

Cost-Effective Performance Measures for Travel Time Delay, Variation, and Reliability

DETAILS

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NCHRP REPORT 618

**Cost-Effective Performance
Measures for Travel Time Delay,
Variation, and Reliability**

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Planning and Administration

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FOREWORD

By **Lori L. Sundstrom**

Staff Officer

Transportation Research Board

State departments of transportation, metropolitan planning organizations, public transit authorities, and other transportation stakeholders increasingly are turning to the use of transportation system performance measures to gain and sustain public and legislative support for investments in managing, maintaining, and constructing transportation infrastructure. Measures that express congestion and mobility in terms that system users can understand and use are needed for use in systems planning, corridor development, priority programming, and operations to inform investment decisions directed at improving system performance. This report presents a framework and cost-effective methods to predict, measure, and report travel time, delay, and reliability from a customer-oriented perspective.

The use of travel time, delay, and reliability as performance measures is hampered by complex data requirements, data accuracy issues, and inadequate procedures for incorporating these measures into the transportation planning process. Few states have invested in comprehensive data collection programs because these measures can be expensive and difficult to generate. A relatively small number of public agencies have the data collection programs or analytical forecasting capabilities to generate reliable estimates of these measures. States that do collect this data typically do so for select corridors, and their sample sizes are typically quite small. There is a need for structured, cost-effective measures of travel time, delay, and reliability that can be used by practitioners in predicting, measuring, monitoring, and reporting transportation performance in support of system investment and management decisions.

The purpose of this guidebook is to provide transportation planners and project programmers with a framework to predict system performance using cost-effective data collection methods, analysis approaches, and applications that most effectively support transportation planning and decision making for capital and operational investments for quality-of-service monitoring and evaluation.

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S U M M A R Y

Cost-Effective Performance Measures for Travel Time Delay, Variation, and Reliability

Introduction

This guidebook presents a framework and cost-effective methods to estimate, predict, measure, and report travel time, delay, and reliability performance data. The framework is applicable to highway vehicular traffic and also can be used for highway-carried public transit and freight vehicles. The guidebook presents and assesses performance measures currently believed to be most appropriate for estimating and reporting travel time, delay, and reliability from a perspective that system users and decision makers will find most understandable and relevant to their experience and information needs. This guidebook also presents various data collection methods, analysis approaches, and applications that most effectively support transportation planning and decision making for capital and operational investments and for quality of service monitoring and evaluation. Methods are presented in a manner to be useful for application in a range of settings and complexity, but are not intended to support real-time applications of travel-time data such as Traveler Information programs.

Organization

The guidebook begins with an introductory chapter (Chapter 1) that sets the context and provides an explanation of why performance measurement is an important agency practice, and how travel-time-based measures can improve the planning process and results. This first chapter provides useful methods and advice, regardless of the specific application, such as how agencies can use performance data to affect decisions and the choices between alternatives more clear, or selecting methods for reporting results appropriate for various planning and decision-making situations.

The technical core of the guidebook is the remaining Chapters 2 through 8. Chapters 2 and 3 describe specific performance measures, as well as methods and procedures for data collection and processing. Chapters 4 through 7 describe fundamental applications that the analyst will invariably tackle, such as before/after studies or alternatives analyses. Chapter 8 provides guidance on reporting performance results, and on using travel-time-based measures in a variety of standard planning and decision-support situations that incorporate the fundamental techniques and applications from Chapters 4 through 7. The paragraphs below provide a more detailed overview of each of the chapters in the guidebook.

1. **Introduction.** This chapter describes the purpose and scope of the guidebook, intended users, and the audience, those who must eventually understand the results and make or influence decisions based on those results. Included is a discussion of travel time, delay, and reliability in transportation systems, and intended applications for the guidebook. Necessary definitions

and nomenclature with enough background and history to establish the foundation and continuity of this guidebook is provided.

This introductory chapter contains several key sections:

Why Measure Travel-Time Performance? The rationale and sales pitch for the use of travel-time-based measures in planning and decision-making. Discuss the various aspects of measurement, such as trip-based versus vehicle-based measures, relevance to freight movements, and how the guidebook will address modes other than autos on freeways and highways.

How to use the guidebook. A description of the information contained here, the organization of the information, and a recommended approach to using the guidebook.

Limitations of the guidebook. A few key caveats regarding uses for which the manual is not intended (e.g., traveler information or public relations programs).

Measuring Mobility and Reliability. An overview of the key steps involved in using travel-time-based measures to define and predict system performance, and how to approach the use of such measures in a planning situation.

2. **Selecting Performance Measures.** What should influence the selection of measures for a given application; relative importance and sequence of agency goals and objectives in determining appropriate measures. We provide a checklist of considerations for measure selection, a quick reference guide to selected measures, and detailed discussion and derivation of the most useful measures that define mobility (in terms of travel time and delay) and reliability (in terms of variability in travel time).
3. **Data Collection and Processing.** This chapter provides guidance on the development of a data collection and sampling strategy for measuring travel time in the field and for managing data quality. It describes how to compute the mean and variance of travel time and delay. It also describes how to compute the basic components of reliability metrics.
4. **Before/After Studies.** This chapter describes how to solve special issues involved in evaluating the effectiveness (in the field) of measures to reduce travel time, delay, and variability.
5. **Identification of Deficiencies.** This chapter describes how to identify travel time, delay, and reliability deficiencies from field data and distinguish actual deficiencies from random variation in the field data. A diagnosis chart is included to assist in identifying the root causes of travel time, delay, and reliability deficiencies.
6. **Forecast/Estimate Travel Time.** This chapter provides procedures for estimating travel time, delay, and reliability from travel volumes. This information is presented to allow prediction of future conditions where a travel model is used to generate future demand volumes, and to accommodate the many agencies that currently do not have continuous data collection processes on the system or facilities they wish to measure.
7. **Alternatives Analysis.** This chapter provides guidance on the generation and evaluation of alternative improvements for reducing travel time, delay, and variability.
8. **Using Travel-Time Data in Planning and Decision Making.** This chapter provides guidance and examples of effective methods for presenting the results of travel time, delay, and reliability performance analysis or forecasts. This chapter also describes the specific steps for using quantitative travel-time performance data to support decisions about transportation investments, using six typical planning applications to illustrate the process for developing and incorporating information into the planning process.

Limitations

The primary intended use of this guidebook is to support planning and decision making for transportation system investments, including capital projects and operational strategies. The level of precision of the methods is consistent with the precision and accuracy of data

typically collected or generated to support planning activities; for example, periodic data collection and use of computer-based forecasting models to estimate future demand for potential system improvements. The procedures here are intended to support a higher-level screening and analysis process to identify needs and deficiencies and to evaluate potential solutions for meeting needs or correcting deficiencies.

CHAPTER 1

Introduction

This guidebook presents methods to measure, predict, and report travel time, delay, and reliability using data and analytical methods within the reach of a typical transportation agency. This analysis framework allows consideration of many, though not all, of the multiple dimensions of surface transportation system performance: time of day; transit and highway modes; passenger and freight vehicles; and levels of aggregation such as facility type and system/corridor/segment perspectives. An analytical framework oriented to the planner or analyst faced with typical questions about system performance, such as identifying existing or future system deficiencies, spotting and reporting trends, evaluating the effectiveness of proposed or completed improvements, comparing alternative courses of action to address a problem or need, and improving the operations and productivity of a fleet of vehicles such as transit buses or trucks, has been developed.

The analysis framework and methods defined below will allow users to develop and apply measures of travel time, delay, and reliability that relate to the user's perspective, but that also are valuable to the decision makers with responsibility for planning and operating transportation facilities or services. While performance measures of all kinds are useful in management and performance reporting by the responsible agencies, travel-time-based measures are of special interest to the traveling public and elected decision makers because these measures relate directly to the user perspective, such as:

- How long will a trip take?
- How much longer/shorter will it take if I leave earlier/later?
- How large a cushion do I need to allow if I cannot afford to be late at all?

Similarly, these methods can be used by system planners to provide answers to decision maker's questions, such as:

- How much longer will a typical trip take if a particular trend continues?

- Which of these competing improvement projects will most favorably affect system congestion and/or reliability?

These methods and measures are useful in system planning, corridor development, priority programming, and operations to improve transportation system performance and to enhance the customer's experience and satisfaction with the system.

The framework presents various data collection methods, analysis approaches, and applications that most effectively support transportation planning and decision-making for capital and operational investments and for quality-of-service monitoring and evaluation. The methods can be applied in settings with different levels of complexity, including agencies ranging from those with continuous data collection procedures and sophisticated data processing and analysis capabilities, to those with more limited resources. Data collection and processing techniques are provided that will allow calculation of travel time- and delay-based performance measures in a variety of agency settings.

Estimating or forecasting the reliability of a transportation facility or system, defined here as the variability in travel time or delay, effectively requires continuous data collection sources. The guidebook does not provide a method for estimating travel-time reliability for data-poor situations. Research and analysis of available data conducted for this project concluded that agencies must have continuous surveillance capabilities, or nearly so, in order to provide useful estimates of reliability.

1.1 Why Measure Travel-Time Performance?

State departments of transportation (DOT), metropolitan planning organizations (MPO), transit authorities, and other transportation stakeholders are increasingly turning to performance measures to gain and sustain public and legislative

support for the management and stewardship of transportation systems. This trend responds to calls for increased accountability for expenditure of public funds, better consideration of user and stakeholder priorities in selecting from among competing project opportunities, and a rational desire to improve the quality of information upon which such decisions are based. At the same time, system users—the traveling public, as well as commercial operators—are increasingly sensitive to delay and unreliable conditions. By measuring travel-time performance, and related system metrics based on travel time, agencies will be better able to plan and operate their systems to achieve the best result for a given level of investment. At the same time, travelers, shippers, and other users of those systems will have better information for planning their use of the system.

Agencies are seeking to develop and employ system performance measures that express congestion and mobility in terms that decision makers and system users can appreciate and understand. Interest specifically in measures of travel time, delay, and reliability is increasing, as system users seek to gain more control over their trip making decisions and outcomes. Interest also is increasing in measurements that individuals can use to reduce the uncertainty and loss of productivity that occur when system reliability is low.

This growing demand for available measures of mobility and congestion that are travel time-based and user-friendly has pointed out the need for improved monitoring and analytical procedures to generate the measures. These methods need to be able to measure and predict how individual travelers and goods movements will be affected by incidents and other sources of nonrecurring delay, as well as by capital and operational improvements to different components of the transportation system.

Use of travel time, delay, and reliability as performance measures is hampered by complex data requirements, data accuracy issues, and inadequate procedures for incorporating these measures into the transportation planning process. One reason these measures have not been more widely implemented is they can be expensive and difficult to generate. A relatively small percentage of public transportation planning agencies have the data collection programs or analytical forecasting capabilities to generate reliable estimates of these measures. In many states, travel-time data are available for relatively few corridors. The high costs associated with more comprehensive data collection programs deter many states from investing in such programs. States and MPOs are using loop detector data and other data collected by intelligent transportation systems (ITSs) or traffic management systems (TMCs) to develop travel time, delay, and reliability measures, but these efforts too are fairly sophisticated, limited in extent, and at present, costly.

As a result, agencies are in need of methods for generating travel-time-based performance measures that are relatively

straight-forward to use and can be driven with existing and readily available data sources. To date, much of the work on travel-time-based measures has focused on utilizing relatively comprehensive and deep data sets generated for traffic management systems via continuous, automatic data collection processes. This guidebook strives to present methods for generating similar measures using data that are more likely to be readily available to the typical transportation planning or operating agency.

Much work previously has been conducted to develop effective measures of congestion, and to present the data collection and analysis methods required to generate the measures. More recently, measures of reliability have similarly been studied and published, making better use of continuous data sources. References to these other excellent resource documents are made where additional detail and context would be useful to some users. We find, however, that most of the existing published work on congestion and reliability measurement focuses on monitoring and reporting existing values and historical trends, and not on application of the measures to the “what-if” type of questions prevalent in system planning. This guidebook, and NCHRP Project 7-15 on which it is based, strive to help fill the need for practical advice on use of relevant mobility and reliability measures in typical planning applications. The main objective of these applications is to inform a planning process (e.g., to identify needs and suggest appropriate solutions) and support decision-making about some future action or investment in the transportation system. Thus, this guidebook places more emphasis on estimating and forecasting future values of performance measures and comparative analysis of hypothetical situations.

1.2 How to Use the Guidebook

This guidebook is intended for use by analysts familiar with various forms of quantitative analysis, including basic statistical analysis. The information presents the fundamental steps necessary to conduct the most common planning analyses for which travel-time-based measures can be useful. The remainder of Chapter 1 presents an orientation to the process of measuring mobility and reliability. While the material in Section 1.4 may be familiar to many readers, it is useful to repeat the logical sequence of activities that describe performance-based planning analysis. This process starts with the guiding vision or goals, and proceeds through such essential steps as identifying the audience; considering possible solutions; selection and calculation of performance measures; testing alternatives; and summarizing results. This discussion provides a point of departure for more detailed material that follows.

The common elements of typical planning applications are explained in detail in Chapters 2 through 7, where specific

guidance is given, formulas for calculating measures are provided, and references made to other well-accepted, published sources of guidance. These steps include selection of appropriate measures, data collection and processing, and specific fundamental or “building block” applications, such as deficiency analysis or alternatives analysis. These steps can be applied in varying combinations to address a high percentage of the planning applications and decisions an analyst is likely to confront for which travel-time, delay, and reliability information will provide useful decision support.

Chapter 8 provides additional guidance on reporting performance results and incorporating those results into planning processes. Six typical planning applications are illustrated, covering a large spectrum of likely applications for travel-time and reliability measures in planning. The approach to each application is described in terms of the building blocks contained in Chapters 2 through 7.

1.3 Limitations of the Guidebook

The focus of this guidebook and its procedures are planning applications. These applications generally involve the assessment of current or future performance for a large regional system of facilities or significant individual components of such a system. The emphasis is on procedures that provide no more precision in the results than is commensurate with the precision with which current measurements or future forecasts can be made for large systems of facilities and whose data needs and analytical requirements are similarly consistent with planning-level applications.

These procedures are not intended to replace or be equal in precision to those procedures commonly used for the evaluation of individual intersections or road segments or even individual facilities. Rather, these procedures are intended to support a higher-level screening process used to identify deficiencies in existing and future system performance, and to identify types of improvements that would be most cost-effective at correcting these deficiencies. When the decision is made to proceed with a specific project to correct a deficiency, the agency designing the project will want to use more specific and precise procedures for assessing whether the improvements meet agency performance objectives, engineering standards, cost constraints, and other relevant considerations.

Where results of a systems planning-level assessment conflict with the results of a detailed facility-specific analysis, the analysis using more precise data is generally more accurate and reliable. However, the analyst should recognize the possibility of procedural or technical errors, regardless of the extent and detail of the data employed in the analysis. Professional judgment and experience should be applied to the interpretation and validation of the results, regardless of the level of detail of the analysis.

Although several of the recommended performance measures presented are derived from the perspective of the individual traveler (e.g., delay per traveler and several of the travel-time-based indexes), the analytical methods defined are not intended to drive traveler information (TI) systems or programs. While travel-time measures are becoming more common components of TI programs, the methods in this report are specifically designed to be applied using less comprehensive, less real-time data than is typically used for TI. In order for reports or estimates of travel time to be useful to system users en route or planning an imminent trip, they need to be based on near real-time and historic data. In contrast, planning applications will be more reliable and useful if they are based on trends and on predictive relationships between commonly available data and system performance.

1.4 Measuring Mobility and Reliability

The need for meaningful mobility and reliability information is best satisfied by travel-time measures. Travel-time measures do not preclude the use of other data, procedures, surrogates, or models when appropriate. The key is that the set of mobility and reliability measures should satisfy the needs of analysts and decision makers, and the presentation of that information should be tailored to the range of audiences.

The decision process used by travelers to select trip modes and routes, and by the transportation or land use professional analyzing alternatives, is influenced by travel time, convenience, user cost, dependability, and access to alternative travel choices. Travel time also is used to justify capital and operating improvements.

A system of performance measurement techniques that uses travel-time-based measures to estimate the effect of improvements on person travel and freight movement offers a better chance of satisfying the full range of potential needs than conventional level of service (LOS) measures. Technical procedures and data used to create the LOS measures can be adapted to produce time-based measures. The procedures were developed in a time when construction was typically the selected option. Operational improvements generally were implemented on a smaller scale and cost level. The more complicated situation that transportation professionals face in the 21st century means that new techniques and data are available, but the analysis needs are broader, must address transportation system management and operations, and often cross traditional modal and funding category boundaries.

Measuring mobility and reliability is a task performed in a variety of ways, in several different types of analysis, and for many purposes. While the measures often are dictated by

legislative or regulatory mandates, it is useful to view the selection of the measure or measures as an important task to be accomplished before the data are collected and the estimation or calculation procedures begin. This section identifies key elements necessary for a complete analysis that includes travel time, speed, and reliability measures. As with any process, the continuous evaluation of assumptions, methods, and techniques will lead to improvement; it is important to compare the measures with the uses throughout the process and adjust the measures as necessary. It also is important to recognize that there are many analytical techniques that relate to mobility and reliability measurement. The steps outlined in this section are part of many of those procedures. Exhibit 1.1 provides an overview of the three-stage process to measure mobility and reliability. Each stage contains one to three considerations that are described in more detail in the following subsections. For additional information on each of the sections described in this chapter, the reader is encouraged to review NCHRP Report 398, *Quantifying Congestion* (1).

1.4.1 Identify the Vision and Goals

The long-range plan for an area or system ideally contains a description of the situation the public wishes to create through investment, operation, and maintenance. As an important element of that plan, existing transportation facilities must be analyzed, and improvements (if any) identified. In order for the selected programs and projects to move the area toward the vision, the measures must enable the selection of transportation improvements of the type and scale appropriate to the situation.

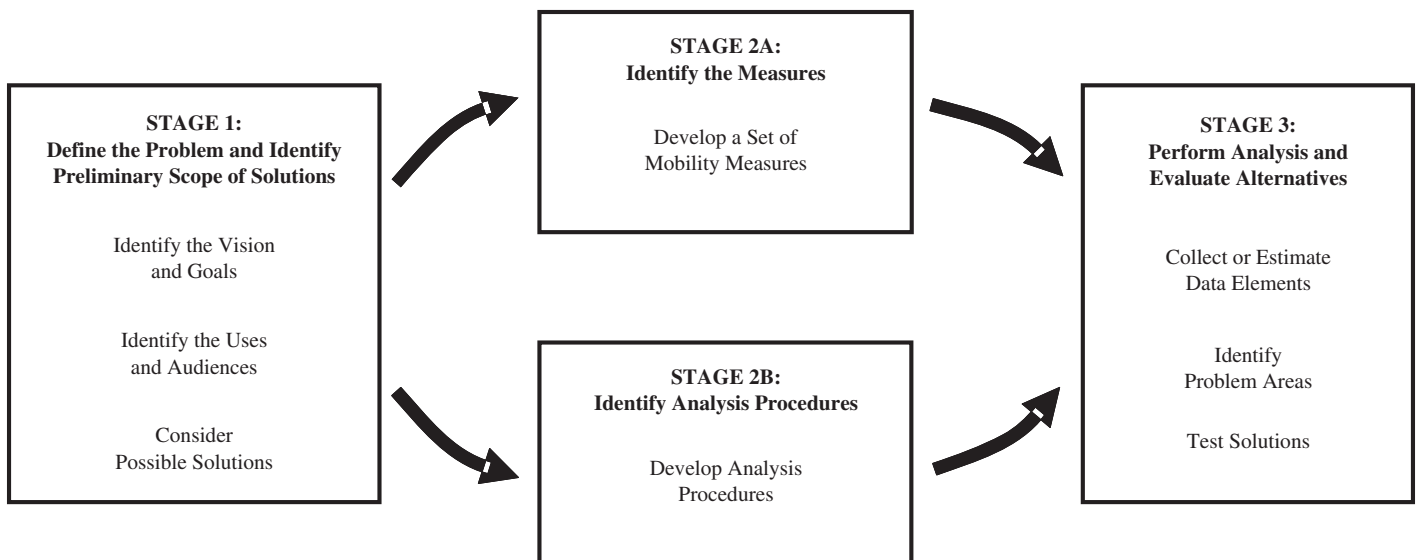
A similar line of thinking applies at the detailed level (e.g., street, bus route, or demand management program). While the improvement options may not be as broad, and the financial investment may not be as great, it is always instructive to think about desirable outcomes or adverse impacts before beginning the analysis. Not only will this ensure proper consideration of all options, it also will lead to selection of measures that can fairly evaluate the range of alternatives.

It is this step where the expectations of the public and policy makers can be formulated into a set of statistics that can be used at the project or program evaluation level. The “agreed upon norms” of the stakeholders are used to identify broad outcome goals to be considered by the engineer, planner, economist, or other professionals who must evaluate the need for an improvement.

It is essential, therefore, that performance measures be consistent with the goals and objectives of the process in which they are being employed. Performance measures are key to controlling process outcome, whether the process is alternative selection, congestion management, growth management, or system management and operation. For example, within congestion management, performance measures are used for problem identification and assessment, evaluation and comparison of alternative strategies, demonstration of effectiveness, and ongoing system monitoring. Variations of the same measure may satisfy a range of uses.

1.4.2 Identify the Uses and Audiences

The analyses and potential targets of the measurement process must be determined before the proper mobility and



Lomax, T., et al. (1).

Exhibit 1.1. Illustration of mobility and reliability analysis process (2).

reliability measures can be selected. The set of measures must be technically capable of illustrating the problems and the effect of the potential improvements. They also must be able to be composed into statistics useful for the variety of potential audiences. Increasing the flexibility of the measures also may improve the ability to use the information beyond the particular analysis. Corridor statistics also may satisfy annual reporting requirements, for example.

Cost and schedule also are key considerations in the performance measure development process. Different uses and audiences frequently have different timelines for the delivery of performance measure results. The available budget is a related consideration. For example, consider the situation if your state legislature were to mandate the development and implementation of a statewide performance measurement program for all state facilities within six months. Clearly, the timeline is established (and short). The quality of the answer will depend upon the available budget for personnel to develop the measures and accompanying estimation procedures. In contrast to such a legislative directive, consider an MPO that would like to fund a regional congestion management program that will develop and implement performance measures over a three-year period. Assuming adequate funding and all else is equal, certainly this example provides more opportunity for delving deeper into potential estimation methods, working with the public to identify performance measures that work for both technical and nontechnical audiences, and perhaps even identifying and improving data sources than a three-month time frame.

1.4.3 Consider Possible Solutions

Before measure selection and data collection begins, it is useful to reflect on the problem areas and consider possible solutions. Possible solutions include potential projects, operational programs, and policies. Understanding the possible solutions will help ensure that key considerations are vetted and understood as measures and procedures are established in the next step. The following questions should be given initial consideration at this stage and should be fully evaluated with prototype results of the analysis.

- Can all the improvement types be accounted for with the typical measures?
- Will the measures be able to illustrate the effect of the improvements by mode?
- Are there aspects of the projects, programs, or policies that will not be covered by the measures?
- Are the measures understandable to all the potential audiences?
- Are the uses of the measures appropriate, and will the procedures yield reliable information?

1.4.4 Develop a Set of Mobility and Reliability Measures

Many analyses, especially multimodal alternatives or regional summaries, require more than one measure to describe the problem. Analyses of corridor improvements might require travel time and speed measures to be expressed in person and freight movement terms. Some analyses are relatively simple, and it may be appropriate to use only one measure. Analyses of traffic signal timing, where carpool and bus treatments are not part of the improvement options, might not require person movement statistics—vehicle volume and delay information may be sufficient.

Poor selection of measures has a high probability of leading to poor outcomes. In contrast, goals and objectives that are measured appropriately can guide transportation professionals to the best project, program, or strategy; analysts and policy-makers can then check (using evaluation results) that the goals and objectives are best served by the solutions offered (3).

1.4.5 Develop Analysis Procedures

While the set of mobility and reliability measures is determined by what we want to know, the accompanying analysis procedures are determined by what data are available or can be obtained. As shown in Exhibit 1.1, identifying the analysis procedures is often done at about the same time as identifying the performance measures. Analysis procedures vary based upon several factors, including the use and/or audiences and how this affects the level of accuracy or precision required; budget and schedule; data formats; and data types. When continuous data sources are available, the estimation procedures typically comprise software programs that compute the performance measures from archived data. Alternatively, in the absence of continuous data, performance measures can be estimated by post-processing the output from transportation models (e.g., travel demand models, economic analysis models).

All estimation methods include quality control and quality assurance of the input data, as well as reasonableness checks of the output. Analysis procedures can be expected to improve over time as the performance measurement program receives feedback from analysts and users of the results and as data collection and/or data elements improve.

1.4.6 Collect or Estimate Data Elements

Data collection can proceed after an analysis of potential sources of information. The level of precision and statistical reliability must be consistent with the uses of the information and with the data collection sources. Estimates or modeling

processes may be appropriate additions to traffic count, travel time, and speed data collection efforts. Statistical sampling procedures may be useful for wide area analyses, as well as for validating models and adapting them to local conditions. Direct data collection may be available from a variety of sources, including specific corridor studies, real-time data collection, and annual route surveys of travel times.

An areawide travel monitoring program will consist of both travel speed data collection and estimated speed information obtained from equations or models. The directly collected data may be more expensive to obtain; statistical sampling techniques will decrease the cost and improve the reliability of the information. It may be possible to focus the data collection on a relatively small percentage of the roadway system responsible for a large percentage of the travel delay. Such a program would be supplemented with travel-time studies on a few sections of road and estimation procedures on the remainder of the system.

1.4.7 Identify Problem Areas

The collected data and estimates can be used to develop measures that will illustrate the problem areas or situations. These should be compared to observations about the system to make a reasonableness check; the measures should identify well-known problem areas. The data will provide information about the relative size of the mobility and reliability problems so that an initial prioritization for treatment can be made.

1.4.8 Test Solutions

Testing the potential solutions against the mobility and reliability measures during the data collection process may improve the data collection effort and the ultimate results. After data collection and estimation are complete, testing solutions for effect will be another chance to determine the need to modify mobility and reliability measures. Even after the analysis is complete, the measures should be evaluated before

similar projects are performed. Inconsistencies or irregularities in results are sometimes a signal that different procedures or data are required to generate the needed products.

1.4.9 Summary of Implementing Mobility and Reliability Measures

The use of a set of mobility and reliability measures may mean more computer-based analyses, which might be perceived as a move away from direct measurement for some levels of analysis. This does not mean that travel-time data will be less useful or less cost-effective to collect. On the contrary, direct measurement of travel time can be used to not only quantify existing conditions, but also to calibrate wide-scale models of traffic and transportation system operation and to perform corridor and facility analyses. Incorporating the important process elements into a sequence of events leading up to a public discussion of alternative improvement plans might result in a series of steps like the following:

- Existing traffic and route condition data are collected directly.
 - Measures are calculated.
 - Results are compared to target conditions determined from public comments during long-range plan discussion.
 - Trip patterns, areas, and modes that need improvement are identified.
 - Solutions are proposed. Areawide strategies should guide the selection of the type and magnitude of specific solutions.
 - A range of the amount and type of improvements is tested.
 - Mobility and reliability measures are estimated for each strategy or alternative, including forecasts of future values of measures as appropriate to the application.
 - Measures are compared to corridor, subarea, and regional goals.
 - Individual mode or facility improvements that fit with the areawide strategy are identified for possible inclusion in the plan, subject to financial analyses.
-

CHAPTER 2

Selecting Appropriate Performance Measures

2.1 Introduction

This chapter helps the user to understand the range of performance measures or metrics available to measure and monitor travel time, delay, and reliability, and to identify appropriate metrics for a given application, taking into account factors such as data availability and the intended use or audience for the results. We have adopted the terms “mobility” and reliability, because these are the desirable outcomes sought for the transportation system user. “Travel time” and “delay” and the variability in those two quantities are key determinants of mobility and reliability.

A system of mobility and reliability measures should be developed only after an examination of the uses and audiences to be served, the consideration of program goals and objectives, and identification of the nature or range of likely solutions. This chapter illustrates a system of travel-time-based measures to estimate mobility and reliability levels. These procedures are useful for roadway systems, person and freight movement modes, and transportation improvement policies and programs. The user should consider the way that measures might be used before selecting the appropriate set of mobility and reliability measures.

The following sections describe techniques for measuring mobility and reliability on various portions of a transportation network. Some of the material in this chapter has been excerpted from the *Keys to Estimating Mobility in Urban Areas: Applying Definitions and Measures That Everyone Understands*, and the reader is encouraged to review that source for more detailed background information (2).

2.2 Measure Selection

Given a basic understanding of the performance measurement process as described in Chapter 1, this section provides several considerations that can be used to identify the most appropriate mobility and reliability measures for a situation.

Because of the wide range and diversity of available measures, it is important to have a clear basis for assessing and comparing mobility and reliability measures. Such an evaluation makes it possible to identify and separate measures that are useful for an analytical task from measures that are either less useful or inappropriate for certain analyses.

2.2.1 Choosing the Right Mobility and Reliability Measures

The ideal mobility and reliability measurement technique for any combination of uses and audiences will include the features summarized in Exhibit 2.1. These issues should be examined before data are collected and the analysis begins, but after the analyst has considered all reasonable responses to the problem or issue being studied. Having an idea of what the possible solutions are will produce a more appropriate set of measures.

2.2.2 The Data Collection Issue

Concerns about the cost and feasibility of collecting travel-time data are frequently the first issues mentioned in discussions of mobility and reliability measures. There are many ways to collect or estimate the travel time and speed quantities; data collection should not be the determining factor about which measures are used. While it is not always possible to separate data collection issues from measure selection, this should be the goal. Chapter 3 discusses data collection in more detail.

2.2.3 Aspects of Congestion, Mobility, and Reliability

The selection of a proper set of mobility and reliability measures includes an assessment of what traveler concerns are most important. This assessment can be drawn from experiences with measuring congestion in roadway systems.

| Checklist Item | Short Discussion |
|--|---|
| Relate to goals and objectives | The measures must indicate progress toward transportation and land use goals that the project or program attempts to satisfy. Measuring transportation and land use characteristics that are part of the desired future condition will provide a continual check on whether the area is moving toward the desired condition. |
| Clearly communicate results to audiences | While the technical calculation of mobility and reliability information may require complicated computer models or estimation techniques, the resulting information should be in terms the audience can understand and find relevant. |
| Include urban travel modes | Mobility and reliability are often a function of more than one travel mode or system. At least some of the measures should contain information that can be calculated for each element of the transportation system. The ability to analyze the system, as well as individual elements, is useful in the selection of alternatives. |
| Have consistency and accuracy | Similar levels of mobility and reliability, as perceived by travelers, should have similar mobility and reliability measures. This is important for analytical precision and also to maintain the perception of relevancy with the audiences. There also should be consistency between levels of analysis detail; results from relatively simple procedures should be similar to those obtained from complex models. One method for ensuring this is to use default factors for unknown data items. Another method is to frequently check expected results with field conditions after an improvement to ensure that simple procedures – those that use one to three input factors – produce reasonable values. |
| Illustrate the effect of improvements | The improvements that may be analyzed should be consistent with the measures that are used. In relatively small areas of analysis, smaller urbanized areas, or portions of urban areas without modal options, this may mean that vehicle-based performance measures are useful. Using a broader set of measures will, however, ensure that the analysis is transferable to other uses. |
| Be applicable to existing and future conditions | Examining the need for improvements to current operations is a typical use of mobility and reliability measures that can be satisfied with data collection and analysis techniques. The ability to relate future conditions (e.g., design elements, demand level, and operating systems) to mobility and reliability levels also is required in most analyses. |
| Be applicable at several geographic levels | A set of mobility and reliability measures should include statistics that can illustrate conditions for a range of situations, from individual travelers or locations to subregional and regional levels. Using quantities that can be aggregated and averaged is an important element of these criteria. |
| Use person- and goods-movement terms | A set of measures should include factors with units relating to the movement of people and freight. In the simplest terms, this means using units such as persons and tons. More complex assessments of benefits will examine the different travel patterns of personal travel, freight shipping, and the intermodal connections for each. |
| Use cost-effective methods to collect and/or estimate data | Using readily available data or data collected for other purposes is a method of maximizing the usefulness of any data collection activities. Focusing direct data collection on significant problem areas also may be a tactic to make efficient use of data collection funding. Models and data sampling procedures also can be used very effectively. |

Exhibit 2.1. Checklist of considerations for mobility and reliability measure selection (1).

A set of four aspects of congestion was discussed at the Workshop on Urban Congestion Monitoring (4) in May 1990, as a way to begin formulating an overall congestion index. These four components provide a useful framework for mobility and reliability estimation procedures as well.

2.2.4 Summarizing Congestion Effects Using Four General Components

While it is difficult to conceive of a single value that will describe all travelers’ concerns about congestion, there are four

components that interact in a congested roadway or system (1). These components are duration, extent, intensity, and variation. They vary among and within urban areas. Smaller urban areas, for example, usually have shorter duration than larger areas, but many have locations with relatively intense congestion. The four components and measurement concepts that can be used to quantify them are discussed below.

1. **Duration.** This is the length of time during which congestion affects the travel system. The peak hour has expanded to a peak period in many corridors, and mobility and

reliability studies have expanded accordingly. The measurement concept that illustrates duration is the amount of time during the day that the travel speed indicates congested travel on a system element or the entire system. The travel speed might be obtained in several ways depending on data sources or travel mode being studied.

2. **Extent.** This is described by estimating the number of people or vehicles affected by congestion and by the geographic distribution of congestion. The person congestion extent may be measured by person-miles of travel or person-trips that occur during congested periods. The percent, route-miles, or lane-miles of the transportation system affected by congestion may be used to measure the geographic extent of mobility and reliability problems.
3. **Intensity.** The severity of congestion that affects travel is a measure from an individual traveler's perspective. In concept, it is measured as the difference between the desired condition and the conditions being analyzed.
4. **Variation.** This key component describes the change in the other three elements. Recurring delay (the regular, daily delay that occurs due to high traffic volumes) is relatively stable. Delay that occurs due to incidents is more difficult to predict.

The relationship among the four components may be thought of as a three-dimensional box describing the magnitude of congestion. Exhibit 2.2 illustrates three dimensions—duration, extent, and intensity—of congestion. These present information about three separate issues: 1) how long the system is congested, 2) how much of the system is affected, and 3) how bad the congestion problem is. The variation in the size of the box from day to day is a measure or indicator of reliability, i.e., the more extreme and unpredictable the variation from one time period to another, the poorer the reliability of the facility or system being measured.

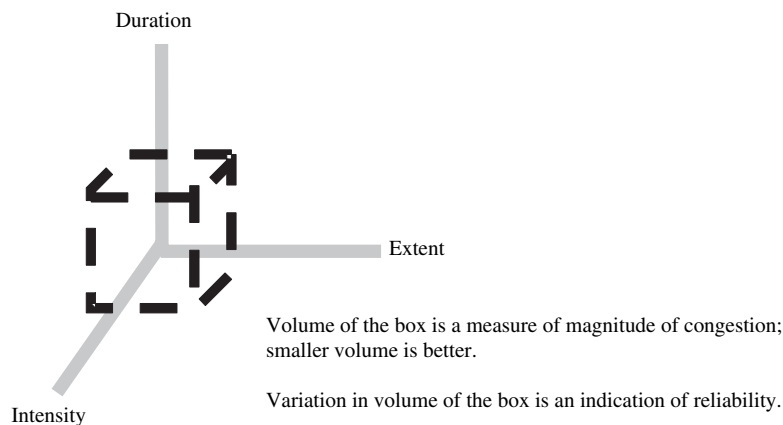


Exhibit 2.2. Components of congestion (2).

2.2.5 Summarizing Mobility and Reliability Effects Using Four General Components

Developing a summary of mobility and reliability using concepts similar to those used for congestion will ensure that the appropriate measures are used. A similar typology uses different terms; there is a positive tone in the phrasing of the definitions and a slightly different orientation from congestion, but the aspects are basically the same. The image of a box also is appropriate to the description of the amount of mobility and reliability provided by a transportation and land use system. The axes are time, location, and level. Reliability is now the change in box volume.

- **Time.** The time that mobility and/or reliability is provided or available is an expression of the variation of mobility and/or reliability through the day, week, or year. It can be a function of the existence of congestion or the presence of transit service, operational improvements, or priority treatments. It can be measured as the times when travelers can get to their destinations in satisfactory travel times.
- **Location.** The places or trips for which mobility and reliability are available is an important aspect of measurement for transportation and land use analyses, as well as for other issues such as economic development and social equity. It can be described by accessibility maps and statistics and travel time contours that illustrate the areas that can be traveled to in a certain period of time. Descriptions of transit routes or special transportation services also can be used to identify locations where mobility and reliability are possible by more than private auto modes.
- **Level.** The amount of mobility and reliability provided is analogous to the intensity of congestion. The amount of time it takes to travel to a destination and whether this is satisfactory are the key elements of the level of mobility and

reliability. It can be measured with a congestion index or accessibility statistics.

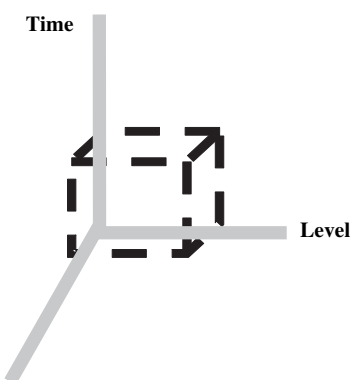
- **Reliability.** The changing times, locations, and levels of mobility and reliability are important characteristics for mobility and reliability measurement. This is particularly important to freight movement operations that rely on the transportation system as an element of their productivity and to measuring the frustration level of travelers faced with an unexpected loss of mobility or reliability.

The total amount of mobility and reliability provided to travelers in an area is the volume of a box with axes of time, location, and level. The reliability of the mobility provided to travelers and residents is the change in the volume of the box from time period to time period or from day to day. Exhibit 2.3 illustrates the description of mobility and reliability with the four aspects. These answer the key questions of travelers and residents: 1) When can I travel in a satisfactory amount of time? 2) Where can I travel in a satisfactory amount of time? 3) How much time will it take? 4) How much will my travel time vary from trip to trip?

Answering the key questions with measures of the four components of mobility and reliability will encompass the needs of residents and travelers, as well as transportation and land use professionals.

2.3 Performance Measure Summary

The overriding conclusion from any investigation of mobility and reliability measures is there is a range of uses and audiences. No single measure will satisfy all the needs, and no single measure can identify all aspects of mobility and reliability—there is no “silver bullet” measure suited to every application or question. Mobility and reliability are complex and, in many cases, requires more than one measure,



Location:

- ✓ The volume of the box is the amount of mobility and reliability provided.
- ✓ A change in volume of the box indicates the reliability of the system. Larger volume is better.

Exhibit 2.3. Components of mobility (2).

more than a single data source, and more than one analysis procedure. Mobility and reliability measures, when combined in a process to uncover the goals and objectives the public has for transportation systems, can provide a framework to analyze how well the land use and transportation systems serve the needs of travelers and businesses and provide the basis for improvement and financing decisions. Exhibit 2.4 provides a quick reference to selected mobility and reliability measures discussed in more detail in this chapter. It illustrates the measures, the input data required, and the general format of the equation required to calculate each measure.

2.4 Individual Measures

Travel time, speed, and rate quantities are somewhat more difficult to collect and may require more effort than the traffic volume counts that currently provide the basis for most roadway analysis procedures. Travel speed-related measures can, however, be estimated as part of many analysis processes currently used. The ultimate implementation of a set of time-related mobility and reliability measures in most urban areas will probably rely on some estimating procedures along with archived data. These measures may include current *Highway Capacity Manual*-based analysis techniques (5), vehicle density measures estimated from detectors in the pavement or from aerial surveys or relationships that estimate travel rate, or speed from generally available volume and roadway characteristics. The use of estimating procedures will be particularly important in setting policy and the prioritization of transportation improvement projects, pavement designing, responding to developer requests for improvement, and performing many other analyses.

The focus of this section is those measures most applicable to the individual traveler. Key characteristics about each mobility and reliability measure are summarized after the measures are presented. Summarizing the measure characteristics illustrates the flexibility of mobility and reliability measures based on time and person or freight movement.

The delay per person or delay per peak-period traveler (in daily minutes or annual hours) can be used to reduce the travel delay value to a figure more useful in communicating to nontechnical audiences. It can normalize the impact of mobility projects that handle much higher person demand than other alternatives, where a measure of total delay might lead to different conclusions about the benefits of a solution. Delay for the primary route or road, in these alternatives, may be higher due to this higher volume, but this also indicates the need to examine the other facilities or operations within the corridor included in the “before” case. To the extent possible, the initial analysis should include as much of the demand that might move to the improved facility, route, or road.

| Individual Measures ¹ | |
|----------------------------------|---|
| Delay per Traveler | $\text{Delay per Traveler (annual hours)} = \left(\frac{\text{Actual Travel Time (minutes)} - \text{FFS or PSL Travel Time (minutes)}}{\text{minutes}} \right) \times \frac{250 \text{ weekdays}}{\text{year}} \times \frac{\text{hour}}{60 \text{ minutes}}$ |
| Travel Time | $\text{Travel Time (person - minutes)} = \frac{\text{Actual Travel Rate (minutes per mile)} \times \text{Length (miles)} \times \text{Vehicle Volume (vehicles)} \times \text{Vehicle Occupancy (persons/vehicles)}}{\text{minutes}}$ |
| Travel Time Index ² | $\text{Travel Time Index} = \frac{\text{Actual Travel Rate (minutes per mile)}}{\text{FFS or PSL Travel Rate (minutes per mile)}}$ |
| Buffer Index ² | $\text{Buffer Index (\%)} = \left[\frac{95^{\text{th}} \text{ Percentile Travel Time (minutes)} - \text{Average Travel Time (minutes)}}{\text{Average Travel Time (minutes)}} \right] \times 100\%$ |
| Planning Time Index ² | $\text{Planning Time Index (no units)} = \frac{95^{\text{th}} \text{ Percentile Travel Time (minutes)}}{\text{FFS or PSL Travel Time (minutes)}}$ |
| Area Measures ¹ | |
| Total Delay | $\text{Total Segment Delay (person - minutes)} = \left[\frac{\text{Actual Travel Time (minutes)} - \text{FFS or PSL Travel Time (minutes)}}{\text{minutes}} \right] \times \text{Vehicle Volume (vehicles)} \times \text{Vehicle Occupancy (persons/vehicle)}$ |
| Congested Travel | $\text{Congested Travel (vehicle - miles)} = \sum \left(\frac{\text{Congested Segment Length (miles)} \times \text{Vehicle Volume (vehicles)}}{\text{minutes}} \right)$ |
| Percent of Congested Travel | $\text{Percent of Congested Travel} = \left[\frac{\sum_{i=1}^m \left(\left(\frac{\text{Actual Travel Time}_i \text{ (minutes)} - \text{FFS or PSL Travel Time}_i \text{ (minutes)}}{\text{minutes}} \right) \times \left(\frac{\text{Vehicle Volume}_i \text{ (vehicles)} \times \text{Vehicle Occupancy}_i \text{ (persons/vehicle)}}{\text{minutes}} \right) \right)}{\sum_{i=1}^n \left(\frac{\text{Actual Travel Rate}_i \text{ (minutes per mile)} \times \text{Length}_i \text{ (miles)} \times \text{Vehicle Volume}_i \text{ (vehicles)} \times \text{Vehicle Occupancy}_i \text{ (persons/vehicle)}}{\text{minutes}} \right)} \right] \times 100$ |
| Area Measures ¹ | |
| Congested Roadway | $\text{Congested Roadway (miles)} = \frac{\sum \text{Congested Segment Lengths (miles)}}{\text{minutes}}$ |
| Accessibility | $\text{Accessibility (opportunities)} = \frac{\sum \text{Objective Fulfillment Opportunities (e.g., jobs), Where}}{\text{Travel Time} \leq \text{Target Travel Time}}$ |

¹“Individual” measures are those measures that relate best to the individual traveler, whereas the “area” measures are more applicable beyond the individual (e.g., corridor, area, or region). Some individual measures are useful at the area level when weighted by Passenger Miles Traveled (PMT) or Vehicle Miles Traveled (VMT).

² Can be computed as a weighted average of all sections using VMT or PMT.

Note: FFS = Free-flow speed, and PSL = Posted speed limit.

Exhibit 2.4. Quick reference guide to selected mobility and reliability measures.

Equations 2.1.a and 2.1.b illustrate the computation of delay per traveler in annual hours. Equation 2.1.a is appropriate for a single section of highway where the delay (i.e., actual travel time minus free-flow travel time) for a number of travelers over the same segment can be averaged and then expanded to annual hours. Equation 2.1.b applies the same concept to a situation involving multiple highway segments of different lengths, and can be used to estimate average delay per traveler over a number of segments, routes or a system. In this case, the number of vehicles and occupants per vehicle is used in the numerator to expand and sum the total individual traveler delay over the various segments, and again in the denominator to reduce the summed traveler delay to an average amount per traveler.

The Travel-Time Index (TTI) is a dimensionless quantity that compares travel conditions in the peak period to travel conditions during free-flow or posted speed limit conditions. For example, a TTI of 1.20 indicates that a trip that takes 20 minutes in the off-peak period will take 24 minutes in the peak period or 20 percent longer. The TTI can be quickly and easily interpreted by most users in both an absolute sense (e.g., a TTI of 1.5 means a free-flow 200-minute trip will take 30 minutes) or a relative sense (the trip will take 50 percent longer.) This dual mode is useful because for a very short trip even a relatively large percent increase in travel time may be insignificant. Conversely, for a longer trip, a relatively small percent increase in travel time may be significant in terms of late arrival.

TTI reflects travelers' perceptions of travel time on the roadway, transit facility, or other transportation network element. This comparison can be based on the travel time increases relative to free-flow conditions (or PSL) and compared to the target conditions. Thus, the same index formula

can be applied to various system elements with different free-flow or posted speeds. Travel rate (in minutes per mile) is a direct indicator of the amount of travel time, which makes it relevant to travelers.

The measure can be averaged for freeways and arterial streets using the amount of travel on each portion of the network. An average corridor value can be developed using the number of persons using each facility type (or modes) to calculate the weighted average of the conditions on adjacent facilities. The corridor values can be computed for hourly conditions and weighted by the number of travelers or person-miles traveled to estimate peak period or daily index values.

The TTI in Equation 2.2 compares measured travel rates to free-flow or PSL conditions for any combination of freeway and arterial streets. Index values can be related to the general public as an indicator of the length of extra time spent in the transportation system during a trip. Equation 2.2 illustrates a relatively simple version of the calculation using VMT, but PMT also could be used, as could a value of time calculation that incorporates person and freight travel.

Travel Rate Index (TRI) is similar to the TTI in that it also is a dimensionless quantity that compares travel conditions in the peak period to travel conditions during free-flow or PSL conditions. The TRI measure is computed in the same way as the TTI, but does not include incident conditions. A typical application of the TRI would be calculating congestion levels from a travel demand forecasting model, because incident conditions are not considered in the model's forecasts. In contrast, continuous data streams allow for the direct measurement of a TTI that includes incidents. For some analysis applications, however, incident conditions would intentionally be excluded.

$$\text{Delay per Traveler (annual hours)} = \left(\frac{\text{Actual Travel Time (minutes)} - \text{FFS or PSL Travel Time (minutes)}}{\text{minutes}} \right) \times \frac{250 \text{ weekdays}}{\text{year}} \times \frac{\text{hour}}{60 \text{ minutes}} \quad (\text{Eq. 2.1.a})$$

$$\text{Delay per Traveler (annual hours)} = \frac{\left(\frac{\text{Actual Travel Time (minutes)} - \text{FFS or PSL Travel Time (minutes)}}{\text{minutes}} \right) \times \text{Vehicle Volume (vehicles)} \times \text{Vehicle Occupancy (persons/vehicle)} \times \frac{250 \text{ week days}}{\text{year}} \times \frac{\text{hour}}{60 \text{ minutes}}}{\text{Vehicle Volume (vehicles)} \times \text{Vehicle Occupancy (persons/vehicle)}} \quad (\text{Eq. 2.1.b})$$

$$\text{Travel Time Index} = \frac{\left[\frac{\text{Freeway Travel Rate}}{\text{Freeway Free-flow or Posted Speed Limit Rate}} \times \text{Freeway Peak Period VMT} \right] + \left[\frac{\text{Principal Arterial Street Travel Rate}}{\text{Principal Arterial Street Free-flow or Posted Speed Limit Rate}} \times \text{Principal Arterial Street Peak Period VMT} \right]}{\text{Freeway Peak Period VMT} + \text{Principal Arterial Street Peak Period VMT}} \quad (\text{Eq. 2.2})$$

For example, when travel time runs are performed for a corridor study, those runs affected by incident conditions are normally removed. This provides an estimate of the nonincident travel time along the corridor. In these conditions, the computed measure would be a TRI rather than a TTI.

Buffer Index (BI) is a measure of trip reliability that expresses the amount of extra buffer time needed to be on time for 95 percent of the trips (e.g., late for work on one day out of the typical 20-work-day month.) As with the TTI, indexing the measure provides a time- and distance-neutral measure, but the actual minute values could be used by an individual traveler for a particular trip length or specific origin-destination (O-D) pair. With continuous data, the index is calculated for each road or transit route segment, and a weighted average is calculated using vehicle-miles or, more desirably, person-miles of travel as the weighting factor. Travel rates for approximately 5-mile sections of roadway provide a good base data element for the performance measure. The BI can be calculated for each road segment or particular system element using Equation 2.3. Note that a weighted average for more than one roadway section could be computed using VMT or PMT on each roadway section. The measure would be explained as “a traveler should allow an extra (BI) percent travel time due to variations in the amount of congestion and delay on that trip.”

$$\text{Buffer Index (\%)} = \left[\frac{\text{95th Percentile Travel Time (minutes)} - \text{Average Travel Time (minutes)}}{\text{Average Travel Time (minutes)}} \right] \times 100\% \quad (\text{Eq. 2.3})$$

The buffer time concept appears to relate particularly well to the way travelers make decisions. Conceptually, travel decisions proceed through questions, such as: “How far is it?” “When do I need to arrive?” “How bad is the traffic likely to be?” “How much time do I need to allow?” “When should I leave?” In the time allowance stage, there is an assessment of how much extra time has to be allowed for uncertainty in the travel conditions. This includes weather, incidents, construction zones, holiday or special event traffic, or other disruptions or traffic irregularities.

Planning Time Index represents the total travel time that should be planned when an adequate buffer time is included. Planning Time Index differs from the BI in that it includes typical delay as well as unexpected delay. Thus, the Planning Time Index compares near-worst case travel time to light or free-flow traffic travel time. For example, a planning time index of 1.60 means, for a 15-minute trip in light traffic, the total time that should be planned for the trip is 24 minutes (15 minutes * 1.60 = 24 minutes). The Planning Time Index is useful because it can be directly compared to the travel-time index on similar numeric

scales. The Planning Time Index is computed as the 95th percentile travel time divided by the free-flow travel time as shown in Equation 2.4.

$$\text{Planning Time Index (no units)} = \frac{\text{95th Percentile Travel Time (minutes)}}{\text{Travel Time Based on Free-Flow or Posted Speed (minutes)}} \quad (\text{Eq. 2.4})$$

On-Time Arrival estimates the percentage of time that a traveler arrives on time based on an acceptable lateness threshold. A value in excess of the travel rate mean, say 10 percent to 15 percent, is used to identify the threshold of acceptable lateness or being “on time.” Required data include a sample distribution of trip times, whether for transit or highway trips. The On-Time Arrival percent is computed according to the following formula:

$$\% \text{OnTime} = \text{PercentTripTimes} < [1.10 * \text{MeanTime}] \quad (\text{Eq. 2.5})$$

where

%OnTime = Percent On-Time Arrivals;

PercentTripTimes = Percent of measured trip times; and

MeanTime = The computed mean of the measured travel time.

Percent Variation is closely related to the Planning Time Index. It is expressed as a percentage of average travel time and is distance/time neutral. Multiplying the average travel time by the percent variation yields the total travel time needed to be on time 85 percent of the time (one standard deviation above the mean). Higher values of percent variation indicate less reliability. It is computed according to the following formula:

$$\%V = \frac{\text{std.dev.}}{\text{Mean}} * 100\% \quad (\text{Eq. 2.6})$$

where

%V = Percent Variation;

Std.dev. = The standard deviation of measured travel time; and

Mean = The computed mean of the measured travel time.

The 90th or 95th percentile travel time is perhaps the simplest measure of travel-time reliability for specific travel routes or trips, which indicates how bad delay will be on the heaviest travel days. The 90th or 95th percentile travel times are reported in minutes and seconds and should be easily understood by commuters familiar with their trips. For this reason, this measure is ideally suited for traveler information. This measure has the disadvantage of not being easily compared across trips, as most trips will have different lengths. It

$$\text{Total Delay (persons - hours)} = \left[\frac{\text{Actual Travel Time (minutes)} - \text{FFS or PSL Travel Time (minutes)}}{\text{minutes}} \right] \times \frac{\text{Vehicle Volume (vehicles)}}{\text{vehicles}} \times \frac{\text{Vehicle Occupancy (persons/vehicle)}}{\text{persons/vehicle}} \times \frac{1 \text{ hour}}{60 \text{ minutes}} \quad (\text{Eq. 2.7})$$

$$\text{Congested Travel (vehicle - miles)} = \sum \left(\frac{\text{Congested Segment Length (miles)}}{\text{miles}} \times \frac{\text{Vehicle Volume (vehicles)}}{\text{vehicles}} \right) \quad (\text{Eq. 2.8})$$

$$\text{Percent of Congested Travel} = \left[\frac{\sum_{i=1}^m \left(\left(\frac{\text{Actual Travel Time}_i \text{ (minutes)} - \text{FFS or PSL Travel Time}_i \text{ (minutes)}}{\text{minutes}} \right) \times \left(\frac{\text{Vehicle Volume}_i \text{ (vehicles)}}{\text{vehicles}} \times \frac{\text{Vehicle Occupancy}_i \text{ (persons/vehicle)}}{\text{persons/vehicle}} \right) \right)}{\sum_{i=1}^n \left(\frac{\text{Actual Travel Rate}_i \text{ (minutes per mile)}}{\text{minutes per mile}} \times \frac{\text{Length}_i \text{ (miles)}}{\text{miles}} \times \frac{\text{Vehicle Volume}_i \text{ (vehicles)}}{\text{vehicles}} \times \frac{\text{Vehicle Occupancy}_i \text{ (persons/vehicle)}}{\text{persons/vehicle}} \right)} \right] \times 100 \quad (\text{Eq. 2.9})$$

also is difficult to combine route or trip travel times into a subarea or citywide average.

Several other statistical measures of variability have been suggested to quantify travel-time reliability, such as standard deviation and coefficient of variation. These are discouraged as performance measures, as they are not readily understood by nontechnical audiences nor easily related to everyday commuting experiences. The 90th or 95th travel time, or indexes such as the BI or Planning Time Index, are recommended as simpler ways to express the variability of expected travel time in a way that travelers can relate more directly to their travel expectations or experience.

2.5 Area Measures

The mobility and reliability measures described in the previous section mainly relate to the individual traveler making a particular trip. The measures described in this section are area measures where the area may be a corridor or region. These measures may be better suited to large scale system planning analysis.

The total delay (in person- or vehicle-hours) for a transit or roadway segment is the sum of time lost due to congestion. Delay can be expressed as a value relative to free-flow travel or relative to the posted speed limit. Total delay in a corridor or an urban area is calculated as the sum of individual segment delays. This quantity is used to estimate the impact of improvements on transportation systems. The values can be used to illustrate the effect of major improvements to one portion of a corridor that affects several other elements of the corridor. The quantity is particularly useful in economic or benefit/cost analyses that use information about the magnitude of the mobility improvement for cost-effectiveness decisions.

Equation 2.7 shows the computation of delay in person-hours. In addition, using a delay measure of hours per mile

of road, hours per 1,000 miles traveled, or hours per 1,000 travelers might be more meaningful to agencies at the corridor level, but the public may not understand these measures since it is difficult to relate to key travel decisions or travel experience.

Congested travel is a measure that captures the extent of congestion. It estimates the extent of the system affected by the congestion. Equation 2.8 illustrates the computation of congested travel in vehicle-miles as the product of the congested segment length and the vehicle volume summed across all congested segments.

The percent of congested travel is an extension of the congested travel measure. It also measures the extent of congestion. When speed and occupancy data are available for each roadway segment, this measure can be computed. It is computed as the ratio of the congested segment person-hours of travel to the total person-hours of travel. Equation 2.9 shows the computation.

Congested roadway is another measure of the extent of congestion. It is the sum of the mileage of roadways that operate under free-flow or posted speed limit conditions. This is shown in Equation 2.10.

$$\text{Congested Roadway (miles)} = \sum \frac{\text{Congested Segment Lengths (miles)}}{\text{miles}} \quad (\text{Eq. 2.10})$$

Accessibility is a measure that often accompanies mobility measures. It quantifies the extent that different opportunities can be realized. These might be accessibility to jobs, a transit station, or other land use or trip attractor of interest. Accessibility is satisfied if the travel time to perform the desired activity is less than or equal to the target travel time as indicated in Equation 2.11.

$$\text{Accessibility (opportunities)} = \frac{\sum \text{Objective Fulfillment}}{\text{Opportunities (e.g., jobs), Where Travel Time} \leq \text{Target Travel Time}} \quad (\text{Eq. 2.11})$$

Misery Index seeks to measure the length of delay of only the worst trips. The metric is computed by subtracting the average travel rate from the upper 10 percent (or 15 or 20 percent) of travel rates. This yields the time difference (as a proportion or percent) between the average trip and the slowest 10 percent of trips. It is computed according to the following formula:

$$MI = \frac{\text{Mean(Top20\%Times)}}{\text{MeanTime}} - 1 \quad (\text{Eq. 2.12})$$

where

MI = Misery Index;

Mean(Top20%Times) = The mean of the highest 20 percent of measured travel times; and

MeanTime = The computed mean of the measured travel time.

For example, if the mean travel time of the slowest 20 percent of trips in a corridor is 90 minutes and the mean travel time of all trips in the same corridor is 60 minutes, the Misery Index is calculated as $(90/60) - 1$, or $1.5 - 1.0 = 0.5$ (i.e., the slowest trips are 50 percent longer than the average trip).

Exhibit 2.5 summarizes key characteristics of the primary mobility and reliability measures described in this section.

The “components of congestion” have been defined as duration, extent, intensity, and variability or variation (2). Duration is the length of time during which congestion affects the system or facility. Extent can describe either the geographic distribution of congestion, or the number of people/vehicles/freight-tons affected by congestion. Intensity is the severity of the congestion, preferably from the traveler’s perspective, and is frequently expressed as the difference

between desired conditions and the conditions being analyzed. Variability refers to both regular and irregular changes in the other three components, and is a distinguishing component of reliability measures versus mobility measures. If enough is known about the variation in these other three components, for example, knowing the statistical distribution of travel times on a given facility, then reliability measures can be calculated that indicate, for example, the likelihood of arriving on time, the incremental amount of time required to be on time 95 percent of the time, etc.

2.6 Basic Data Elements

This section describes the basic data elements used to define the mobility and reliability measures described previously. The units are noted for typical urban analyses.

Travel time (in minutes) is the time required to traverse a segment or complete a trip. Times may be measured directly using field studies or archived data from traffic management centers, or can be estimated using empirical relationships with traffic volume and roadway characteristics, computerized transportation network models, or the projected effects of improvements.

Segment or trip length (in miles) is the distance associated with the travel time. Length can be measured directly with a vehicle odometer or scaled from accurate maps but is typically an established item in a transit or roadway inventory database.

Average speed (in miles per hour) for a segment can be used to calculate travel rate or travel times if field data are not readily available.

Average travel rate (in minutes per mile) is the rate a segment is traversed or a trip is completed (Equation 2.13). Travel rates may be determined directly using travel-time

| Performance Measure | Congestion Component Addressed | Geographic Area Addressed |
|--|--------------------------------|------------------------------------|
| Delay per Traveler | Intensity | Region, Subarea, Section, Corridor |
| Travel-Time Index | Intensity | Region, Subarea, Section, Corridor |
| Buffer Index | Intensity, Variability | Region, Subarea, Section, Corridor |
| Planning Time Index, Percent Variation | Intensity, Variability | Region, Subarea, Section, Corridor |
| Percent On-Time Arrival | Variability | Facility, Corridor, System |
| Total Delay | Intensity | Region, Subarea, Section, Corridor |
| Congested Travel | Extent, Intensity | Region, Subarea |
| Percent of Congested Travel | Duration, Extent, Intensity | Region, Subarea |
| Congested Roadway | Extent, Intensity | Region, Subarea |
| Misery Index | Intensity, Variability | Region, Subarea, Corridor |
| Accessibility | Extent, Intensity | Region, Subarea |

Exhibit 2.5. Key characteristics of mobility and reliability measures.

field studies, or can be estimated using transit schedules or empirical relationships (e.g., Bureau of Public Roads formula) between traffic volume and roadway characteristics (e.g., capacity).

$$\text{Travel Rate} \left(\frac{\text{minutes}}{\text{per mile}} \right) = \frac{\text{Travel Time} \left(\frac{\text{minutes}}{\text{Segment Length}} \right)}{\left(\frac{\text{miles}}{\text{Average Speed}} \right)} = \frac{60}{\text{Average Speed} \left(\frac{\text{mph}}{\text{mph}} \right)} \quad (\text{Eq. 2.13})$$

Person volume is the number of people traversing the segment being studied. The person volume can be collected for each travel mode or estimated using average vehicle occupancy rates for different types or classes of vehicles.

Freight volume is the amount of goods moved on a transport segment or system. It can be measured in units of ton-miles if the data are available, or it can be described more simply from truck percentages in the traffic stream. Freight volume may be particularly important in analyses dealing with travel-time reliability due to the sensitive nature of “just-in-time” manufacturing processes and goods delivery services.

Person-miles of travel is the magnitude of travel on a section of the transportation system or on several elements of the system. It is a particularly useful measure in corridor and areawide analyses where total travel demand is used in calculations. Equation 2.14 indicates it is the product of distance and person volume. Person volume can be estimated as the product of vehicle volume and average vehicle occupancy.

$$\text{Person-miles of Travel (PMT)} = \text{Person Volume} \times \text{Distance} \quad (\text{Eq. 2.14})$$

Target travel time (in minutes) is the time that indicates a system or mode is operating according to locally determined performance goals. It focuses on the door-to-door trip time from origin to destination. The target travel time can be differentiated by the purpose of the travel, the expectation for each mode within the transportation system, the type of activity, and the time of day. It should be influenced by community input, particularly on the issue of the balance between transportation quality, economic activity, land use patterns, and environmental issues.

Target travel rate (in minutes per mile) is the maximum rate (slowest speed) a segment is traversed or a trip is completed without experiencing an unsatisfactory level of mobility. The target travel rate is based on factors similar to the target travel time. This is similar to the process used by many states and cities where a target level of service (LOS) is used to determine the need for additional transportation improvements.

In practice, there also will be a need for a corridor average travel rate value. This would be used as the target for facility

expansions, operating improvements, program enhancements, or policy implementations. The facility/mode target travel rates can be used for evaluation, but improvement strategies and amounts should be based on corridor-level decisions.

2.7 Definition and Discussion of Speed Terms

This section provides definitions of primary speed measures and guidance on their use in mobility and reliability analyses.

FFS is the average speed that can be accommodated under relatively low traffic volumes (i.e., no vehicle interactions) on a uniform roadway segment under prevailing roadway and traffic conditions. It can be calculated or estimated in a number of ways, with a common approach being to use the 85th percentile speed in the off-peak period. The off-peak periods can be defined by time period (e.g., overnight = 10:00 p.m. to 6:00 a.m., or midday = 9:00 a.m. to 4:00 p.m.) or vehicle volume. Vehicle headways of 5 seconds or more could be used to define FFS operating conditions (i.e., traffic volumes of approximately 700 vehicles per hour per lane [vphpl]). Ideally, a continuous data source (e.g., ITS, Weigh-in-motion [WIM], Automatic Traffic Recorder [ATR], etc.) could be used to identify the FFS using at least one year of valid data.

PSL is the posted speed of the roadway. For specific facilities or sections thereof this value is obtained by field data collection. Posted speed is a typical roadway inventory data element; therefore, posted speeds can be obtained from such roadway inventories, particularly for a system-level analysis that includes numerous facilities.

Target speed is the speed associated with the target TTI. The target speed can be computed given the target TTI and the free-flow travel rate or the PSL travel rate.

2.7.1 Threshold Speed Values

Many analyses begin with the question, “What should we compare to?” The issue usually can be framed as a choice between using a desirable condition or using an achievable condition given the funding, approval, and other constraints.

It should be noted that PSLs are included in most roadway inventory files and should be readily available for analytical procedures. Computerized analysis procedures should be modified so that a negative delay value is not included in the calculations. If estimated FFS are used in the calculation of delay, the speed data collected from field studies may include values with very fast speeds (above the FFS). FFSs higher than the PSL may present an illegal

appearance problem when used in public discussions. In addition, it may be difficult to justify delay being calculated for travel at the PSL.

2.7.2 When Would I Use Free-Flow Speed in Mobility and Reliability Measure Computation?

Delay and congestion index measure computations can be computed relative to FFS. Using FFS for these computations is most appropriate when continuous data sources that allow for the computation of the 85th percentile speed in the off-peak period are available. The use of a FFS provides an automated and consistent method for computing delay and index values across different metropolitan areas. The FFS also could be used when the analyst does not have ready access to posted speeds along the corridors included in a mobility and reliability analysis, particularly large areawide analyses.

2.7.3 When Would I Use a Posted Speed Limit in Mobility and Reliability Measure Computation?

PSL also can be used to compute delay and index measures. PSL can be used when continuous data are not available for the mobility or reliability analysis. PSLs are an easy to communicate threshold, are more stable than FFSs, and do not require value judgments of assessments of goals or targets.

2.7.4 How Can the 'Maximum Productivity' Concept be Used?

Maximum productivity (i.e., the combination of relatively high vehicle volume and relatively high speed that provides the most efficient roadway operation) is a goal for traffic management professionals. It is gaining a useful place in communication with nontechnical audiences as the target for agencies moves from free-flow travel to reliable service at all times. This target reflects the general acceptance of congestion for a few hours each day in major metropolitan regions. The concept can be used in the same manner that a target condition is implemented by both planners and operators.

2.7.5 How Does the Target Travel-Time Index Relate to the Computed Measures?

Target TTI values could be developed with input from citizens, businesses, decision makers, and transportation professionals. The target values represent the crucial link between two objectives: 1) the vision that the community has

for its transportation system, land uses, and its quality of life issues and 2) the improvement strategies, programs, and projects that government agencies and private sector interests can implement. Planners can use the targets to identify problem areas and judge which strategy meets both objectives. The values are desirably the result of a process integrated with the development of the long-range plan, but they must be reasonable and realistic since overstatement or understatement could distort the assessment of congestion.

Urban areas should approach the use of a target TTI with a corridor and system strategy. The target value may be developed for every mode or facility as a way to identify individual performance levels, but the key application will be as a corridor or system target. Individual facility deficiencies can be addressed through improvements to that mode or route or by other travel mode improvements, strategies, or policies. For example, the freeway main lanes may not satisfy the target value, but if an HOV lane is successful in moving a large number of people at high speeds, the average TTI, when weighted by person volume, may achieve the target value.

Target TTI value can be "adjusted" appropriately irrespective of whether a FFS or a PSL is used in the calculation of the TTI. For example, if FFS is used, the target TTI value might be 1.4, whereas the target TTI value might be 1.3 if the PSL is used.

2.7.6 Summary and Guidance

FFS is better for matching how people drive given the roadway operating conditions (i.e., "I was traveling 5 mph over the PSL, and I was still being passed"). PSLs are sometimes set for public policy reasons, rather than being tied to actual conditions making comparisons between regions or comparisons over several years difficult. PSLs could go down, reducing the apparent delay, and yet if peak-period speeds declined, which should show more congestion, there could be less reported delay.

These considerations should be evaluated when determining the appropriate reference (FFS or PSL) in delay and index computations for the community and stakeholders involved with the analysis.

2.8 Other Data Elements

Several other factors are needed to perform mobility and reliability analyses, including the following:

- Hourly volumes, expressed in vehicles or persons, may be very useful for the peak period or 24-hour periods. Many roadway and transit analyses focus on the peak hour, but in most large cities this is not enough information to assess the mobility and reliability situation or to analyze alternatives.

A range of improvements, including demand management, advanced traveler information systems, and HOV lanes, have an effect on other hours in the peak period.

- Daily volume variation is the variability in person or vehicle volume from day to day. These data are particularly important in analyses that examine mobility and reliability levels on particularly heavy volume days (e.g., Fridays or days before holidays) or days/time periods with different travel patterns (e.g., special events or weekends).
- Incident information includes the number and duration of crashes and vehicle breakdowns that occur on roadway segments and transit routes. This information is used in analyses of the variation in mobility and reliability. The reliability of transportation systems is a particular concern in analyses of incident management programs, value pricing projects, and freight movement studies.
- Weather information can explain a significant amount of the variation in travel conditions. Snow, ice, fog, and rain can be noted in a database used for mobility and reliability analyses.
- Road work information includes construction and maintenance activities and their location. This includes the location, number of lanes affected, and time period.
- Peak direction hourly travel demand and volume are two measures of person or vehicle travel used in system analyses. The two may be the same for uncongested corridors. Demand is higher than volume in congested corridors, however, and the “excess” volume travels on the main route in hours adjacent to the peak hour and on alternate routes. Improvements to primary routes or travel modes may result in higher traffic volumes in the peak hour that can be predicted if demand is estimated.

2.9 Time Periods for Analysis

Selecting the appropriate time period is an important part of building the data collection plan and analysis framework. Considerations include the nature of the problem(s) to be addressed through the analysis, the geography of the study area, and the presence of any special seasonal events or conditions that could dramatically alter data or interpretation of results.

2.9.1 Peak and Off-Peak Period Analysis

Peak period is the time period most often used for urban mobility and reliability analyses. Off-peak periods may be of interest to study the extent of peak spreading at one area compared to another area. The TTI is computed relative to the FFS or PSL. If the analyst is investigating the TTI of an off-peak period that is beginning to experience congestion, the TTI could be used to illustrate the increased congestion if the

actual travel rate during the off-peak is higher than the target value. The BI and delay measures also could be useful in the off-peak period in locations that may be experiencing some congestion in the off-peak.

2.9.2 Daily Analysis

Analysis using daily averages is often less useful with the TTI and BI. Using 24-hour speeds for computing the TTI is not meaningful because the measure is meant to compare peak and off-peak travel conditions. Likewise, the BI is intended to be a measure of reliability during a peak period. Daily values “wash out” the effect of congestion in peak periods with the longer off-peak periods. Total delay is more meaningful as a daily congestion measure. Though the total delay in person- or vehicle-hours is less meaningful to an individual driver, it is a good measure for analyzing trends from year to year. Daily delay is used in this manner in the FHWA-sponsored Mobility Monitoring Program (MMP).

2.9.3 Seasonal Analysis

Investigating variations in mobility and reliability over the seasons of the year also may be of interest. Many areas have unique peaking characteristics due to seasonal events (e.g., academic calendars, sporting events, and tourism). These activities can alter the length and extent of the peak period. All of the measures discussed in this chapter can be used in a mobility or reliability analysis that compares peak or off-peak period measure changes by month of year.

2.9.4 Urban or Rural Analysis

The preceding discussion has assumed an urban mobility or reliability analysis. Rural locations also can be the subject of mobility and reliability analyses. For example, there might be an interest in freight movements in rural areas. Special events and tourism activities also are situations that may generate interest in a rural analysis.

As mentioned previously, continuous data sources provide speed (travel time), volume, and classification information in some urban areas. Point-to-point travel-time information also is of interest for rural freight operations. As with travel conditions on an urban congestion map, such point-to-point travel-time information would allow insight into rural freight operations. Transponders could be used to provide the continuous information. The University of Washington is investigating such applications in rural areas in the state of Washington. Of the primary measures discussed in this chapter, TTI and delay measures could be used for this rural application. The TTI could be used to compare current travel rates to a

target travel rate for goods movement over the corridor of interest. If continuous data sources are available (e.g., toll tags or cellular telephone), the BI also could be computed for freight carriers. Prior to real-time systems, estimation measures could be used to estimate delay for goods movement.

Special events and tourism also may invite mobility and reliability analyses in a rural area. If real-time equipment already is installed, it could be used to obtain travel rate information to compare to a target travel rate. Delay also could be computed. For a special event, and possibly for a tourism activity/season, portable readers also could be installed to monitor mobility and reliability along rural corridors of interest.

2.10 The Right Measure for the Analysis Area

Exhibit 2.6 summarizes the mobility and reliability measures that should be used for several types of analyses and for different size areas or modal combinations (6, 1). Individual traveler measures such as travel rate and the TTI are very useful for analysis up to the corridor level. At higher levels of analysis, magnitude statistics such as delay and accessibility also are useful. Examples of the application of these measures to situations based on the level of analysis are included in the following sections.

Most mobility and reliability studies should be conducted at geographic areas higher than individual locations and short sections of roadway. At relatively small areas, the studies will typically be limited to near-term analysis of operational improve-

ments where new modes or facilities are not realistic options and even the operational improvements will be limited. These analyses may proceed using HCM-type procedures. Total delay, delay per person, and travel-time difference are most useful for intersections or individual locations due to problems identifying the length needed for the rate-based measures.

Larger scale analyses, where more detailed analytical tools are used and a wider choice of improvement options is considered, are more frequently identified as mobility or reliability studies. The analysis and presentation of mobility and reliability data can be accomplished by the TTI, BI, TRI, total delay, and accessibility as primary measures. Secondary measures also may be used for cumulative analyses of several improvements and estimation of benefits.

Mobility and reliability for larger areas of analysis, such as long roadway sections and corridors can be quantified with some individual statistics if the roadways are of the same type. But if freeways, streets, and/or other travel modes are included, **cumulative statistics**, **TTI**, and **BI** are very appropriate. Index statistics become useful at this higher level of analysis when multiple roadways and large numerical values (e.g., statistics expressed in thousands or millions of hours) make interpretation of relative conditions difficult.

2.11 The Right Measure for the Type of Analysis

The recommended uses in Exhibit 2.7 are another illustration of how the mobility and reliability measures vary by the scope of the analysis, but not by mode or facility included in

| Mobility and Reliability Measures | | | | | | | | | | |
|---|-------------|-------------|---------------------------|-------------------|--------------|-------------|------------------|-----------------------------|-------------------|---------------|
| Analysis Area | Travel Time | Travel Rate | Annual Delay Per Traveler | Travel-Time Index | Buffer Index | Total Delay | Congested Travel | Percent of Congested Travel | Congested Roadway | Accessibility |
| Individual Locations | S | | S | P | P | S | | | | |
| Short Road Sections | P | P | S | P | P | S | | | | |
| Long Road Sections, Transit Routes or Trips | | S | S | P | P | S | | | | |
| Corridors | | S | S | P | P | P | | | | S |
| Subareas | | S | P | P | P | P | P | P | P | P |
| Regional Networks | | S | P | P | P | P | P | P | P | P |
| Multimodal Analyses | | S | P | P | P | P | | | | P |

P = Primary measure, and S = Secondary measure.

Note: Measures with delay components can be calculated relative to free-flow or posted speed conditions.

Exhibit 2.6. Recommended mobility and reliability measures for analysis levels (1).

| Uses of Mobility and Reliability Measures | Mobility and Reliability Measures | | | | | | | | | |
|---|-----------------------------------|-------------|--------------------|-------------------|--------------|-------------|------------------|-----------------------------|-------------------|---------------|
| | Travel Time | Travel Rate | Delay per Traveler | Travel-Time Index | Buffer Index | Total Delay | Congested Travel | Percent of Congested Travel | Congested Roadway | Accessibility |
| Basis for government investment or policies | | | P | P | P | P | P | P | P | P |
| Basis for national, state, or regional policies and programs | | | P | P | P | P | P | P | P | P |
| Information for private-sector decisions | P | P | S | P | P | S | P | P | P | |
| Measures of land development impact | P | P | P | P | P | P | S | S | S | P |
| Input to zoning decisions | P | P | | P | P | | | | | P |
| Inputs for transportation models | P | P | | | P | | | | | |
| Inputs for air quality and energy models | P | P | P | | P | | | | | |
| Identification of problems | P | P | P | P | P | S | S | S | S | |
| Base case (for comparison with improvement alternatives) | | | S | P | P | P | S | S | S | P |
| Measures of effectiveness for alternatives evaluation | | P | P | P | P | P | S | S | S | P |
| Prioritization of improvements | | | P | P | P | P | | | | S |
| Assessment of transit routing, scheduling, and stop placement | P | P | P | P | P | S | | | | |
| Assessment of traffic controls, geometrics, and regulations | P | P | | | P | | | | | |
| Basis for real-time route choice decisions | P | P | P | P | P | | | | | |

P = Primary measure; and S = Secondary measure.

Exhibit 2.7. Recommended mobility and reliability measures for various types of analyses (1).

the analysis (1). Travel time and speed measures, and data and estimating techniques used to create them, are flexible analysis tools. When combined with person and freight movement quantities, they illustrate a range of mobility and reliability situations. Different values will be used for the target travel rate or target travel time depending on the facility type or travel mode, but the calculation and application of the measures are identical.

While it is difficult to cover every type of mobility and reliability analysis, Exhibit 2.4 illustrates recommended measures for many common types of studies and information requirements. As with Exhibit 2.6, the analyses where small areas are analyzed or quick answers are needed use simple measures. More complex analyses, those that typi-

cally cover larger areas or multiple modes and those targeting nontechnical audiences, use index measures and summary statistics.

2.12 Index Measure Considerations

Following are a few additional considerations to take into account when using performance measures, particularly those dimensionless indexes such as the TTI or BI that are not expressed in familiar units such as minutes or miles per hour. Setting targets or benchmarking to a regional or national standard is one possible approach. Expressing targets and performance results in a user-familiar context such as the door-to-door trip time is another.

2.12.1 How Much Congestion Is Too Much?

Analyses of system adequacy, the need for improvements, or time-series analyses conducted in a corridor or area can benefit from comparisons using target conditions.

Free-flow conditions will not be the goal of most large urban transportation improvement programs, but using them provides a consistent benchmark relevant for year-to-year and city-to-city comparisons. The attainment of goals standard also might be used at the national or state level, but will be used more often during a discussion of planning and project prioritization techniques.

The use of a target travel rate can improve the guidance provided to system planners and engineers. If the target travel rates are a product of public discussion, they will illustrate the balance the public wishes to have between road space, social effects, environmental impacts, economic issues, and quality of life concerns. Areas or system elements where the performance is worse than the target can be the focus of more detailed study. A corridor analysis, for instance, might indicate a problem with one mode, but the solution may be to improve another mode or program that is a more cost-effective approach to raising the corridor value to the target. The amount of corridor or area-wide person-travel that occurs in conditions worse than the locally determined targets can be used to monitor progress toward transportation goals and identify problem areas.

2.12.2 Relationship to Door-to-Door Travel-Time Measures

The measure of system performance closest to the concern of travelers is door-to-door travel time. Any performance measure should relate to door-to-door travel time as closely as possible. Calibrating the user view of system performance with measures that can be more readily collected from existing data sources is the key to the efficient and effective presentation of mobility and reliability information. Periodic updates of public opinion can be used to adjust corridor and areawide

determinations of service quality. Ten pairs of O-D trip patterns, for example, could be used to show the change in travel time. The information for these key travel patterns can be updated daily, monthly, or annually with system monitoring equipment. Every five years the key patterns could be reexamined for relevance to the existing and future land use development patterns and transportation system.

Using target conditions as the comparison standard provides the basis for a map or table showing system deficiencies in a way readily understood and uniquely relevant to improvement analyses. A map showing the target travel rates on the system links would accompany such a presentation. This approach also could be easily used in a multi-modal analysis, with a target TTI for the corridor. Future travel rates for the corridor can be changed by improving a facility or service, or by shifting travel to other modes/facilities. The target comparison standard would be broader than simply a mobility or reliability measure since it would directly incorporate the idea that the goal for a corridor is not always high-speed travel. It could be used in conjunction with an areawide planning effort to relate the link speeds, used in estimating the TTI, to the outcome measures of door-to-door trip satisfaction.

2.12.3 Impact on Data Collection

One outcome of a move to the travel-time-based measures would be the ability to include directly collected travel-time data from the various transportation system elements. Many areas do not collect this information, but the initial statistics can be developed from estimates of travel speed. As travel-time studies are conducted or archived data systems developed, the actual data can be used to replace the estimates in the index, as well as to improve the estimation processes. The information derived from systems that automatically collect and analyze travel speed over sections of freeways provide a significant resource for travel-time-based performance measure calculation.

CHAPTER 3

Data Collection and Processing

3.1 Introduction

This chapter provides guidance on the collection of travel time, delay, and variability data from TMC, as well as other sources. The purpose of this chapter is to advise the analyst on the development of a data collection plan to support measures of travel time, delay, and reliability data for use in typical planning applications.

This chapter is designed to address two very different data collection situations that the analyst is likely to confront. Most agencies will either be data-rich or data-poor. A data-rich agency will have continuous surveillance capabilities on some of the facilities being studied, usually from a TMC. A data-poor agency may have typical traffic volume data, but must put in place temporary data collection equipment or vehicles to gather travel-time data.

Both data-rich and data-poor agencies can estimate mean travel time and mean delay using the strategies described in this chapter. This guidebook provides methods for estimating mean travel time and mean delay for either data-rich or data-poor situations. Recommended minimum sample sizes are provided in this chapter.

In contrast, data-poor agencies generally cannot measure travel-time reliability very well in the field without significant expense to gather the required data. An agency must have continuous surveillance capabilities, or nearly so, in order to develop useful, cost-effective measures of reliability. As such, this guidebook does not provide a method for estimating travel-time reliability for data-poor situations, and no minimum sample sizes are provided for estimating travel-time reliability. The analyst generally must have continuous monitoring capabilities in order to adequately estimate reliability.

3.2 Data Collection Methods

Analysts have the option of conducting their own travel-time data collection effort or obtaining the needed data from another

agency or source. Before initiating an independent data collection effort the analyst should first see if the data they need is already being collected by other agencies. If so, analysts should assess the extent to which this data meets their needs.

Using data being collected for other purposes saves on data collection costs, which are not insignificant. Using data already being used for other purposes also is likely to ensure that the data is of acceptable quality. However, the data may not be in exactly the format or contain all of the variables required by the analyst. Additional time and effort may be needed to fill gaps and reformat the data to satisfy the needs of the analyst.

A custom data collection effort has the advantage that the analyst gets exactly the data they need for the study. However, the set-up time and cost of custom data collection efforts are high. Exhibit 3.1 lists some of the typical advantages and disadvantages of using data collected for other purposes to generate travel time performance measures. The term typical is used to alert the reader that conditions, cost, and quality vary; each situation should be examined to reveal its unique characteristics.

Exhibit 3.2 highlights typical agency or third-party travel time and delay data collection programs.

The FHWA publication, *Travel-Time Data Collection Handbook* is an excellent source of information on the strengths, weaknesses, and costs of various travel-time data collection methods. Exhibits 3.3 and 3.4 highlight the strengths and weaknesses of various travel-time data collection methods.

3.3 Data Collection Sampling Plan

It is necessary to develop a sampling plan to collect data for selected time periods and at selected locations within the region. Data collection that supports the desired analysis and measures will be more cost-effective and less problematic if a rigorous sampling plan is first developed.

| Option | Typical Advantages | Typical Disadvantages |
|----------------------------|--|--|
| Custom Data Collection | <ul style="list-style-type: none"> • Tailor to specific analysis needs • Greater quality control | <ul style="list-style-type: none"> • Expensive • Time-consuming to collect |
| Obtaining Data from Others | <ul style="list-style-type: none"> • Less expensive • Readily available | <ul style="list-style-type: none"> • May not be exactly what is needed • Quality less well known |

Exhibit 3.1. Advantages/disadvantages of using data collected for other purposes.

3.3.1 Sampling Strategies for O-D Trip Time Monitoring

The collection of origin to destination trip times can be very expensive because of the numerous possible origins and destinations within any region. A region divided into 1,000 traffic analysis zones will have 1,000,000 possible O-D combinations. In addition, there are numerous paths between each O-D pair to further complicate the process of trip-time measurement.

The analyst must therefore adopt a stratified sampling approach to reduce the measurement problem to a tractable size. A wide range of sampling strategies may be pursued, depending on the objectives of the analysis. Two strategies are described here to illustrate the general approach.

The first sampling strategy described here seeks to gather travel-time data representative of the region as a whole. Possible O-D pairs are grouped into 10 categories (The number of categories is determined by the analyst based upon the resources available to perform the data collection.) according to the minimum path trip length between each O-D pair. For example the O-D pairs might be grouped into those with trip lengths under 5 miles, those with trip lengths between 5 and 10 miles, etc. The analyst then randomly selects three O-D pairs from each category and measures the travel time several times for each O-D pair. The results can be summed to obtain regional totals by weighting the average travel time results for each category by the number of trips contained within each category.

Another strategy would be to group the zones into super-districts. Three zones would then be randomly selected from each super-district and the travel times measured for the selected zone pairs. The results can be aggregated weighting the average travel times according to the number of trips represented by each super-district.

3.3.2 Sampling Strategies for System Monitoring

If it is desired to develop travel-time information for the regional freeway system (or surface street system), collection of travel time for 100 percent of the road system will probably be

beyond the means of most urban areas (unless the system is 100 percent instrumented with permanent vehicle detectors or travel time data collection devices). Even if the system is 100 percent instrumented, the number of locations and the volume of data may be much greater than the analyst can handle. In either case it becomes desirable to reduce the resources required by focusing on a select sample for freeway or road system segments within the region.

A wide variety of sampling strategies are possible. The following two are described to illustrate the approach.

If the objective of the study is to obtain travel-time measurements that could be used to characterize overall system performance then one sampling strategy would be to collect data every 5 miles (or every 10th detector) on the system. The length and mean speed for each sample location would be measured. The travel-time results for the individual sample segments would be expanded to system totals and averages using the ratio of total system miles to sample miles, or the ratio of total system vehicle-miles traveled to the vehicle-miles traveled on the sample sections.

If the objective of the study is to identify system deficiencies, then the analyst might adopt a different sampling strategy that focuses on system bottlenecks. Travel-time information would be collected only for the congested periods or days and only on the higher volume segments of the regional freeway system.

3.3.3 Sample Size Requirements for Estimating Mean Delay or Travel Time

Travel time varies randomly from hour to hour, day to day, and week to week throughout the year. It is never adequate to measure travel time only once. The analyst must measure the travel time between two points several times and compute the average travel time from the data.

This section describes how to estimate the minimum number of travel-time observations that would be required. The minimum number of observations is determined by precision desired by the analyst. If the analyst needs to know the mean travel time very precisely, a large number of observations will be required.

| Agency | Comments |
|----------------------------------|---|
| State DOTs | <ul style="list-style-type: none"> On freeways within major urban areas the state DOT may have continuous count stations with counts and point speeds available every half mile of freeway and most ramps. In some states (e.g., Washington and California) the data may be available on a real-time basis over the Internet.¹ Floating car measurements of mean segment speed may be gathered on an annual basis for certain freeways in major urban areas as part of a congestion monitoring program. For freeways outside of major urban areas (and conventional state highways everywhere in the State), the state DOT may have a couple of weeks of hourly count data collected quarterly at scattered count stations. Speed, travel time, and delay data are not typically gathered at count stations outside of major urban areas. Counts, speed, and other data are often collected on an “as-needed” basis for upcoming highway improvement projects. |
| Traffic Management Centers | <ul style="list-style-type: none"> TMCs gather real-time speed and volume data for freeway segments at intervals that typically range from one-third to one mile. Data in some cases stored for longer than 24 hours. Detector reliability can be low depending on maintenance budget. A few TMCs (Los Angeles ATSAC for example) gather real-time volume data for city streets. TMC speed data for urban streets are generally considered less reliable. |
| MPOs | <ul style="list-style-type: none"> MPOs conduct travel behavior surveys every 5 to 10 years in which they ask travel-time information. MPOs involved in congestion management may commission annual surveys of peak-period speeds and travel times on specific road segments. |
| Local Agencies | <ul style="list-style-type: none"> Counties and cities gather traffic count data generally as part of specific studies for improvement projects. Speed data on road segments may be measured every few years in support of enforcement efforts (radar spot speed surveys). |
| Private Company | <p>Several private companies collect travel time or speed data to disseminate as real-time traffic information. Other companies offer vehicle fleet monitoring services for real-time fleet management and dispatching, and may save “anonymized” vehicle position data that could be used to calculate travel time-based measures. A key consideration for this type of data is the negotiation of data rights such that the privately owned data can be used as needed by public agencies.</p> |
| American Community Survey | <p>The ACS is the annual replacement for the decennial census travel data. Some commuting measures are available if a region has invested in additional surveys to ensure statistical reliability at the local level.</p> |
| National Household Travel Survey | <p>As states have taken a more active role in measuring and forecasting travel demand, the NHTS is becoming more important as a source of state-level indicators for transportation planning and performance measurement. Products, such as the state profiles, freight data and statistics, seasonality statistics, etc., provide agencies with improved ability to apply national travel behavior data to local, regional, and state performance measurement and forecasting.</p> |

¹The California Department of Transportation (Caltrans) has teamed with Partnership for Advanced Technology on Highways (PATH) at the University of California, Berkeley, to store traffic data and make it available on-line. Access to this data, known as the Freeway Performance Measurement System (PeMS), can be requested at <http://pems.eecs.berkeley.edu/public/index.phtml>. The Minnesota Department of Transportation (Mn/DOT) has a data collection and storage center at its Twin Cities office that integrates traffic, weather, and traffic incident data. Mn/DOT’s Regional Transportation Management Center (RTMC) can be reached at www.dit.state.mn.us/tmc/index.html. Interested parties may visit their office and download desired data onto a storage device. The State of Washington’s DOT, the first to archive real-time traffic data in the United States, will download requested information onto a suitable storage device such as a CD (see <http://www.wsdot.wa.gov/traffic/seattle/traveltimes>).

Exhibit 3.2. Potential sources of travel time, delay, and reliability data.

| Method | Accuracy for General Purpose Vehicle Travel Time | Variability | Geographic | Time of Day | Modes | Comments |
|---|--|--|--|---|--|---|
| Floating Cars <ul style="list-style-type: none"> • GPS • DMI | Excellent. | Limited ability to collect variability data. | Best for single facilities. Very costly to acquire data for extensive geographic area. | Best for limited peak periods. Too costly for obtaining 24-hour data. | Not practical for gathering bike data. | <ul style="list-style-type: none"> • Floating cars are cost inefficient for gathering travel time and delay, but the technology is commonly available and easy to apply. • Too costly to collect data over broad arterial network or in nonpeak periods. Not practical for OD travel times. • Feasible, but very costly to collect data for transit and freight modes. |
| Transit Schedules | Fair. | Does not provide data on variance. | Full coverage of region is inexpensive. | No data outside service hours. | Transit only. | <ul style="list-style-type: none"> • Average transit travel times can be approximated with transit schedules if transit agency has good schedule compliance. • Not uniformly reliable for individual routes; may supplement with on-time performance statistics. • Not reliable for systems that do not routinely monitor on-time performance. |
| Retrospective survey <ul style="list-style-type: none"> • Home Telephone • Employer • Piggyback on Other Efforts | Limited because of respondents' memories and tendency to round travel times. | Limited ability to collect variability data due to rounding of reported times. | Full geographic area coverage possible; costs vary. | Unlikely to obtain good travel-time data for light travel periods of day (overnight). | No Freight. | <ul style="list-style-type: none"> • Retrospective surveys which rely on travelers' memories are generally less precise than prospective surveys. • Good for obtaining OD trip times, although times not likely to be more accurate than to nearest 5 to 10 minutes. • Costs decrease as tolerance for bias increases (sampling can be less rigorous (e.g., using employee surveys or web surveys)). • Other variations on sampling possible. • Many MPOs currently conduct commuter surveys; may be possible to piggyback on those current surveys. |
| Prospective Home Survey (Manual Trip Diary) | Fair to Good. | Fair. | Full coverage costly. | Unlikely to obtain good travel-time data for light travel periods of day (overnight). | No Freight. | <ul style="list-style-type: none"> • Prospective survey where the traveler is contacted in advance and asked to record all trip making the next day are generally more precise than retrospective surveys. • Good for obtaining OD trip times. • Most expensive and most accurate traveler survey method. • GPS diaries have excellent accuracy but increase costs and require a long-term implementation timeframe. |

Exhibit 3.3. Travel-time data collection methods requiring little or no technology investment.

| Method | Accuracy | Variability | Geographic | Time of Day | Modes | Observations |
|---|---|----------------------------------|--------------------------------------|-------------|--|---|
| Freight Tracking <ul style="list-style-type: none"> • Logs • GPS | Excellent. | Yes, but limited by sample size. | Coverage dependent on participants. | All | Only Freight. | <ul style="list-style-type: none"> • Reliance on carriers to provide data likely impractical due to imposition on carrier. • Loaner GPS units costly but provide incentive for carrier participation and increase accuracy. |
| TMC Roadside Sensors <ul style="list-style-type: none"> • Loops/RTMS (spot speeds) | Excellent (for spot speeds, assuming adequate maintenance). | Excellent | Full coverage costly. | All | Best for freeways. | <ul style="list-style-type: none"> • Loop infrastructure unreliable without significant maintenance commitment. • Possible to extrapolate travel time from speed data, depending on accuracy need. • Vehicle signature matching, under development; may generate travel-time data in the long term. |
| ETC Passive Probes | Excellent. | Excellent. | Full coverage costly. | All | All, bike possible. | <ul style="list-style-type: none"> • ETC tags cheap, but roadside readers costly; therefore costly to get broad coverage, especially on arterials and therefore on transit. • Deployed successfully for other purposes. • Vehicle type identification nontrivial to implement. |
| Areawide Passive Probes (GPS) | Excellent. | Good. | Full coverage inexpensive. | All | No bike. | <ul style="list-style-type: none"> • GPS units currently expensive and complicated to install (by operators); costs may decrease, but this is a risk factor. • Collecting data from GPS units is costly, and likely inconvenient. • The only nonsurvey method that can collect door-to-door travel time. |
| Transit Monitoring Systems | Good. | Yes, but limited by sample size. | Depends on routes and roads covered. | All | Transit; may be used to estimate general purpose travel as well. | <ul style="list-style-type: none"> • Transit agencies are using a variety of tracking systems to provide on-time data to their patrons. This data can be synthesized for use in general-purpose traffic monitoring. |
| License Plate Matching with OCR | Excellent. | Excellent. | Full coverage costly. | All | No bike. | <ul style="list-style-type: none"> • Manual matching possible in short-term, but cost prohibitive without (long term) advances in OCR. • Video equipment also expensive, especially to cover broad arterial network; therefore limited transit coverage. |

Exhibit 3.4. Travel-time data collection methods requiring major technology investment.

The minimum number of observations required to establish a target confidence interval for the mean travel time or the mean delay is given by the following equation:

$$N = 4 * \left[t_{(1-\alpha/2), N-1} * \frac{s}{CI_{1-\alpha\%}} \right]^2 \quad (\text{Eq. 3.1})$$

where

N = Minimum required number of observations;

$CI_{(1-\alpha)\%}$ = The confidence interval for the true mean with probability of $(1-\alpha)\%$, where “alpha” equals the probability of the true mean not lying within the confidence interval;

$t_{(1-\alpha/2), N-1}$ = The Student’s t statistic for the probability of two-sided error summing to alpha with $N - 1$ degrees of freedom; and

s = The standard deviation in the measured travel times and the square root of the variance.

Exhibit 3.5 illustrates the minimum number of observations required for various target levels of precision, expressed here in units of the standard deviation of the measured travel times or delay times. The desired precision is defined as the desired confidence interval (CI) in seconds divided by standard deviation (S) in seconds. For example, if the standard deviation in the delay is 1.5 seconds and the desired confidence interval is 3.0 seconds, the desired precision is 2.0 (i.e., 3.0 divided by 1.5 equals 2.0 standard deviations). It will take a minimum of eight observations to estimate the mean delay to within plus or minus 1.5 seconds (a total range or CI of 3.0 seconds) at a 95 percent confidence level.

It is rare for an analyst to actually know what the standard deviation will be before conducting the delay or travel-time measurements. So the usual strategy is to take 10 measurements of the delay (or travel time), and then compute the sample standard deviation from those 10 measurements. The confidence interval for the mean is then computed, and if the computed confidence interval is satisfactory (e.g., less than the desired precision for the mean), no more measurements are required. If the computed confidence interval is unsatisfactory (e.g., too large), additional measurements of delay (or travel time) are made. Equation 3.1 is used to compute the total number of measurements required. The required number of additional measurements is the difference between the total computed per Equation 3.1 and the number of measurements already completed (in this example, 10 measurements already would have been completed).

3.4 Collecting Data from TMCs

Collecting data from TMC requires some special considerations. Most TMCs were created to monitor existing traffic conditions for the purpose of relaying information to the

public and to decrease response time to incidents for safety and congestion relief reasons. Most TMCs gather real-time traffic data using stationary devices such as in-pavement induction loop detectors, closed circuit television cameras, and other mounted systems. The future of data collection may include gathering moving vehicle information from mobile phones and in-vehicle Global Positioning Systems (GPS) components. On freeways, in-pavement induction loop detectors are most common and collect traffic flow (vehicles per hour per lane), instantaneous speeds at the detector, and detector occupancy (fraction per time interval that vehicles occupy the detector). If the detectors in a roadway segment or facility are mostly functional and are located close together (no more than one mile apart), reasonable travel-time estimates can be made from the instantaneous speed data.

A few agencies store this data and make it available to persons outside of the agency. Some TMCs, however, do not store their real-time data for more than 24 hours and do not make the stored data accessible to persons outside of the agency. Storage and dissemination of traffic data are technically feasible. What is often the barrier is the lack of appointed responsibilities within the agency for data archiving, lack of a use for the data beyond the operation of the roadway, and developing policies for public access to the data. TMCs that collect real-time traffic data are primarily concerned with real-time operations and are not funded or given directives for archiving data for nonagency use. Nonetheless, as transportation analysis incrementally includes more quantitative performance measures related to travel time and delay, the necessity to collect and archive data, develop funding mechanisms, and implement policies on data access will become more pressing and agencies can be expected to respond positively.

Planners conducting travel-time-related analysis on instrumented highways should first explore what the TMC has to offer in terms of data before instituting a primary data collection effort. If a planning agency anticipates regular need for this type of data, it would be cost-effective to work with the TMC to develop general policies and protocols for obtaining TMC data. Once the planner has established a data collection plan, the following steps will provide useful guidance in collecting travel-time data on roadways covered by the TMC.

Step 1. Identify TMC(s) and Traffic Manager(s)

The first step is to identify the relevant TMC and agency operator collecting data for the desired geographic area and facility types. Some major urban areas have more than one TMC. If you are unsure where to begin, the state department of transportation is a good default starting point. State-operated TMC may focus exclusively on freeways,

| Desired Precision (CI/S) | Desired Confidence | Minimum Observations |
|--------------------------|--------------------|----------------------|
| 0.5 | 99% | 130 |
| 0.5 | 95% | 83 |
| 0.5 | 90% | 64 |
| 1.0 | 99% | 36 |
| 1.0 | 95% | 23 |
| 1.0 | 90% | 18 |
| 1.5 | 99% | 18 |
| 1.5 | 95% | 12 |
| 1.5 | 90% | 9 |
| 2.0 | 99% | 12 |
| 2.0 | 95% | 8 |
| 2.0 | 90% | 6 |

CI = desired confidence interval in seconds; and S = standard deviation in seconds.

Exhibit 3.5. Minimum observations to obtain desired confidence interval.

while locally operated TMCs often focus exclusively on city and county streets. Once all relevant TMCs have been identified, contact the traffic manager for each, who is usually located in the Operations Department.

Step 2. Communicate Data Collection Needs

Determining the suitable data for your planning application will require direct contact with the TMC Traffic Manager or operations staff. Calculating performance measures will require real-time traffic surveillance data for the roadway segments and time periods that are the focus of your analysis. This data must be archived (i.e., one or more days of data stored in readily retrievable format) to be useful. Ideally, the TMC will collect and archive speed and traffic flow data. If so, proceed to the next step regarding data access policies. If not, ask whether other agencies or private companies collect speed and traffic flow data for the study area roadway segments. If not, the planner will probably need to institute a primary data collection effort to generate measures of reliability.

Step 3. Ascertain Data Access Policies

Determine whether TMC policy allows access to real-time and/or archived data for downloading, and whether the agency will provide a copy of the unprocessed data for the roadway segments and times you specify. Asking for verbatim copies of unprocessed data bypasses most institutional problems for agencies lacking policies and protocols for sharing

data. Access to archived data will allow the planner to collect needed data in one pass. Access only to real-time data will require an extended collection effort, the length of which is determined by your sampling plan. If access is granted, proceed to Step 4. If traffic managers are unable or unwilling to allow data access, ask if they share their data with Value Added Resellers (VAR) and, if so, whom. You may be able to obtain data from VARs for a fee. If not, the planner will probably need to institute a primary data collection effort.

Step 4. Acquire Data

The analyst can be quickly buried under the enormous amounts of detailed data available from TMCs, and should therefore establish in advance what locations, what times of day, what days of the week, and which weeks the data will be collected. The analyst should consult with the TMC staff regarding the reliability of the traffic detectors and whether certain locations tend to be more reliable than others. There are some readily available algorithms and techniques that can be used to manage these large datasets; the analyst should not sample the real-time data.

If the traffic manager or VAR is able and willing to allow access to the database or make a copy of unprocessed data, you will need to ascertain what computer software is required for copying and/or reading the data. For answers to this question, the analyst may need to speak with IT personnel at the TMC.

Depending on the TMC and the data requirements of the analyst, data acquisition may be feasible over the Internet or require the installation of specialized equipment at the

TMC. The analyst should monitor (or acquire from the TMC) any incident reports (accidents, work zones, bad weather, police actions, etc.) for the time periods of the data collection effort.

3.5 Processing/Quality Control

Before proceeding to the computation of means, variances, and confidence intervals, the analyst should first review the travel time and delay data for errors.

3.5.1 Identification and Treatment of Errors and Outliers in Data

An error is an obvious mistake in the measured data. An outlier is an observation that lies so far from the other observations that the investigator suspects that it might be an error.

The analyst should first evaluate the measured travel times or delay data to eliminate obvious errors. The analyst should reject any data that violates physical limitations, such as negative travel times or speeds more than twice the design speed of the roadway. Any measured travel times or delays that are greater than the duration of the study are suspect as well. Most data analysis software packages or spreadsheet programs can be used to automatically flag any data record whose value violates a defined minimum or maximum.

The analyst also should check records for unusual events occurring during data collection, including accidents, work zones, police actions, and bad weather. In most cases the analyst will *not* want to eliminate travel time and delay data gathered during unusual events, as this variation is what allows the data to describe variability in travel time or delay. If data are being collected to calibrate the speed-volume relationship in a transportation planning model, however, removing the incidents and events that regularly occur may be appropriate.

The search for outliers is more subtle. A scatter plot of the data can be very helpful to the analyst in quickly spotting the few data points that do not seem to belong with the rest. A more mechanical search for outliers can be made by identifying all points greater than 3 standard deviations above the mean, or less than 3 standard deviations below the mean travel time (or delay).

Statistically, these outliers are not necessarily invalid observations, however, they are unlikely. The analyst should review the raw data sheets for the outlier observations and verify that no simple arithmetic error was made. If an error is found, it can be corrected. If no obvious error is found, the analyst must make a judgment call whether or not to retain the outliers in the data set.

The analyst has four options for dealing with errors and outliers in the data:

1. Correct the error;
2. Repeat the field measurement;
3. Replace the outlier with a maximum or minimum acceptable value; or
4. Drop the data point from the data set.

3.5.2 Computation of Mean and Variance (Travel Time and Delay)

The mean travel time is equal to the sum of the measured travel times (T) divided by the number of measurements (N).

$$\text{Mean}(T) = \frac{\sum_i^N T_i}{N} \quad (\text{Eq. 3.2})$$

The variance is a measure of the spread of the distribution of observed travel times.

$$\text{Var}(T) = \frac{\sum_i^N T_i^2 - \left[\sum_i^N T_i \right]^2}{N-1} \quad (\text{Eq. 3.3})$$

where

Mean(T) = The mean of the measured travel times;

Var(T) = The estimated variance of the measured travel times;

T_i = The measured travel time for observation number i ; and

N = Total number of observations of travel time.

The mean delay and its variance are computed similarly, using the above two equations, substituting delay for travel time. Both the mean and variance can be estimated for travel times (or delay) from any desired sampling timeframe (e.g., throughout a 24-hour period) from the peak period or peak hour only, etc. Similarly, they can be computed including or excluding unusual incident-generated data points that lie outside the typical range of observations for periods of recurring congestion (i.e., nonincident).

3.5.3 Computation of Confidence Intervals (Travel Time and Delay)

The confidence interval is the range of values within which the true mean value may lie. The confidence interval for the mean travel time or the mean delay is given by the following equation:

$$\text{CI}_{1-\alpha\%} = 2 * t_{(1-\alpha/2), N-1} \sqrt{\frac{\text{Var}(T)}{N}} \quad (\text{Eq. 3.4})$$

where

$CI_{(1-\alpha)\%}$ = The confidence interval for the true mean with probability of $(1-\alpha)\%$, where “alpha” equals the probability of the true mean not lying within the confidence interval;

$t_{(1-\alpha/2), N-1}$ = The Student’s t statistic for the probability of two-sided error summing to “alpha” with $N - 1$ degrees of freedom, where “ N ” equals the number of observations; and

$\text{Var}(T)$ = The variance in the measured travel times.

The confidence interval for the true mean of delay also can be estimated with the above equation by substituting delay for travel time.

Chapter 6 contains more detailed directions for data sampling and calculation of travel time/delay variance and reliability measures using estimated data, rather than observed or TMC data.

CHAPTER 4

Before/After Studies

4.1 Introduction

This chapter provides guidance on the evaluation of the effectiveness of improvements designed to reduce travel time, delay, and variability. Once an improvement is implemented it is generally desirable to assess its effectiveness in meeting stated objectives or delivering promised benefits. This helps the agency understand the effectiveness of the components of its program and to better design new programs in the future. A common method for evaluating the effectiveness of improvements in the field is the before/after study, which measures system performance before and after implementation of a specific improvement. A variation on the before/after methodology is the use of estimated data to conduct a hypothetical “what if” or “with and without project” type of analysis to support planning decisions about future investments. The concept is the same: to isolate the impact of the proposed project or action, and to apply valid statistical tests to determine whether the change is significant and can in fact be attributed to the project being evaluated.

The major task of a before/after study is to distinguish between random results and actual differences between the before and after conditions. The ability to distinguish actual differences from random results hinges on the ability of the analyst to gather a sufficient sample size. Data-rich agencies (those with continuous surveillance technology in place on some of their facilities) will be able to distinguish smaller actual differences from random variations in results simply because of their ability to gather more data. Data-poor agencies will have to go to greater expense to gather the before and after data and will generally be able to distinguish only larger actual differences from random results.

This chapter describes a standard statistical method, called hypothesis testing, for determining if the results of the before and after study could have resulted from luck (i.e., random

variation in observed results). If the result could have been the result of luck, that does not necessarily mean there is no real difference. It just could mean the analyst was unable to gather enough data to be able to tell the difference between luck and actual effects.

The statistical test described in this chapter is limited to determining whether the before mean value of the performance measure (e.g., a travel time or delay-based measure) is significantly different from the after mean. The test cannot be used for determining the significance of changes in the variance of travel time or delay, which is necessary to determine whether an improvement in the BI or other similar measure of reliability is statistically significant. To determine whether the before and after standard deviations (or variances) are significantly different, the reader should consider applying Levene’s test for equality of variances. Information on Levene’s test and alternate tests on the equality of variances, as well as example applications, can be found in the National Institute of Standards and Technology *Engineering Statistics Handbook*, Section 1.3.5.10, viewable and downloadable at <http://www.itl.nist.gov/div898/handbook/eda/section3/eda35a.htm>.

Barring application of such sophisticated statistical tests, the analyst would rely on professional experience, familiarity with the specific situation, and confidence in the data collection methods to make a professional judgment whether a change in the BI resulted from the specified capital or operational improvement, as opposed to random variation or luck. Another approach is to track trends in the BI over time and compare to changes in total delay over the same period. Improvements in reliability, as evidenced by a lower BI, can occur irrespective of increases in average total delay. Operational strategies such as freeway service patrols, for example, can contribute to a reduction in the magnitude of the few worst occurrences of delay, and thus have a bigger impact on reliability than on average delay.

4.2 Common Pitfalls of Before/After Studies

The validity of any conclusions drawn from a before/after study hinges on the validity of the assumption that all other conditions (except for the improvement itself) are identical when both the before and after measurements are made. It is generally impossible to achieve perfect validity in the real world since so many conditions change over time.

A common problem for before/after studies is traffic demand grows over time. Ideally the before study is done just before the start of construction of the improvement and the after study is performed as soon after the improvement is completed and opened to traffic. However, it takes time for people to adapt to a new improvement, thus it is not a good idea to gather after data within the first few days or weeks after a project is opened. One must find a compromise point in time when most travelers are thought to have adapted to the new project and the least amount of elapsed time since the before study was completed.

There also are several potential additional (often unknown) differences between the before and after conditions that can affect the results, usually without the investigator's knowledge. Examples include changes in gasoline prices, highway improvements elsewhere in the region, accidents on the day of the study at other facilities in the region, etc.

Another common problem of before/after studies is that you may not be surveying all of the travelers impacted by the project in your before and after studies. New travelers may show up on the facility who were not there before it was constructed. Odds are that the travel times of these new travelers on the facility were not captured in your before study of the facility, unless other routes serving the same trip patterns also were studied. So you may be underestimating the benefits to the public of the improvement if you only consider the net change in travel times on the facility itself.

These are weaknesses of any before/after study the analyst must seek to minimize, but can never completely eliminate.

Another common pitfall, but one the analyst can avoid, is obtaining insufficient numbers of before measurements. The number of before measurements of travel time or delay, and the variance among the measurements will determine the ultimate sensitivity of the before/after test. The analyst should consult Section 3.3 and use the methods there to determine an adequate number of measurements for the before condition.

4.3 Selection of Performance Measures for Before/After Studies

The analyst needs to select the set of performance measures that will be used to determine if the improvement has resulted

in the desired improvement in system performance. In choosing between the use of travel time or delay as a performance measure, the analyst should recognize that travel time incorporates a component (free-flow travel time) that is often large and relatively insensitive to most facility improvements. This makes travel time a difficult measure to use for the detection of performance improvements, particularly over a large area or multiple segments or facilities.

Delay is a much more sensitive measure for detecting performance improvements. However, delay is more volatile, requiring more measurements in order to determine its average within an acceptable confidence interval. So there is an explicit tradeoff in terms of level of confidence one may have in the results of the before/after analysis and the cost or resource requirements of that analysis.

4.4 Determining if Conditions Are Significantly Better

It is tempting to measure the mean travel time (or delay) before the improvement and the mean travel time after the improvements and decide that conditions are better based solely on a comparison of the two means. However, since you do not measure travel times every hour of every day of the year, it could have been the result of plain luck, not an actual difference. Statistical hypothesis testing is used to determine if your results could have been due to luck and not the improvement.

Hypothesis testing determines if the analyst has performed an adequate number of measurements for the before and after conditions to truly tell if the improvement was effective at the analyst's desired level of confidence.

The test begins with the specification of a null hypothesis that you hopefully will be able to reject: "The measured difference in mean travel time for the before and after conditions occurred by random chance. There really is no significant difference in the mean travel time between the before and after conditions." A statistic is computed for a selected level of confidence, and if the difference between the two means is less than that statistic, then the null hypothesis is accepted and it is concluded that there is insufficient evidence to prove that the after condition is better than the before condition. The analyst can accept this outcome, or alternatively, either make more measurements of travel time for each condition (to improve the sensitivity of the test) or relax standards (confidence level) for rejecting the null hypothesis.

The specification of the problem is:

Null hypothesis:

$$H_0 : \mu_x - \mu_y = 0$$

against

$$H_1 : \mu_x - \mu_y \neq 0$$

where

μ_x = The mean travel time (or mean observation of some other relevant measure, such as delay) for alternative x (before); and

μ_y = The mean for alternative y (after).

This is a two-sided t test with the following optimal rejection region for a given alpha (acceptable Type I error).

$$\bar{x} - \bar{y} > t_{(1-\alpha/2);(n+m-2)} \cdot s_p \sqrt{\frac{1}{n} + \frac{1}{m}}$$

where

$\bar{x} - \bar{y}$ = The absolute value of the difference in the mean results for alternative x (before) and alternative y (after);

s_p = The pooled standard deviation;

t = The Student's t distribution for a level of confidence of $(1 - \alpha)$ and $(n + m - 2)$ degrees of freedom;

n = Sample size for alternative x (before); and

m = Sample size for alternative y (after).

$$s_p^2 = \frac{(n-1)s_x^2 + (m-1)s_y^2}{(m+n-2)}$$

where

s_p = Pooled standard deviation;

s_x = Standard deviation of results for alternative x (before);

s_y = Standard deviation of results for alternative y (after);

n = Sample size for alternative x (before); and

m = Sample size for alternative y (after).

The probability of mistakenly accepting the null hypothesis is alpha (alpha is usually set to 5 percent to get a 95 percent confidence level test). This is Type I error.

There also is the chance of mistakenly rejecting the null hypothesis. This is called Type II error and it varies with the difference between the sample means, their standard deviation, and the sample size. (Analysts should consult standard statistical textbooks for tables on the Type II errors associated with different confidence intervals and sample sizes.)

4.5 What to Do If the Null Hypothesis Cannot Be Rejected

If the null hypothesis of no significant difference in the mean results for the before and after conditions cannot be rejected, the analyst has the following options:

1. Change to a more sensitive performance measure. For example, delay will tend to be much more sensitive to improvements than travel time because a large component of travel time is often the free-flow travel time, which is unaffected by most improvements.
2. Increase the number of measurements made for the after condition in the hopes that the variance of the mean will decrease sufficiently to reject the null hypothesis.
3. Reduce the confidence level from 95 percent to a lower level where the before and after conditions are significantly different, and report the lower confidence level in the results.
4. Accept results that the improvement did not significantly improve conditions.

CHAPTER 5

Identification of Deficiencies

5.1 Introduction

This chapter describes how to use travel time and delay to identify real performance deficiencies in the transportation system and how to distinguish these deficiencies from random variations in the data. A diagnosis chart is provided to help analysts identify the likely root causes of identified travel time, delay, and variability deficiencies.

The guidance in this chapter is designed to be applied after the analyst has identified the agency's performance standards and collected the data (or forecasts) on system performance. This chapter provides limited guidance on the inclusion of uncertainty in the treatment of forecasted travel time and delay based upon a limited set of data from California. Ideally, agencies will be able to develop their own data on variability and apply it in lieu of default values provided here.

The chapter starts by reiterating the key considerations involved in defining agency performance standards and collecting data for the purpose of deficiency assessments. Readers are referred to the appropriate chapter for additional background information and guidance on selection of performance measures, setting of performance standards, data collection, and forecasting of travel time and delay.

Guidance is then provided on the statistical tests needed to distinguish between apparent violations of agency standards (due to sampling error) and actual violations. Additional guidance is provided on the incorporation of uncertainty into the use of forecasted system performance for assessing deficiencies. Finally, the chapter provides a diagnosis chart for identifying the likely root causes of travel time, delay, and reliability deficiencies.

5.2 Quantifying Agency Standards

To know if a patient is sick or not, you need to have some established methods for measuring health (such as body temperature) and standards for each measure that

distinguish between healthy and sick. Similarly an agency must establish what it considers to be good health for its transportation system or its vehicle fleet operations. Acceptable levels for transportation system performance measures must usually be determined based on the agency's experience of what constitutes acceptable performance for its decision makers and the constituents they report to. Chapter 2 provides a discussion on the selection of appropriate measures and the setting of acceptable values for each measure.

Note that when assessing deficiencies using field measurements, the agency performance standards for the facility or the trip must be more precise than simply Level of Service D. The standard must state over how long the measurement is taken and whether or not brief violations can be tolerated.

5.3 Data Collection

The development of a data collection plan and determining the required sample size for measurements are discussed in Chapter 3. If travel time and delay data cannot be measured directly, they must be estimated using the methods in Chapter 6.

5.4 Comparing Field Data to Performance Standards

Analysts must take great care to ensure that they have measured performance in the field using a method consistent to the performance standard set by the agency.

For example, an agency may have a LOS standard for the peak hour of "D" for traffic signals. HCM (5) defines the threshold for LOS "D" as no more than 55 seconds of control delay averaged over the worst contiguous 15 minutes of the peak hour. Thus, there may be individual signal cycles where the average delay for vehicles is greater than 55 seconds, but

if the average for the highest volume 15-minute period is less than that, then it is LOS “D” or better. Indeed almost half of the vehicles during the worst 15 minutes may experience delays greater than 55 seconds and the intersection would still be LOS “D.”

Analysts also must exclude delay measurements not related to the performance standard from their computations. For example, HCM (5) excludes from its LOS standards delays caused by accidents, poor weather, etc. Only delay caused by the signal control (control delay) is included in the performance measurement for establishing signal LOS. Analysts also will need to determine if holidays, weekends, and days with special events are to be excluded from the comparison to the agency performance standard. Other performance measures described in Chapter 2, such as the TTI, include nonrecurring delay from incidents and other causes mentioned above, but also can be calculated excluding such events. If the situation and analytical framework call for consideration of nonrecurring delay in the identification of deficiencies and testing of solutions, these measurements should be left in the data computations, and the appropriate performance measures used in the analysis.

5.4.1 Taking Luck Into Account In Field Measurements

Once the standards have been set and the performance data have been gathered, the next task is to determine if one or more of the performance standards have been violated. With field data, this is more difficult than simply comparing the results to the agency standards. There is usually a great deal of day-to-day, hour-to-hour, and even minute-by-minute fluctuation in travel times, and especially in delays, for a transportation system component. So the analyst must assess the degree “luck” played a part in meeting or failing to meet the performance standards. Statistical hypothesis testing provides the tool for ruling out luck as a contributor to meeting or failing to meet the agency’s performance standards.

To determine whether or not you have gathered sufficient evidence to establish that the agency is meeting or failing to meet its transportation system performance standards, it is necessary to perform a statistical hypothesis test of the difference between the mean result of your field measurements and the agency’s performance standard.

To perform a statistical test, analysts must adopt a baseline (null) hypothesis that they then can reject if the test is successful. The null hypothesis can either be:

1. The actual performance in the field violates the agency’s performance standards, or
2. The actual performance in the field meets the agency’s performance standards.

Any statistical test is subject to two types of error. The probability of mistakenly accepting the null hypothesis is a Type I error, called “alpha” in the equations below. This is usually set quite small (e.g., at 5 percent to get a 95 percent confidence level test).

There also is the chance of mistakenly rejecting the null hypothesis. This is called Type II error and it varies with the difference between the sample means, their standard deviation, and the sample size. (Analysts should consult standard statistical textbooks for tables on the Type II errors associated with different confidence intervals and sample sizes.) The analyst has less control over this type of error and its probability can be quite a bit larger than the Type I error.

The usual approach is to adopt the null hypothesis for which a Type II error (mistakenly rejecting the null hypothesis when it is really true) has the least consequences for the agency. This results in the apparently perverse approach of adopting as your null hypothesis the very condition you do not want to be true (e.g., the actual performance violates agency standards).

Analysts who wish to be very sure they do not say there is a deficiency when in reality there is no deficiency will adopt the first null hypothesis above (i.e., “everything is not fine”). The test then will have a low probability (completely controlled by the analyst) of mistakenly accepting this null hypothesis (a Type I error) and in effect concluding there is a deficiency when in reality there is no problem.

Conversely, analysts who wish to be very sure they do not say that everything is fine, when in reality there actually is a problem will adopt the second null hypothesis (i.e., “everything is fine”). Again, the test will have a low probability of mistakenly accepting the null hypothesis and concluding there is no problem when in fact there is a problem.

An example of the first condition might be where the risk or opportunity cost for mistakenly identifying a problem when none exists is very high (e.g., condemning property to expand a facility when the benefits of the expansion are not statistically significant). An example of the opposite situation might involve public safety (e.g., failing to identify a statistically significant increase in accidents at a given location).

For each null hypothesis the test is as follows.

5.4.2 First Null Hypothesis (Don’t Cry Wolf Needlessly)

The analyst will reject the null hypothesis that the system fails to meet agency standards (with confidence level equal to 1-alpha) if the following equation is true.

$$\bar{x} < q + t_{(1-\alpha);(n-1)} \cdot \frac{s}{\sqrt{n}} \quad (\text{Eq. 5.1})$$

where

- \bar{x} = The mean of the performance measure as measured in the field;
- q = The maximum acceptable value for the performance measure;
- s = The standard deviation of the performance measure as measured in the field;
- n = The number of measurements of the performance measure made in the field; and
- t = The Student's t distribution for a level of confidence of $(1-\alpha)$ and $(n - 1)$ degrees of freedom (see standard statistics text book, spreadsheet function, or Exhibit 5.1 below for values to use).

5.4.3 Second Null Hypothesis (Cry Fire at the First Hint of Smoke)

Reject the null hypothesis that the system meets agency standards (with confidence level equal to $1-\alpha$) if the following equation is true.

$$\bar{x} > q - t_{(1-\alpha);(n-1)} \cdot \frac{s}{\sqrt{n}} \tag{Eq. 5.2}$$

where all variables are as explained above for previous equation.

5.5 Comparing Forecasted Performance to Performance Standards

Generally the degree of uncertainty present in forecasts or estimates of travel time or delay is not known. Common practice is to completely ignore any uncertainty in the

forecasts, which tends to result in agencies “painting themselves into corners” by planning very precisely for ultimately uncertain future conditions.

For a first attempt to introduce the concept of uncertainty into the forecasting process, the analyst can use the known and measured uncertainty of direct field measurements of travel time and delay. It is assumed the variance of the forecasts is at least equal to, if not actually greater than that measured in the field, since in addition to all the other uncertainties in the field, forecasts have uncertainty as to the actual number of vehicles present. So as a first approximation, the analyst might use the field measured variance in travel time and delay (if available) and perform the hypothesis tests described above for field measured data. One merely substitutes the forecasted values for the field measured mean values into the equations and uses the standard deviation of the field measured values for the standard deviation in the equations.

The effect of introducing the above described hypothesis tests into the assessment of future deficiencies is to provide for a margin of error in planning for the future.

5.6 Diagnosing the Causes

Once one or more deficiencies have been identified, it is valuable to be able to assign a primary cause to the deficiency. This will aid the analyst later in generating alternative improvement strategies to mitigate the problem. Exhibit 5.2 below provides some initial suggestions for identifying the root causes of travel time, delay, and variability deficiencies. Other significant resource documents are available for this purpose, and the reader is referred to Section 7.3 for several references that cover both highway and transit modes.

| N | Confidence Level | | | | |
|-------|------------------|------|------|------|------|
| | 50% | 85% | 90% | 95% | 99% |
| 5 | 0.74 | 1.78 | 2.13 | 2.78 | 4.60 |
| 10 | 0.70 | 1.57 | 1.83 | 2.26 | 3.25 |
| 50 | 0.68 | 1.46 | 1.68 | 2.01 | 2.68 |
| 100 | 0.68 | 1.45 | 1.66 | 1.98 | 2.63 |
| 1,000 | 0.67 | 1.44 | 1.65 | 1.96 | 2.58 |

Exhibit 5.1. Student's t values.

| Deficiency | Proximate Causes | Likely Root Causes |
|--|--|---|
| Travel Time is excessive, but no significant delay or reliability deficiencies. | <ul style="list-style-type: none"> • Free-flow speeds are too low or travel distances are too great. | <ul style="list-style-type: none"> • Low-speed facility perhaps due to inadequate design speed (not a freeway). • Road System does not provide a straight line path between origin and destination (such as in mountainous terrain). |
| Delay is regular but excessive. (There may be excessive variability in travel time, but delay recurs regularly.) | <ul style="list-style-type: none"> • Inadequate capacity when compared to demand. | <ul style="list-style-type: none"> • Insufficient number of lanes. • Inadequate design. • Poor signal timing. • Too much demand. • Lack of alternative routes or modes for travelers. |
| Excessive Variability in Delay. | <ul style="list-style-type: none"> • Facility is prone to incidents and/or response to incidents is inadequate. • There may be surges in demand. | <ul style="list-style-type: none"> • Facility is accident prone due to poor design. • Frequent days of poor weather. • Incident detection and response is poorly managed or nonexistent. • Travelers not provided with timely information to avoid segments with problems. • There are unmeted surges of demand (often from large special generators). |

Exhibit 5.2. Diagnosis chart for travel time, delay, and variability deficiencies.

CHAPTER 6

Forecast Future Performance

6.1 Introduction

The purpose of this chapter is to provide guidance on the estimation of trip travel times, delays, and reliability when direct measurement of these performance measures is not feasible. Two methods are provided: a sketch planning method that requires minimal data and a planning method that requires data to compute the capacity and FFS of the facility.

This chapter focuses on planning applications. Methods provided here are designed for rapid application to large batches of facilities requiring minimal field data collection on the characteristics of the facilities. Methods are applicable to the estimation of travel-time, delay, and reliability for trips made on all types of highway facilities. The methods provided here are not as precise as field measurements of travel time, delay, and reliability. They also are not as accurate or as sensitive to variations in traffic controls as methods employing microsimulation or HCM (5) techniques. Since this chapter deals with forecasting future performance, the same procedures apply whether or not the agency is data-rich (with continuous surveillance on some of its facilities), or data-poor.

The chapter is split into three major sections: estimating/forecasting travel time, estimating delay, and estimating reliability. The travel time section is split into two parts: estimation of trip times, and estimation of road segment travel times. The road segment travel times section provides two methods for estimating segment travel times, a sketch planning method and a planning method. The sketch planning method requires only average daily traffic, signal spacing, and number of lanes. The planning method requires additional information on the road segment to estimate capacity and FFS.

6.2 Estimating/Forecasting Travel Time

To estimate trip travel time you need to know the time of day when the trip will be made, the starting point, the end point, and the route taken for the trip.

For a trip on a given route at a given time of day, over several different facility types and segments of facilities, it is necessary to estimate the travel time for each road segment and sum them. The estimated travel time for each road segment should include any delay incurred when transitioning from one segment to the next (for example the delay in making a left turn from one street to another).

The road segment travel time can be estimated by dividing the segment length by the mean speed of the traveler over the length of the segment and adding in any segment transition delay.

$$TT = \sum_i T_i \quad (\text{Eq. 6.1})$$

$$T_i = \frac{L_i}{S_i} + d_i \quad (\text{Eq. 6.2})$$

where

TT = Trip Travel Time (hours);

T_i = Road Segment Travel Time (hours);

L_i = Length of road segment i (miles);

S_i = Mean speed of vehicle over length of road segment i (mph); and

d_i = Transition Delay. The delay incurred moving from the end of segment i to the start of the next segment.

6.2.1 Identification of Road Segments

The route taken by a given trip must be divided into road segments. A road segment is the portion of the road or highway over which neither demand nor capacity varies by more than 10 percent of their average value for the segment. The selected route for the given trip is divided into a series of road segments, and each can be presumed to have relatively uniform demand and capacity over its length.

6.2.2 Sketch Planning Techniques for Estimating Segment Speeds

The following equations for estimating road segment speeds are designed for sketch planning purposes. They do

not require that the capacity be known, nor the PSL. They require information only on the average daily traffic (ADT), lanes, the number of signals per mile, and the number of interchanges per mile.

For freeways:

$$\text{Speed (mph)} = 91.4 - 0.002 [\text{ADT/Lane}] - 2.85 [\text{Access Points Per Mile}] \quad (\text{Eq. 6.3})$$

For Class I arterials:

$$\text{Speed (mph)} = 40.6 - 0.0002 [\text{ADT/Lane}] - 2.67 [\text{Signals Per Mile}] \quad (\text{Eq. 6.4})$$

For Class II and Class III arterials:

$$\text{Speed (mph)} = 36.4 - 0.000301 [\text{ADT/Lane}] - 1.56 [\text{Signals Per Mile}] \quad (\text{Eq. 6.5})$$

where

Speed = Mean speed during weekday peak hours, average of both directions (mph);

ADT = Average daily traffic (total of both directions for weekdays) for road segment;

Lane = number of through lanes (total of both directions) on road segment;

Access Points Per Mile = Average number of freeway interchanges per mile for freeway segment. Treat partial interchanges as full interchanges for purpose of computing the average access points per mile;

Signals Per Mile = Average number of traffic signals per mile on road segment;

Arterial Class I = Signalized arterial street with at least 1 signal every 2 miles, and with posted speed limit in excess of 40 mph;

Arterial Class II = Signalized arterial street with at least 1 signal every one-quarter mile, and with posted speed limits of 30 to 40 mph, inclusive; and

Arterial Class III = Signalized arterial street with at least 1 signal every one-quarter mile, and with posted speed limit less than 30 mph.

The above equations, taken from NCHRP Report 398, *Quantifying Congestion (1)*, were developed by applying linear regression to various data sets available to the researchers. As such, these equations are unlikely to be accurate for extreme situations not covered in the original NCHRP 398 data sets, such as roads in mountainous terrain.

The above NCHRP 398 equations also are not designed to be applied to multilane-rural highways or two-lane rural roads. However, in the absence of better information, the analyst may cautiously use the equivalent arterial speed equations according

to the posted speed limit on the highway. Similarly, if the signal density (number of signals per mile) is less than the minimums listed above for each arterial class, the equations for the appropriate speed limit may still be applied, but the results should be used with caution.

A superior approach to using the equations listed above would be to measure speeds in the local region using the methods described in Chapter 3 and using linear regression to fit equations that are more accurate for conditions in the area. Assuming good data collection practices, locally developed equations almost always will be superior in accuracy to the national average equations presented in this Guidebook.

6.2.3 Planning Method for Estimating Speeds

The planning method for estimating speed is designed to be applied to specific hours of the day and to specific street segments. The method is sensitive to the posted speed limit, volume, and capacity. A method is provided to estimate capacity based on signal timing and the physical characteristics of the facility. This method is taken from *NCHRP Report 387: Planning Techniques for Estimating Speed and Service Volumes for Planning Applications (7)*.

If it is desired to estimate mean speed over a 24-hour period, then one can either use the “one-hour” method below, applying it 24 times, for each hour of the day, or one can use the following equations from *NCHRP Report 398*.

The recommended speed estimation technique is an update of the Bureau of Public Roads (BPR) speed-flow curve. The new curve has been fitted to updated speed-flow data contained in the HCM and has been validated against speed flow data for both uninterrupted flow facilities and interrupted flow facilities.

The facility space mean speed is computed in three steps:

1. Estimate the FFS;
2. Estimate capacity; and
3. Compute the average speed.

Look-up tables of defaults can be used to skip the first two steps, but poor choices of the FFS and capacity can seriously compromise the accuracy of the technique.

Step 1. Estimate Free-Flow Speed

FFS of a facility is defined as the space mean speed of traffic when volumes are so light that they have negligible effect on speed. The best technique for estimating FFS is to measure it in the field under light traffic conditions, but this is not a feasible option when several thousand street links must be analyzed.

The paragraphs below provide a recommended set of equations for estimating FFS in the absence of field measurements of FFS.

Option 1a. Equations for Facilities Without Signals

Two separate linear equations are provided for estimating free-flow speed for facilities with less than one signal every 2 miles (3.2 km). One equation is for facilities with posted speed limits in excess of 50 mph (80 kph). The other equation is for facilities with lower posted speed limits.

High-Speed Facilities [PSL in excess of 50 mph (80 kph)].

$$S_f (\text{mph}) = 0.88 * S_p + 14 \quad (\text{Eq. 6.6})$$

$$S_f (\text{kph}) = 0.88 * S_p + 22 \quad (\text{Eq. 6.7})$$

Low-Speed Facilities [PSL is 50 mph (80 kph) or less].

$$S_f (\text{mph}) = 0.79 * S_p + 12 \quad (\text{Eq. 6.8})$$

$$S_f (\text{kph}) = 0.79 * S_p + 19 \quad (\text{Eq. 6.9})$$

where

S_f = FFS in either mph or kph; and

S_p = PSL in either of mph or kph.

Option 1b. Equations for Signalized Facilities

FFS for signalized facilities must take into account both the FFS measured mid-block between signals and the signal delays along the street (which occur even at low volumes). The mean FFS (including signal delay) is computed using the following equation that adds together the free-flow travel time between signals and the delay time at signals (under free-flow conditions).

$$S_f = \frac{L}{\frac{L}{S_{mb}} + N * \left(\frac{D}{3600}\right)} \quad (\text{Eq. 6.10})$$

where

S_f = FFS speed for urban interrupted facility (mph or kph);

L = Length of facility (miles or km);

S_{mb} = Mid-block FFS (mph or kph);
 = 0.79 (PSL in mph) + 12 (mph); and
 = 0.79 (PSL in kph) + 19 (kph);

N = Number of signalized intersections on length L of facility; and

D = Average delay per signal per Equation 6.11 below (seconds).

The average delay per signal is computed using the following equation:

$$D = DF * 0.5 * C(1 - g/C)^2 \quad (\text{Eq. 6.11})$$

where

D = The total signal delay per vehicle (seconds);

g = The effective green time (seconds);

C = The cycle length (seconds);

If signal timing data is not available, the planner can use the following default values:

$C = 120$ seconds; and

$g/C = 0.45$.

$DF = (1 - P)/(1 - g/C)$

where P is the proportion of vehicles arriving on green.

If P is unknown, the following defaults can be used for DF :

$DF = 0.9$ for uncoordinated traffic actuated signals;

$DF = 1.0$ for uncoordinated fixed time signals;

$DF = 1.2$ for coordinated signals with unfavorable progression;

$DF = 0.90$ for coordinated signals with favorable progression; and

$DF = 0.60$ for coordinated signals with highly favorable progression.

Option 1c. Default FFS

Planners may wish to develop a look-up table of FFSs based upon the facility type and the area type where it is located in order to simplify the estimation of FFSs. Depending upon local conditions, the planning agency may wish to add terrain type (e.g., level, rolling, mountainous) and frontage development types (commercial, residential, undeveloped) to the general development types used in Exhibits 6.1 and 6.2.

The accuracy of the speed estimation procedure is highly dependent on the accuracy of the FFS and capacity used in the computations. Great care should be taken in the creation of local look-up tables that accurately reflect the FFSs present in the locality.

Step 2. Estimate Link Capacity

The HCM (5) provides a set of procedures for estimating facility capacity for operations analysis purposes. These procedures vary by facility type and generally require a great deal of information on the facility. The following equations simplify the application of the HCM methods for use in planning applications.

Option 2a. Capacity Equation for Freeways

The following equation is used to compute the capacity of a freeway at its critical point:

$$\text{Capacity (vph)} = \text{Ideal Cap} * N * F_{hw} * PHF \quad (\text{Eq. 6.12})$$

| Area Type | Freeway | Expressway | Arterial | Collector | Local |
|---------------------------|---------|------------|----------|-----------|-------|
| Central Business District | 50 | 45 | 40 | 35 | 30 |
| Urban | 55 | 50 | 45 | 40 | 35 |
| Suburban | 60 | 55 | 50 | 45 | 40 |
| Rural | 65 | 60 | 55 | 50 | 45 |

Exhibit 6.1. Example default FFSs (in miles per hour).

where

Ideal Cap = 2,400 passenger cars per hour per lane (pcphl) for freeways with 70 mph (110 kph) or greater FFS; and

= 2,300 (pcphl) for all other freeways [FFS < 70 mph (110 kph)];

N = Number of through lanes. Ignore auxiliary lanes and exit only lanes.

F_{hv} = Heavy vehicle adjustment factor.

= 100/(100 + 0.5 * HV) for level terrain;

= 100/(100 + 2.0 * HV) for rolling terrain; and

= 100/(100 + 5.0 * HV) for mountainous terrain.

HV = The proportion of heavy vehicles (including trucks, buses, and recreational vehicles) in the traffic flow. If the HV is unknown, use 0.05 heavy vehicles as default.

PHF = Peak-hour factor (the ratio of the peak 15-minute flow rate to the average hourly flow rate). If unknown, use default of 0.90.

Option 2b. Capacity Equation for Unsignalized Multilane Roads

The following equation is used to compute the capacity of a multilane road with signals (if any) spaced more than 2 miles apart:

$$\text{Capacity (vph)} = \text{Ideal Cap} * N * F_{hv} * \text{PHF} \quad (\text{Eq. 6.13})$$

where

Ideal Cap = 2,200 (pcphl) for multilane rural roads with 60 mph FFS;

= 2,100 (pcphl) for multilane rural roads with 55 mph FFS;

= 2,000 (pcphl) for multilane rural roads with 50 mph FFS;

N = Number of through lanes; ignore exclusive turn lanes;

F_{hv} = Heavy vehicle adjustment factor;

= 100/(100 + 0.5 * HV) for level terrain;

= 100/(100 + 2.0 * HV) for rolling terrain;

= 100/(100 + 5.0 * HV) for mountainous terrain

HV = The proportion of heavy vehicles (including trucks, buses, and recreational vehicles) in the traffic flow. If the HV is unknown, use 0.05 heavy vehicles as default;

PHF = Peak-hour factor (the ratio of the peak 15-minute flow rate to the average hourly flow rate). If unknown, use default of 0.90;

Option 2c. Capacity Equation for Two-Lane Unsignalized Roads

The following equation is used to compute the capacity (in one direction) for a two-lane (total of both directions) road with signals (if any) more than 2 miles apart:

$$\text{Capacity (vph)} = \text{Ideal Cap} * N * F_w * F_{hv} * \text{PHF} * F_{dir} * F_{nopass} \quad (\text{Eq. 6.14})$$

| Area Type | Freeway | Expressway | Arterial | Collector | Local |
|---------------------------|---------|------------|----------|-----------|-------|
| Central Business District | 80 | 72 | 64 | 56 | 50 |
| Urban | 88 | 80 | 72 | 64 | 56 |
| Suburban | 96 | 88 | 80 | 72 | 64 |
| Rural | 104 | 96 | 88 | 80 | 72 |

Exhibit 6.2. Example default FFSs (in kilometers per hour).

where

Ideal Cap = 1,400 (pcphl) for all two-lane rural roads;

F_w = Lane width and lateral clearance factor;
= 0.80 if narrow lanes and/or narrow shoulders are present;

= 1.00 otherwise;

Narrow lanes are less than 12 feet (3.6 m) wide;

Narrow shoulders are less than 3 feet wide (1.0 m);

F_{hv} = Heavy vehicle adjustment factor;

= $1.00/(1.00 + 1.0 * HV)$ for level terrain;

= $100/(100 + 4.0 * HV)$ for rolling terrain;

= $100/(100 + 11.0 * HV)$ for mountainous terrain;

HV = The proportion of heavy vehicles (including trucks, buses, and recreational vehicles) in the traffic flow. If the HV is unknown, use 0.02 heavy vehicles as default;

PHF = Peak-hour factor (the ratio of the peak 15-minute flow rate to the average hourly flow rate). If not known, use default of 0.90;

F_{dir} = Directional Adjustment Factor;

= $0.71 + 0.58 * (1.00 - \text{Peak Direction Proportion})$;

Peak Direction Proportion is the proportion of two-way traffic going in peak direction. If not known, use default of 0.55 peak direction;

F_{nopass} = No-Passing Zone Factor;

= 1.00 for level terrain;

= $0.97 - 0.07 * (\text{NoPass})$ for rolling terrain;

= $0.91 - 0.13 * (\text{NoPass})$ for mountainous terrain;

NoPass is the proportion of length of facility for which passing is prohibited; and

If NoPass is unknown, use 0.60 NoPass for rolling terrain and 0.80 for mountainous terrain.

HV = The proportion of heavy vehicles (including trucks, buses, and recreational vehicles) in the traffic flow. If the HV is unknown, use 2 percent heavy vehicles as default;

PHF = Peak-hour factor (the ratio of the peak 15-minute flow rate to the average hourly flow rate). Use 0.90 as default if PHF not known;

F_{park} = On-street parking adjustment factor;

= 0.90 if on-street parking present and parking time limit is one hour or less;

= 1.00 otherwise;

F_{Bay} = Left-turn bay adjustment factor;

= 1.10 if exclusive left-turn lane(s) (often as a left-turn bay) are present;

= 1.00 otherwise;

F_{CBD} = Central Business District (CBD) Adjustment Factor;

= 0.90 if located in CBD;

= 1.00 elsewhere;

g/C = Ratio of effective green time per cycle;

If no data available, use following defaults;

Protected left-turn phase present: $g/C = 0.40$;

Protected left-turn phase NOT present: $g/C = 0.45$;

Other defaults may be developed by the local planning agency based upon local conditions. Additional defaults might be developed based upon the functional classes of the major and crossing streets; and

F_c = Optional user specified calibration factor necessary to match estimated capacity with field measurements or other independent estimates of capacity (no units). Can be used to account for the capacity reducing effects of left and right turns made from through lanes.

Option 2d. Capacity Equation for Signalized Arterials

The following equation is used to compute the one direction capacity of any signalized road with signals spaced 2 miles or less apart:

$$\text{Capacity (vph)} = \text{Ideal Sat} * N * F_{hv} * \text{PHF} * F_{park} * F_{Bay} * F_{CBD} * g/C * F_c \quad (\text{Eq. 6.15})$$

where

Ideal Sat = Ideal saturation flow rate (vehicles per lane per hour of green) = 1,900;

N = Number of lanes (exclude exclusive turn lanes and short lane additions);

F_{hv} = Heavy vehicle adjustment factor;

= $1.00/(1.00 + HV)$;

Option 2e. Construction of Localized Capacity Look-Up Table

The accuracy of the speed estimates is highly dependent on the quality of the estimated capacity for the facility. Consequently it is recommended that each planning agency use capacities specific to the critical point of the selected study section whenever possible. However it is recognized that this is not always feasible for planning studies. Consequently the following two tables show a procedure for selecting default values and computing a look-up table of capacities by facility type, area type, and terrain type. Other classification schemes may be appropriate, depending on the nature of local roadway conditions.

Exhibit 6.3 shows a set of selected default parameters for the calculation of capacity for freeways, divided arterials,

| Functional Class | Area Type | Terrain Type | Lanes | Free Speed | Lane Width | % Heavy PHF Vehicles | Direction Split | % No Pass | Parking | Left-Turn Bay | G/C |
|--------------------|-----------|--------------|-------|------------|------------|----------------------|-----------------|-----------|---------|---------------|------|
| Freeway | Rural | Level | All | > 70 mph | | 0.85 5% | | | | | |
| | | Rolling | All | > 70 mph | | 0.85 5% | | | | | |
| | | Mountain | All | < 70 mph | | 0.85 5% | | | | | |
| | Urban | All | All | < 70 mph | | 0.90 2% | | | | | |
| Divided Arterial | Rural | Level | >2 | 60 mph | | 0.85 5% | | | | | |
| | | Rolling | >2 | 55 mph | | 0.85 5% | | | | | |
| | | Mountain | >2 | 50 mph | | 0.85 5% | | | | | |
| | Suburb | All | All | | | 0.90 2% | | | No | Yes | 0.45 |
| | Urban | All | All | | | 0.90 2% | | | Yes | Yes | 0.45 |
| | CBD | All | All | | | 0.90 2% | | | Yes | Yes | 0.45 |
| Undivided Arterial | Rural | Level | 2 | | Standard | 0.85 5% | 55% | 0% | | | |
| | | Rolling | 2 | | Standard | 0.85 5% | 55% | 60% | | | |
| | | Mountain | 2 | | Narrow | 0.85 5% | 55% | 80% | | | |
| | Suburb | All | All | | | 0.90 2% | | | No | No | 0.45 |
| | Urban | All | All | | | 0.90 2% | | | Yes | No | 0.45 |
| | CBD | All | All | | | 0.90 2% | | | Yes | No | 0.45 |
| Collector | Urban | All | All | | | 0.85 2% | | | Yes | No | 0.40 |

Exhibit 6.3. Example default values for computing capacity by functional class and area/terrain type.

undivided arterials, and collectors. Each facility type is further subclassified according to the area type (urban or rural), terrain type (level, rolling, mountainous), and number of lanes (total of two lanes both directions, or more). A separate set of default parameters is then selected for each subclassification of each facility type.

For example, a rural freeway in level or mountainous terrain is assumed to have a FFS in excess of 70 mph (112 kph), 5 percent heavy vehicles, and a peak-hour factor of 0.85. An urban freeway is assumed to have a FFS below 70 mph (112 kph), 2 percent heavy vehicles, and a peak-hour factor of 0.90 to reflect the lower design speeds, heavier passenger car volumes, and flatter peak volumes in urban areas.

Divided arterials in rural areas are assumed to have FFS that decrease as the difficulty of the terrain increases. The assumed FFS for level terrain is 60 mph (96 kph), for rolling terrain 55 mph (88 kph), and for mountainous terrain 50 mph (80 kph).

Any road in a rural area is assumed in this table to have signals (if any) spaced farther than 2 miles apart. Urban area roads are assumed in this table to have signals at least 2 miles apart. The local planning agency should modify these assumptions if they are not appropriate for its particular jurisdiction. Exhibit 6.3 shows assumptions only for two-lane rural undivided arterials, but the planning agency can add additional rows of data for multilane rural undivided arterials.

Exhibit 6.4 shows the computation of the capacities by facility type based upon the assumptions contained in Exhibit 6.3. The results have been rounded off to the nearest 50 or 100 vehicles per hour per lane. The capacities per lane contained

in this table would then be multiplied by the number of lanes (in one direction) at the critical point to obtain the critical point capacity for the facility.

Step 3. Compute Average Speed

If it is desired to compute mean speed for each hour of a day, then once the link capacity and free-flow speed are known, the updated BPR equation (Equation 6.16) can be used to predict the space mean vehicle speed for the link at forecasted traffic volumes. The same equation is used for both metric and customary units. This method requires that capacity be measured or estimated.

$$s = \frac{s_f}{1 + a(v/c)^b} \tag{Eq. 6.16}$$

where

- s = predicted space mean speed;
- s_f = FFS;
- v = volume;
- c = capacity;
- a = 0.05 for facilities with signals spaced 2 miles or less apart, and
= 0.20 for all other facilities; and
- b = 10.

The two keys to success in applying the updated BPR curve are to have an accurate estimate of the FFS and the capacity for the facility. Once those two key parameters are accurately known, the updated BPR curve can estimate speeds for both

| Functional Class | Area Type | Terrain Type | Lanes | Ideal Cap | PHF | Fhv | Fw | Fdir | Fnopass | Fpark | Fleft | Fcbd | G/C | Cap/Lane |
|--------------------|-----------|--------------|-------|-----------|------|------|------|------|---------|-------|-------|------|------|----------|
| Freeway | Rural | Level | All | 2400 | 0.85 | 0.98 | | | | | | | | 2000 |
| | | Rolling | All | 2400 | 0.85 | 0.91 | | | | | | | | 1900 |
| | | Mountain | All | 2300 | 0.85 | 0.80 | | | | | | | | 1600 |
| | Urban | All | All | 2300 | 0.90 | 0.98 | | | | | | | | 2000 |
| Divided Arterial | Rural | Level | >2 | 2200 | 0.85 | 0.98 | | | | | | | | 1800 |
| | | Rolling | >2 | 2100 | 0.85 | 0.91 | | | | | | | | 1600 |
| | | Mountain | >2 | 2000 | 0.85 | 0.80 | | | | | | | | 1400 |
| | Suburb | All | All | 1900 | 0.90 | 0.98 | | | | 1.00 | 1.10 | 1.00 | 0.45 | 850 |
| | Urban | All | All | 1900 | 0.90 | 0.98 | | | | 0.90 | 1.10 | 1.00 | 0.45 | 750 |
| | CBD | All | All | 1900 | 0.90 | 0.98 | | | | 0.90 | 1.10 | 0.90 | 0.45 | 650 |
| Undivided Arterial | Rural | Level | 2 | 1400 | 0.85 | 0.95 | 1.00 | 0.97 | 1.00 | | | | | 1100 |
| | | Rolling | 2 | 1400 | 0.85 | 0.83 | 1.00 | 0.97 | 0.93 | | | | | 900 |
| | | Mountain | 2 | 1400 | 0.85 | 0.65 | 0.80 | 0.97 | 0.81 | | | | | 500 |
| | Suburb | All | All | 1900 | 0.90 | 0.98 | | | | 1.00 | 1.00 | 1.00 | 0.45 | 750 |
| | Urban | All | All | 1900 | 0.90 | 0.98 | | | | 0.90 | 1.00 | 1.00 | 0.45 | 700 |
| | CBD | All | All | 1900 | 0.90 | 0.98 | | | | 0.90 | 1.00 | 0.90 | 0.45 | 600 |
| Collector | Urban | All | All | 1900 | 0.85 | 0.98 | | | | 0.90 | 1.00 | 1.00 | 0.40 | 550 |

Exhibit 6.4. Example computation of default capacities by functional class and area/terrain type.

arterials and freeways with accuracies approaching those of the HCM and simulation models.

6.2.4 Estimating Transition Delays

Delay incurred by a traveler moving from the end of one segment to the beginning of the next segment usually can be neglected in the case of freeways, highways, and rural roads.

The segment to segment transition delay also can be neglected for through travel along a signalized arterial street since the methods described for estimating segment speeds include a nominal delay per signal in their estimates.

If the analyst is evaluating a route that involves left turns on signalized streets, the analyst may wish to improve the accuracy of the travel time estimate by adding a nominal delay per left turn to the estimated total travel time for the trip.

Actual field measurements of delay are best. HCM is the next best method for estimating left-turn delay, but this requires a great deal of information on signal timing and turning movements at the intersection. In the absence of this data, an estimate of one-half the cycle length for the signal may be used for the left-turn delay. (This assumes that a left turner is equally likely to arrive at any point in the signal cycle, so the average wait for the left-turn arrow will be half the cycle length of the signal.)

$$d_i = \frac{C_i}{2 * 3600} \tag{Eq. 6.17}$$

where

d_i = Average left-turn delay at signal at end of segment i (hours).

C_i = average cycle length of signal at end of segment i (seconds). If cycle length is not known, assume 120 seconds for suburban intersection, 90 seconds for downtown intersection.

6.2.5 Verification and Calibration of Travel-Time Estimates

The above equations for estimating trip travel time are based on national average conditions. It is good practice for the analyst to verify the estimates produced by these equations for a select sample of trips in the local area. Chapter 3 suggests the appropriate methods for developing local measurements of travel time for verifying the estimates produced by the methods in this chapter.

If the selected field measurements of trip travel times are within an acceptable range of the estimated trip travel times, the method can be considered to be verified against local conditions. The methods described in Chapter 3 can be used to determine the acceptable range for the results.

If the results are not acceptable, the analyst should check for errors in the data used to estimate the travel times. Once the possibility of input data error has been ruled out (or at least reduced to an acceptably low probability), the analyst should calibrate the estimated trip travel times to better match observed times in the field.

If the sketch planning method was used to estimate segment travel times, the analyst should enter field measured and estimated travel times for each segment into a spreadsheet and use the linear regression function to find the appropriate parameters for ADT/lane, signals per mile, access points per mile, and constant.

If the planning method was used to estimate travel times, the field data and the estimated trip times should be entered into a spreadsheet and the optimization function used in the spreadsheet to find the values of the parameters a and b in Equation 6.16 that minimize the squared error between the field data and the estimates. The search should be limited to positive values for a and to values greater than 1.00 for b .

6.3 Estimating Delay

Once travel time is known, delay can be estimated by subtracting the ideal travel time (often the travel time during uncongested periods of the day) from the actual travel time.

6.3.1 Definition of Ideal Travel Time

The ideal travel time against which delay is measured should be set by agency policy. Several definitions of the ideal travel time are possible; two are provided here:

One perspective is to take the “no other cars on the road” travel time as the ideal travel time. This method would assume that all signals are green, so that all travel is at the PSL. This is often called the FFS or zero-flow travel time.

FFS however is not readily measurable in the field. So an approximation of the FFS would be the mean travel time and speed measured under low flow conditions. This method of measuring speed and travel time includes nominal delays at signals due to modest amounts of traffic on the main street and the side street. This speed would be defined as the mean speed measured over the length of the trip during a nonpeak hour, say 10:00 a.m. to 11:00 a.m. or 2:00 p.m. to 3:00 p.m. This speed would generally be lower than the posted speed limit for signalized streets, but could be higher than the PSL for freeways, highway, and rural roads.

6.3.2 Computation of Delay

Delay is the difference between the actual and ideal travel time.

$$d = T_a - T_0 \quad (\text{Eq. 6.18})$$

where

d = Delay (hr:min:sec);

T_a = Actual Travel Time (hr:min:sec); and

T_0 = Ideal Travel Time (hr:min:sec).

6.4 Estimating Reliability

All of the reliability metrics can be computed from the travel-time variance data. This section provides a method to predict the variance in the travel time given the variance in the volume and the variance in the capacity.

Traffic operations improvements generally affect the probability of the facility being able to deliver a given capacity, and have minor effects on the variability of the volume of traffic. Thus this method predicts how changes in the variability of the delivered capacity for the facility affect the travel-time variance and ultimately reliability.

6.4.1 Predicting Changes in Capacity Variance

The expected (mean) value of the inverse of capacity and the square of the inverse of capacity are needed to predict the travel-time variance. If the expected value of capacity can be considered as the ideal capacity (C_0) minus a random variable (x), then the expected values of the inverse values can be computed using the following formulae.

$$E\left(\frac{1}{C}\right) = \sum_{i=1}^N P(x_i) * \frac{1}{C_0 - x_i} \quad 0 \leq x_i \leq C_0 \quad (\text{Eq. 6.19})$$

$$E\left(\frac{1}{C^2}\right) = \sum_{i=1}^N P(x_i) * \frac{1}{(C_0 - x_i)^2} \quad 0 \leq x_i < C_0 \quad (\text{Eq. 6.20})$$

For each study segment Exhibit 6.5 would be constructed.

The probability of a given capacity reduction ($a_i * C_0$) is computed as a function of the frequency of that event type occurring each year and the average number of hours that the capacity reduction endures for each event.

$$P(x = a_i * C_0) = \frac{\text{Events/Year} * \text{Hours/Event}}{\text{Hours/Year}} \quad (\text{Eq. 6.21})$$

It also is possible that an ITS project might cause an incident to have a lesser impact on capacity. Then one would create two incident types, one before ITS, and the same one after ITS. Each event type would have a different capacity reduction. The probability of after ITS incident happening before would be set to zero; the same for the before ITS incident happening after.

6.4.2 Computation of Travel-Time Variance

The travel-time variance is a function of the variance in the volume/capacity ratio (A simple linear travel-time function with a breakpoint at $v/c = 1.0$ has been assumed to facilitate the computation of the travel-time variance from the v/c variance).

| Capacity Reducing Event | Capacity Reduction | Probability Before ITS | Probability After ITS |
|-------------------------|--------------------|------------------------|-----------------------|
| No Incident | $x=0$ | $P_b(x=0)$ | $P_a(x=0)$ |
| Shoulder Incident | $x = a_1 * C_0$ | $P_b(x=a_1 * C_0)$ | $P_a(x=a_1 * C_0)$ |
| Bad Weather – Type 1 | $x = a_2 * C_0$ | $P_b(x=a_2 * C_0)$ | $P_a(x=a_2 * C_0)$ |
| Bad Weather – Type 2 | $x = a_3 * C_0$ | $P_b(x=a_3 * C_0)$ | $P_a(x=a_3 * C_0)$ |
| Shoulder Work Zone | $x = a_4 * C_0$ | $P_b(x=a_4 * C_0)$ | $P_a(x=a_4 * C_0)$ |
| Single-Lane Closure | $x = a_5 * C_0$ | $P_b(x=a_5 * C_0)$ | $P_a(x=a_5 * C_0)$ |
| Two-Lane Closure | $x = a_6 * C_0$ | $P_b(x=a_6 * C_0)$ | $P_a(x=a_6 * C_0)$ |
| Three-Lane Closure | $x = a_7 * C_0$ | $P_b(x=a_7 * C_0)$ | $P_a(x=a_7 * C_0)$ |
| Total Closure | $x = C_0 - 1$ | $P_b(x= C_0 - 1)$ | $P_a(x= C_0 - 1)$ |

Note: “x” is never allowed to exceed C_0-1 . This avoids divide by zero problems when computing the expected value of $1/C$.

Exhibit 6.5. Capacity reductions.

For $v/c \leq 1.00$
 $Var(T) = a^2 * Var(v/c)$ (Eq. 6.22)

For $v/c > 1.00$
 $Var(T) = b^2 * Var(v/c)$ (Eq. 6.23)

where

T = predicted travel time (hours);
 T_0 = Free-flow travel time (hours);

T_C = Travel time at capacity;
 a = Calibration parameter = $T_C - T_0$; and
 $b = 0.25$ (average delay per deterministic queuing theory).

The variance of the travel time is equal to the variance in the v/c ratio times the square of the slope of the linear travel-time function for the facility.

According to the HCM, the following free-flow and capacity travel-time rates (hours/mile) are appropriate (Exhibit 6.6).

| HCM Facility Type | Free-Flow Speed (MPH) | Speed at Capacity (MPH) | Free-Flow Travel-Time Rate (T_0) (Hours/Miles) | Capacity Travel-Time Rate (T_C) (Hours/Mile) | Calibration Parameter $a=T_C-T_0$ (Hours/Mile) |
|-------------------|-----------------------|-------------------------|--|--|--|
| Freeway | 75 | 53.3 | 0.0133 | 0.0188 | 0.0054 |
| | 70 | 53.3 | 0.0143 | 0.0188 | 0.0045 |
| | 65 | 52.2 | 0.0154 | 0.0192 | 0.0038 |
| | 60 | 51.1 | 0.0167 | 0.0196 | 0.0029 |
| | 55 | 50.0 | 0.0182 | 0.0200 | 0.0018 |
| Multilane Highway | 60 | 55.0 | 0.0167 | 0.0182 | 0.0015 |
| | 55 | 51.2 | 0.0182 | 0.0195 | 0.0013 |
| | 50 | 47.5 | 0.0200 | 0.0211 | 0.0011 |
| | 45 | 42.2 | 0.0222 | 0.0237 | 0.0015 |
| Arterial | 50 | 20.0 | 0.0200 | 0.0500 | 0.0300 |
| | 40 | 17.0 | 0.0250 | 0.0588 | 0.0338 |
| | 35 | 9.0 | 0.0286 | 0.1111 | 0.0825 |
| | 30 | 7.0 | 0.0333 | 0.1429 | 0.1095 |
| Two-Lane Highways | 55 | 40.0 | 0.0182 | 0.0250 | 0.0068 |

- Sources:
 1. Freeways: Exhibit 23-2 HCM.
 2. Multilane Highways: Exhibit 21-2 HCM.
 3. Arterials: HCM Exhibits 15-8, 15-9, 15-10, 15-11, Middle Curve.
 4. Two-lane Highways: Exhibit 20-2, HCM.

Exhibit 6.6. Free-flow and capacity travel-time rates per HCM.

The variance in the volume/capacity ratio can be computed from the expected value (the mean) of the volume (v), the volume squared, the inverse of the capacity, and the inverse of the capacity squared.

$$\text{Var}(v/c) = E(v^2) * E(1/c^2) - [E(v)]^2 * [E(1/c)]^2 \quad (\text{Eq. 6.24})$$

6.4.3 Computation of Reliability Metrics

The following equations are for use with forecasted travel times, where only the mean and variance are known. The distribution of times in this case must be assumed. For these equations we have assumed that travel time is Gamma distributed with mean equal to mean (T) and variance equal to Var (T).

Percent Variation

The following equation is used to compute percent variation based on the forecasted mean and variance in travel times.

$$\%V = \frac{\sqrt{\text{Var}(T)}}{\text{Mean}(T)} * 100\% \quad (\text{Eq. 6.25})$$

Buffer Index

BI is computed according to the following equation, which assumes a Gamma distribution for the travel times.

$$BI = \left[\frac{3.0 * \text{Var}(T)}{\text{Mean}(T)^2} - 1 \right] * 100\% \quad (\text{Eq. 6.26})$$

On-Time Arrival

The Percent On-Time Arrival is computed using the following equation, which assumes a Gamma distribution for the travel times.

$$\%OnTime = \Gamma[1.10 * \text{Mean}(T)] \quad (\text{Eq. 6.27})$$

where Gamma is the cumulative Gamma probability distribution with Mean = Mean (T) and variance = Var (T).

Misery Index

The Misery Index is computed according to the following equation, which assumes a Gamma distribution for the travel times. Since it is inconvenient to compute the mean of the top 20 percent of the values of a function, we have approximated this value with the 85 percentile highest value for the distribution. For Gamma (T):

$$MI = \frac{\Gamma^{-1}[85\%]}{\text{Mean}(T)} - 1 \quad (\text{Eq. 6.28})$$

where Gamma⁻¹ is the inverse of the cumulative Gamma distribution with Mean = Mean (T) and variance = Var (T).

CHAPTER 7

Alternatives Analysis

7.1 Introduction

This chapter describes how to identify alternative improvements or strategies to mitigate identified existing or future deficiencies and how to determine which improvements are most effective in addressing those deficiencies. It goes on to provide guidance on how to assess the effectiveness of improvements once they are in the field.

7.1.1 Purpose

The purpose of this chapter is to help the analyst avoid common pitfalls in the evaluation of alternatives for reducing travel time, delay, and improving reliability. These common pitfalls include the following:

- Selection of improvements that solve a problem that is different from the real problem, that is, the search for solutions is misdirected; and
- Overlooking improvements that could solve the problem, that is, the search is too narrow.

7.1.2 Scope and Limitations

This chapter covers the generation, evaluation, and programming of transportation system improvements designed to reduce travel time, reduce delay, and increase reliability. This chapter is necessarily brief and is not designed to replace standard planning textbooks on alternatives analysis. “Alternatives analysis” in this context is informal and refers to a generalized analytical process of evaluating different possible operational strategies, capital projects, etc., to determine the benefits of each and help the analyst draw conclusions about which course of action is likely to be the most effective in addressing the identified deficiency or problem. The term as used here should not be equated with the formal alternatives analysis process described in federal requirements for

preparation of Environmental Impact Statements or for entry into the Federal Transit Administration (FTA) Section 5309 New Starts project development process and funding program. While the methods described here can be used to support a formal alternatives analysis process, the entire process is not discussed here.

7.1.3 Organization

The chapter is organized into the following six steps:

1. Problem definition;
2. Generation of project alternatives for analysis;
3. Selection of performance measures;
4. Evaluation of alternatives;
5. Develop improvement program; and
6. Effectiveness evaluation (before/after studies).

7.2 Defining the Problem

Before embarking on developing alternatives, the problem to be solved by the alternative improvements must be defined. The first step in alternatives analysis is to identify and diagnose deficiencies in current or forecasted system operations, as described in Chapters 5 and 6, respectively.

The more precisely the analyst can define the problem that the alternative improvements are supposed to solve, the more precisely the analyst can focus the analysis. The problem definition drives the entire alternatives analysis process, from generation of improvement alternatives, to the selection of performance measures for evaluating each improvement option.

Example problem definitions that this guidebook is designed to address include:

- Peak-period delay exceeds agency’s performance targets; and
- Travel-time reliability during off-peak periods is below agency’s standards.

7.3 Generation of Project Alternatives for Analysis

The analyst should consult one or more of the following references for strategies and actions that are appropriate for reducing travel time, delay, and variability. Exhibits 7.1 and 7.2 highlight some of the actions and strategies discussed in these references, but should not be considered a replacement for consulting these references.

1. *Unclogging Arterials: Prescriptions for Relieving Congestion and Improving Safety on Major Local Roadways* (FHWA-OP-03-069) (2003).

This guidebook presents 15 strategies for increasing mobility and safety of travel on arterial streets. The guidebook also contains 10 case studies of local agencies that have employed these strategies, an action checklist and appendices showing example documents, such as memoranda of understanding and city legislation that readers can use as models in their own areas. Contact the Operations/ITS Helpline, (866) 367-7487 or itspubs@fhwa.dot.gov.

2. *A Toolbox for Alleviating Traffic Congestion and Enhancing Mobility* (1997).

This document provides local elected officials, business leaders, and other community leaders with information on traffic congestion and strategies that can be used to deal with it. Types of strategies discussed include increasing transportation capacity (both through widening or expansion of roads, and new techniques such as ITS), public transportation, demand management, and funding and other institutional issues. For each strategy, the report provides a description, the estimated costs and benefits, steps needed to implement it successfully, and a detailed bibliography. Available at http://www.itsdocs.fhwa.dot.gov/jpdocs/repts_te/5dz01!.pdf, EDL# 6983.

Also available: Michael D. Meyer, *A Toolbox For Alleviating Traffic Congestion And Enhancing Mobility*, Institute Of Transportation Engineers, Washington, D.C., 1996 (available at <http://ntl.bts.gov/lib/8000/8700/8780/toolbox.pdf>).

| Problem | Likely Cause | Solution Strategies | Improvement Alternatives |
|--|------------------------|--|--|
| Excessive Peak-Period Delay (on average day without incidents) | Peak Demand > Capacity | Travel Demand Management to shift demand to other corridors, other time periods, and/or other modes. | <ul style="list-style-type: none"> • Establish TDM Program for Employers • Staggered work hours • Construct Transit improvements • Increased transit service • Construct HOV lanes • Carpool parking • Construct bypass for bottleneck(s) • Peak-hour tolls • Auto restricted zones • Service vehicle hour restrictions • Parking supply management • Concierge shopping services • Satellite work stations • Work at Home Program • Ramp and signal metering |
| | | Increase capacity at bottlenecks. | <ul style="list-style-type: none"> • Add lanes • Change signal timing • Correct substandard geometry • Allow peak period shoulder lane use • Reversible lanes • Peak period turn prohibitions • Ramp metering • Heavy vehicle restrictions |

Exhibit 7.1. Alternative improvements to solve delay problems.

| Problem | Likely Cause | Solution Strategies | Improvement Alternatives |
|--|--|---|---|
| Excessive Variability in Peak Travel Times | Demand exceeds capacity, and incidents are too frequent and too damaging | Reduce probability of incidents. | <ul style="list-style-type: none"> • Bring road design up to agency standards • Accident history investigation • Vehicle regulations • Reduce roadside distractions • Reduce in-vehicle distractions |
| | | Reduce incident detection times. | <ul style="list-style-type: none"> • Real-Time Monitoring of traffic flow |
| | | Improve emergency response times. | <ul style="list-style-type: none"> • Establish roving response teams • Service patrols |
| | | Reduce incident clearance times. | <ul style="list-style-type: none"> • Integrate 911 emergency responders and maintenance operations • Contract towing services dedicated to road sections • Off-road pullouts for exchanging accident info |
| | | Reduce impacts of incidents on capacity. | <ul style="list-style-type: none"> • Wider shoulders • Off-road pullouts for exchanging accident info • Gawker Screens |
| | | Traveler information systems to help people avoid incident locations. | |

Exhibit 7.2. Alternative improvements to solve reliability problems.

3. *TCRP Report 95: Traveler Response to Transportation System Changes.*

Includes discussion of transit scheduling and frequency, and other operational actions that impact ridership.

4. *TCRP Report 100: Transit Capacity and Quality of Service Manual, Second Edition, TRB, Washington, D.C., 2003.*

This comprehensive manual includes information on capital and operating strategies for bus, rail, and water transit, covering vehicles, routes/alignments, and stations.

7.4 Selection of Performance Measures

Performance measures (also called measures of effectiveness, or M.O.E.) are the system performance statistics that best characterize the degree to which a particular alternative meets the agency’s objectives. Chapter 2 describes the selection of appropriate measures of effectiveness for evaluating current operations, future operations, and alternatives for reducing travel time, delay, and variability.

The selected set of performance measures should be as sparse as possible, consistent with the defined problem. A large set of measures strains the analyst’s resources and increases the probability of conflicting results, clouding the selection and prioritization process.

7.5 Evaluation of Alternatives

Once the problem to be solved has been defined, the performance measures selected, and the alternatives to be evaluated have been identified, then the evaluation of the effectiveness of each alternative is generally quite straight forward.

The analyst uses the methods described in Chapters 2 and 3 to estimate the travel-time, delay, and reliability measures that will be used to compare the performance of each improvement alternative.

For example, if analysts were to define their problem as excessive delay and excessive unpredictability in the delay, then they might select the mean person-hours of delay and the variance in the person-hours of delay as their performance measures. The analyst might then develop four alternative improvement strategies for addressing the problem. They might be: do nothing, add capacity (Alt. A), manage demand (Alt. B), and improve incident response (Alt. C). Computation of the person-hours of delay and their variance might present results like those shown in Exhibit 7.3. (Person-hours traveled are shown as well as delay, because the total person-hours traveled is needed to obtain delay.)

The question then becomes, “Which alternative is best?”

If simply looking at the mean person-hours traveled, then you would select Alternative A as the best, since it provides

| Alternative | Mean | | Variance | |
|---------------|-----------------------|-----------------------|-----------------------|-----------------------|
| | Person Hours Traveled | Person Hours of Delay | Person Hours Traveled | Person Hours of Delay |
| Do Nothing | 1,230,000 | 61,500 | 184,500 | 15,375 |
| Alternative A | 1,199,250 | 30,750 | 119,925 | 6,150 |
| Alternative B | 1,214,625 | 46,125 | 145,755 | 9,225 |
| Alternative C | 1,223,850 | 55,350 | 171,339 | 5,535 |

Exhibit 7.3. Example results of alternatives evaluation.

the lowest mean person-hours of delay. If simply looking at the variance of the delay, then you would select Alternative C since it produces the lowest variance in delay.

The analyst needs to introduce other information such as monetary, societal, and environmental costs to the evaluation of alternatives. This might be done through a cost-effectiveness analysis over the lifetime of each alternative. There are several references available for guidance on conducting this type of analysis. They include:

1. *Economic Analysis Primer*, U.S. Department of Transportation, Federal Highway Administration, Office of Asset Management, FHWA-IF-03-032 (web document), August 2003. It is available at: <http://www.fhwa.dot.gov/infrastructure/asstmgt/primer.htm>.
2. *NCHRP Synthesis 142: Methods of Cost-Effectiveness Analysis for Highway Projects*, Transportation Research Board, Washington, D.C. 1988.
3. AASHTO Red Book – American Association of State Highway and Transportation Officials: *A Manual on User Benefit Analysis of Highway and Bus Transit Improvements*, 1977. (See also final report for NCHRP Project 2-23, *Development of an Update to the 1977 AASHTO Redbook*.)

A weighting scheme is then developed by the analyst (reflecting the relative importance to the agency of minimizing

costs and achieving each objective). The relative weight of each cost and each objective is combined to yield a single numerical value for each alternative. The recommended alternative is the one with the best overall numerical value.

7.6 Develop Improvement Program

Once the best alternative has been selected it is necessary to develop a program for implementing the improvements. This program identifies responsible agencies, sources of funds, and a schedule for improvements. An implementation monitoring program is useful to ensure that the improvements are implemented as planned.

7.7 Evaluate Effectiveness of Implemented Solutions

An evaluation of the effectiveness of the solution(s) that have been implemented can be conducted using the before and after methods described in Chapter 4. Because this requires forethought in setting up the before/after comparison and defining data collection needs prior to actual implementation, the decision to conduct this type of effectiveness evaluation needs to be made early, and certain actions taken before construction of the chosen improvement (or initiation of a new service or program, if a noncapital improvement).

CHAPTER 8

Using Travel Time Data in Planning and Decision Making

8.1 Introduction

This section provides guidance on how to utilize travel-time-based performance information in typical planning applications faced by departments of transportation, regional planning agencies, transit system operators, and other agencies with similar roles and responsibilities. The selection and presentation of information in this chapter reflects the finding that a very large percentage of reported travel time, delay, and reliability data is used primarily for reporting on current conditions or historical trends. Many of the published or web-based sources of travel time data are used to inform the public, stakeholders, and decision makers about how well a system is currently performing and/or what has been the impact of a particular program of investment. Less evident is the application of similar types of data to drive typical planning functions, such as current and projected future needs (or deficiencies) identification, comparison of alternatives, or hypothetical before/after (or “what if”) studies prior to actual project selection and implementation. This guidebook is intended to help fill that gap and provide practitioners with accessible, effective methods for bringing travel-time-based data into the decision process for potential future actions, as well as to identify and evaluate needs by looking at both historical and projected trends.

8.2 Scope and Limitations

This material is primarily suited to support planning decisions about investment in system expansion, and to a lesser extent, on system operations. It focuses on using travel-time-related measures of system performance to discern looming trends, identify needs, and distinguish between alternative courses of actions. It is not intended to provide advice on short-term system management and detailed operational analyses based upon archived TMC data, nor on traveler information systems based on real-time data. There are other excellent

sources of detailed information and practical guidance covering that topic, including most recently NCHRP Project 3-68, *A Guide to Effective Freeway Performance Measurement*, which covers a wide range of material related to reporting conditions on freeway systems using TMC type data.

8.3 Organization

The next several subsections provide context for applying travel time and related performance data to planning processes and decisions, drawing examples from the case study research. These findings illustrate some of the important technical and institutional steps or approaches that should be considered to improve the quality and utility of performance data in these applications. In the remainder of the chapter, we offer six different example planning applications frequently confronted by planning agencies, and offer step-by-step approaches for applying the technical methods and approaches provided in the earlier chapters of this guide.

8.4 Creating a Performance-Based Decision-Making Environment

Performance measures have been used to evaluate both system condition and quality, as well as to track the level of activity required to build, maintain, and operate a system. Planners talk of output or activity-based measures that quantify the level of effort that goes into the system, such as incident detection and clearance time, as well as outcome or quality of service measures that describe the resulting effect of investment choices (e.g., total annual delay per person). There is an even longer history of using performance data to track the physical condition of the transportation system, for example, in pavement and bridge management.

The literature search, agency interviews, and case studies conducted during the course of this project suggest that use of travel time and delay data for planning purposes is currently

limited. Most agencies do not actively use such data or projections in their planning processes. Much more common is the use of travel time, delay, and to some extent reliability statistics, for reporting current operational conditions and historical trends, and possibly identifying congested corridors for further analysis. What is still relatively new for most agencies is the use of the quality of service measures based on measured and modeled travel times, used in conjunction with other measures and factors, to help decision makers choose the most effective course of action. Actual ongoing application of such data to specific needs identification, alternatives analysis, or before and after studies (including the hypothetical before/after or “what if” analysis comparing synthetic forecasts) is much more limited. Yet travel time and delay statistics can be useful in helping analysts, decision makers, and the general public to understand the potential payoff of different capital and operating investments in terms that are most immediately relevant to daily trip-making of system users.

8.4.1 Using Travel Time and Delay Measures

Transportation project complexity and costs are continuing to grow significantly. The costs for design, materials, energy, construction, and environmental review and mitigation, among other elements, are all escalating at rates higher than general inflation or transportation funds. Project costs of \$100 million (and in some case much more) are no longer unusual. Simultaneously, agency planners, decision makers, and even the lay public are increasingly aware of the important benefits that stem from good system investments, in terms of improved economic vitality, more efficient movement for personal and commercial purposes, and a resulting overall higher quality of life than would be present without the investment. In short, most stakeholders are looking for greater return on investment from transportation expenditures. Because travel time and delay affect this broader stream of benefits, there is a compelling case for including analysis of these factors in deciding on future investments. Identifying, selecting, and implementing the best performing projects, not simply the least expensive projects, are increasingly important as the cost of building, operating, and maintaining a modern transportation system grows, and its importance to the overall well-being of the community grows as well.

At the same time, members of the traveling public do not always understand why the large amount of ongoing transportation expenditures (which are visually evident to any system user, due to ever-present construction and maintenance) do not result in more significant improvements to the quality of their travel experience, regardless of mode.

Finally, decision makers, elected or appointed officials, face increasing pressure to deliver quantifiable results. This phenomenon is not unique to transportation. It encompasses

education (tracking test scores), welfare (tracking numbers of welfare recipients), environment (particles per million), and other disciplines in the public’s eye. Congestion mitigation (if not outright reduction) and mobility management are still high on the list of decision makers’ objectives, and even the concept of travel time reliability has worked its way into the regular dialog of decision makers and even the general traveling public.

Of course, the private sector has faced this type of accountability for decades. Publicly traded for-profit companies have to maximize shareholder value by producing financial results that reflect profitability, revenue growth, positive cash flows, and other indicators believed to be central to a company’s mission and objectives. Even though these companies adopt and track other metrics for success (e.g., number of registered patents, effective knowledge management, retaining key staff, minimizing work-related accidents), ultimately they are judged by profitability and growth or, more generally speaking, return on investment.

The same can be said for transportation. One could argue that even though many performance outcomes should be considered in evaluating each project or investment (e.g., safety, environmental quality, social equity, geographic equity, etc.), travel time and reliability of travel time are the most important and immediate indicators of system performance and mobility for most customers. People want to be able to get from point A to point B in a reasonable time with reasonable predictability. These two attributes should be among the key factors for any transportation planning process and for any decision-making process, in most cases. The selected performance measures should offer decision makers an understanding of the differences in travel time and reliability that would result from alternative courses of action. These can be aggregated to the region or system level, or reported individually for specific project corridors or segments.

Our experience in working directly with numerous public agencies in performance-based planning and management suggests several important considerations. The case studies and agency interviews conducted for this research project support these findings and recommendations as well.

8.4.2 Make Performance Part of Everyone’s Daily Discussions

Much has already been written about the institutional aspects of developing a successful performance-based management approach. A frequently cited tactic is to raise the visibility of performance data and performance monitoring to the point that every division in the organization is engaged in some aspect of performance delivery, knows the relevant metrics and desired targets or objectives, and is comfortable discussing them. This is much easier said than done. To illustrate this point, ask yourself: how many people in the organization

know the average travel time (or total daily delay) in their region (or state) and the reliability of travel time? How many know what the agency’s prediction for the next five years is for these two measures? What are the reasons for these predictions, and how are they tracking their progress? This means that every planning product, every presentation to decision makers, every staff recommendation for investment must be performance driven or at least include a discussion on performance impacts. Clearly, this takes time and effort. But as discussed before, performance-based planning and decision making have become an imperative, not a choice. Achieving the best results from an investment requires an up-front investment in planning analysis.

8.4.3 Develop an In-Depth Understanding of Trends and Measures

For performance data to have an impact on agency decisions, there needs to be wide understanding within the organization of the agency actions and external trends that are driving performance, the measures that are used to gauge performance, and the relationship between the two. Again, this seems easier than it really is. For instance, several agencies we have reviewed evaluate measures of mobility (e.g., travel time, delay, speed) independently from reliability (e.g., on-time arrival, percent variation of travel time, buffer index). Yet, these two measures are interdependent. If the number of accidents are reduced (by implementing safety projects) and/or accident clearance times are reduced (by investing in incident management strategies), planners and decision makers expect an improvement in the reliability measure. Yet, in some instances that may not happen. Since delays due to accidents are reduced, the average travel time over a month (or year) also will be reduced. This, in turn, changes what on-time arrival means, what the percent variation means, and what the buffer index (as a percent of travel time) refers to. Therefore, it is critical to look at the trends of both travel time and reliability together. The hypothetical example in Exhibit 8.1 illustrates this point. Clearly, the after scenario reflects an improvement over the before scenario, even if it does result in an increase in the variability as measured by the buffer index. Yet, unless the two

types of measures are considered together, planners and decision makers may reach the wrong conclusion about the benefits of the project.

Another example relates to the use of delay as a planning evaluation measure. In its 2004 Regional Transportation Plan, the Southern California Association of Governments (SCAG) projected future delays and compared them to the base year delay. At first, the results of this comparison were disappointing. Despite a variety of potential system investments over 25 years costing more than \$100 billion, total delay was projected to increase significantly between the base year and the horizon year of 2030.

Yet, SCAG recognized that total system delay does not reflect the individual customer’s experience, or their expectations. Rather, delay per trip was deemed a more appropriate measure, since it is linked to something the traveler actually experiences and can measure on their own (even if only casually or subconsciously) (i.e., the excess time required to make a particular trip due to congestion). In some cases, growth in delay is more meaningful to the traveler than growth in travel time, since travel time may be expected to increase due to land use policies, personal location decisions, etc. As shown in Exhibit 8.2, the two examples lead to different conclusions about the future system performance and the benefits of the improvement program. As these graphs show, delay per capita is projected to stay almost constant despite the increase in demand. To many transportation professionals, this projection, if it holds true, would be a major accomplishment. And to many system users, it also would seem a reasonable outcome, if taken from a realistic perspective of population growth and continued economic prosperity in the region.

The point made here is that adopting and generating performance measures are not enough. An organization must spend significant time to understand the measure, the results, and the limitations of the measure before basing decisions on the measure.

8.4.4 Invest in Data

Perhaps the seemingly most under-valued investment is the collection and storage of good monitoring data. The

| | Average Travel Time | Buffer Index | On-Time Arrival (Within 5 Minutes of Average) |
|--------|---------------------|--------------|---|
| Before | 22 minutes | 30% | 65% |
| After | 18 minutes | 32% | 65% |

Exhibit 8.1. Example before-after comparison of different travel time measures.

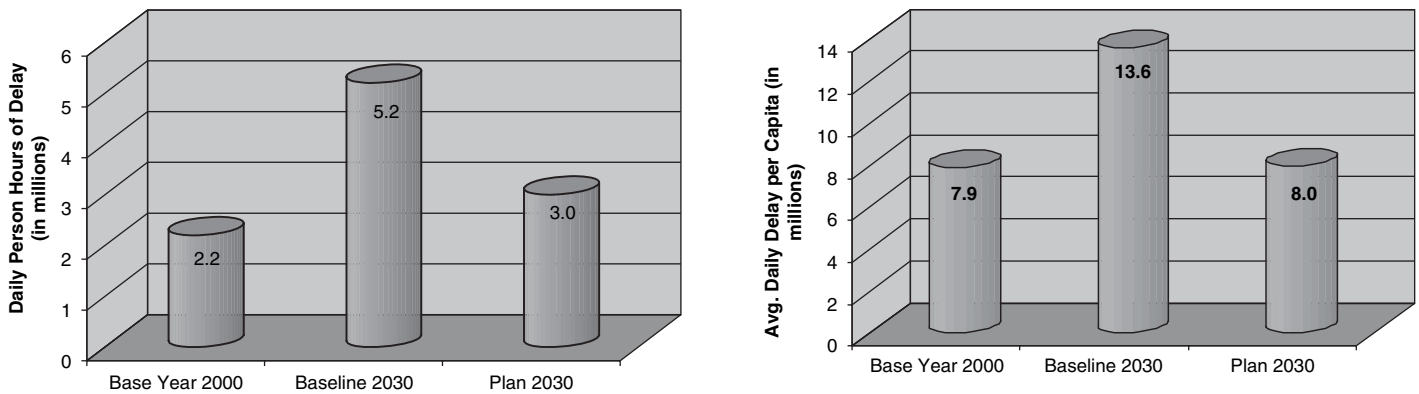


Exhibit 8.2. Delay and delay per capita projected for 2030 in the SCAG region.

number of planning studies conducted by state and local agencies that must rely only on existing, readily available data from secondary sources suggests as much. Yet, monitoring data is used not only to measure what is. It is also used to calibrate the models that eventually project what will be. It is, therefore, important for both decision-makers and planning professionals to embrace the need for more frequent and regular data collection, and to view data and data systems as assets to be developed and valued. A review of the private sector confirms the importance that should be placed on data if decisions are to be based on performance. Wal-Mart has implemented systems that let them know what item is sold when, as well as the trends for each item on a daily and weekly basis. FedEx can tell where a shipment is at all times and can project when it will be delivered. And, of course, Internet companies can learn from online transaction and search trends to tailor advertisements for each individual. Without good data, performance measurement cannot succeed as a basis for planning and decision making. Fortunately, developments in data collection equipment strongly suggest that automated detection systems are becoming more affordable and easier to install. Such systems are especially important to evaluate trends in travel time and reliability. Moreover, over the longer term, they are likely to prove more cost effective than manual data collection efforts.

8.4.5 Understand the Limitations of Tools and Continually Improve Them

With the ever increasing computer power and the continuous advancement of the science of transportation and traffic engineering, it is important for agencies to understand the limitations of their current tools and, when possible, invest in improving them. For instance, 4-step travel demand models have limitations in terms of evaluating operational strategies (e.g., incident management, auxiliary lanes, ramp metering). Therefore, agencies that are about to focus on

such strategies must look for alternative tools, such as microsimulation tools. Moreover, as more data is available, travel demand models can be improved through better calibration. Again, we see this commitment to improving tools across the private sector. Financial firms, for instance, have abandoned many of the traditional stock and option valuation models over recent years as new data illustrated serious flaws in them. Car companies have developed new computer tools to help them assess wind resistance and the impact on fuel utilization. The list goes on, but the principle remains: if the tools are important for decision-making, improving the tools must be a priority. Research projects, such as these and many others like it, ultimately provide planners with the necessary tools to estimate and apply travel time performance data in a broad variety of situations.

8.4.6 Understand and Embrace the Difference Between Policy and Technical Analysis

We have all witnessed the frustration of technical staff when decision makers do not allocate the suggested investment to their area (e.g., pavement rehabilitation, highway expansion, operational strategies). This frustration is understandable and perhaps even needed. After all, each program area needs advocacy. However, agency technical staff also must recognize that their primary job is to adequately inform decision makers of the performance ramifications of their potential decisions from a technical perspective (e.g., what are the cost ramifications in the future of deferring maintenance in order to address a critical capacity deficiency). This way, staff can focus on technical analysis, risk analysis, and performance measurement to provide an accurate picture as possible to decision makers. Using available tools and methods to generate with and without estimates of volume, speed, travel time, and physical condition, analysts can generate measures that help identify the difference between these two choices.

8.4.7 Do Not Attempt to Use a Black Box Approach

Sophisticated tools that build a prioritized list of improvement projects may appeal to technical staff, but more rarely are appreciated by decision makers and the public. It is critical to work with the stakeholders during the evaluation process, and to explain the strengths and weaknesses of the tools during the entire planning process. Otherwise, the first time a credible source provides a negative critique of the tools used, decision makers may lose faith or withdraw support for the entire set of recommendations.

Ultimately, integrating performance results into planning and decision making takes time. A review and revision/enhancement of each tool and product may be required. But small steps can yield superior results that only can help enforce the overall commitment to the concept.

8.5 Using Travel Time, Delay, and Reliability in Planning Applications

This section and the subsequent section summarize how the detailed methods and approaches described in Chapters 2 through 7 can be applied to typical transportation planning analysis in support of decisions. The material in Chapter 2 provides guidance for the selection of performance measures suitable for particular applications, and Chapter 3 provides data collection steps and actual equations for calculating the various measures. Chapters 4 through 7 describe specific analyses that can be performed using travel time and delay data.

Exhibit 8.3 presents a recommended short list of measures for reporting travel time, delay, and reliability. These measures are organized according to whether they report primarily travel time, congestion-related delay, or reliability in planning applications. This table also indicates which component of congestion is reported, and the geographic area(s) best addressed by each measure. In fact, many measures can be applied at multiple scales (e.g., region, subarea, section, and corridor), which makes the measures useful for multiple applications (e.g., long-range planning), as well as corridor-specific alternatives analysis.

There are numerous variants to the recommended measures that may be useful depending upon the audience and application. For example, some measures may be expressed as an absolute number, as well as a percentage (e.g., percent or number of system lane miles operating at or below the defined threshold of congestion). The raw number of congested miles, in this example, may not give the lay person adequate sense of the magnitude of the problem, since they are unlikely to know the total extent of the system mileage. For that person it may

be adequate to simply know that, for example, two-thirds of the system operate at acceptable levels under peak conditions, or that a proposed operational improvement covering a significant portion of the system (stepped-up freeway patrols, for example) might reduce congested miles by several percentage points. Conversely, for the decision-maker or elected official with budget concerns, knowing the absolute number of congested miles may be useful as it highlights more dramatically the extent of the problem and immediately conveys at least a gross sense of the size of undertaking and resources required to address the problem.

Indexing a quantity (e.g., annual hours of delay) to some baseline quantity, such as an area's population or miles of travel may help to normalize the influence of background population growth when comparing current to future congestion levels, as demonstrated in the previous example from SCAG. This information may be more meaningful to agencies studying conditions at the corridor or regional level, for example, hours of delay per lane-mile of road, person hours of delay per 1,000 person miles traveled, or hours per 1,000 travelers. The general public may not gain much added benefit from these variant measures since it is more difficult to relate to personal travel decisions or travel experience to some of the indexed quantities.

Again, the analyst should be guided by the primary audience for the performance data and choose accordingly. The concepts and calculations are similar regardless of the variant, and most analysts will be readily able to adapt measures to suit their particular needs.

8.6 Typical Planning Applications

This section describes applications for measures of travel time, delay, and reliability in the planning process. Six typical planning applications were selected, based upon review of the research conducted for this project and the needs of practitioners as perceived by the research team and project panel:

1. Evaluate trends in travel time, delay, and reliability;
2. Identify existing deficiencies;
3. Evaluate the actual effectiveness of improvements (before-after study);
4. Predict future conditions/identify future needs and deficiencies;
5. Alternatives analysis; and
6. Improve fleet operations and productivity.

These six applications address a very large percentage of the situations in which a planner or analyst might want to apply measures of travel time, delay, and reliability in order to shed more light on a trend or need, discern differences between alternative courses of action, etc. Each of these

| Recommended Performance Measures | Congestion Component Addressed | Geographic Area Addressed | Typical Units Reported |
|--|--------------------------------|------------------------------------|---|
| Travel Time Measures | | | |
| Travel Time | Duration | Region | Person-minutes/day, person-hours/year |
| Total Travel Time | Duration | Region | Person or vehicle hours of travel/year |
| Accessibility | Extent, Intensity | Region, Subarea | # or % of “opportunities” (e.g., jobs) where travel time ≤ target travel time |
| Delay and Congestion Measures | | | |
| Delay per Traveler | Intensity | Region, Subarea, Section, corridor | Person-minutes/day, person-hours/year |
| Total Delay | Intensity | Region, Subarea, Section, Corridor | Person- or vehicle-hours of delay/year |
| Travel Time Index or Travel Rate Index | Intensity | Region, Subarea, Section, Corridor | Dimensionless factor that expresses ratio of travel conditions in the peak period to conditions during free-flow (e.g., TTI of 1.20 = congested trip is 20% longer than free-flow trip) |
| Congested Travel | Extent, Intensity | Region, Subarea | Vehicle-miles under congested conditions |
| Percent of Congested Travel | Duration, Extent, Intensity | Region, Subarea | Congested person-hours of travel (PHT) as % or ratio of total PHT |
| Congested Roadway | Extent, Intensity | Region, Subarea | # (or %) of miles of congested roadway |
| Misery Index | Duration, Intensity | Region, Subarea, Corridor | Proportion or percentage (e.g., 1.50) (expressing time difference between the average trip and the slowest 10 percent of trips) |
| Reliability Measures | | | |
| Buffer Index | Intensity, Variability | Region, Subarea, Section, Corridor | % extra time to be allowed to ensure on-time arrival, e.g., “BI of 30%” |
| Percent On-Time Arrival | Variability | Facility, Corridor, System | % of trips meeting definition of “on time” |
| Planning Time Index | Intensity, Variability | Region, Subarea, Section, Corridor | Dimensionless factor applied to normal trip time, e.g., PTI of 1.20 x 15-min. off-peak trip = 18-min. travel time for travel planning purposes |
| Percent Variation | Intensity, Variability | Region, Subarea, Section, Corridor | % of average travel time required for on-time arrival of given trip, similar to Planning Time Index |
| 95 th Percentile | Duration, Variability | Section or Corridor | Trip duration in minutes and seconds |

Exhibit 8.3. Recommended measures for reporting travel time, delay, and reliability.

applications involves one or more fundamental tasks, such as identifying the most suitable measures, data collection, forecasting performance under a hypothetical or future condition, reporting the results, etc. These building blocks are each addressed in Chapters 2 through 7, and several of these building blocks might be used in each of the above planning applications.

For example, the fourth example application is prediction of future conditions. This is typically conducted in order to identify corridors, facilities, or specific locations that at some future point will fail to meet an agency’s standards or require

additional investment to serve growing demand in developing areas. The analyst also typically will use the existing and projected future performance data to identify probable cause of the failures, as well as to suggest potential solutions to be evaluated in a subsequent alternatives analysis. The description of this particular planning application identifies five distinct steps to be taken:

- Step 1. Determine agency performance standards,
- Step 2. Determine scope of analysis,
- Step 3. Select forecast approach,

Step 4. Conduct forecasts, and

Step 5. Process results.

Each of these steps then is covered in detail in a particular chapter (e.g., Chapters 2 and 5 contain guidance for identifying and quantifying agency standards, and Chapter 6 describes various methods for estimating or forecasting future values of travel time depending upon the data available).

This modular approach is offered because the six planning applications share many common steps (e.g., identification of desired measures, data collection, and forecasting future values of input variables to the performance measures). Presenting these steps or building blocks in discrete chapters eliminates the need to repeat the steps for multiple planning applications. This format also allows the planner or analyst to assemble various steps, as appropriate, to conduct a planning application other than the six defined in this guidebook. The six applications described here will cover a large percentage of applications that might be found in a transportation planning context, and with slight modification can be extended to cover most all situations.

8.6.1 Application 1: Evaluate Trends in Travel Time, Delay, and Reliability

The objective of this application is to identify and track overall trends in travel time, delay, and reliability for the purposes of preparing a report on agency performance. Many agencies regularly do this, and the typical reporting agency might be a MPO, congestion management agency, state DOT, or transit operator, but also could be city or county transportation units, freight operators, or a national DOT. The report may be prepared monthly, quarterly, or annually. In some cases, the reports are directed at high-level decision makers and stakeholders; and in other cases, may be intended for a broader audience of lay system users or taxpayers.

The following is an overview of the recommended procedure. References are given to the appropriate chapters for the necessary technical guidance. Within those chapters, additional references are given, where appropriate, to more specific technical background on a particular subject.

Step 1. Identify Desired Metrics

- Select metrics for travel time, delay, and/or reliability, depending upon issues, audience, and availability of real-time data.
(Chapter 2)

Step 2. Determine Study Bounds

- Decide if O-D times, facility times, or segment times desired; and

- Decide on length of analysis periods and time slices within analysis period.
(Chapter 2)

Step 3. Determine Sampling Plan

- Determine if suitable data already exist or if sampling is required;
- Decide on number of days, hours, seasons of year for which data desired; and
- Determine which hours, days, and weeks to sample.
(Chapter 3)

Step 4. Prepare Data Collection Plan

- Determine required accuracy (confidence interval) of results.
- Estimate minimum samples required.
- Identify segments, facilities to be sampled.
- Determine if the available data covers the necessary geographic areas, facilities, time periods, days, seasons of the years needed for the analysis.
- If necessary data not available, select one of the following to supplement or fill gaps in available data:
 - Step 4A. Data collection technology (loop detectors, GPS/AVI vehicles); or
 - Step 4B. Estimation methodology (sketch planning, HCM, or BPR curve).
- Estimate data collection (and/or estimation) costs and personnel required.
- Revisit study bounds and accuracy requirements, and technology if resources insufficient.
(Chapter 3)

Step 5. Conduct Baseline Data Collection

- For field data collection methods see appropriate data collection guide (e.g., *Travel Time Data Collection Handbook*, *FHWA Traffic Monitoring Guide*, etc.); and
- Simultaneously collect weather and incident logs for times and locations of data collection (to be used later to address outlier data).
(Chapter 3)

Step 6. Process Baseline Results

- Set reasonableness bounds for data and eliminate outliers;
- Set travel time standard (free-flow, speed limit, or other) against which additional travel time is considered delay;
- Compute mean and variance for travel time and delay;
- Compute confidence intervals for mean travel time and mean delay;

- Compute desired metrics, selecting from initial list; and
- Prepare report and graphics. (Chapter 3)

Step 7. Conduct Trend Data Collection

- See Step 5, Conduct Baseline Data Collection for guidance. (Chapter 3)

Step 8. Process Trend Results

- See Step 6, Process Baseline Results for guidance. (Chapter 3)

Step 9. Compare Trend to Baseline

- Determine extent to which differences between base and trend year are due to sampling error;
- Fit trend line to data; and
- Prepare report and graphics. (Chapters 3 and 8)

Exhibit 8.4 shows how results from two related measures can be compared to one another to help tell a more complete story of trends. This figure illustrates four-year trends in the travel-time index and the planning-time index at the system level. The TTI (represented by the shorter, lighter-colored bars) shows that the typical (i.e., average observed) peak-period trip takes about 30 percent to 40 percent longer than the same trip at FFS, and that trends may be improving in the most recent year presented. The planning time index (PTI,

taller, darker-colored bars) represents the additional proportion of time travelers should add to a typical free-flow travel time when a 95 percent likelihood of on-time arrival is desired. As defined in Chapter 2, the PTI differs from the TTI, as it is based on the 95th percentile trip time or rate, rather than the average rate. The PTI compares near-worst case travel time to light or free-flow travel time, whereas the TTI compares average (measured or estimated) travel time (or rate) to free-flow conditions.

In this example, reporting both the TTI and PTI in a comparative graph may help in interpreting the underlying causes of change in the measures. The trend data suggest that the observed reduction in TTI in the final year of data (2003) may be due in large part to a decrease in the longest trip times, as indicated by the even sharper drop in the PTI. The PTI will be more sensitive to the 95th percentile trip time (or rate) value, indicating the longest trip times have declined measurably since the previous year of data. This type of result may have been the effect of an improved systemwide incident management program, or other system-level improvement that had a more significant impact in reducing the amount of nonrecurring or incident-generated delay. This reduces the spread between the average trip time and the slowest trips on the system. The PTI uses a different standard of performance than the TTI and indicates that travelers need to allow a larger margin than would be suggested by the TTI; it indicates the amount of time that must be planned for important trips. Exhibit 8.4 also includes the miles of freeway included each year in the system-level analysis, and while this information is not essential, it provides the user with a yardstick to confirm that

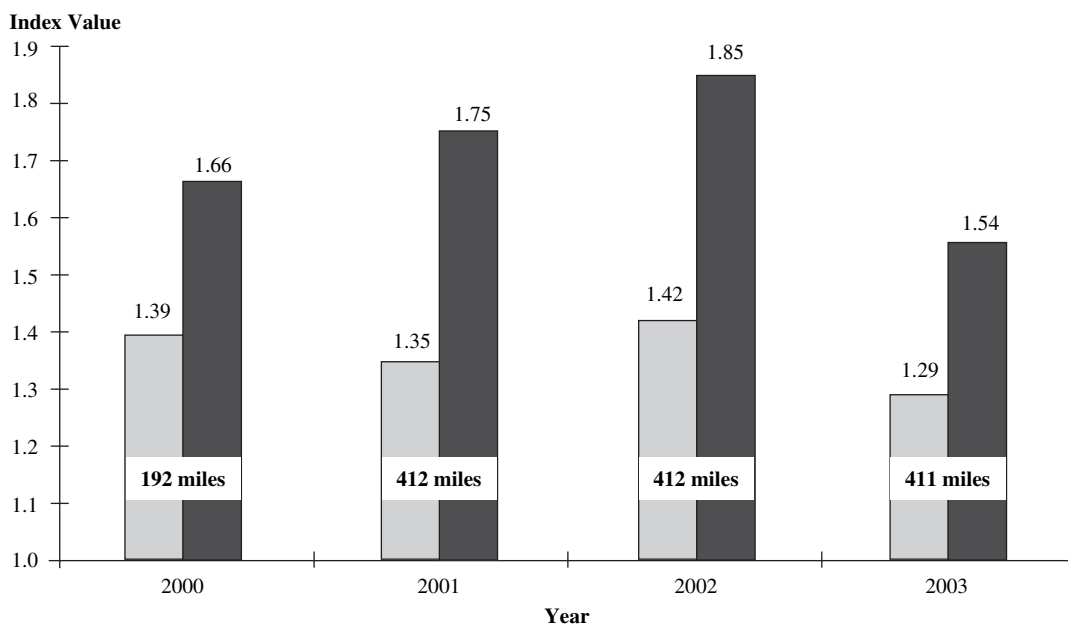


Exhibit 8.4. Use of congestion and reliability measures to exhibit two differing trends.

system miles have not changed notably in the final three years of data, and thus average trip times (as indicated by the TTI) have not changed simply as a result of expanded system miles.

In a planning application such as identifying the likely future impact of a proposed solution, travel demand model outputs of travel time and congestion will typically not include the component of nonrecurring delay. In these cases, the TRI (see Section 2.4) is used, which does not include incident-generated delay. The TRI is also the appropriate measure when travel-time runs are conducted to estimate travel rates, since those runs affected by incident conditions are normally removed from the data set. The TTI and PTI are most appropriate where continuous data streams allow for direct measurement that includes incidents.

8.6.2 Application 2: Identify Existing Deficiencies

The objective of this application is to identify and diagnose existing deficiencies in travel time, delay, and reliability for the purposes of determining appropriate agency actions. The outcome of the analysis is usually a report identifying facilities and locations failing to meet the agencies' performance standards, and identifying the probable causes of the failures. The report may even go on to recommend specific improvements. However, the development of these recommendations will be covered under the alternatives analysis application, which is described later.

The typical agency may be a transit operator, freight operator, city, county, MPO, congestion management agency, state DOT, or a national DOT. The analysis may be performed when the agency first becomes aware of a problem or may be done annually, or linked to some other regular period (e.g., a budget cycle, a long-range plan update, etc.).

Step 1. Determine Agency Performance Standards

- Select metrics for travel time, delay, and reliability;
- Decide if agency performance will be measured in terms of O-D times, facility times, or segment time delay and/or reliability; and
- Determine agency performance standards for each metric. (Chapters 2 and 5)

Step 2. Determine Sampling Plan for Determining Compliance

- Decide on number of days, hours, seasons of year for which data desired; and
- Determine which hours, days, and weeks to sample. (Chapter 3)

Step 3. Prepare Data Collection Plan

- Determine whether real-time detector data exists;
- Determine required accuracy (confidence interval) of results;
- Estimate minimum samples required;
- Identify facilities and segments to be included;
- Determine if the available detector data covers the necessary geographic areas, facilities, time periods, days, seasons of the years needed for the analysis;
- If necessary detector data is not available, select data collection technology (loop detectors, GPS/AVI vehicles) or estimation methodology (sketch planning, HCM, or BPR curve) to supplement or fill gaps in available detector data;
- Estimate data collection costs and personnel required; and
- Revisit study bounds and accuracy requirements, and technology if resources insufficient. (Chapters 3 and 5)

Step 4. Conduct Data Collection

- For field data collection methods see *Introduction to Traffic Engineering - A Manual for Data Collection* (8) or *ITE Manual of Traffic Engineering Studies* (9); and
- Simultaneously collect weather and incident logs for times and locations of data collection (to be used later for diagnosis). (Chapters 3 and 5)

Step 5. Process Results

- Set reasonableness bounds for data and eliminate outliers;
- Set travel time standard (free-flow, speed limit, or other) against which additional travel time is considered delay;
- Compute mean and variance for travel time and delay;
- Compute confidence intervals for mean travel time and mean delay;
- Compute desired reliability metrics; and
- Identify deficient segments and facilities (Chapter 5)

Step 6. Diagnose Causes of Deficiencies

- Cross-tabulate incident log against measured performance deficiencies;
- Note geometric constraints;
- Identify volume increase locations;
- Identify cause of deficiency; and
- Prepare report. (Chapters 5 and 8)

Exhibit 8.5 presents an example of trend data plotted against agency performance standards. In this case the measure is the

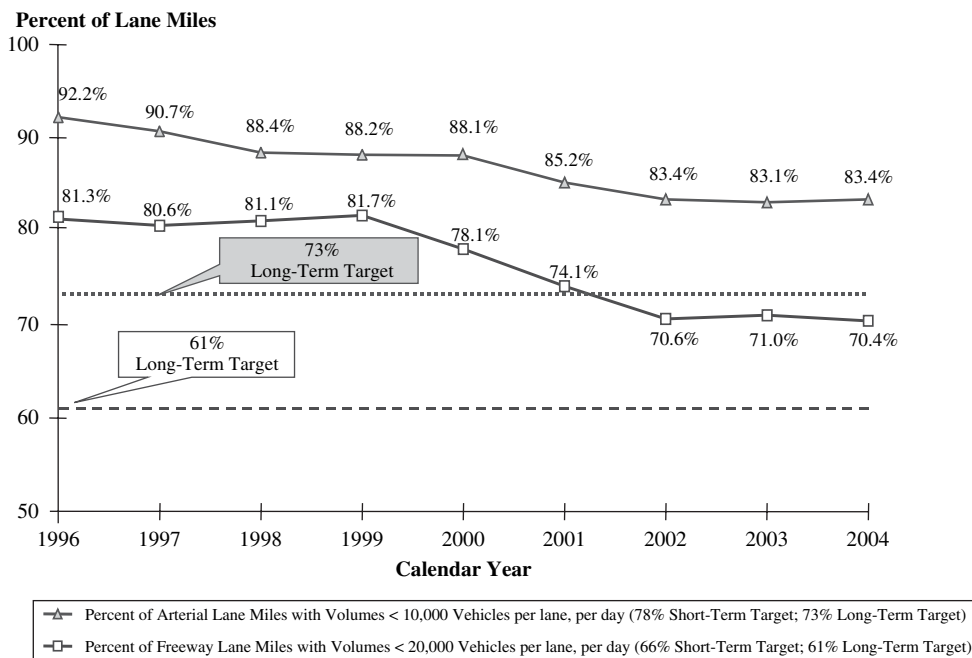


Exhibit 8.5. Comparison of trend to agency performance standard. Percentage of lane miles with average annual volumes below congested levels.

percentage of lane miles that are operating at uncongested levels. The agency performance standard is set as a minimum (i.e., they want to see no less than 73 percent of their lower-volume roads, and no less than 61 percent of their higher-volume roads), operating at uncongested levels. The trend data indicate that although both lower- and higher-volume roadways still exceed the agency performance standard, there has been a steady downward trend (i.e., negative) over the years data is presented. Depending upon the underlying causes for the gradual degradation in performance (e.g., rising VMT and density per highway lane mile), the data suggest that more aggressive countermeasures, possibly both capital and operating, will be needed to maintain above-target performance over the long term.

8.6.3 Application 3: Evaluation of Effectiveness of Improvements

The objective of this application is to determine if an implemented improvement or action actually resulted in the desired improvement in travel time, delay, or reliability. This type of analysis allows an agency to better assess the cost effectiveness of specific actions and also to assess the effectiveness of their planning analysis and decision processes. Any typical agency with responsibility and accountability for expenditure of funds for system improvements and operations may at times need to conduct a careful before/after analysis such as this. The report would be prepared one time only for

each improvement evaluated, rather than on an ongoing or periodic basis. Chapter 4 contains specific guidance on the before/after type of application.

Step 1. Identify Desired Metrics

- Select metrics for travel time, delay, and reliability. In this particular application where comparison of before and after performance is required, special attention must be given to measure selection to ensure that data and measures from the two time periods are in fact comparable. This constraint may limit the range of measures available for the comparison, particularly if the decision to conduct the before/after analysis was not made until after implementation of the improvement, in which case, the analyst is limited to data on-hand representative of the before-project conditions. It is always preferable, though not always possible, to develop the before/after analysis framework and data collection plan before any construction on the improvement has taken place. (Chapters 2 and 4)

Step 2. Determine Study Bounds

- Decide if O-D times, facility times, or segment times desired; and
- Decide on length of analysis periods and time slices within analysis period. (Chapter 2)

Step 3. Determine Sampling Plan

- Decide on number of days, hours, seasons of year for which data desired; and
- Determine which hours, days, and weeks to sample. (Chapter 3)

Step 4. Prepare Data Collection Plan

- Determine desired lag time between implementation of the facility or system improvement and the measurement of its success or failure;
- Identify segments and facilities to be sampled;
- Determine if the available detector data covers the necessary geographic areas, facilities, time periods, days, and seasons needed for the analysis;
- Determine required accuracy (confidence interval) of results;
- Estimate minimum samples required;
- If necessary detector data not available, select data collection technology (loop detectors, GPS/AVI vehicles) or estimation methodology (sketch planning, HCM, or BPR curve) to supplement or fill gaps in available detector data;
- Estimate data collection (and/or estimation) costs and personnel required; and
- Revisit study bounds and accuracy requirements, and technology if resources insufficient. (Chapter 3)

Step 5. Conduct Baseline (Before) Data Collection

- For field data collection methods, see *ITE Data Collection Guide*; and
- Simultaneously collect weather and incident logs for times and locations of data collection (to be used later to address outlier data). (Chapter 3)

Step 6. Process Baseline Results

- Set reasonableness bounds for data and eliminate outliers;
- Set travel time standard (free-flow, speed limit, or other) against which additional travel time is considered delay;
- Compute mean and variance for travel time and delay;
- Compute confidence intervals for mean travel time and mean delay;
- Compute desired reliability metrics; and
- Prepare report and graphics. (Chapter 3)

Step 7. Conduct "After" Data Collection

- See Step 5, Conduct Baseline Data Collection for Guidance. (Chapter 3)

Step 8. Process After Results

- See Step 6, Process Baseline Results for guidance. (Chapter 3)

Step 9. Compare Before and After Results

- Determine extent to which differences between base and trend year are due to sampling error;
- Conduct hypothesis tests of before/after results improvements to determine statistical significance of results;
- Prepare report and graphics; and
- Revise monitoring plan for future analyses. (Chapter 4)

8.6.4 Application 4: Prediction of Future Conditions

The typical objective of this application is to identify and diagnose future deficiencies in travel time, delay, and/or reliability for the purposes of determining appropriate agency actions. The outcome of the analysis is usually a report identifying facilities and locations failing to meet the agencies' standards at some future date, and identifying the probable causes of the failures.

The performance report may go on to recommend specific improvements to address deficiencies. However, the development of these recommendations will be covered later under the alternatives analysis application.

Step 1. Determine Agency Performance Standards

- Select metrics for travel time, delay, and reliability;
- Decide if agency performance will be measured in terms of O-D times, facility times, or segment times delay and/or reliability; and
- Determine agency performance standards for each metric. (Chapter 2)

Step 2. Determine Scope of Analysis

- Determine temporal scope of analysis;
- Decide on number of days, hours, seasons of year for which results desired;
- Determine which existing and forecast years, hours, days, and weeks to evaluate;
- Determine geographic scope of analysis;
- Determine which trip O-Ds, which facilities, and/or which segments of facilities to evaluate; and
- Determine required outputs of analysis and accuracy (confidence interval) of results. (Chapters 2 and 3)

Step 3. Select Forecast Approach

- Determine resources (funds, time, personnel) available for analysis;
- Select desired analytical approach (e.g., sketch planning, 4-step, mesoscopic, HCM, micro-simulation); and
- Revisit accuracy requirements, proposed analytical approach, and number of candidate improvements if inadequate resources or time.
(Chapter 6)

Step 4. Conduct Forecasts

- For 4-step model approach, see the FHWA *Guide on Travel Forecasting*;
- For microsimulation, see the FHWA *Guide on Microsimulation*;
- For HCM analysis, see *HCM*; and
- For sketch planning, see *NCHRP 398: Congestion Measurement*.
(Chapter 6)

Step 5. Process Results

- Set reasonableness bounds for forecasts and eliminate outliers;
- Set travel time standard (free-flow, speed limit, or other) against which additional travel time is considered delay;
- Compute mean and variance for travel time and delay;
- Compute confidence intervals for mean travel time and mean delay;
- Compute desired reliability metrics;
- Identify deficiencies; and
- Prepare report and graphics.
(Chapter 3)

8.6.5 Application 5: Alternatives Analysis

The objective of this application is to develop and evaluate a set of alternative actions to improve facility or system performance. Presumably, the operator already has conducted Application 2: Identification of Existing Deficiencies, and has diagnosed the underlying causes of the existing problems. The operator also should have conducted a future analysis (Application 4) and identified future deficiencies and their projected causes.

The outcome of the alternatives analysis is usually a report identifying facilities that currently fail and/or in the future will fail to meet the agency's standards, reviewing the probable causes of the failures, and recommending actions by the agency (and potentially other agencies) to alleviate the existing and/or future deficiencies.

The typical agency may be a transit operator, freight operator, city, county, MPO, congestion management agency, state DOT, or a national DOT. The analysis may be performed when the agency first becomes aware of a problem, usually as the outcome of a periodic monitoring of system performance, such as might be produced by Application 2: Identification of Deficiencies. Many agencies also conduct regional system or corridor analyses to identify projected future deficiencies and test the efficacy of different capital and operating strategies.

Step 1. Conduct Studies to Identify and Diagnose Existing and Future Deficiencies

- These studies should be completed prior to conducting the alternatives analysis: Application 2: Identification of Existing Deficiencies and Application 4: Predictions of Future Conditions.

Step 2. Determine Candidate Improvements

- The analyst should consult a number of sources to identify potential solutions that address the identified deficiencies. Chapter 7 presents in table format a collection of typical problems, likely causes, and improvement strategies and actions. It also references several published reference documents that can guide the analyst to strategies and actions that are specifically appropriate for reducing travel time, delay, and variability.
(Chapter 7)

Step 3. Determine Scope of Analysis

- Determine temporal scope of analysis;
- Decide on number of days, hours, seasons of year for which results desired;
- Determine which existing and forecast years, which hours, which days, which weeks to evaluate;
- Determine geographic scope of analysis;
- Determine which trip O-D's, which facilities and/or which segments of facilities; and
- Determine required outputs of analysis and accuracy (confidence interval) of results.
(Chapters 2 and 3)

Step 4. Select Evaluation Approach

- Determine resources (funds, time, personnel) available for analysis;
- Select desired analytical approach (e.g., sketch planning, 4-step, mesoscopic, HCM, micro-simulation); and

- Revisit accuracy requirements, proposed analytical approach, and number of candidate improvements if inadequate resources or time.
(Chapter 3)

Step 5. Evaluate Improvements

- Estimate mean travel time, delay, reliability before and after improvement (The methodology provided here will vary according to the selected approach in the prior step.);
- Compute reliability metrics as desired;
- Determine confidence intervals for results;
- Estimate cost-effectiveness of each candidate improvement;
- Determine if candidate improvements are sufficient to meet operator standards; and
- Select final list of improvements.
(Chapter 3)

Step 6. Develop Improvement Program

- Determine funds available for improvements;
- Determine desired timeline and sequence for improvements;
- Prioritize and schedule improvements;
- Determine needed funding schedule;
- Prepare report and graphics; and
- Revise monitoring plan for future analyses.
(Material not explicitly presented in this Guidebook.)

8.6.6 Application 6: Improve Fleet Operations and Productivity

The objective of this application is to develop a set of actions to improve fleet operations and productivity. Presumably, the operator already has conducted Application 2: Identification of Existing Deficiencies, and has diagnosed the existing causes of the problems. The operator may have arrived at this point after conducting a future analysis (Application 4) and identifying future deficiencies.

The outcome of the analysis for Fleet Operations and Productivity is usually a report identifying vehicle routes that currently fail and/or in the future will fail to meet the operator's standards, reviewing the probable causes of the failures, and recommending actions by the operator (and potentially other agencies) to alleviate the existing and/or future deficiencies.

The typical fleet operator may be a transit operator or a freight operator, or a planning agency with responsibility for oversight of transit performance.

The analysis may be performed when the agency first becomes aware of a problem, either through customer feedback

or perhaps as the outcome of periodic monitoring of system performance, such as might be produced by Application 2: Identify Existing Deficiencies.

Step 1. Conduct Studies to Identify and Diagnose Deficiencies

- These studies should be completed prior to conducting the alternatives analysis: Application 2: Identification of Existing Deficiencies and Application 4: Predictions of Future Conditions.

Step 2. Determine Candidate Improvements

- Exhibit 7.1 in Chapter 7 may be used to identify appropriate candidate improvements to consider for solving the identified deficiencies, particularly if the deficiencies are related to roadway system capacity, and are impacting movement of trucks or transit vehicles on the general purpose highway network. For deficiencies specific to the fleet operation itself (e.g., maintenance, route designation and run scheduling), more specialized resource materials, outside of the scope of this effort, should be consulted. Suggested references include *TCRP Report 95: Traveler Response to Transportation System Changes*, and *TCRP Report 100: Transit Capacity and Level of Service Manual*. These reports are available on-line at TRB.org/TRB/publications.

Step 3. Determine Scope of Analysis

- Determine temporal scope of analysis;
- Decide on number of days, hours, seasons of year for which results desired;
- Determine which existing and forecast years, which hours, which days, which weeks to evaluate;
- Determine geographic scope of analysis;
- Determine which trip O-D's, which facilities and/or which segments of facilities; and
- Determine required outputs of analysis and accuracy (confidence interval) of results.
(Chapters 2 and 3)

Step 4. Select Evaluation Approach

- Determine resources (funds, time, personnel) available for analysis;
- Select desired analytical approach (e.g., sketch planning, 4-step, mesoscopic, HCM, micro-simulation); and
- Revisit accuracy requirements, proposed analytical approach, and number of candidate improvements if inadequate resources or time.
(Chapter 3)

Step 5. Evaluate Improvements

- Estimate mean travel time, delay, reliability before and after improvement (the methodology provided here will vary according to the selected approach in the prior step);
- Compute reliability metrics as desired;
- Determine confidence intervals for results;
- Estimate cost-effectiveness of each candidate improvement;
- Determine if candidate improvements are sufficient to meet operator standards; and

- Select final list of improvements.
(Chapters 3 and 4)

Step 6. Develop Improvement Program

- Determine funds available for improvements;
 - Determine desired timeline and sequence for improvements;
 - Prioritize and schedule improvements;
 - Determine needed funding schedule;
 - Prepare report; and
 - Revise monitoring plan for future analyses.
(Material not explicitly presented in this guidebook.)
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Abbreviations and acronyms used without definitions in TRB publications:

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| AAAE | American Association of Airport Executives |
| AASHO | American Association of State Highway Officials |
| AASHTO | American Association of State Highway and Transportation Officials |
| ACI-NA | Airports Council International-North America |
| ACRP | Airport Cooperative Research Program |
| ADA | Americans with Disabilities Act |
| APTA | American Public Transportation Association |
| ASCE | American Society of Civil Engineers |
| ASME | American Society of Mechanical Engineers |
| ASTM | American Society for Testing and Materials |
| ATA | Air Transport Association |
| ATA | American Trucking Associations |
| CTAA | Community Transportation Association of America |
| CTBSSP | Commercial Truck and Bus Safety Synthesis Program |
| DHS | Department of Homeland Security |
| DOE | Department of Energy |
| EPA | Environmental Protection Agency |
| FAA | Federal Aviation Administration |
| FHWA | Federal Highway Administration |
| FMCSA | Federal Motor Carrier Safety Administration |
| FRA | Federal Railroad Administration |
| FTA | Federal Transit Administration |
| IEEE | Institute of Electrical and Electronics Engineers |
| ISTEA | Intermodal Surface Transportation Efficiency Act of 1991 |
| ITE | Institute of Transportation Engineers |
| NASA | National Aeronautics and Space Administration |
| NASAO | National Association of State Aviation Officials |
| NCFRP | National Cooperative Freight Research Program |
| NCHRP | National Cooperative Highway Research Program |
| NHTSA | National Highway Traffic Safety Administration |
| NTSB | National Transportation Safety Board |
| SAE | Society of Automotive Engineers |
| SAFETEA-LU | Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005) |
| TCRP | Transit Cooperative Research Program |
| TEA-21 | Transportation Equity Act for the 21st Century (1998) |
| TRB | Transportation Research Board |
| TSA | Transportation Security Administration |
| U.S.DOT | United States Department of Transportation |