has been established, including standard statistical measures (e.g., standard deviation), percentile-based measures (e.g., 95th percentile travel time, Buffer Index), on-

¹ The definition of free flow conditions is somewhat problematic. Analysts can use local values if so desired. However, for the purpose of compiling national results, standard values are required, with recommended standard free flow speeds as follows: 60 mph (urban freeways), 65 mph (rural freeways), and 45 mph (signalized arterials).

time measures (e.g., percent of trips completed within a travel time threshold), and failure measures (e.g., percent of trips that exceed a travel time threshold).

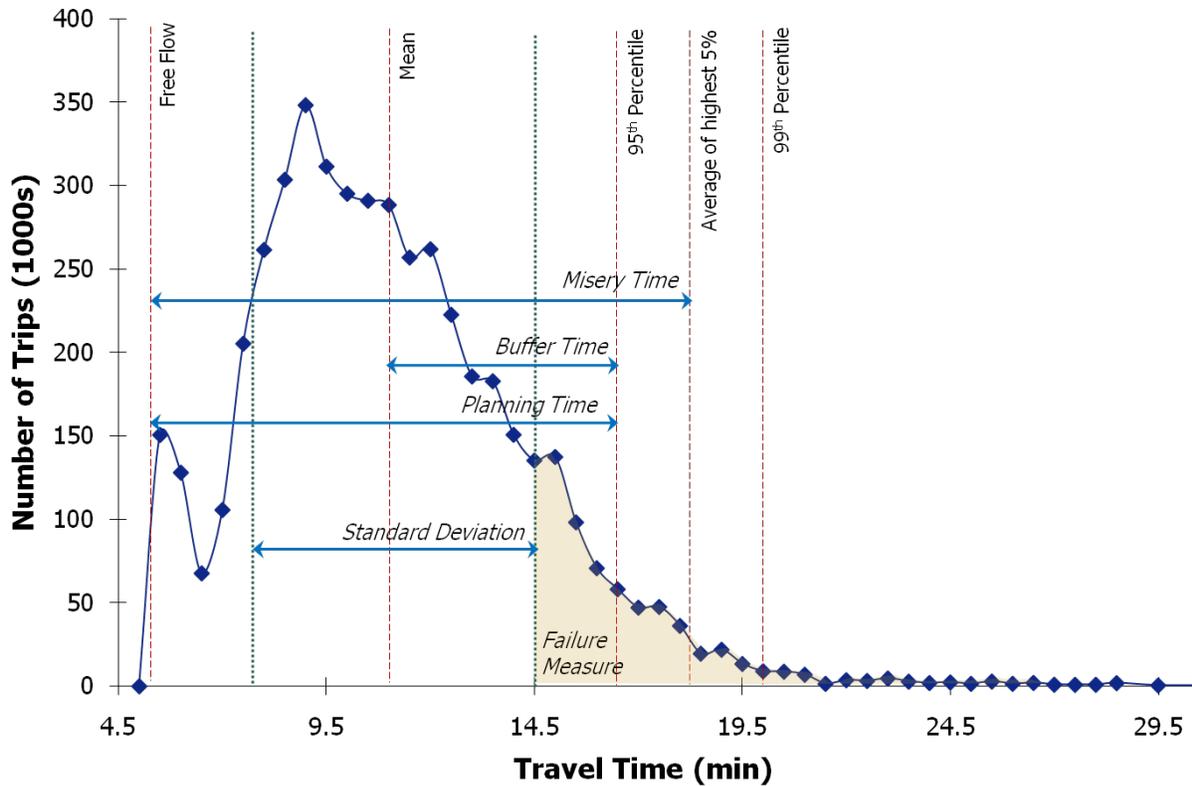


Figure 2. The travel time distribution is the basis for defining reliability metrics.

This guidebook recommends the following reliability metrics as a core set of metrics; analysts may supplement these metrics with additional metrics based on individual analysis needs:

- Planning time index (PTI): the 95th percentile travel time divided by the free flow travel time
- 80th percentile travel time index
- Misery index (rural only): the average of the highest five percent of travel times divided by the free-flow travel time, approximated by the 97.5th percentile.

Safety

For project evaluations, observed crashes from state-maintained data systems are greatly preferred. In some instances, crash prediction methods, such as those in the *Highway Safety Manual*, may also be used. The recommended safety performance measures are

- Number of crashes: total
 - By vehicle type (passenger car, truck)
 - By severity category (fatal, injury, property damage only).
- Total crash rate: total crashes divided by VMT (VMT in millions) for roadway segments and total crashes divided by millions of vehicles entering for intersections.

3.2 Performance Measures for the Causal Factors of Congestion

In addition to providing outcome measures, before-and-after evaluations should also provide additional descriptive measures to develop a complete picture of performance. These measures are used to describe the underlying causal factors for congestion. Specifically, they are used to interpret the outcome results—in particular, to identify if an observed change in travel times is caused at least in part by a change in the underlying conditions. In addition, many operational strategies specifically target causal factors (e.g., incident management, work zone management, weather mitigation), and understanding the change in a targeted factor can provide insight for future deployments. Table 1 presents recommended descriptive measures. These measures must be developed for the same analysis periods selected for the outcome measures (e.g., peak periods).

Table 1. Performance Measures for Tracking the Causal Factors of Congestion

Category	Data Items
Incident Characteristics	Total incidents by type: crashes, stalls, and debris
	Incident rate (incidents per 100 million VMT)
	Incident duration: mean and standard deviation
	Lane-hours lost due to incidents ^a
	Shoulder-hours lost due to incidents ^a
Work Zone Characteristics	Number of work zones
	Lane-hours lost due to work zones ^a
	Shoulder-hours lost due to work zones ^a
Weather	Hours with rainfall $\geq 0.1''$
	Hours with frozen precipitation
	Hours with visibility restricted
Demand	Vehicle-miles of travel (VMT; total for passenger vehicles and trucks combined)
	Person-miles of travel (PMT)
Capacity (by individual segment or intersection)	Number of through lanes (excluding auxiliary lanes)
	Number of auxiliary lanes
	HCM-calculated capacity

^a This is the number of lanes closed multiplied by the number of hours they are closed. As a reference for future studies, lane-hours lost and shoulder-hours lost indices should also be computed. These are the lane-hours lost and shoulder-hours lost divided by the original number of lanes.

If capacity does not change from the before period to the after period, just provide a schematic showing the lane configuration, including the location of on- and off-ramps, lane drops, system interchanges, and weaving sections. See the case study in Appendix D for a sample schematic.

Step 4: Define Analysis Parameters

4.1 Establish Experimental Control

A two-stage experimental control plan is used for TSM&O evaluations. It is based on combining classical control group analysis with examining the causal factors for congestion.

- The first stage of control uses classic definitions of control groups typically used in safety analysis. These controls are relevant not just for the safety portion of a TSM&O evaluation, but also for the congestion analysis portion.
- The second stage tracks trends in the underlying causes of congestion to check if those causes could be influencing the primary congestion measurement; for example, changes in travel times. If a check of the underlying causes of congestion reveals that the underlying causes are substantially dissimilar, then modeling is used so that the congestion effect can be isolated.

Control Groups

The following procedures are adopted from the *Highway Safety Evaluation Procedural Guide* (FHWA 1981) and should be used in selecting control sites:

1. Identify and list candidate control sites. Candidate sites must have operation and geometric characteristics similar to the test sites. Variables to be considered include roadway functional class, adjacent land use, horizontal and vertical alignment, number of lanes, lane width, access control traffic volume, peak direction, peak period, traffic composition, traffic control/law enforcement, roadway geometric, incident/work zone occurrence, and climate condition.
2. Select the candidate sites whose performance is within $\pm 10\%$ of the test site in terms of
 - a. Average annual daily traffic (AADT) for all segments on the site
 - b. Travel time index for the entire facility
 - c. Total crash rate

3. Select the final control sites based on judgment.

A larger number of control sites will result in a higher confidence that performance changes observed at the control sites would be typical to what would be observed at the test sites if no improvement were implemented. It is recommended to use a minimum of two control sites.

Tracking the Sources of Congestion

Even without defining control groups, tracking trends in the contributing causes of congestion can reveal if the observed changes in travel times were unduly influenced by external causes. The causes of congestion that must be tracked are the following:

- Incidents
- Work zones
- Demand
- Weather

The performance measures presented in Table 1 are used to track the sources of congestion.

If one or more of the contributing causes of congestion is substantially different in the before and after periods, it is likely to have influenced the observed travel times. In this case, modeling is used to estimate “what would have happened if before and after conditions were similar.”

4.2 Determining Sample Sizes

It is highly desirable to obtain continuously collected data for all performance categories. In particular, reliability cannot be established without continuously collected travel time data. If continuous travel time data are not available, the procedures in the *Travel Time Data Collection Handbook* (FHWA 1998) can be used. These procedures establish sampling equations based on coefficient of variation, z-statistic (or t-statistic for samples less than 30), and relative permitted error.²

Demand (traffic volume) data are also best collected continuously. This approach allows direct computation of companion demand values for travel times. If these data are not available, then the procedures in FHWA’s *Traffic Monitoring Guide* should be used to estimate demand.

Step 5: Assemble Data and Compute Metrics

A description of the data required to conduct before-and-after analyses appears in Appendix A. The following is a description of how these data are processed into performance metrics.

² *Travel Time Data Collection Handbook*, FHWA, 1998, page 2–10.

5.1 Calculate Travel Time–Based Measures for the Analysis Period

Traffic-related data are the basis for computing congestion and demand metrics. Appendix A shows how these data are processed from their raw state to basic measures of travel times, volumes, VHT, and VMT. At this point, the data have been summarized to the analysis section level at the lowest level of temporal aggregation (e.g., five minutes). The next step is to compute the performance measures for the before and after study periods separately.

Compute Weighted Travel Time Metrics

After the procedures in Appendix A are applied to develop the basic metrics for the study section, distributions for both travel times and TTIs exist. From these distributions, for both the before and after periods, the VMT-weighted median, mean, 80th, 95th and 97.5th percentile travel times and TTIs, as well as any other moments of the distribution the analyst wishes to use, are computed. It is important to weight the observations by VMT because each travel time in the distribution is based on different numbers of vehicles.

Compute Delay (vehicle-hours and person-hours)

The vehicle-hours and person-hours of delay are computed. These are based on the time spent traveling in excess of the time it would take under free-flow conditions. For the study section in question, delay rate (hours per mile) is calculated first:

$$\text{Delay Rate} = (\text{VHT}/\text{VMT}) - (1/\text{FreeFlowSpeed})$$

Delay rate is then multiplied by VMT to get the section vehicle-hours of delay. Person-hours of delay are computed as vehicle-hours of delay multiplied by average vehicle occupancy.

5.2 Crashes

As a starting point, input (or raw) data should be organized by functional class (rural vs. urban; arterials, collectors, locals, etc.). This step may be skipped when the geographic scope of the analysis consists of a single functional class. For example, if the scope is limited to a portion of an urban arterial, then the entire target (raw) dataset is already limited to one functional class. However, if the study covers an area with several road types, then this step becomes necessary.

Specific performance measures are then extracted. The output data may include fatalities, injuries, or any specific type or combination of crashes. (Data could be aggregated or disaggregated, in accordance with the needs of the analysis.) Fatalities or crash numbers can be transformed into fatality rates (such as number of fatalities per population) or crash rates (number of crashes per number of VMT).

5.3 Secondary Crashes

Although secondary crashes have been often mentioned in past performance studies, there is still no commonly accepted procedure to quantify them. FHWA has adopted the following definition for secondary crashes:

“Secondary incidents are unplanned incidents (starting at the time of detection) for which a response or intervention is taken, where a collision occurs either (a) within the incident scene or (b) within the queue (which could include the opposite direction) resulting from the original incidents.”³

There is no consensus on the exact approach to quantify such a definition. Most past studies have used fixed spatial and temporal parameters, such as an influence area of 2 miles upstream, and a clearance time equal to the time required to clear the primary incident plus 15 minutes. Other studies have used dynamic spatial and temporal parameters based on cumulative arrival and departure curves, or applied regression models based on the primary incident’s duration, severity, number of lanes blocked, and environmental factors such as pavement, rain, visibility, and wind. Because of the wide variety of methods used in these studies, a wide range of secondary crash occurrences were reported.⁴

5.4 Calculating Lane-Hours Lost Due to Incidents and Work Zones

Some incident and work zone data sets allow direct calculation of lane-hours lost. These data identify the number of lanes lost and the duration of that loss for each incident. Because the number of lanes blocked can change over the course of an incident, changes in lane blockage should be tracked over the course of an individual incident. If these data are not available, the following procedure can be used for incidents:⁵

$$ILHL = \text{NumberIncidents} \times \text{LanesBlocked} \times \text{IncidentDuration}$$

$$ILHL = \text{Incident lane-hours lost}$$

$$\text{NumberIncidents} = \text{Number of annual incidents (Incident rate and VMT should be computed for the particular time slice under study, e.g., the peak period.)}$$

$$= \text{IncidentRate} \times \text{VMT}$$

$$\text{LanesBlocked} = \text{Lanes blocked per incident}$$

$$\text{IncidentDuration} = \text{Average incident duration (hours), defined as the time between when the incident started and the last lane or shoulder has been cleared.}$$

If the incident rate is unavailable locally, it may be estimated by multiplying the crash rate by 4.5, which assumes that crashes are 22% of all incidents (remaining incidents are primarily vehicle breakdowns and debris on the roadway);

³ Federal Highway Administration Focus States Initiative: Traffic Incident Management Performance Measures, Final Report, 2009.

⁴ Identification of Secondary Crashes and Recommended Countermeasures, Kentucky Transportation Cabinet, 2011.

⁵ Analytics Procedures for Determining the Impacts of Reliability Mitigation Strategies, SHRP 2 Project L03, Cambridge Systematics et al., Transportation Research Board of the National Academies, 2013.

If lanes blocked per incident data are unavailable locally, it can be estimated using the following factors, developed from two years of incident data from Atlanta:

- 0.476 if a usable shoulder is present and it is local policy to move lane-blocking incidents to shoulder as rapidly as possible. (A usable shoulder is capable of safely storing the disabled vehicle and emergency vehicles. This is the policy in Atlanta.)
- 0.580 if lane-blocking incidents are not moved to the shoulder. (Developed by considering lane-blocking incidents that were moved to the shoulder, and reassigning them back to lane-blocking status.)
- 1.140 if usable shoulders are unavailable.

Step 6: Before-and-After Comparison

The purpose of this step is to assess the adequacy of the experimental controls, and to note the changes in congestion and safety performance. Sections 6.1 and 6.2 should be applied for both congestion and safety metrics. If the experimental controls for congestion are deemed to be inadequate after applying these procedures, then detailed modeling is called for (Step 7). Otherwise, the results may be summarized and presented (Step 8).

6.1 Qualitative Test of Control Sites

Hauer (1997) established a general qualitative test of comparability between test sites and control sites for crash measures based on time series plots.⁶ The same principle applies here. Figure 3 shows a time series of travel time indexes for test sites and control sites. An improvement was implemented at the test sites in January 2009. Visual inspection shows that the selected control sites are similar to the test sites during the months before the improvement.

⁶ *Observational Before-After Studies in Road Safety*, E. Hauer, 1997.

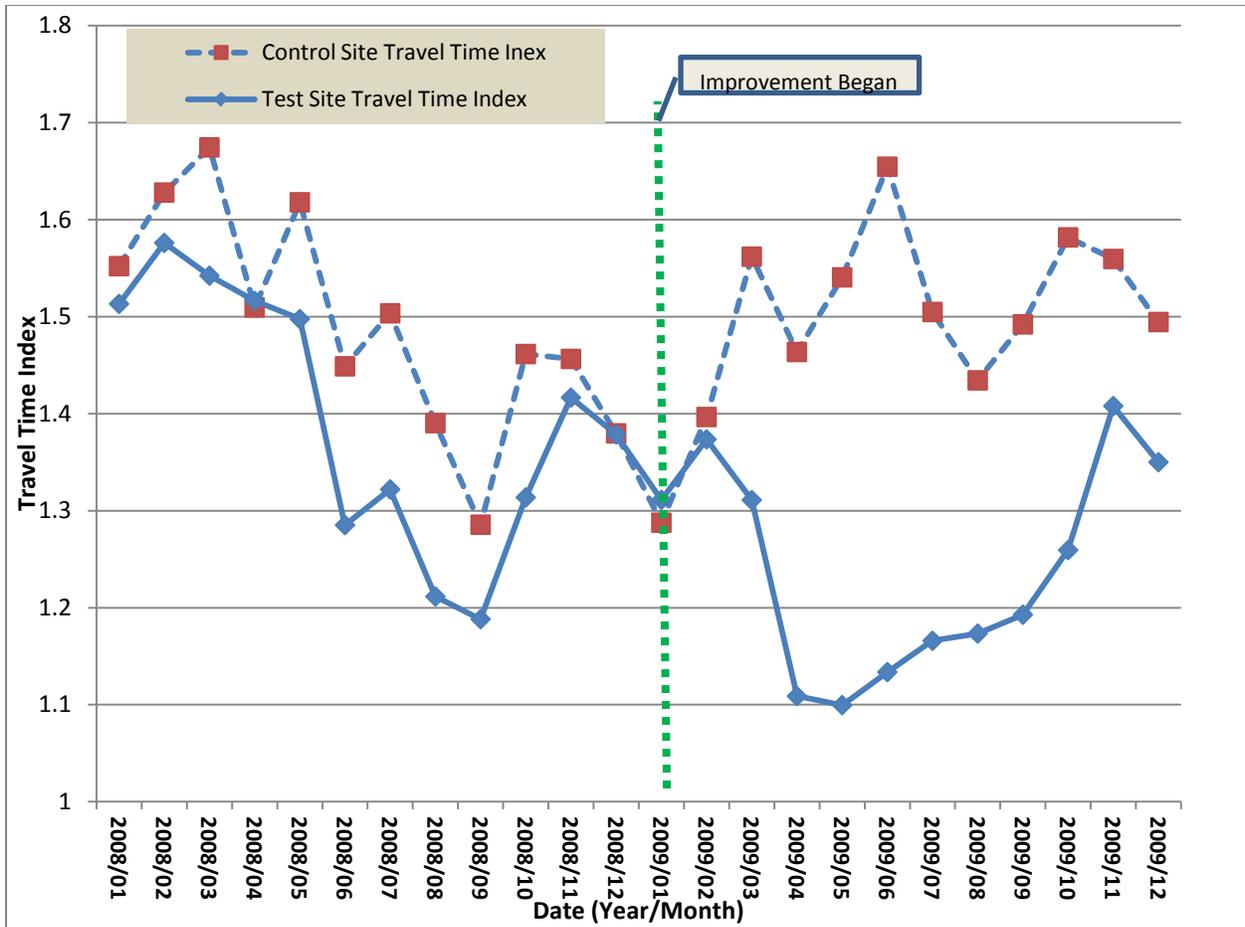


Figure 3. Example time plot of travel time index on test sites and control sites.

6.2 Quantitative Tests for Similar Congestion Causal Factors in the Before and After Periods

The two procedures described above have been adapted from the literature on safety analysis and are appropriate for establishing the change (if any) in crashes between the before and after periods. However, congestion is the result of a complex mix of causal factors that can directly affect observed changes in congestion. Therefore, an additional test is warranted for congestion.

This test is especially important when suitable control sites are not present. For example, a new ramp metering scheme may be deployed at the same time on all major freeways in the region, making it impossible to find a freeway section that has not been affected by the ramp metering.

In these cases, the first step is to check changes in operational conditions in the test sites during the before and after periods. Specifically, if lane-hours lost, VMT, and weather conditions are similar in the before and after periods, a simple comparison of before and after performance measures would be sufficient. However, if any of these conditions vary substantially from the before period to the after period, a simple before-and-after comparison will not be reliable. Instead, a series of simulation modeling runs will be required to estimate roadway performance

under the theoretically unchanged before condition. In essence, simulation software is a tool that is used to generate control group measures (Step 7).

6.3 Before-and-After Study with Control Sites

If the study has been designed with control sites and if the above tests all show that the observations at treatment sites can be trusted, then this step is applied for both congestion and safety: travel time and total crashes are the metrics that should be used, at a minimum.

After the standard computations are conducted on the test sites and control sites during the before and after periods, the next step is to calculate the expected values of performance measures and the expected percent changes in those measures. The expected values at the test sites (as if no improvements are implemented) are derived from the control sites.

Expected Values

The performance measures are averaged for the before period and after period, respectively. Note that the before and after periods for the control and test sites should be the same. Expected values are calculated as follows:

$$E_t = B_t \left(\frac{A_c}{B_c} \right)$$

where:

E_t = Expected performance measures at the test sites if the improvement project had not been implemented

B_t = Before period performance measures at the test sites

A_c = After period performance measures at the control sites

B_c = Before period performance measures at the control sites

Percent Change in Performance

The effectiveness of the improvement on the test sites can be calculated as the percent change:

$$\text{Percent Change} = [(A_t - E_t)/E_t] 100$$

Where:

E_t = Expected performance measures at the test sites if the improvement project had not been implemented

A_t = After period performance measures at the test sites

Step 7: Conduct Modeling Tests, If Required

If the comparison to control sites is inconclusive or if the demand, weather, and incident characteristics in the before and after conditions are substantially different, then modeling should be pursued as a form of control. The idea is to create before and after scenarios based on the same demand, incident, and weather conditions as in the before case. This allows the analyst to answer the question: “What would have happened without the treatment?”

The best form of analysis for evaluating project-level conditions is simulation modeling, either mesoscopic or microscopic simulation models. Macroscopic models may also be considered if resources are limited and they are capable of modeling traffic disruptions, especially incidents and weather. For the purpose of this guidance, the following procedures are adopted from the methodology developed for *Analysis, Modeling, and Simulation of Integrated Corridor Management*, which used microscopic simulation.⁷

7.1 Calibrate the Model

Several metrics should be used to evaluate the model’s performance, including freeway volumes, speed profiles, and congestion patterns and bottleneck locations. The volumes should represent the typical or average condition. In addition to the before-year baseline model calibration, a known incident scenario should be evaluated to test the sensitivity of the simulation model to a major incident.

7.2 Develop Scenarios for Different Operating Conditions

TSM&O strategies need to be evaluated under all conditions, not just normal or average conditions. As such, a series of scenarios should be set up covering different demand, incident or work zone, and weather conditions. Note that current simulation software cannot use weather condition as a direct model input, as little is known about how drivers change their acceleration and deceleration behavior during inclement weather. For now, the recommendation is to ignore inclement weather.

The development of scenarios requires that the analyst have access to data on incidents and demand levels for a minimum of one year in the before period. The next step is to develop the scenarios for the demand and incident parameters. The idea is to create enough scenarios so that a realistic representation of conditions over the course of a year can be made without having to undertake an exhaustive amount of simulation runs. The following steps are recommended to establish the before condition:

- Demand (volume). Develop a distribution from the data for weekdays/nonholidays for the period of interest (e.g., the peak period) for a point on the mainline of the study section that is considered to be representative of the section. Identify the mean, 85th percentile, and 15th percentile volumes. Define factors for three levels of demand:

⁷ *Integrated Corridor Management: Analysis, Modeling, and Simulation Results for the I-15 Corridor in San Diego, California*, U.S. DOT 2010.

- Low: factor = 85th percentile volume/mean volume
- Medium: should be the mean volume and ideally the same as the calibration volume
- High: factor = 15th percentile volume/mean volume

For a given scenario, multiply all of the calibration volumes by the appropriate factor.

- Incidents. Define three levels:
 - No incident
 - Minor incident, 33%–50% of original lanes blocked—duration is the mean of all single lane closures.
 - Major incident, 60%–75% of original lanes blocked—duration is the mean of all two-lane closures.
- Calculate joint probabilities. Construct a matrix as shown in Table 2. The column totals for demand will be roughly equal to 33⅓% if the 15th percentile, mean, and 85th percentile are the boundaries. For the incident boundaries (row totals), examine the incident data to observe the percent of incidents in each severity class (60%, 30%, and 10% are used here as an example). To calculate the joint probability for each cell, multiply the appropriate row and column totals.

Table 2. Joint Probability Calculation Matrix

	Demand			
Incidents	15th percentile	Mean	85th percentile	Total
None				0.600
Minor lane closure				0.300
Major lane closure				0.100
Total	0.333	0.333	0.333	

7.3 Determine the Effect of the Treatment

The analyst must now find a way to represent the treatment in the selected model. In some cases, the treatment can be directly modeled by the simulation model (e.g., the addition of ramp meters). In other cases, the analyst needs to determine the effect the treatment has on basic model parameters: demand decrease, capacity increase, incident duration reduction, and incident frequency reduction (handled by decreasing the probability of incidents).

7.4 Calculate Key Performance Measures from Simulation Outputs

For each combination of demand and incidents, conduct a simulation run for the before condition and the after condition. Multiple runs may be necessary to handle the *internal* stochastic variation in simulation models (e.g., the assignment of driver types). The detailed procedures for computing performance measures are listed in Appendix C. These procedures are based on the report, *Integrated Corridor Management: Analysis, Modeling, and Simulation for the I-15 Corridor in San Diego, California*.

Combine the performance measures from the individual simulation runs into a single (composite) set of performance measures by applying the joint probabilities associated with each run.

The simulated performance measures for before conditions should be compared with observed conditions to ensure that the simulation produces similar results. Once the analyst is satisfied with the simulated before results, the model is then used to represent the control sites and the evaluation procedures for a before-and-after study with control sites (Step 6.3) are applied.

Step 8: Produce Results and Prepare Inputs to Benefit-Cost Analysis

The final step is to compile and present the results. Information from this compilation can then be used as an input to benefit-cost analysis, if so desired. Table 3 presents a prototype for summarizing the results. In addition, because reliability is a major impact area for congestion, reliability profiles should be constructed for the before and after periods individually. (See Figure 4). The basis for the profile is the travel time distribution with the causal factors also displayed. This representation gives the analyst a strong visual method for evaluating congestion and reliability impacts.

Table 3. Example Display of Results

Performance Metric	Before	After	Pct. Change
<i>Congestion</i>			
Travel time, avg. (min.)	7.2	6.2	-13.9%
TTI	1.440	1.220	-15.3%
95th percentile TTI	1.810	1.700	-6.1%
80th percentile TTI	1.650	1.560	-5.5%
Misery Index	2.000	1.920	-4.0%
Delay (veh-hrs)	18,333	10,072	-45.1%
Delay (person-hrs)	20,167	11,079	-45.1%
<i>Safety</i>			
Passenger car crashes	12	12	0.0%
Large Truck crashes	3	3	0.0%
Total crashes	15	15	0.0%
Fatal crashes	1	0	-100.0%
Injury crashes	5	9	80.0%
PDO crashes	9	6	-33.3%
<i>Demand</i>			
Passenger car MVMT	2.100	2.111	0.5%
Large Truck MVMT	0.400	0.407	1.7%
Total MVMT	2.500	2.518	0.7%
<i>Incident Characteristics</i>			
Total incidents	31	29	-6.5%
Incident duration, mean (min.)	28.5	27.4	-3.9%
Incident duration, std. dev.	20.1	19.2	-4.5%
Incident lane-hrs lost	101	110	8.9%
Incident shoulder-hrs lost	212	199	-6.1%
<i>Work Zone Characteristics</i>			
Number of work zones	0	0	0.0%
Work zone lane-hrs lost	N/A	N/A	
Work zone shoulder-hrs lost	N/A	N/A	
<i>Weather Characteristics</i>			
Hours with rainfall \geq 0.1 in.	12	15	25.0%
Hours with frozen precipitation	2	0	-100.0%
Hours with visibility restricted	17	12	-29.4%

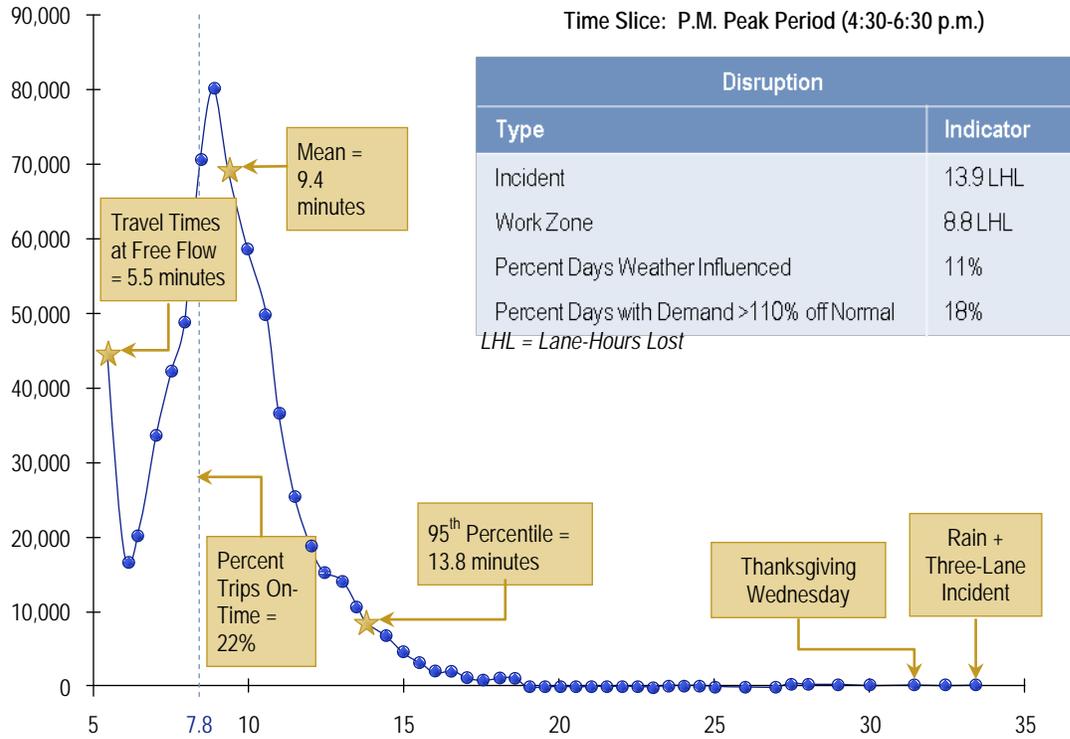
Analysis Period: 4:30–6:30 p.m.

Section Length: 5.0 miles

Before Period: 04/02/09–03/31/10

After Period: 09/01/10–08/31/11

Corridor: I-75 Northbound
I-285 to Roswell Road



Incident Analysis			
Category	Number	Duration (minutes)	
		Mean	95 th Percentile
All	94	32.1	75.5
Lane-Blocking	90	32.4	75.5
Large Truck	2	20.3	38.6

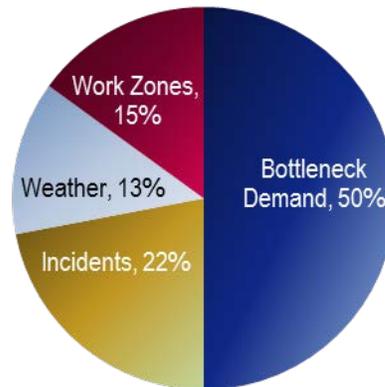


Figure 4. Prototype of the reliability profile.

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- Quality Control Procedures for Archived Operations Traffic Data: Synthesis of Practice and Recommendations*, Final Report. FHWA, U.S. Department of Transportation, 2007, p. 29.
- Private Sector Data for Performance Management*, Final Report. FHWA, U.S. Department of Transportation, 2011.
- Travel Time Data Collection Handbook*. FHWA, U.S. Department of Transportation, 1998, pp. 2–10.

Appendix A

REQUIRED DATA FOR OBSERVATIONAL BEFORE-AND-AFTER STUDIES OF TSM&O DEPLOYMENTS

Traffic Data

For TSM&O evaluation needs, the relevant traffic data are traffic volume, speed, and travel times, and the most common freeway data source is the archive of the traffic operations data collected by many state DOT intelligent transportation systems (ITS). Most ITS deployments utilize point sensors to collect data for each travel lane. These sensors are usually spaced one-third to one-half mile apart. Point sensors collect traffic volume, speed, occupancy, and vehicle classification in some ITS systems. Other ITS systems rely on probe vehicles to provide speed and/or travel time along the traveling routes. Some ITS systems also archive the real-time travel time data posted on roadside message boards. The observation interval of operations data can range from 20 seconds to 15 minutes. Archive data are most often saved as plain text files, where each row represents one observation interval at a detection location identified by unique location references such as detector ID and lane ID.

Besides traffic operations data, most state DOTs also maintain various counting programs. Some of these counts are continuously made at permanent sites such as automatic traffic recorders (ATR), automatic vehicle classifiers (AVC), and weigh-in-motion (WIM) sites, while other counts are made for short periods of time, with no fixed locations. The data formats used by counting programs are similar to those used for traffic operations data; however, the minimum observation interval is usually one hour, which might be too long for TSM&O evaluations.

For evaluation sites not included in a state DOT's data coverage, agencies that undertake TSM&O evaluations should conduct their own data collection. Details on how to conduct data surveys should follow published FHWA guidelines, such as the *Traffic Detector Handbook*, *Traffic Monitoring Guide*, *Travel Time Data Collection Handbook*, and *Highway Performance Monitoring System Field Manual*.

Another option is to purchase commercial traffic data from private vendors. Private vendors provide speed and travel time data on selected roadway sections by using Global Positioning System (GPS), Bluetooth, or wireless location techniques. Some vendors could also provide separate speed data on trucks. Private speed data formats are similar to archived ITS data, where each row represents one observation interval at one location. However, their location-referencing method is different. They use traffic message channel (TMC) links, which are not widely known outside of the private traveler information industry; thus extra effort is required to use the commercial traffic data in TSM&O evaluations. Table A-1 provides an overview of the data sources.

Table A.1. Potential Data Sources

Traffic Data Type	Source	Data Format	Observation Level	Collection Type	Data Coverage
Volume	State DOT	Sensor data archives	Lane level, by vehicle types in some systems	ITS sensors	Usually spaced one-third to one-half mile apart along major freeways and some major arterials
	State DOT	Traffic count reports from permanent or short-term traffic collection devices	Station level by vehicle types	ATR devices	Sparsely located throughout the state highway system
Speed and/or Travel Time	State DOT	Sensor data archives	Lane level	ITS sensors	Usually spaced one-third to one-half mile apart along major freeways and some major arterials
	State DOT	Probe data archives	DOT-defined segment level	Toll tag reader, license plate reader	Along roadway segments between exit/entry and roadside reader devices.
	State DOT	Travel time archive	DOT-defined segment level	ITS sensors	Live travel time posted on roadside message boards throughout major commute routes as well as on the TMC's web site
	Private vendor	Speed data archive	Traffic Message Channel segment level, by vehicle types with some vendors	GPS probe, Bluetooth probe, cell phone location tracking	Along predefined roadway segments on major freeways and arterials.

Disruption Data

Incidents and Work Zones

For TSM&O evaluations, the most relevant incident and work zone data are the records that show when and where any travel lane has been blocked and when it is cleared. Most of ITS systems also archive incident and work zone activities as incident logs. When traffic operations personnel identify an incident, they assign a unique incident ID to it and record each new activity as a new line in the log until the incident is cleared. Logs usually record such information as incident and work zone start and end time, duration, type, severity, impact, and location.

In addition to incident data collected by traffic operations personnel, another common data source is accident reports from state public safety agencies.

Private traveler information vendors could also provide incident data; however, their incident data are geospatially referenced to the same TMC links that their traffic data have been referenced to. Therefore, they have the same shortcomings as private traffic data.

The typical inclement weather events that impact traffic operations are rain, snow, dense fog, and high wind. For TSM&O evaluations, the required data are when and where the inclement weather started and ended, the amount of rainfall and snowfall, visibility, pavement condition, sky condition, wind speed, and wind direction.

Inclement weather data could be obtained from state DOT road weather information system (RWIS) environmental sensor stations (ESS). Most ESS stations report at 20-minute intervals, although some report at 10-minute intervals. ESS data have a limited geographic scope and many available weather stations have limited capabilities—for example, some ESS stations do not measure precipitation intensity, making it difficult to assess the impact of rain or snow on traffic flow.

Another potential weather data source is the National Weather Service Automated Surface Observing System (ASOS). These stations are located at airports. Many ASOS stations have one-minute data archives. Although ASOS data are updated more frequently than state DOT ESS stations, they are limited to airport locations, making them inadequate to capture local variations in precipitation levels.

A third option is to purchase commercial weather data from private vendors. These private weather stations are much more densely spaced than either ESS or ASOS stations, making it easier to find a weather station that is close to traffic detection locations. Many of these weather stations collect data continuously. The weather data that are collected include precipitation rate, daily rain, temperature, dew point, pressure, wind direction, wind speed, humidity, and clouds.

Table A.2 summarizes sources of disruption data.

Table A.2. Sources of Disruption Data

Data Type	Source	Data Format	Detection Coverage
Incident/work zone	State DOT	Incident logs	Freeways covered by freeway service patrol/roadside assistance.
	State Highway Patrol	Accident reports	Statewide
	Private vendor	Incident logs	Throughout major urban areas
Inclement Weather	State DOT ESS station	Weather archives	Sparsely located throughout the State Highway System
	ASOS station	Weather archives	Located near airports
	Private vendor	Weather archives	More densely located than ESS or ASOS stations

Roadway Geometric Data

For the purpose of evaluating TSM&O strategies, the most relevant roadway geometric data are

- *Ramp locations*, to create freeway sections between interchanges;
- *Intersection locations*, to create arterial sections between major intersections;
- *Number of lanes*, to aggregate lane-level traffic data; and
- *Roadway length between detection locations*, to calculate travel times between two detection locations.

Traffic operations data collected from ITS systems usually come with a detector configuration file that provides detector information such as lane number, direction, distance to upstream and downstream detectors, and location. Some ITS systems reference detection locations by milepost or latitude and longitude. Other ITS systems reference their detector locations by crossroad names. While it is easy to convert mileposts into distance, calculating distance based on crossroad names requires extra effort, since the detection locations must be first manually identified in a geographic information system (GIS) map. Likewise, latitude and longitude coordinates need to be matched to road locations, and then the actual road distance between the locations needs to be calculated (an extra step, compared with mileposts).

Private data use TMC segments for their detection locations. These data come with TMC link configurations such as link ID and link length. One or more adjacent TMC links combined would produce a roadway section.

Operations Data

For evaluating TSM&O strategies, the relevant operating data are the operations policies that are implemented on the study roadways. Operations policies include

- Managed lanes: high-occupancy vehicle (HOV) and high-occupancy toll (HOT), truck only, toll lanes, etc.
- Special shoulder/ramp function: queue bypass lane during peak hours.
- Speed zones: speed limits, zone type (school zone, work zone), different speed limit for trucks, variable speed limit.
- Intersection configuration: signal control, turning lanes, pedestrian crossing.

Quality Control

The quality of traffic operations data has been identified as a concern in past studies. In 2010, FHWA issued the following rules regarding real-time data quality in the Section 1201 traveler information requirements of the Safe, Accountable, Flexible, and Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU) (Code of Federal Regulations Title 23 Section 511 Part 511):

- **Information accuracy.** The designed accuracy for a real-time information program shall be 85% accurate at a minimum, or have a maximum error rate of 15%.
- **Information availability.** The designed availability for a real-time information program shall be 90% available at a minimum.

It is essential to apply appropriate quality control procedures when using operations data for performance measure purposes. A standard set of quality control procedures is outlined in FHWA's *Quality Control Procedures for Archived Operations Traffic Data* and shown in Table A.3.⁸

⁸ *Quality Control Procedures for Archived Operations Traffic Data: Synthesis of Practice and Recommendations*, Final Report, FHWA, U.S. Department of Transportation, 2007, p. 29.

Table A.3. Standard Quality Control Procedures

Validity Criteria	Default Parameter
Prescreening Criteria	
Controller error codes (e.g., -1, 255, etc.)	n.a.
Check consistency of elapsed time and poll cycles	n.a.
Check for duplicate records (location ID, date, time identical)	n.a.
If VOL=OCC=SPD=0, then set SPD=missing/null (no vehicles present)	n.a.
Univariate Range Criteria	
Minimum volume	0 vehicles
Maximum volume	3000 vphpl (adjust for appropriate time interval)
Minimum occupancy	0%
Maximum occupancy	100%
Minimum speed	0 mph
Maximum speed	100 mph
Multivariate Logical Consistency	
Maximum consecutive identical volume & occupancy & speed values (including VOL=OCC=SPD=0)	Number of reporting intervals that corresponds to 30 consecutive minutes (max.) with no vehicles detected
If volume>0 & speed=0 then invalid	n.a.
If volume=0 & speed>0 then invalid	n.a.
If volume=speed=0 & occupancy>0 then invalid	n.a.
If occupancy=0 and volume>volume _{max} (based on maximum possible volume when occupancy value is truncated to 0)	$VOL_{max} = [(2.932 \times SPEED \times ELAPSED_TIME) / 600]$

Source: *Quality Control Procedures for Archived Operations Traffic Data*

Private vendors perform their own quality control on their speed data and usually provide quality control indicators such as sample size, standard deviation, and confidence interval. Most vendors indicate that their data meets the Section 1201 requirement.⁹

Data Fusion

Data fusion is the process of bringing traffic data, disruption data, roadway data, and operating data together for a common facility location and during a common time period. (See Figure A.1.)

Data fusion for DOT data is relatively easy because DOT data typically use latitude and longitude or milepost as the location referencing system. On the other hand, most private data use TMC as a georeferencing system, which is not widely known outside of the transportation community.

There are two common types of data fusion:

- Combining DOT traffic count program volume data with private speed data; and

⁹ *Private Sector Data for Performance Management*, Final Report, FHWA, U.S. Department of Transportation, 2011.

- Combining DOT traffic operations data with DOT traffic-count program volume data.

Both types of data fusion would employ the following steps:

Step 1: Find Common Spatial Link

The first step of data fusion is to establish a common geospatial link among the data. As mentioned before, state DOT data are commonly referenced to roadway milepost or latitude and longitude, while private data are referenced to TMC links. The TMC links must be imported into GIS maps so that the DOT data can be linked to the TMC data. Private data do not provide speeds at lane level, so any lane-level volumes would need to be aggregated.

Step 2: Find Common Time Intervals

Different datasets might use different time intervals. For example, speed data are frequently provided at 15-minute intervals, while volume data are typically hourly or daily. Therefore, a common interval needs to be established. If a 15-minute period is found to be appropriate for TSM&O evaluations, for example, the hourly or daily volumes would be transformed into 15-minute volumes based on historical hourly and 15-minute peak factors.

Step 3: Find Common Vehicle Types

Some traffic datasets may report data for different vehicle types (e.g., trucks and other motorized vehicles), while other datasets provide data for the traffic stream as a whole. TSM&O evaluation needs to select an appropriate common vehicle type. For example, it could be desirable to measure performance separately for trucks. Therefore, if truck speed data can be obtained, but no truck volume data are available, truck volumes would need to be estimated based on historical truck percentages.

Processing Traffic Data to Basic Metrics (Travel Times, VHT, and VMT)

Computing Basic Study Section Statistics from Roadway Detector Data

The analyst must first define the time periods to be analyzed. At a minimum, the morning and afternoon peak periods for nonholiday weekdays should be used, since these are the times when congestion will be most apparent. The beginning and ending times of the peak periods should be based on local knowledge of traffic patterns. The ending time should be late enough to capture queuing that begins earlier.

If fixed roadway sensors measuring point-based speeds and volumes are used, the procedure described in this section should be used. If probe data are used, the procedure described in the next section should be used instead.

When point-based speeds and volumes are used, travel times are synthesized for the lowest level of aggregation present in the data using the spot speeds. The assumption is that the spot speeds are uniform across a length of highway equal to half the distance to the nearest upstream and downstream detectors. Detector spacing significantly affects the accuracy of this

assumption—the closer the spacing, the more reasonable the assumption is. The steps in this aggregation process are these:

Step 1: Combine lane data into station data

If data are reported by lane, the lane-by-lane data are combined into a “station” (e.g., all lanes in a direction). Traffic volumes are summed across all lanes, and the traffic speed is reported as a weighted average, with weighting based on the respective lane traffic volumes. If volume data are missing for any of the lanes, the total station volume is factored up by the ratio of the total number of lanes to the number of lanes with valid data.

Step 2: Calculate link statistics

Link properties are estimated from station data by assuming that each station has a zone of influence equal to half the distance to the detectors immediately upstream and downstream (detector zone length). The measured speeds are then assumed to be constant within each zone of influence.

$$\begin{aligned}
 VMT &= Volume \times DetectorZoneLength \\
 VHT &= VMT / (Min(FreeFlowSpeed, Speed)) \\
 TravelTime \text{ (hrs)} &= DetectorZoneLength / Speed
 \end{aligned}$$

Step 3: Calculate Section Statistics

Adjacent freeway links with similar characteristics are then combined into analysis sections that are typically 5 to 10 miles long. The beginning and end points of analysis sections typically coincide with major highway interchanges or other locations where traffic conditions are expected to change because of traffic or roadway characteristics.

Section VMT, VHT, and travel time is the sum of these measures for each link within the section. If any data are missing for any of the stations, the total section VMT, VHT, or travel time is factored up by the ratio of the total section length to the total length of stations with valid data.

The following metrics are the computed for the section:

$$\begin{aligned}
 SpaceMeanSpeed &= VMT / VHT \\
 TravelRate &= 1 / SpaceMeanSpeed \\
 TTI &= MAX(1.0, (TravelRate / (1 / FreeFlowSpeed)))
 \end{aligned}$$

Computing Basic Study Section Statistics from Probe-Based Data

Since vehicle probe-based measurement systems provide direct measurements of travel time, section-level travel times for the lowest level of data aggregation can be summed from the link travel times. However, a major issue with probe-based travel times is that there are no corresponding volume measurements, unless a permanent counting device happens to be located within the study section. If this is the case, VMT is computed from the permanent device. Two caveats apply to this approach:

- First, the data aggregation level may be longer than that used for travel times. It is common for state traffic monitoring groups to set the lowest level of aggregation at one hour.
- Second, using a single counting device for the entire study section (which may include multiple interchanges or intersections where traffic volume changes) assumes that the volume is representative of the entire section. If traffic patterns are roughly the same in the before and after periods, this assumption should not pose a problem for the analysis.

If a permanent traffic counting device is not present within the section, short duration counts and adjustment factors must be used. All DOTs maintain an extensive short count program on major highways, producing estimates of average annual daily traffic (AADT). Since these are 24-hour estimates, a procedure must be used to split out traffic to at least the hourly level. Local hourly factors are best for this purpose. If they do not exist, the factors in Appendix B may be used. These factors were developed by analyzing data from over 700 permanent traffic counters from around the U.S.

Once both travel times and volumes are obtained, the analyst then proceeds with the preceding (point-based) methodology to compute the basic metrics.

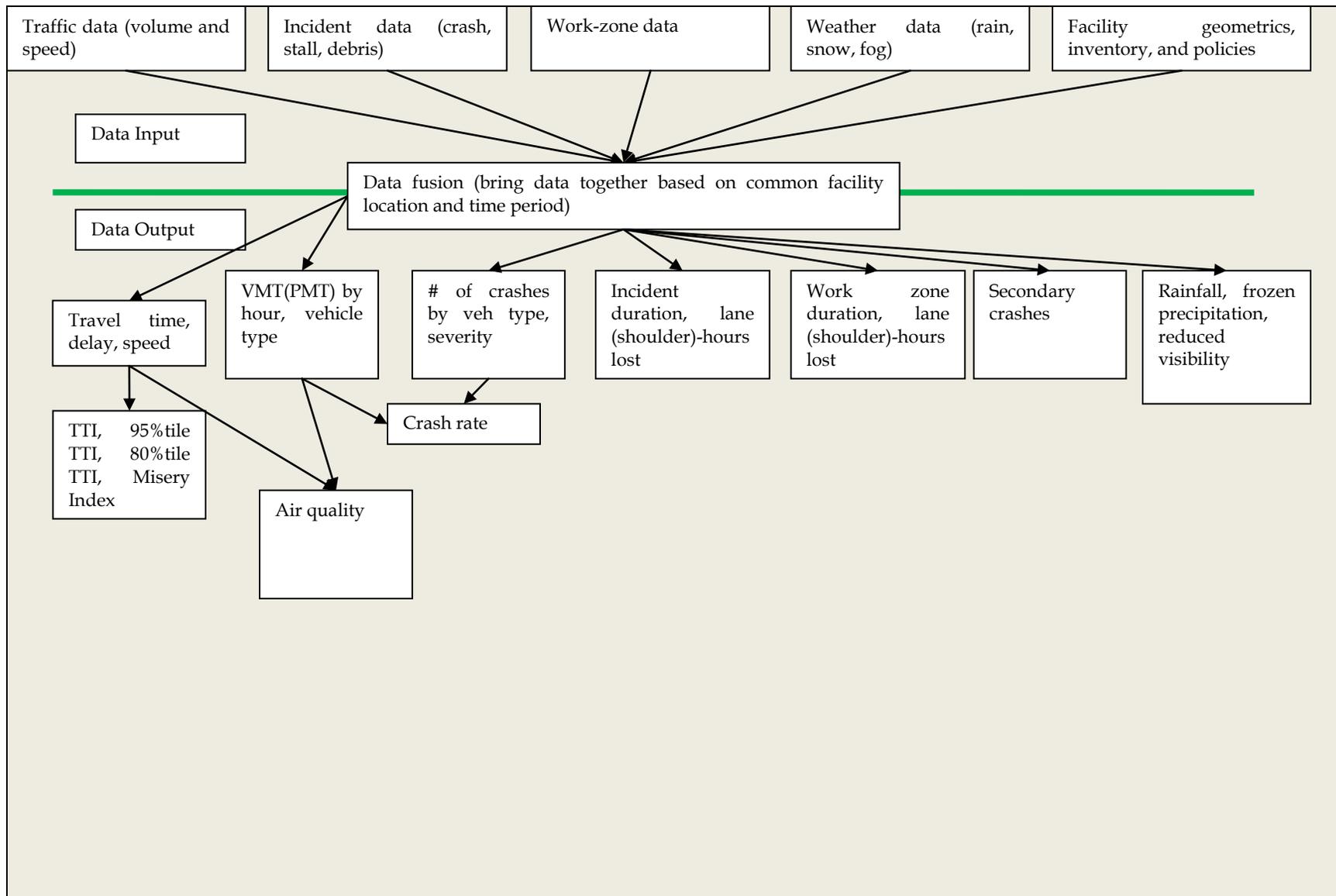


Figure A.1. Data fusion flowchart.

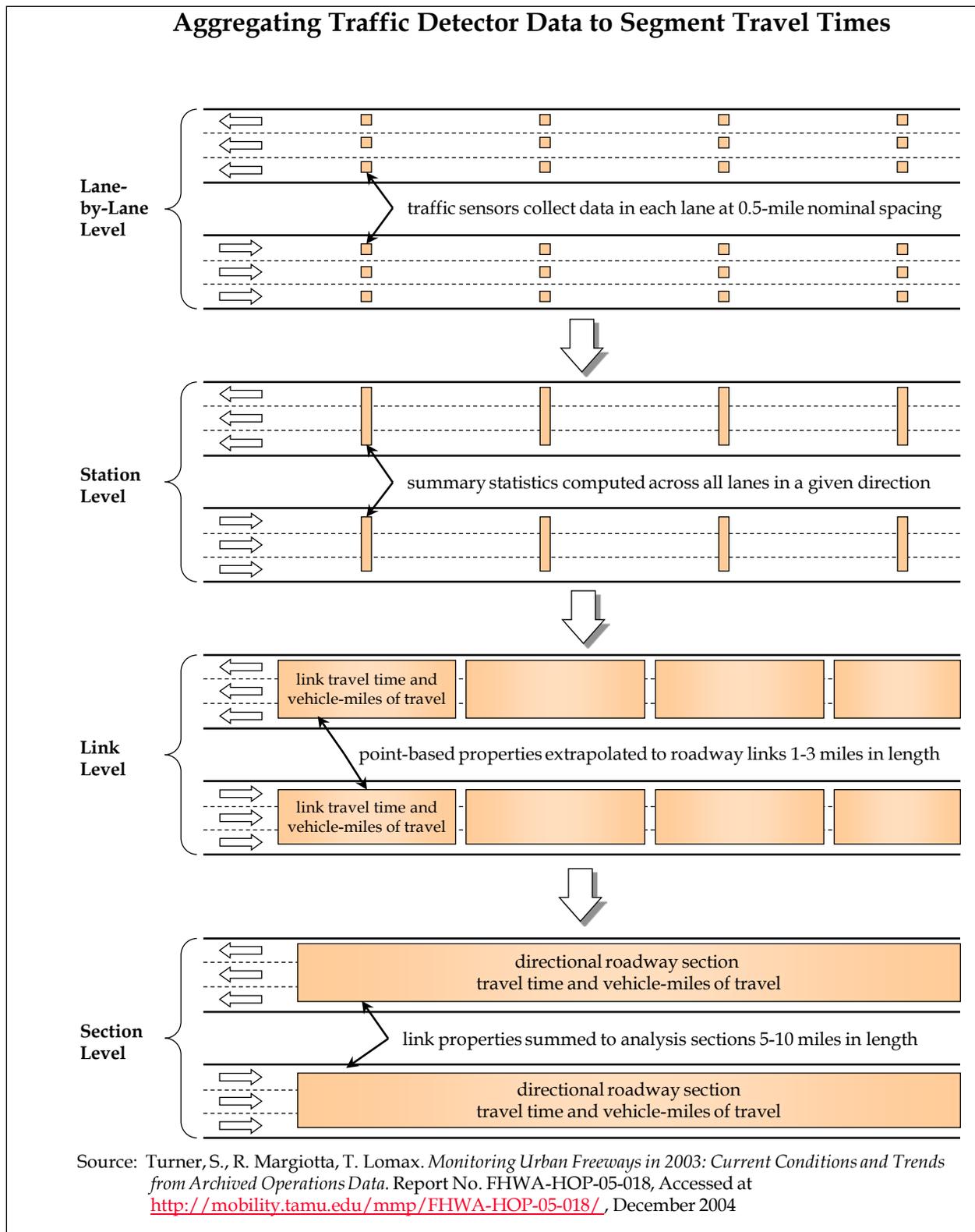


Figure A.2. Aggregating traffic detector data to segment travel times.

Appendix B

Default Hourly Distribution Factors

Type of Facility: Freeway

Arterial

Hour	AADT/C						AADT/C					
	LE 7.0		7.1 - 11.0		GT 11.0		LE 7.0		7.1 - 11.0		GT 11.0	
	Peak Direction		Peak Direction		Peak Direction		Peak Direction		Peak Direction		Peak Direction	
	AM	PM										
	Pct. of	Pct. Of										
Daily	Daily	Daily	Daily	Daily	Daily	Daily	Daily	Daily	Daily	Daily	Daily	Daily
Volum	Volume	Volume										
e												
1	0.42	0.58	0.44	0.57	0.47	0.54	0.34	0.47	0.37	0.47	0.41	0.49
2	0.27	0.33	0.27	0.34	0.27	0.32	0.21	0.28	0.23	0.27	0.24	0.28
3	0.23	0.25	0.22	0.26	0.20	0.24	0.15	0.18	0.17	0.18	0.18	0.20
4	0.23	0.22	0.21	0.21	0.18	0.18	0.14	0.14	0.16	0.15	0.17	0.18
5	0.38	0.29	0.35	0.28	0.31	0.25	0.24	0.18	0.28	0.20	0.33	0.27
6	1.17	0.68	1.12	0.69	1.06	0.72	0.74	0.42	0.81	0.48	1.03	0.67
7	3.26	1.75	3.16	1.90	2.86	2.18	2.23	1.19	2.35	1.27	2.55	1.72
8	4.83	2.90	4.59	3.05	3.90	3.27	4.11	2.28	3.85	2.39	3.57	2.79
9	3.56	2.57	3.80	2.76	3.66	3.04	3.45	2.33	3.42	2.39	3.09	2.78
10	2.58	2.24	2.75	2.30	2.94	2.53	2.64	2.29	2.69	2.31	2.68	2.47
11	2.46	2.33	2.50	2.34	2.68	2.49	2.64	2.56	2.65	2.54	2.62	2.57
12	2.56	2.56	2.61	2.61	2.73	2.69	2.90	3.02	2.90	2.98	2.83	2.89
13	2.65	2.71	2.68	2.75	2.75	2.78	3.20	3.35	3.17	3.30	3.04	3.13
14	2.70	2.77	2.75	2.81	2.82	2.86	3.14	3.24	3.14	3.22	3.06	3.13
15	2.93	3.12	2.93	3.15	2.97	3.15	3.18	3.44	3.116	3.37	3.21	3.34
16	3.26	4.01	3.21	3.87	3.21	3.60	3.40	4.13	3.35	3.93	3.41	3.78
17	3.47	4.81	3.38	4.43	3.28	3.82	3.46	4.78	3.49	4.49	3.47	3.92
18	3.42	4.85	3.32	4.39	3.29	3.77	3.31	4.83	3.45	4.55	3.39	3.86
19	2.66	3.23	2.66	3.20	2.82	3.22	2.68	3.23	2.75	3.31	2.82	3.12
20	1.95	2.23	1.97	2.25	2.12	2.36	2.14	2.41	2.18	2.53	2.28	2.53
21	1.54	1.78	1.54	1.79	1.62	1.86	1.73	1.97	1.75	2.07	1.83	2.09
22	1.40	1.63	1.44	1.69	1.54	1.74	1.49	1.71	1.50	1.77	1.55	1.80

23	1.14	1.30	1.19	1.39	1.27	1.46	1.10	1.26	1.11	1.25	1.22	1.29
24	0.79	0.98	0.83	1.05	0.89	1.07	0.74	0.94	0.75	0.90	0.83	0.97
TOTAL	49.87	50.13	49.92	50.08	49.84	50.16	49.36	50.64	49.67	50.33	49.71	50.29
L												

1. Source: COMSIS Corporation, et al., Development of Diurnal Traffic Distribution and Daily, Peak, and Offpeak Vehicle Speed Estimation Procedures for Air Quality Planning, prepared for FHWA, Work Order B-94-06, April 1996.

Appendix C

Calculation Procedures for Key Performance Measures from Simulation Outputs

Introduction

This appendix presents methods for computing travel time measures to be used in the empirical before-and-after studies presented in this guidebook. Typically, some level of manipulation is required for simulation output to develop measures not included in their standard reports. The purpose is to standardize the computation of these measures so they are directly comparable across studies.

Travel Time

The basic unit of observation is a trip i made between an origin o and a destination d , starting within a particular time interval τ using mode m .

The travel time from a single run of the simulation under operational conditions k for this unit of observation is $t_i^k = t_{o,d,\tau,m}^k$. Let k be a specific operational condition and the set of all conditions K . Note that each condition has a probability of occurrence p_k and that the total probability of all conditions in K is 1; that is, $\sum_k p_k = 1$.

The average travel time of trips with a specific origin and destination, using a specific travel mode, that start in this time interval is

$$T_{o,d,\tau,m}^k = \frac{\sum_{i \in I_{o,d,\tau}^k} t_i^k}{n_{o,d,\tau,m}^k} \quad (1)$$

where $n_{o,d,\tau,m}^k > 0$.

The travel time is set to zero when the number of modal trips between the origin and destination in the time interval is zero; that is $T_{o,d,\tau,m}^k = 0$ when $n_{o,d,\tau,m}^k = 0$.

The calculation of Equation 1 must also include some estimated travel time for trips that cannot reach their destinations by the end of the simulation period.

Equation 2 finds the average travel time by mode for all trips from o to d starting in interval τ over all conditions where at least one trip is made, $k \in K'_{o,d,\tau,m}$.

$$T_{o,d,\tau,m} = \frac{\sum_{k \in K'_{o,d,\tau,m}} T_{o,d,\tau,m}^k p_k}{\sum_{k \in K'_{o,d,\tau,m}} p_k} \quad (2)$$

The average number of trips by mode from o to d starting in interval τ over all conditions $k \in K$ is

$$n_{o,d,\tau,m} = \sum_{k \in K} n_{o,d,\tau,m}^k p_k \quad (2a)$$

Combining across modes, the average travel time of trips from o to d starting in interval τ under operational condition k is

$$T_{o,d,\tau}^k = \frac{\sum_m T_{o,d,\tau,m}^k n_{o,d,\tau,m}^k}{n_{o,d,\tau}^k} \quad (3)$$

where $n_{o,d,\tau}^k > 0$. Let $T_{o,d,\tau}^k = 0$ when $n_{o,d,\tau}^k = 0$.

The average travel time for all trips from o to d starting in interval τ under $K'_{o,d,\tau}$ for the subset of conditions where $n_{o,d,\tau}^k > 0$, $K'_{o,d,\tau} \subseteq K$ is

$$T_{o,d,\tau} = \frac{\sum_{k \in K'_{o,d,\tau}} T_{o,d,\tau}^k p_k}{\sum_{k \in K'_{o,d,\tau}} p_k} \quad (4)$$

The average number of trips from o to d starting in interval τ over all conditions $k \in K$ is

$$n_{o,d,\tau} = \sum_{k \in K} n_{o,d,\tau}^k p_k \quad (4a)$$

Equation 5 defines the trip-weighted average travel time of the system across all o,d,τ :

$$\bar{T} = \frac{\sum_{\forall o,d,\tau} T_{o,d,\tau} n_{o,d,\tau}}{\sum_{\forall o,d,\tau} n_{o,d,\tau}} \quad (5)$$

Delay

Delay can be broadly defined as travel time in excess of some *subjective minimum* travel time threshold. Often, discussions of delay that focus solely on roadway-only travel focus on either travel time at posted speeds or 85th percentile speeds.

Calculate the zero-delay threshold for each O-D pair by mode by looking across all operating conditions and all time intervals:

$$T_{o,d,m}^0 = \min_{k \in K, \tau \in T} \left\{ T_{o,d,\tau,m}^k \right\} \quad (6)$$

Using zero-delay thresholds $T_{o,d,\tau,m}^0$, calculate average trip delay under condition k for each o, d, τ, m :

$$D_{o,d,\tau,m}^k = \max \left[T_{o,d,\tau,m}^k - T_{o,d,\tau,m}^0, 0 \right] \quad (7)$$

Combining across all operational conditions, calculate the average delay for each o, d, τ, m over $K'_{o,d,\tau,m}$, the subset of conditions where $n_{o,d,\tau,m}^k > 0$:

$$D_{o,d,\tau,m} = \frac{\sum_{k \in K'_{o,d,\tau,m}} D_{o,d,\tau,m}^k p_k}{\sum_{k \in K'_{o,d,\tau,m}} p_k} \quad (7a)$$

Combining across modes, the average delay for trips from o to d starting in interval τ is

$$D_{o,d,\tau} = \frac{\sum_{m} D_{o,d,\tau,m} n_{o,d,\tau,m}}{n_{o,d,\tau}} \quad (8)$$

where $n_{o,d,\tau} > 0$. Let $D_{o,d,\tau} = 0$ when $n_{o,d,\tau} = 0$.

The systemwide average trip delay is:

$$D = \frac{\sum_{\forall o,d,\tau} D_{o,d,\tau} n_{o,d,\tau}}{\sum_{\forall o,d,\tau} n_{o,d,\tau}} \quad (9)$$

Aggregating this average delay over all trips produces total system delay:

$$\hat{D} = \sum_{\forall o,d,\tau} D_{o,d,\tau} n_{o,d,\tau} \quad (10)$$

Travel Time Reliability

To identify the 95th percentile travel time, first generate an ordered list of travel times for each combination of o, d, τ, m across all operating conditions:

$$T_{o,d,\tau,m} = \left[T_{o,d,\tau,m}^1, T_{o,d,\tau,m}^2, \dots, T_{o,d,\tau,m}^J \right] \text{ where } T_{o,d,\tau,m}^j \leq T_{o,d,\tau,m}^{j+1} \text{ for all } j = 1 \dots J. \quad (11)$$

The 95th percentile travel time from this list is identified using the probabilities associated with each operational condition.

$$T_{o,d,\tau,m}^{[95]} = T_{o,d,\tau,m}^j \text{ where } \sum_{k=1}^j p_k = 0.95 \quad (11a)$$

Equation 12 defines the planning time index for each combination of o, d, τ, m based on the ratio of the 95th percentile travel time to the zero-delay travel time for trips from o to d starting in interval τ using mode m over all conditions $k \in K$:

$$\rho_{o,d,\tau,m} = \frac{T_{o,d,\tau,m}^{[95]}}{T_{o,d,\tau,m}^0} \quad (12)$$

Equation 12a defines the planning time index by combination of o, d, τ across all modes:

$$\rho_{o,d,\tau} = \frac{\sum_m \rho_{o,d,\tau,m} n_{o,d,\tau,m}}{n_{o,d,\tau}} \quad (12a)$$

The average systemwide planning time index considers all combinations of o, d, τ , with the average weighted by trip volume:

$$\rho = \frac{\sum_{\forall o,d,\tau} \rho_{o,d,\tau} n_{o,d,\tau}}{\sum_{\forall o,d,\tau} n_{o,d,\tau}} \quad (13)$$

An analyst may also be interested in calculating a trip-weighted planning time index within a mode across all combinations of o, d, τ :

$$\rho_m = \frac{\sum_{\forall o,d,\tau} \rho_{o,d,\tau,m} n_{o,d,\tau,m}}{\sum_{\forall o,d,\tau} n_{o,d,\tau}} \quad (13a)$$

A similar procedure is used to calculate the 80th and 97.5th percentile travel times. To compute the 97.5th and 80th percentile TTIs, divide the travel time percentiles computed above by the free-flow travel time. The misery index is approximated by dividing the 97.5th percentile travel time by the free flow travel time.

Appendix D

Example Application

Geographic Scope and Analysis Period

A ramp metering test pilot program has been implemented since January 2009 at all entrance ramps in both directions of a 6-mile-long freeway section in a major metropolitan area. Another freeway in the same metro area had no ramp meters during that time. Figure D.1 shows the freeway network in the study area, where black lines represent the locations of the treatment (test) section and the control section.

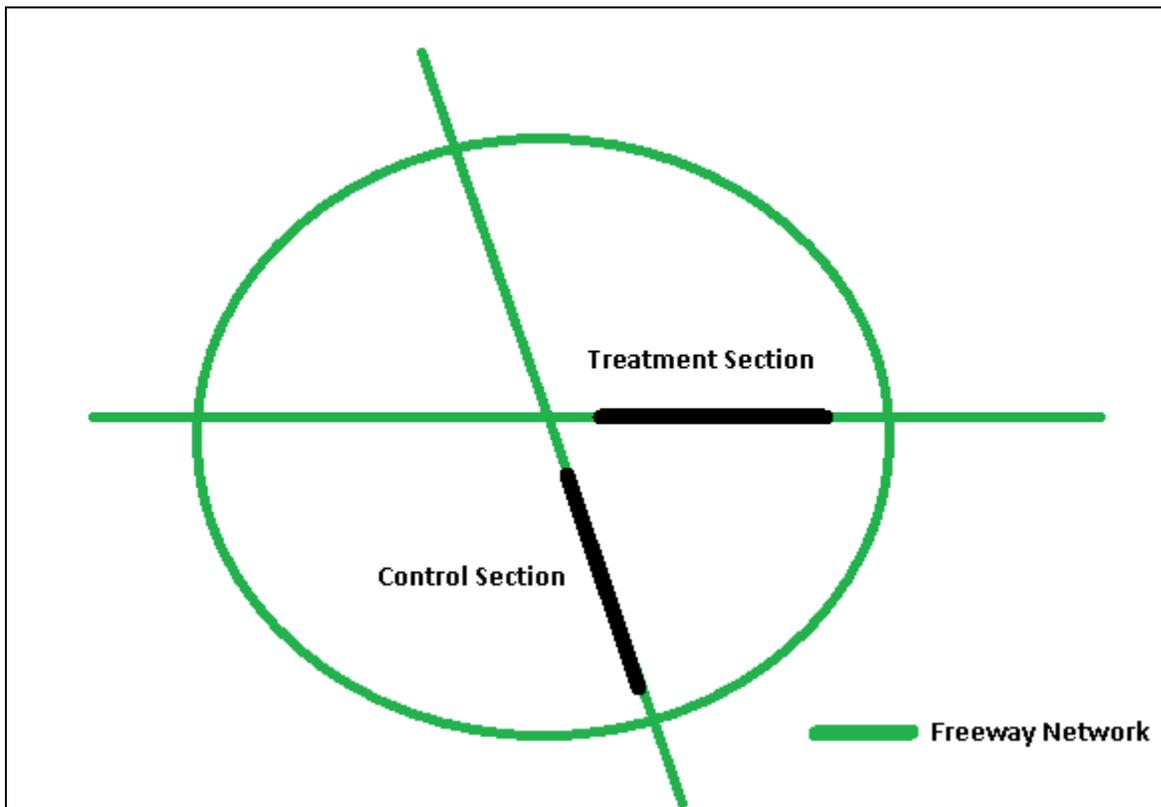


Figure D.1. Location map.

The treatment freeway section (i.e., where ramp meters have been added) serves as a major commute route for the metro area, and it has consistent traffic patterns and roadway configurations shown in Figure D.2. The highest traffic volumes occur in the eastbound direction during afternoon peak hours.

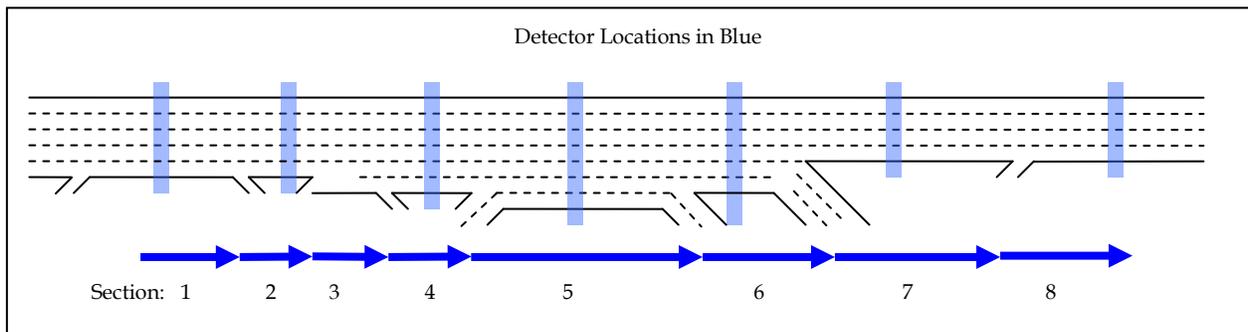


Figure D.2. Schematic of test section.

The control section is another 6-mile-long section of a different freeway where no ramp meters have been installed. The control section is also a major commute route, and peak traffic volumes occur southbound during the afternoon peak hours, which is similar to the treatment section. Roadway characteristics on these two sections are also similar.

The analysis period is 3 p.m. to 8 p.m. The before period covers the 12 months from January 2008 to December 2008, while the after period covers January 2009 to December 2009.

Assemble Data and Compute Performance Measures

Traffic Data

Both the test and control sections are equipped with loop detectors that record 20-second traffic volumes, detector occupancy, and speed data, which are subsequently archived. Following the procedures in this guidebook, the original speed data are converted into freeway section travel times. The calculated section travel times are then used to evaluate all the travel time-based performance measures. Congestion-based performance measures are calculated quarterly and yearly, and reliability measures are determined on a yearly basis.

Continuously collected traffic and travel time data for on-ramps and nearby signalized highways are not available for this study. Therefore, *the analysis is focused solely on the freeway facility*. Spot checks were made of several key ramp locations immediately before ramp meter implementation and a month after implementation. Ramp queues in the after period were not excessively long but occasionally did spill back onto the nearby arterial for short durations.

Demand Data

Volume data are collected from nearby state ATR sites, one on each freeway section. ATR counts are locally considered to be more reliable than the volume counts from the ITS system because they are continuously maintained.

Incident Data

Crash data for each section for each time period are produced from the state DOT crash analysis reporting system. Once the data have been collected, the incident measures such as total incidents, incident rate, duration, and lane-hours lost are calculated for each of the 12-month before and after periods on both test section and control section.

Weather Data

Weather data comes from climate recording stations located within the two sections of roadway. Weather-related measures such as hours of rainfall, frozen precipitation, and visibility restricted are calculated for each of the 12-month before and after periods on both the test section and the control section.

Test of Control Sections

The goal of the test of the control sites is to ensure that the control sections have similar traffic conditions to the treatment sections during the before period.

Qualitative Test

The qualitative test is performed by visually examining the quarterly travel time index (Figure D.3) and the annual average peak period VMT (Figure D.4) on the test and control sections during the period before ramp metering. This test shows that changes in travel conditions within the two groups track each other well during the before period, as indicated by the similar directions and magnitudes of changes of the two lines in the two graphs prior to the start of ramp metering.

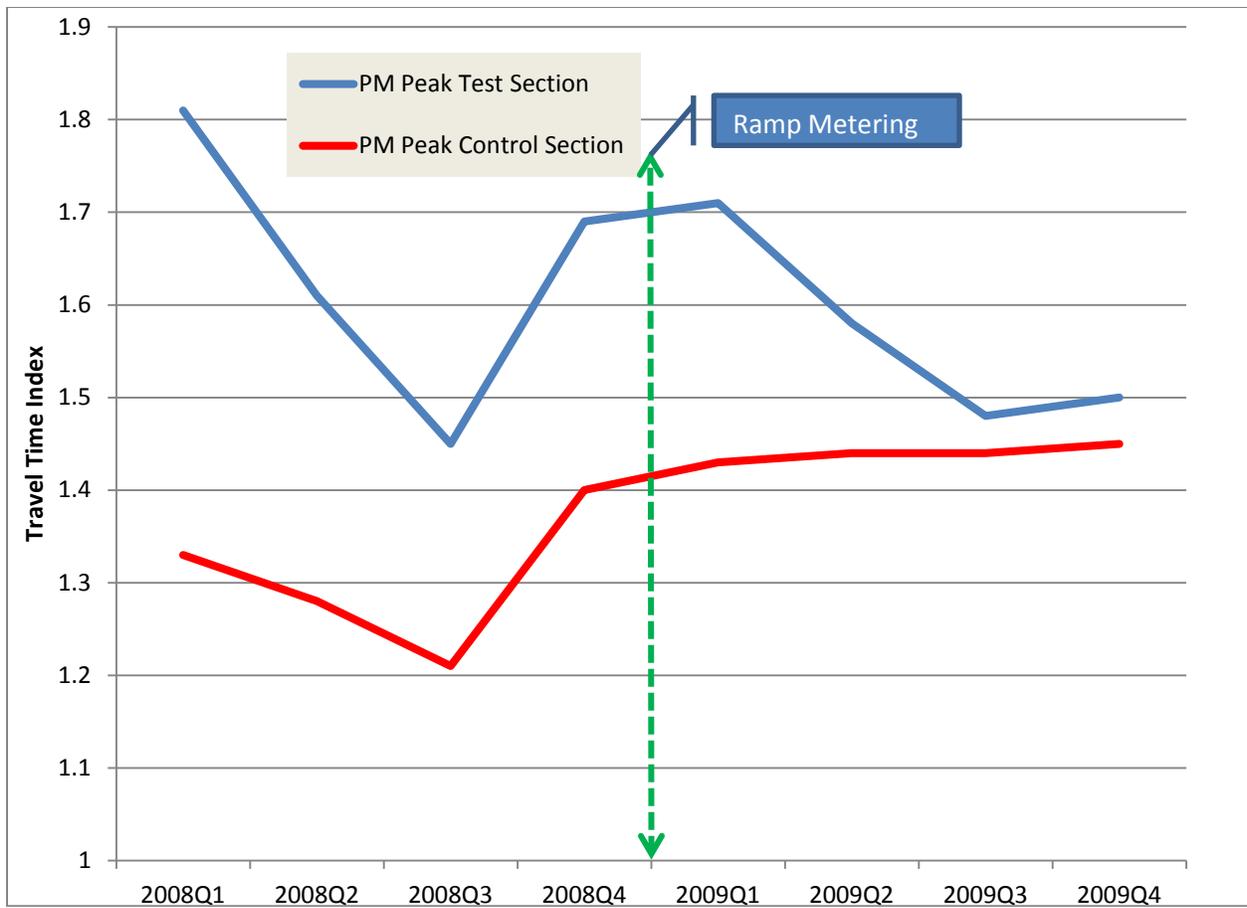


Figure D.3. Travel time index during the p.m. period.

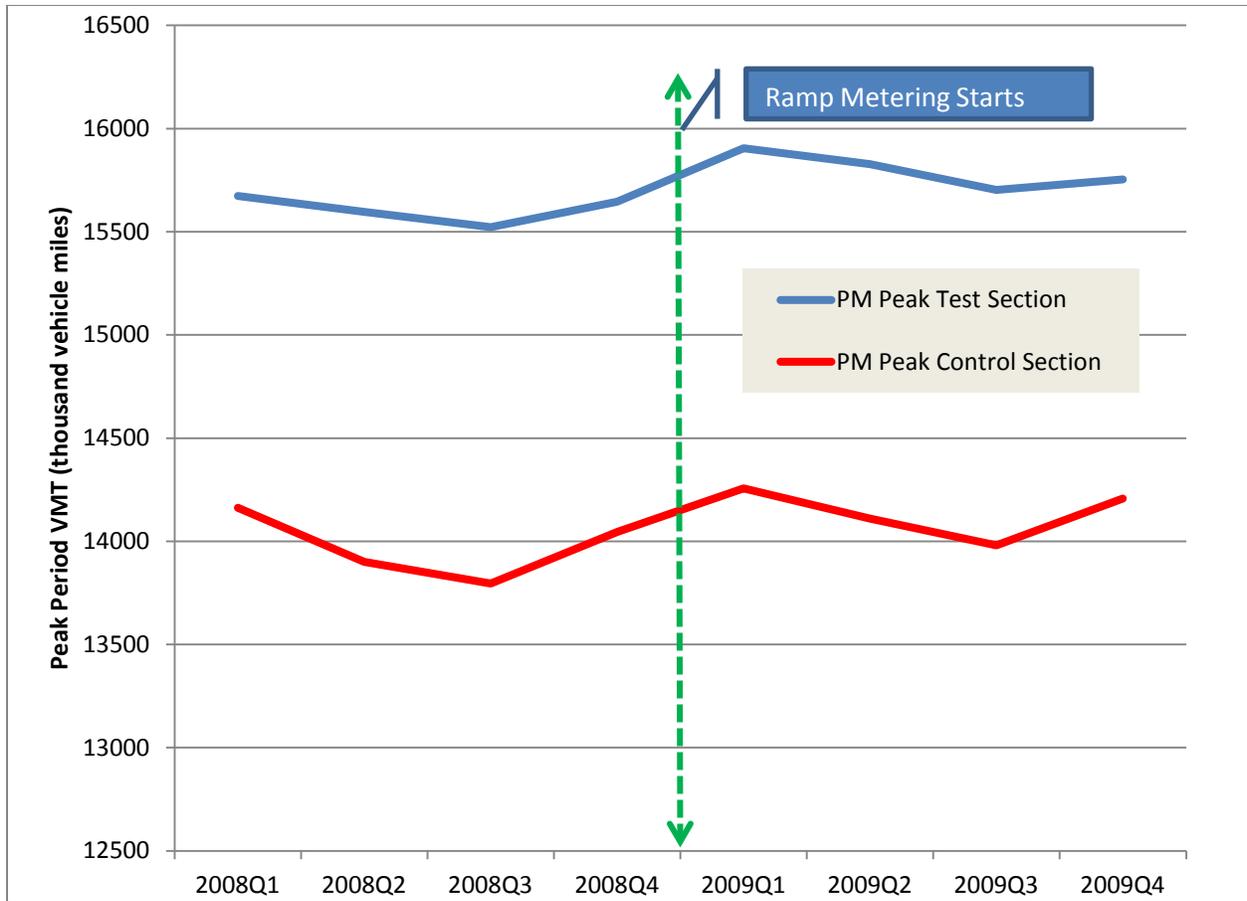


Figure D.4. Peak period VMT during the p.m. period.

Quantitative Test

The quantitative test is to calculate the percent differences between the select quarterly measures on control and test groups during the before period. The select measure is peak period VMT. The results show that p.m. VMT differences are close to the $\pm 10\%$ standard (Table D.1).

Table D.1. VMT Trends at the Test Site

Sections	VMT			
	2008Q1	2008Q2	2008Q3	2008Q4
Test Section	15673	15597	15522	15645
Control Section	14163	13901	13796	14046
% differences	-9.63%	-10.87%	-11.12%	-10.22%

Tests for Similar Congestion Causal Factors

Table D.2 shows the congestion source characteristics in the before and after periods on the test section. The results indicate that congestion factors are essentially the same in both periods, so that the observed changes in congestion level can be directly compared without additional modeling.

Table D.2. Congestion Source Performance Measures, Before and After Improvement

Congestion Source Metrics	Before	After
Total incidents (types not available)	250	259
Incident rate (incidents per 100 million VMT)	410	399
Incident duration: mean and standard deviation (minutes)	32/30	33/30
Lane-hours lost due to incidents	62.5	64.8
Shoulder-hours lost due to incidents	N/A	N/A
Number of work zones	0	0
Lane-hours lost due to work zones	0	0
Shoulder-hours lost due to work zones	0	0
Hours with rainfall $\geq 0.1''$	22	17
Hours with frozen precipitation	0	0
Hours with visibility restricted	5	8
Number of through lanes (excluding auxiliary lanes)	4.7 (avg)	4.7 (avg.)
Number of auxiliary lanes	See schematic	
<i>HCM</i> -calculated capacity		

Before-and-After Study with Control Sites

Table D.3 shows the select congestion/reliability measures of the before-and-after study. The expected values at the test sites (as if no improvements are implemented) are first derived from control sites, and then percentage changes between the expected measures on test sites and the measures on test sites during the after period are calculated. A simple percentage between after and before on test sites is also calculated.

Table D.3. Congestion Measures, Before and After Periods

Performance Metric	Measure s on Control Section During Before	Measure s on Control Section During After	Measure s on Test Section During Before	Measure s on Test Section During After	Expected Measure on Test Section During After	Pct Change between Test After & Expected Test After	Pct Change between Test After & Test Before
<i>Congestion/Reliability</i>							
TTI	1.31	1.44	1.64	1.57	1.81	-13.38%	-4.42%
95th percentile TTI	2.22	2.41	3.13	3.03	3.40	-10.83%	-3.19%
80th percentile TTI	1.60	1.75	2.20	2.15	2.41	-10.65%	-2.27%
Delay (veh- hrs)	284,260	386,236	664,292	600,130	902,601	-33.51%	-9.66%

The results show that ramp metering reduced 13% of travel time index on the test section, while a simple before-and-after calculation shows only 4% reduction of TTI on the test section.