SELECTING TRAVEL RELIABILITY MEASURES

by

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May 2003

ACKNOWLEDGEMENTS

The researchers who prepared this report benefited from the help and guidance of many people. The sponsoring states and the Federal Highway Administration provided technical resource staff persons who identified the need for a reliability measure and reviewed the analysis during the project. The authors would like to thank them for their time.

John Wolf, California Department of Transportation
Tim Baker, Colorado Department of Transportation
Gordon Morgan, Florida Department of Transportation
Rob Bostrom, Kentucky Transportation Cabinet
James Dooley, Maryland State Highway Administration
Timothy Henkel, Minnesota Department of Transportation
Gerard Cioffi, New York State Department of Transportation
Brian Gregor, Oregon Department of Transportation
Kevin Lancaster, Texas Department of Transportation
Catherine McGhee, Virginia Transportation Research Council
Vince Pearce and Dale Thompson, Federal Highway Administration

The authors would also like to thank Dr. Christine Johnson, Jeffery Paniati and Jeffrey Lindley of the Federal Highway Administration for their support of this research.

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INTRODUCTION

Reliability and variability in transportation are being discussed for a variety of reasons. The two terms are related, but different in their focus, how they are measured, how they are communicated and, in some respects, how they might frame the discussion about potential solutions.

- **Reliability** is commonly used in reference to the level of consistency in *transportation service* for a mode, trip, route or corridor for a time period. Typically, reliability is viewed by travelers in relation to their experience.
- **Variability** might be thought of as the amount of inconsistency in *operating conditions*. This definition takes more of a facility perspective and, therefore, relates to the concerns of transportation agencies.

Both of these concepts are useful, but the term reliability may have a more "marketable" connotation for the purposes of reporting performance measures to the public because it relates to an "outcome" of transportation—the quality of the service provided. Variability seems to be more related to the change in transportation system operations. The traveling public and a variety of companies or product sectors use the term *reliability* in their goal statements and it would seem this is the term that should be used with a performance measure.

This report discusses the background for developing reliability measures as a component of mobility performance metrics, the factors to consider before selecting a measure and defines the calculation procedures for typical reliability analyses. This might involve a change in thinking about how mobility service is conceptualized and communicated. The terms "recurring" and "non-recurring" congestion are misnomers—variations in weather, traffic volume and a range of other factors can be termed "recurring" but have traditionally been included outside the "regular" congestion label.

THE IMPORTANCE OF RELIABILITY STATISTICS

Most cities are developing a comprehensive program of improvements to address congestion. In addition to pursuing strategies to reduce the growth of congestion and provide mobility options, transportation agencies are also concerned with improving the reliability of the transportation system. To fully inform the discussion, there should be measures of both average conditions and indications of how often and/or how much the performance varies from the average.

The increase in just-in-time (JIT) manufacturing operations has made a reliable travel time almost more important than a delay-free travel time for some segments of the US economy. JIT relies on the transportation system to take advantage of low-cost labor and manufacturing plant development costs. Producing components in several manufacturing plants and bringing them together in one location at the same time to produce the final product can reduce inventory requirements and total costs, but requires a controlled environment for travel times. If one component does not arrive due to improper product scheduling or due to traffic delays, an assembly line can be shut down, or costly building space has to be used for inventory storage, rather than for manufacturing or assembly operations.

The importance of the reliability issue might also be illustrated in some ways that urban residents react to congestion. Travelers adjust their trip patterns and expectations to accommodate expected levels of congestion. Unexpected congestion, changes in bus availability or any of several possible service interruptions can significantly decrease traveler satisfaction and increase frustration. The places most likely to view mobility as the most important public policy concern are cities where congestion has rapidly increased over a few years. This is common to rapidly growing areas regardless of the size or congestion level. Congestion is perceived in relative ways, and the stress of uncertainty is part of the phenomenon.

What Are We Trying To Measure?

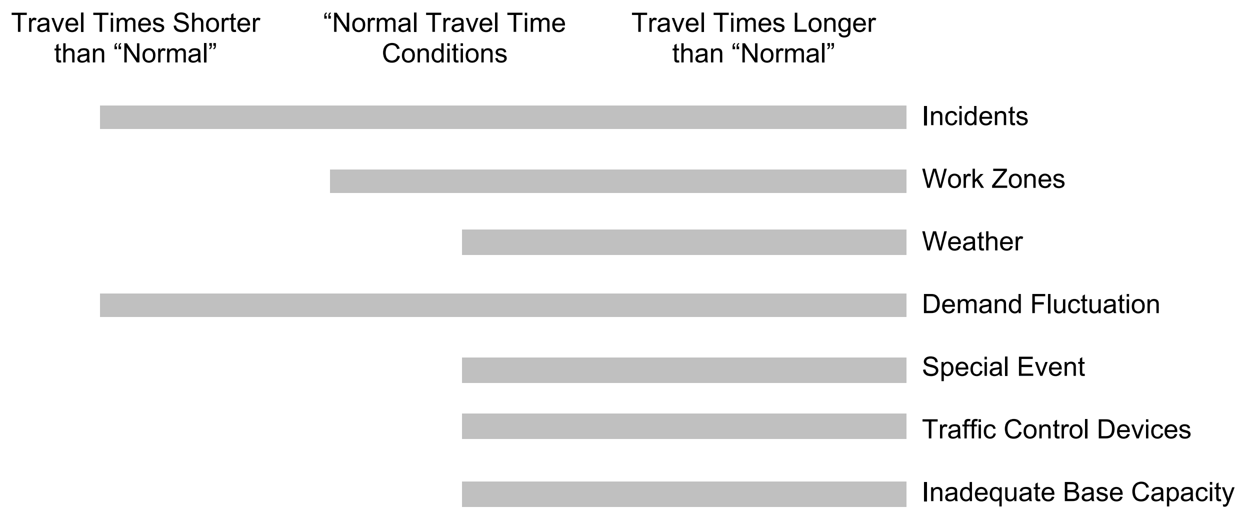
It is important to recognize that part of what is illustrated by reliability measures is due to explainable and regular factors. Holidays are periods when travel conditions typically vary from the average, whether they are widely observed days such as Thanksgiving, or government employee holidays where daily traffic volume may only decline by a few percent. Reliability statistics collected from real-time traffic data collections devices will include these events as changes relative to the average conditions. They might appear as part of an unreliable or unpredictable system, but travelers and shippers will understand and be able to predict their occurrence much better than days when collisions or vehicle breakdowns increase delay.

The recently completed research plan for the reliability topic of the Future Strategic Highway Research Program (1) included a list of the sources of travel time variability. These seven sources describe the underlying conditions that change over time, and cause travel time to vary. In many "real world" situations these seven sources interact, further complicating the evaluation and prediction of reliability.

- Incidents—collisions, vehicle breakdowns and debris that disrupt the normal flow of traffic, whether the event occurs on a shoulder or in the main travel lanes.
- Work Zones—construction or maintenance activity.
- Weather—the full range of vision-affecting events—from obscured visibility due to fog/snow/rain to bright, sunshine in driver's eyes—to roadway surface conditions that affect driver behavior.
- Fluctuations in Demand—day-to-day variations caused by changes in activity levels or patterns.
- Special Events—causing dramatically different travel patterns or volumes in the vicinity of the event.
- Traffic Control Devices—poorly timed signals or periodic signal events such as railroad crossings or drawbridges.
- Inadequate Base Capacity—normally congested roads are more susceptible to effects from any of the other six factors.

The effect on trip travel time can also vary across a relatively broad range (Exhibit 1). If a traveler enters the roadway, for example, downstream of a serious collision, the resulting decrease in traffic volume past the collision scene can improve travel conditions. Most of the variability sources, however, result in longer than normal travel times.

Exhibit 1. The Conceptual Effect of the Seven Sources of Travel Time Variation



From a measurement perspective it is important to capture not only the total variability and the total impact due to all of these factors—because that is what users experience—but also to account for the contribution of each of the factors to total variability in condition when possible. Both total impact and the factors involved are interesting for program evaluation and monitoring purposes.

WHAT RELIABILITY COMPONENTS SHOULD BE INCLUDED IN A MEASURE?

One key difference in the way some measures are constructed is whether the variation in individual traveler behavior is being studied, or whether the variation from day-to-day of the average of all travelers is being examined. The former seems to be more interesting to social scientists studying the interaction between the behavior of travelers and the freedom of decision-making as determined by physical and operational constraints. Travel speed variation is greater in the off-peaks when travelers are better able to choose their own speed. The latter version of the measurement goal is more likely to be interesting to sets of travelers or those interested in the variation in service quality provided to the users.

Trip planning decisions can be informed by data that is targeted for the expected variation in travel time at their usual departure time. Measures that might be useful would typically focus on specific trip patterns or corridors and specific hours of the day—areawide or sub-regional measures grouped in long time blocks would be less useful for this purpose. System or corridor evaluations, however, might be best identified with hour-to-hour, day-to-day and annual trend information. These might be less trip-specific and more amenable to average areawide statistics.

The effect of incident management programs could also be tracked with these sorts of measures. A set of descriptive statistics such as crash rates would also be required to identify some of the reason for variation in annual or corridor measures.

The solutions or remedial actions for various causes of reliability problems are different. A disaggregated description is useful to system operators who can target improvement strategies. For example:

- Weather-related traffic problems may be significant, but nothing can be done about the weather itself. The impacts of weather conditions, however, might be addressed by some information strategies, and travel time should be predictable within some range.
- The need for accident-related strategies is perhaps less predictable with regard to location, but knowing the impact and frequency of the problem will identify the level of commitment that might be reasonable.
- Construction and maintenance activity delay can be addressed in several stages of planning and implementation; data and measures about the effects can target high priority corridors and trip patterns.

A single corridor value or concept cannot really describe the effect of collisions for all travelers. Trips that enter a freeway downstream of an area where collisions frequently happen may actually see improved travel times on incident days. The bottlenecks that are created by incidents have a metering effect on downstream traffic volumes and depending on the corridor data limits, incident days may appear to perform better than average days.

Sorting out the incident locations and the magnitude of the effects will require a level of detail and study beyond the scope of some analyses. If incident records are sufficiently detailed and electronically recorded, there may be ways to automate much of the analysis. Evaluating particular treatments may be easier if some of the descriptive elements are included in the database, but the performance measures should typically seek to include all of the "unreliability," because that is the system the users experience. Evaluating particular treatments may be easier if some of the descriptive elements are included in the database, but the performance measures should typically seek to include all of the "unreliability," because that is the system the users experience. Until then, the other databases that are developed, the measures, data requirements and public understanding can be tested with the statistics that are available.

DEVELOPING AN APPROACH TO RELIABILITY MEASURES

The most important aspect of travel time variations may be the one related to predictability of travel times for the same trip from day-to-day. This emphasis factors into the concepts of reliability measurement, the calculation steps and the construction of the data archive. While the data measures can significantly improve the amount of detail and analytical flexibility, there are also some characteristics to consider before using the data.

BENEFITS FROM THE EXPANDED LEVEL OF DETAIL PROVIDED BY CONTINUOUS MONITORING SYSTEMS

The data archive has several benefits to the system operators, and it is becoming obvious that a great many other facets of transportation will benefit from these data as well. Some of the improvements in monitoring and decision-making are identified below.

- **Mobility and reliability comparisons will benefit from archived data**—The time-of-day, day-of-year, and corridor level data can provide enormous insight for the system operators and users, and are relatively easy to create. They can assist in monitoring congestion levels, programming improvements, scheduling maintenance operations, deploying staff and justifying investments in a range of improvements.
- **While in most areas local analysis of archived data has been a daunting task, the effort pays off in better information about performance**—Many data archiving systems are still considered "first generation." Data is logged to an extremely large text file or to thousands of smaller text files. Even though these are not readily accessible or usable by most users, they have stimulated plans to improve the accessibility and ease of use of archived data.
- **Able to develop data about some issues to much greater degree**—There are significant gains that can be made in some areas that have not been studied before due to lack of useful data. Issues like the reliability or variation in travel time are much more easily studied and communicated with archived data than with modeled or estimated statistics. The effect of events such as collisions, vehicle breakdowns, weather problems, etc., will also be described in greater detail. Problems such as "rubbernecking" that are discussed without any supporting information may be analyzed in ways that might lead to funding support and solutions.
- **Can help connect a variety of databases**—"Event" databases such as incident, weather and work zone location can connect the travel conditions with the causes and explain many of the unusual results. The archived data can also be used to identify the elements of congestion and unreliability that might be affected by various improvement programs.
- **Can connect road monitoring to survey findings**—A robust and easily updated information system can consist of survey information tied to trip travel time, speed and volume monitoring data. The surveys would provide the trip level detail to identify when and where people and goods are traveling and could be periodically updated. Facility monitoring, which is much easier to accomplish, can relate the facility conditions to survey responses about the experiences of the trip.

- **Assist with local archived data usage**—Improvement in data and measures will ultimately hinge on local developers and users exploring the range of archived data system benefits. Archived data quality and completeness will improve quickly if the responsible agencies are using the data for preparation of congestion management system reports and other products. Therefore, the archived data usage might involve more local control, with Federal and state reports being just one of many uses of the data by local agencies. Standards and technical assistance are needed to support the transition to local control.

THE CHALLENGES OF USING ARCHIVED DATA TO CREATE PERFORMANCE MEASURES

With the greater level of detail and expanded time coverage from the archived data collection systems, there is a tendency to believe that the information is perhaps more comprehensive and accurate than it really is. Many of the archived data characteristics are significant improvements over other methods to generate performance statistics. There are, however, some important cautionary features that must be included in the discussion. Some of these are discussed below.

- **Mostly freeways**—The available data are almost solely for freeway sections. And the near future consists primarily of freeway data. The importance of the freeways to urban travel makes this an appropriate place to start, but there are problems with this limitation. Ramp delay is not included in most databases. Very few sections of street are monitored with systems that provide data archiving possibilities. Some transit systems are archiving the travel time and passenger loading information, but most are behind the freeway data archiving trends. The next few years will see some expansions of monitoring, but there are significant portions of the travel network that will require some way to estimate the performance statistics.
- **Not all the freeways**—The few cities that have monitoring equipment and archiving activities have them on less than half of the freeway system. Most areas begin with one corridor and expand to other freeways as they are rebuilt or as operating improvements are extended.
- **Not many cities—**ITS Deployment statistics note that 68 areas have monitoring capabilities and 59 areas archive the data that come from these systems, but relatively few use the data for decision-making beyond real-time operational decisions. Many of the cities listed include only one or two freeways in the archiving/monitoring system.
- **Few real users of data**—There are two negative effects of this limitation. Relatively few data users mean the benefits are not well-known and the archiving activity may not be extended or might be reduced. In addition, when the data are used for analysis, problems are identified, data quality assurance procedures and analysis techniques can be improved, and the database enhanced.
- **A variety of data accuracy needs—**There are several uses for the data and there are a range of volume and speed accuracy needs. The principal operating agency and the original or primary use of the system often governs calibration and data accuracy standards. Traditional traffic management strategies, such as incident management, ramp metering, and identification of major queues, do not require the same level of resolution as performance

trend monitoring. The question is usually framed as: "are speeds 60 mph or 20 mph?" rather than, "are speeds 38 mph or 33 mph?" As operation strategies become more sophisticated (e.g., more refined traveler information is developed) this may change, but existing systems are usually geared to getting a coarse understanding of system performance.

- **Traffic volume and speed will not be representative under some circumstances—**During incident conditions, for example, vehicles leave the freeway and use alternate routes. This not only results in fewer vehicles being counted by the monitoring systems, it also means the delay that those vehicles experience is not counted. And since the diverted vehicles often use routes that are typically congested, the addition of those trips can mean significantly greater than normal delays. In addition, some quality control procedures eliminate very low speed data due to accuracy problems with the detectors when speeds are below 5 mph.
- **Connections to other databases are not in place**—When developed, other datasets will allow full evaluation of the effect of events such as incidents, weather, construction, maintenance and special events. The databases that describe those factors are either not developed or not easily linked to the travel conditions database. In addition, operations improvements (e.g., ramp meters, incident management, signal coordination) and transit operations are difficult to evaluate due to the same lack of connectivity between the databases.
- **Simulation models will be needed**—It is useful to recognize that archived data will not satisfy all the analysis needs. Comparing current and future alternatives will always require some estimation techniques.
- **Data collection techniques are subject to a certain amount of variation and error**—Most travel time, speed and volume data is collected by some sort of vehicle detector located at a point in or near the road. A variety of technologies are being used to collect spot speeds including single- and double-inductance loops, radar, passive acoustic, and video image processing. The systems estimate the speed of vehicles at that point, and that speed is assumed to represent the speed for a distance equal to half the distance to the next detector. This "influence zone" concept is fairly standard and works reasonably well if no direct travel time information is available. Tests by Minnesota DOT have shown that various non-intrusive sensor technologies can produce comparable results, although testing continues and should be monitored. Speeds estimated from single inductance loops may be a particular problem. As agencies adopt the next generation of technologies this issue may take care of itself, but in the short-term it remains a concern.
- **Speed estimation equations used in the archived data systems can be improved**—Several speed estimation procedures have been developed for use with single loop detectors, some of them very sophisticated. These might include time-of-day changes, traffic composition changes or other traffic-adaptive procedures. The complexity, however, has been a hurdle for implementation. Some cities were not aware of the speed estimation procedures in their system because they were embedded in the software and not clearly documented.
- **The data collection technologies and systems in each area produce different patterns and statistics**—These could be misinterpreted as real differences in the transportation systems, when they are merely a function of the data collection devices. Some of these are easily understood such as the difference between point detector speed estimates and roadway

link travel times. Other differences that result from radar, single loops or double loops, or from data stored in a per-lane format or for the total road cross section are not well understood.

- **There are no clear findings regarding the optimum type of traffic sensor for mobility monitoring**—Whatever speed sensors are used should be able to accurately measure speed and vehicle volumes at a relatively frequent spacing (0.5 to 1.0 mile). Vehicle probe systems that directly collect travel time (such as the AVI system in Houston) also present challenges for accurately estimating vehicle volumes that correspond to travel times.

DATA COLLECTION COVERAGE

Supporting information for travel time analyses can be generated from three basic approaches—travel time data collection from floating car or other vehicle-based sampling procedures, data from traffic operations center archives and estimation or modeling techniques. Each of these approaches has strengths and shortcomings. None of the approaches can be used for all analyses and none of them include all the information required for a comprehensive assessment of congestion and reliability issues. Exhibit 2 compares the coverage of three data collection dimensions by the three approaches.

VEHICLE-BASED TRAVEL TIME DATA

Floating car or probe vehicle travel time observations typically consist of a few trips on relatively few roads in a corridor or city. The observations are made on a few days and on a sample of roads or on only a few major roads. Data concerning some non-ideal conditions can be collected, but the sample size is typically small.

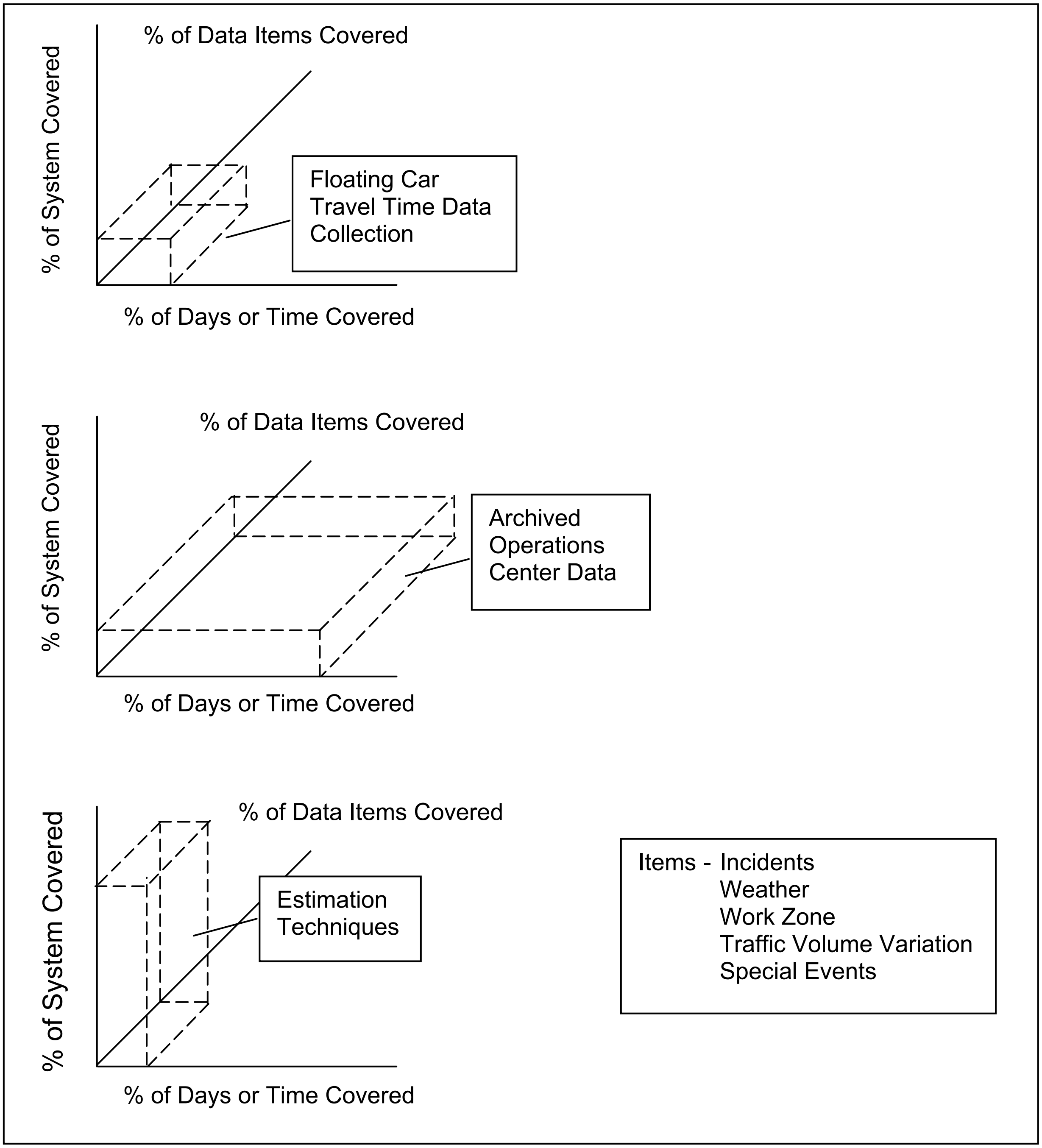
ARCHIVED TRAFFIC OPERATIONS CENTER DATA

Traffic volume and speed data can be automatically collected and saved for each day of the year. These data will include many days when non-ideal conditions exist which greatly improves the usefulness of the information. Unfortunately, in almost every city, freeways are the only roadway type where data is archived and usually only a small portion of the freeway system.

ESTIMATION TECHNIQUES

Equations, simulation models and other estimation techniques are used when areawide or comprehensive network assessments are needed. Of necessity, these are simplifications of the day-to-day variation in conditions and travel patterns. They can be used to estimate the effect of some non-ideal conditions such as construction, maintenance, special events, weather, vehicle breakdowns and collisions, although these models cannot show the complexity of interactions or variations.

Exhibit 2. Summary of Data Collection Techniques



MEASURE OVERVIEW

The choices for performance measures to indicate reliability in transportation service can be grouped into three broad categories. The differences are most apparent on the communication side of the issue, but also are present on the calculation end. Since the Urban Mobility Study (2) and the Mobility Monitoring Program (3,4) are most concerned with developing performance measures to improve the use and understanding of transportation information, the communication differences are highlighted. Calculation steps are addressed in a subsequent section of this report.

- Statistical Range—These represent the most often theorized or conceptualized measures. They typically use standard deviation statistics to present an estimate of the range of transportation conditions that might be experienced by travelers. The measures typically take the form of an average value plus or minus a value that encompasses the expectations for 68% to 95% of the trips (1 or 2 standard deviations on each side of the mean). These usually appear as "variability" measures.

- Buffer Time Measures—These measures indicate the effect of irregular conditions in the form of the amount of extra time that must be allowed for a traveler to achieve their destination in a high percentage of the trips. The measure does not necessarily refer to the average trip time, but could be presented as either a percentage of the average trip time, or a value in minutes per mile or minutes of some typical trip. In practice this might be thought of as "I need to allow enough time so that I arrive on-time for (some percent) of my trips." These measures usually illustrate "reliability".

- Tardy Trip Indicators—This measure form answers the question "how often will a traveler be unacceptably late?" This measure also does not refer to the average travel time, but uses a threshold to identify an acceptable late arrival time. The time can be either a percentage of the trip time, an increased time in minutes above the average or some absolute value in minutes. These indicators usually measure "reliability."

Several measures for these broad concepts are discussed subsequently.

CALCULATING RELIABILITY STATISTICS

It is important to recognize that reliability measures are more widely discussed now because there is access to much more detailed information from the point and segment detectors on many freeways and a few streets in the US. The travel speed and time information that is either obtained directly or estimated from such systems makes the variation in travel conditions much easier to study. All of the measurement concepts can be calculated or estimated in some way from the information that is collected by most traffic management centers. The 2001 Mobility Monitoring Program research effort by Texas Transportation Institute and Cambridge Systematics for Federal Highway Administration focused on the freeway elements from 21 of these centers following the study of 2000 data from 10 centers http://mobility.tamu.edu/mmp (4).

Reliability statistics are most easily calculated from continuous and calibrated data collection systems that are used as part of a monitoring and information system. These are more often found on large city freeways and infrequently on urban streets. Florida DOT tested an approach that uses a several-day sample of travel volume and speed to produce a reliability measure. Florida DOT monitored three locations in this way, but found it difficult to obtain meaningful data and projected that it would be expensive to maintain a program of this type.
The data would desirably be checked for quality, adjusted or revised, and stored in a readily accessible database for a variety of agencies and purposes. If the data are used, there is a greater likelihood that the quality will improve, data collection equipment will be maintained and the decisions and programs supported by the data will improve.

REPRESENTATIVE TRIP OR LENGTH NEUTRAL?

One decision that is required to operationalize some of these measures is to either decide on an average or representative trip length(s), or to develop statistics in length-neutral terms. The current presentation of average statistics using the travel time index (TTI) is a length-neutral measure, with an accompanying footnote that explains the relationship to trip travel time. Travel rate (in minutes per mile) variation can be used as a length-neutral surrogate for trip time variation. Selecting a representative trip length might be more difficult and gives rise to concerns expressed in a form similar to "the average trip here is twice as long as that" which might detract from message clarity.

Measures where trip time and length are integral, like accessibility measures, could continue to use variability statistics with units of minutes. These measures are usually applied to local analyses or subregional evaluations when indexing or length-neutral aspects are not as important. And measures that use indices with a value that is length-neutral would also be consistent with this approach.

A local approach to measuring reliability might also include an examination of a small set of important trips in the urban area. The Seattle area uses "11 Famous Commutes" in their monitoring program (5). The average travel time, current travel time and the distance are displayed. Archived travel time data can also be viewed from the website and are used in WSDOT's performance measure process. While these 11 trips are not a statistically representative portrayal of peak conditions, they are geographically dispersed and incorporate significant regional activity centers (Exhibit 3).

Exhibit 3. Seattle's 11 Famous Commutes

Roads Used on the Route	Cities at Each End of Route (Travel Time Displayed in Both Directions Between These Two Locations)	Route Distance (miles)
I-5	Everett and Seattle	23.7
I-5	SeaTac and Seattle	13.0
I-405	Bothell and Bellevue	9.7
I-405	Tukwila and Bellevue	13.5
SR 167	Auburn and Renton	9.8
I-90/I-5	Issaquah and Seattle	15.5
SR 520/I-5	Redmond and Seattle	14.8
I-405/I-90/I-5	Bellevue and Seattle	10.7
I-405/SR 520/I-5	Bellevue and Seattle	10.5
SR 520/I-405	Redmond and Bellevue	7.2
I-90/I-405	Issaquah and Bellevue	9.5

Source: Reference 5

The time periods for analysis might also include several variations. Peak period might be most useful, but daily and peak hour measures would present some interesting views, especially in corridors where congested time is expanding. Off-peak period analyses are also useful for a variety of purposes. The off-peak periods are expected to be free of congestion and variation in travel time can be more disruptive to personal, business and freight travel. Calculating the measures by direction would also give more detail into the causes and extent of the problems. Most archived databases can provide this disaggregated information with relatively little additional effort.

CREATING THE DATABASE

Archived data can provide much more information about the operation of freeway systems in normal time, during special or irregular events or after the implementation of programs and techniques designed to improve operations. There are some cautionary notes, however, and this report includes some of the lessons learned from early programs. Until the technologies are more widely deployed, it will be difficult to compare performance characteristics from one area to another. The data collected from continuous monitoring systems results in different performance measure values than those calculated from estimation techniques for a variety of reasons. Any estimation program will have difficulty replicating actual conditions, but the current real-time data collection devices suffer from the lack of coverage of the travel system elements (see Exhibit 4). When events cause travelers to leave the monitored portion of the roadway, the performance measure accuracy suffers.

The data concepts can be divided into four broad categories. Each represents a set of data needs, but fundamentally they are ways of thinking about the desired information and how to get it. Travelers and shippers appear to want information about travel time—both the average and the variation—that indicates how much time should be planned for particular trips or sets of trips. There are a number of ways to obtain this kind of information and several ways to display or communicate it. The data collection concepts are discussed below in descending order of desirability (as ranked by the performance measures that might be developed by each type of collection technique). There are ranges even within each of these levels, but these four concepts provide a good framework for the discussion of archived data collection and use.

- A computer chip in each person or each unit of cargo—Massive personal privacy concerns are involved, but as a concept this would allow us to understand how people move around the city. It would give us door-to-door (D2D) travel time, allow us to monitor travel on all modes and all facilities and provide us with information about route, departure time travel time, variation in travel time and mode choice decisions.

- Travel time and volume detection over sections of road, transit systems, bike lanes and sidewalks—This would allow us to monitor travel on most facilities or modes and provide a significant portion of the D2D trip time data. Trip information could be estimated from the monitored data and supplemented with targeted surveys.

- Detectors of speed and volume at locations along the systems—estimating the volume and speed using point detectors is the practice of most archived data systems. The techniques are relatively well defined, but the level of detail does not provide information at the trip level. Travel time must be estimated using the point speed to indicate the average speed over the adjacent road sections.

- Estimates based on volume and roadway inventory—Equations or computer models that relate volume per lane and speed will always be needed for future condition mobility analyses or for evaluating improvements to existing conditions. The estimating procedures also provide information for portions of the system that are not continuously monitored. These procedures can be improved with information from the continuous monitors.

DATA COLLECTION PRACTICES

Data on operations (for example traffic volume, traffic density, speed or travel time) is archived at some traffic management centers (TMCs). For most cities in the Mobility Monitoring Program (4), the data are collected at point locations using a variety of technologies including single- and double-inductance loops, radar, passive acoustic, and video image processing (some areas use multiple technologies; see Exhibit 4). These technologies establish a small, fixed "zone of detection" and the measurements are taken as vehicles pass through this zone. The Houston travel times are collected via their automatic vehicle identification (AVI) system. This system detects vehicles with toll tags and provides a direct measurement of travel time between sensors spaced at two- to five-mile intervals.

Exhibit 4. Summary of Archived Data Characteristics for 2001

Participating City	Freeway System Monitored, %	Traffic Sensor Technology	Data Level of Detail	
			Time	Space
Albany, NY	10 % (10 of 104 mi.)	Single and double loop detectors	15 minutes	by lane
Atlanta, GA	18 % (53 of 300 mi.)	Video imaging and microwave radar	15 minutes	by lane
Austin, TX	22 % (23 of 105 mi.)	Double loop detectors	1 minute	by lane
Charlotte, NC	12 % (13 of 92 mi.)	Microwave radar	30 seconds	by lane
Cincinnati, OH/KY	27 % (47 of 176 mi.)	Double loop detectors, video imaging, microwave radar	15 minute	by direction
Detroit, MI	39 % (110 of 282 mi.)	Single and double loop detectors	1 minute	by lane
Hampton Roads, VA	11 % (19 of 181 mi.)	Double loop detectors	2 minutes	by lane
Houston, TX	61 % (225 of 368 mi.)	Probe vehicle (AVI), limited double loop detectors	Anonymous individual probe vehicle travel times by link. Loop data are 20 seconds by lane.	
Long Island, NY	36 % (85 of 235 mi.)	Loop detectors and video imaging	5 minutes	by lane
Los Angeles, CA	86 % (579 of 676 mi.)	Single loop detectors	5 minutes	by lane
Louisville, KY	9 % (12 of 137 mi.)	Microwave radar, loop detectors, video imaging	15 minutes	by direction
Milwaukee, WI	100% (111+ of 111 mi.)	Loop detectors, microwave radar	5 minutes	by lane
Minneapolis-St. Paul, MN	60 % (190 of 317 mi.)	Single loop detectors	30 seconds	by lane
Orlando, FL	20 % (32 of 157 mi.)	Double loop detectors	1 minute	by lane
Philadelphia, PA	37 % (128 of 347 mi.)	Microwave radar, passive acoustic detectors	1 minute	by lane
Phoenix, AZ	30 % (53 of 179 mi.)	Double loop detectors, passive acoustic detectors	5 minutes	by lane
Pittsburgh, PA	27 % (78 of 284 mi.)	Microwave radar, passive acoustic sensors	1 minute	by lane
Portland, OR	39 % (54 of 137 mi.)	Double loop detectors	15 minutes	by lane
San Antonio, TX	36 % (77 of 211 mi.)	Double loop detectors, acoustic detectors	30 seconds	by lane
San Diego, CA	66 % (163 of 248 mi.)	Loop detectors	30 seconds	by lane
Seattle, WA	41 % (116 of 241 mi.)	Mostly single loop detectors, some double loops	5 minute	by lane

Source: Reference 4

Data collection and processing procedures have been developed individually and the details of the archiving vary from site to site. However, there are several procedures that are common to all sites. In general, the process works as follows for each city (with Houston being slightly different):

- Data are collected by field sensors and accumulated in roadside controllers. These field measurements are by individual lane of traffic. At 20-second to 2-minute intervals, the roadside controllers transmit the data to the TMC.
- Some areas perform quality control on original data, but this screening is typically simple and based on minimum and maximum value thresholds. These steps eliminate obviously incorrect data, but do not identify all of the problems.
- Areas that use single inductance loops as sensors (Exhibit 3) can only directly measure traffic volume and lane occupancy. In these cases, algorithms are used to estimate speeds for the combinations of volume and occupancy. The algorithms vary from site to site.
- Internal processes at the TMC aggregate the data to specified time intervals for archival purposes. These intervals vary from 20 seconds (no aggregation) to 15 minutes. In some cases, the data are also aggregated across all lanes in one direction at a sensor location.
- The aggregated data are then stored in text files or databases unique to each TMC. CDs are routinely created at the TMCs to reduce some of the storage burden and to satisfy outside requests for the data.

THE IMPORTANCE OF MAINTAINING AN ACCURATE INFORMATION COLLECTION SYSTEM

An area of potential immediate benefit and continuing concern is maintenance of the data collection infrastructure. Funding limitations affect the ability to correct deficiencies even when devices are known to be producing erroneous or no data. The problem is exacerbated where sensors in the pavement are used because most agencies are reluctant to shut down traffic on heavily traveled freeways just for monitoring equipment repair. Maintenance is often postponed to coincide with other roadway activities, which helps spread the cost burden, but may delay repairs.

Field checking of sensors is done periodically, but no standardized procedures are used across all areas. If a detector is producing values that are clearly out of range, inspection and maintenance are usually performed. However, calibration to a known standard is rarely, if ever, performed. This means that more subtle errors may go undetected. Bearing in mind that TMCs typically do not require highly accurate data for most of their operations, this approach is reasonable and practical. Work zones exacerbate these problems and contractors often unknowingly sever communication lines or pave over inductance loops.

Calibration—at least to very tight tolerances—is not seen as a priority, given that operators focus on a broad range of operating conditions rather than precise speed/travel time estimates. This philosophy may be changing as a result of more stringent data requirements for traveler information purposes, e.g., TMC-based posting of expected travel times to destinations using variable message signs. However, the current data resolution used by TMCs is quite coarse; it supports their traditional operations activities, such as incident detection and ramp meter control.

RELIABILITY PERFORMANCE MEASURES

Drawing from research by TTI, Cambridge Systematics, Inc. and an excellent Master's thesis by Dena Jackson (of Texas A&M University and the consulting firm of Reynolds, Smith and Hill in Florida) (6,7) the measure ideas represent those that are calculable or can be estimated for freeways from automatically collected data.

STATISTICAL RANGE MEASURES

This type of measure is generally characterized by information presented in a relatively unprocessed format. The measures draw on concepts familiar to statisticians. They are not overly complicated, but some are difficult to explain to non-statisticians. They can also be difficult to explain to individual travelers or to relate to trip decision-making.

A brief summary of a few basic statistical concepts is necessary to understand the measures. The standard deviation represents the amount of variation in the data. If the value of the standard deviation is added to and subtracted from the average value, approximately 68% of the data values will be between those two values. (The 85th percentile used in setting speed limits is the value that contains all speeds below a value one standard deviation above the average). Two standard deviations above and below the average will encompass approximately 95% of the data.

Exhibit 5 shows these concepts using a "normal" (or balanced) distribution. Travel time distributions for a roadway, corridor or urban area are typically "log-normal"—the value does not go below zero and there is a longer tail to the right (high travel times). Most of the description below assumes a normal distribution for the ease of discussion. The differences between normal and log-normal will be important if these measures are used. For instance, the log of a value might be used in the calculation rather than the value itself. These do not affect the description of the measures or how they would be used.

Travel Time Window—The standard deviation of travel time or travel rate can be combined with the average for any of several measures to create a variation or reliability measure (8). This would take the form of a "plus or minus" type expression that would give the reader an idea of how much the travel time will vary (Equation 1). Using one standard deviation will encompass 68% of the days, peak periods or whatever time period is chosen for analysis.

$$\text{Travel Time Window} = \text{Average Travel Time} \pm \text{Standard Deviation} \qquad \text{(Eq. 1)}$$

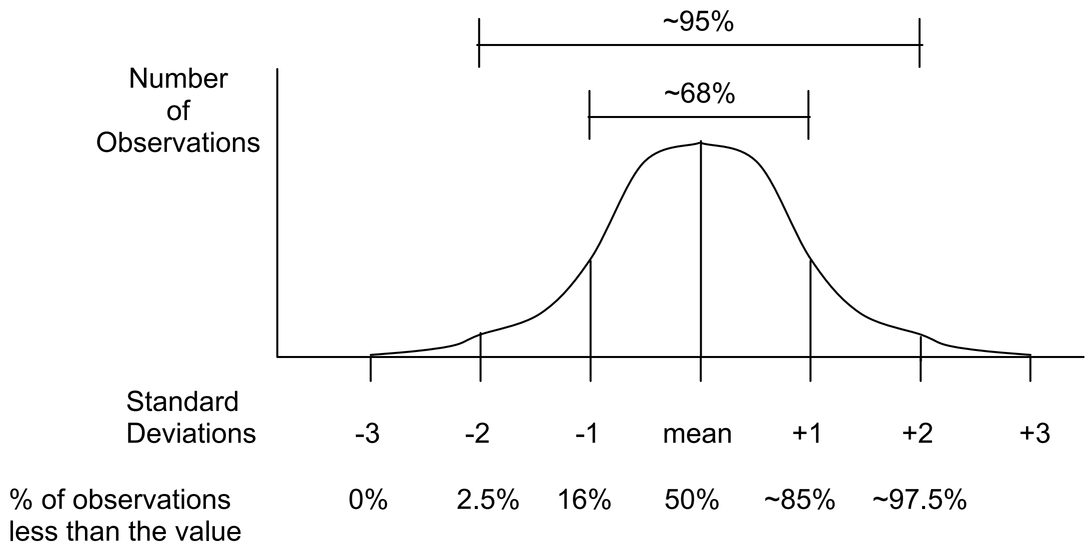


Exhibit 5. Illustration of Standard Deviation

A multiplier can be applied to the standard deviation value to increase the number of trips described within the range of the interval. The concept of using the inter-quartile range (the difference between the 25th and 75th percentiles) might also be used in this measure.

This measure can be used for any mode of travel and can be used for a range of network sizes. Combining the different network portions or several modes is a process of weighting each segment by the number of users or the travel distance in person-miles.

Percent Variation—The average and standard deviation values can also be combined in a ratio to produce a value that the 1998 California Transportation Plan (6,9) calls percent variation (Equation 2). This is a form of the statistical measure coefficient of variation. Analyzing travel time data sets using the coefficient of variation provides a clearer picture of the trends and performance characteristics than the standard deviation by itself by removing trip length from the calculation.

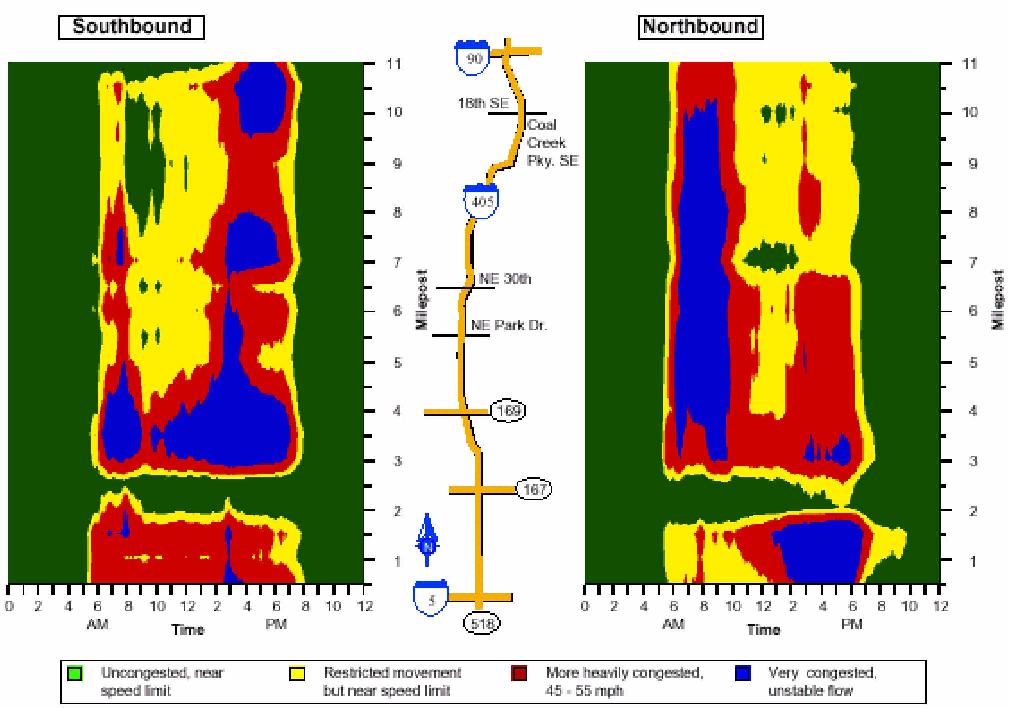
$$Percent\ variation = \frac{Standard\ deviation}{Average\ travel\ time} \times 100\% \qquad \text{(Eq. 2)}$$

A factor of this type provides the ability to discuss the travel conditions of a variety of different trip lengths in a way similar to the travel rate index description of average travel conditions. The data can be presented for individual segments or corridors as well as for a combination of modes.

Variability Index—A view of the reliability issue that may have application beyond a single measure is illustrated in the variability index (6,10). The index is a ratio of peak to off-peak variation in travel conditions. The index is calculated as a ratio of the difference in the upper and lower 95% confidence intervals between the peak period and the off-peak period (Equation 3). The interval differences (which represent 2 standard deviations above and below the average) in the peak periods are usually larger than in the off-peak and the variability index value is therefore greater than 1.0.

$$\text{Variability Index} = \frac{\begin{array}{c}\text{Difference in peak - period confidence intervals}\\ (\text{Upper 95\% value - Lower 95\% value})\end{array}}{\begin{array}{c}\text{Difference in off - peak period confidence intervals}\\ (\text{Upper 95\% value - Lower 95\% value})\end{array}} \quad \text{(Eq. 3)}$$

Displaying Variation—Either the Percent Variation or Variability Index can be shown for sections of a freeway and periods of time. A graph like the picture in Exhibit 6 could be used. This approach is similar to a topographic map with colors or shading indicating conditions. Exhibit 6 shows average conditions, but the shading could be linked to the variability measures as well. This type of graph can also be used for several years to identify year-to-year changes in congestion and reliability.



Source: Reference 5

Exhibit 6. Interstate 405 South Traffic Profile: General Purposes Lanes, 1999 Weekday Average.

BUFFER MEASURES

The buffer time concept may 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?" "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. Comparing the real traffic conditions to those that occur on the average day or most frequently can relate the effect of uncertainty on decision-making.

Buffer Time—A measure that uses minutes of extra travel time needed to allow the traveler to arrive on time can be relatively easily calculated and give a good idea of the amount of uncertainty. The problem is defining an average trip that should be used as the base. Karl Wunderlich of Mitretek (11) is using a measure similar to this in evaluating the traveler information system in Washington DC and in the HOWLATE computer simulation model.

A standard of "I can be late to work 1 day a month without getting into too much trouble" translates into using a 95th percentile travel time (1 day out of 20± work days). The buffer time would be the difference between the average travel time and the 95th percentile travel time as calculated from the annual average (Equation 4).

$$\begin{matrix}\textit{Buffer time}\\(\textit{in minutes})\end{matrix} = \begin{matrix}95^{th}\ \textit{Percent Travel}\\\textit{Time for a Trip}\\(\textit{in minutes})\end{matrix} - \begin{matrix}\textit{Average Travel Time}\\(\textit{in minutes})\end{matrix} \qquad \text{(Eq. 4)}$$

Buffer Time Index—Using the Buffer Time concept along with the travel rate (in minutes per mile), rather than average travel time, can address the concerns about identifying an average trip. This can also be easily calculated with the real-time traffic monitoring data. The information would include an average of the section-by-section variation for a corridor, subarea or area of interest weighted by the amount of travel in each segment. The Index could also be calculated, however, with travel times from roadway sections with relatively similar average travel time (e.g., within 10 or 15 minutes) as in Equation 5. Travel rates for approximately five-mile sections of roadway provide a good base data element for the performance measure. The Buffer Time Index can be calculated for each road segment or particular system element using Equation 5.

$$\begin{matrix}\textit{Buffer}\\\textit{Time}\\\textit{Index}\end{matrix} = \begin{matrix}\textit{Average of}\\\textit{All Sections}\\\left(\begin{matrix}\textit{Using VMT to}\\\textit{Weight the Section}\end{matrix}\right)\end{matrix}\left[\frac{\begin{matrix}\textit{95th Percentile Travel Rate}\\(\textit{in minutes per mile})\end{matrix} - \begin{matrix}\textit{Average Travel Rate}\\(\textit{in minutes per mile})\end{matrix}}{\begin{matrix}\textit{Average Travel Rate}\\(\textit{in minutes per mile})\end{matrix}}\right]\times 100\% \qquad \text{(Eq. 5)}$$

The measure would be explained as "a traveler should allow an extra BTI% travel time due to variations in the amount of congestion delay on that trip." The measure can be calculated from the real-time datasets either using roadway links combined into corridors or just the individual links.

Planning Time Index—The upper end of the Buffer Time Index is also a useful measure in some situations. The 95th percentile Travel Time Index or the travel rate (expressed in minutes per mile) provides a travel time budget expectation and is calculated as part of the Buffer Time Index process. It is also relatively easy to communicate and could be used as a trip planning measure for trips that require on-time arrivals.

Planning Time Index = 95th Percentile Travel Time Index (of all peak period travel) (Eq. 6)

Buffer Measure Illustrations

Exhibit 7 illustrates the relationship between average conditions and the Buffer Time Index concept. The Travel Time Index is a measure of the average travel time (in minutes per mile) that would be experienced by the system users during the analysis period. The Buffer Time Index can be thought of as representing the amount of additional time (above the average) needed to include 95 percent of the travel time data points. Exhibit 7 illustrates this relationship for an average day and Exhibit 8 displays the data for the weekdays in a year. The average line is a demonstration of the Travel Time Index (the percentage of extra time above free-flow travel). The space between the average and 95th percentile lines is the graphical representation of the Buffer Time Index.

The average values for the day presented in Exhibit 7 can be thought of as a single point on the graph in Exhibit 8 (i.e., the lines in Exhibit 7 are perpendicular to the page in Exhibit 8). The same type of graphs could be done as peak period only illustrations.

Exhibit 9 from the University of Washington Seattle Freeway study (5) is another method of depicting average and extreme conditions on the same graph. The average and 95th percentile travel times are depicted as lines along with the frequency of relatively slow trips shown as shaded vertical bars. This illustration is for a particular trip, but the concept is relatively easy to apply to other cases.

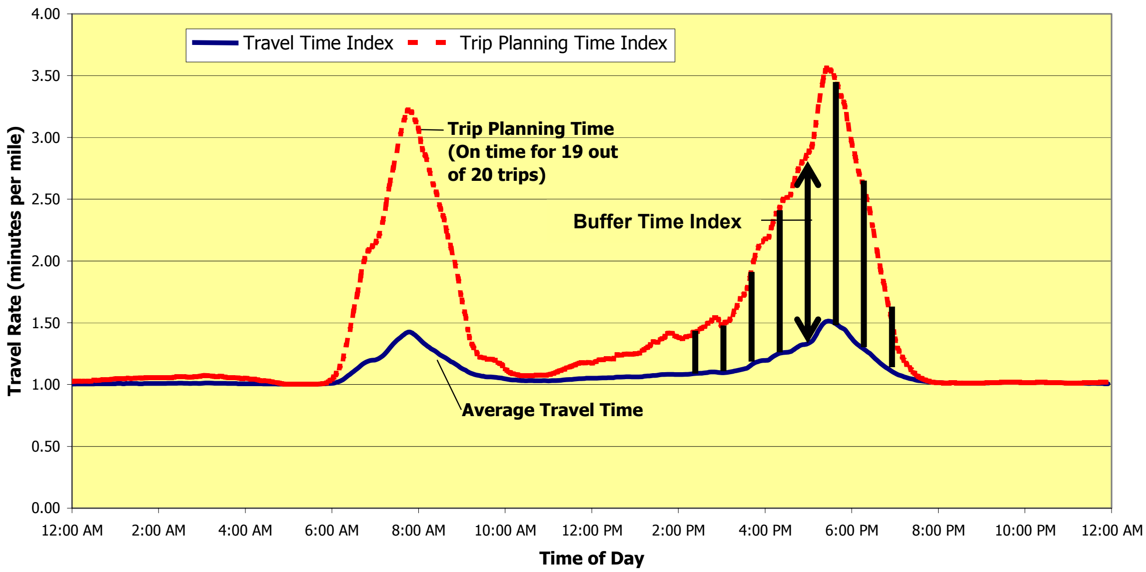


Exhibit 7. Average Travel Time and Planning Time—Variation During a Day

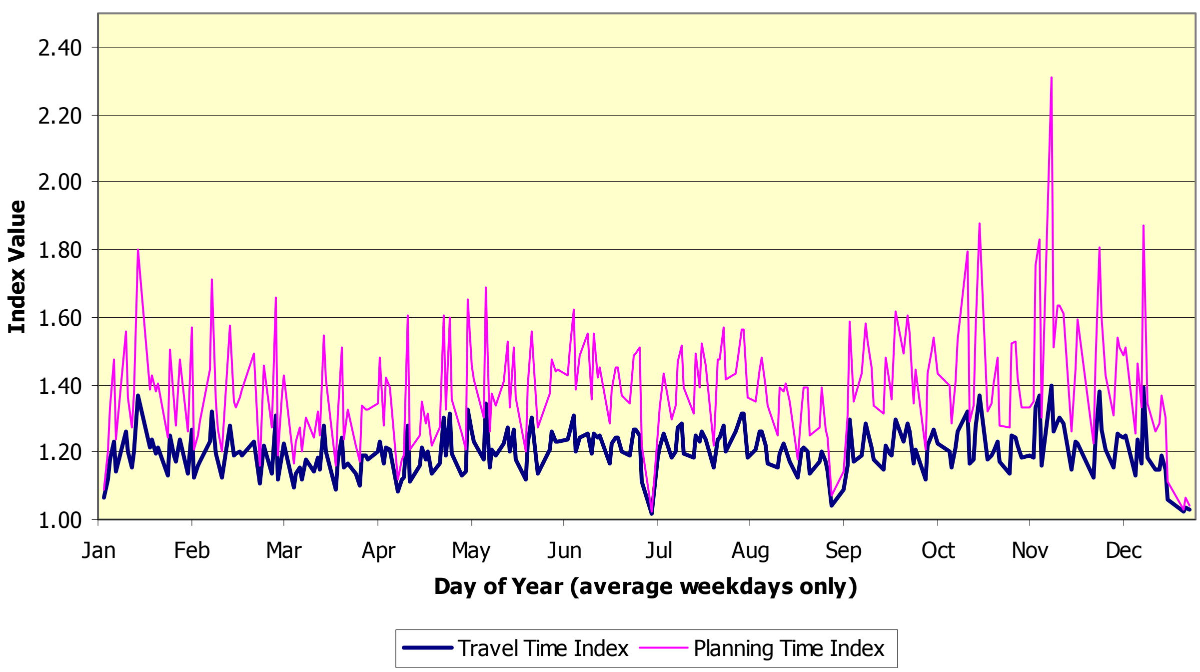
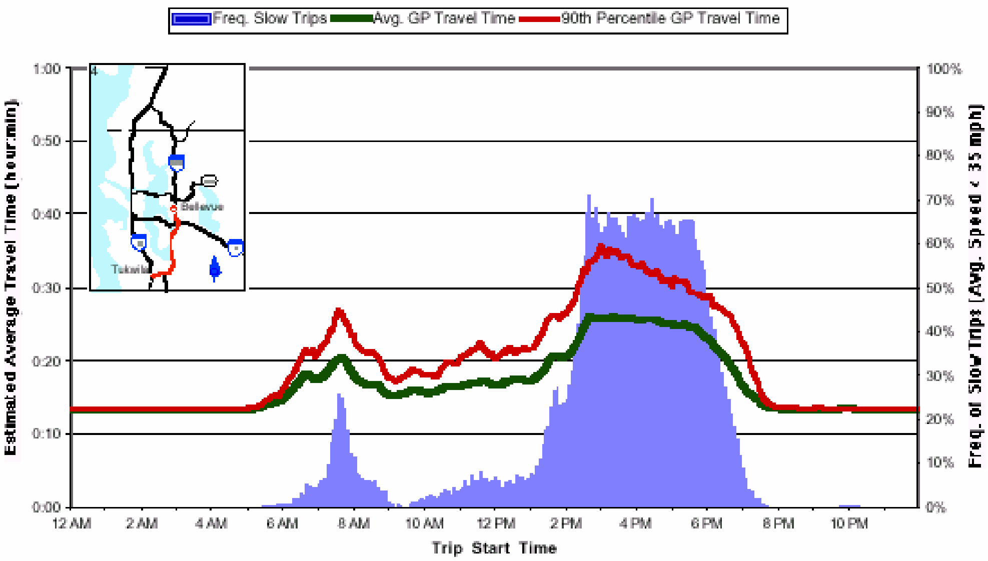


Exhibit 8. Average Travel Time and Planning Time—Variation During the Year



Source: Reference 5

Exhibit 9. Estimated Average Weekday Travel Time (1990): Bellevue CBD to Tukwila, General Purpose Lanes (13.5 mi).

Travel Rate Envelope—Plotting the 5th and 95th percentiles for each peak period provides a view of the variation in conditions that is similar to other Buffer Time concepts. Exhibit 10 shows 80 days of operation for the evening peak period on a freeway. Days with significantly bad travel times stand out very clearly. The graph, however, is relatively confusing. The 240 data points (80 days with three data points per day) present a very cluttered picture. It is difficult to identify days with significantly unreliable conditions (e.g., large distance between 95th and 5th percentile)—there are too many data points too close together. Unreliable days would be easier to spot if the data points for each day were connected vertically, rather than having all the points of one percentile connected. The longer vertical lines such as those shown in Exhibit 11 indicate greater variation in conditions for that day.

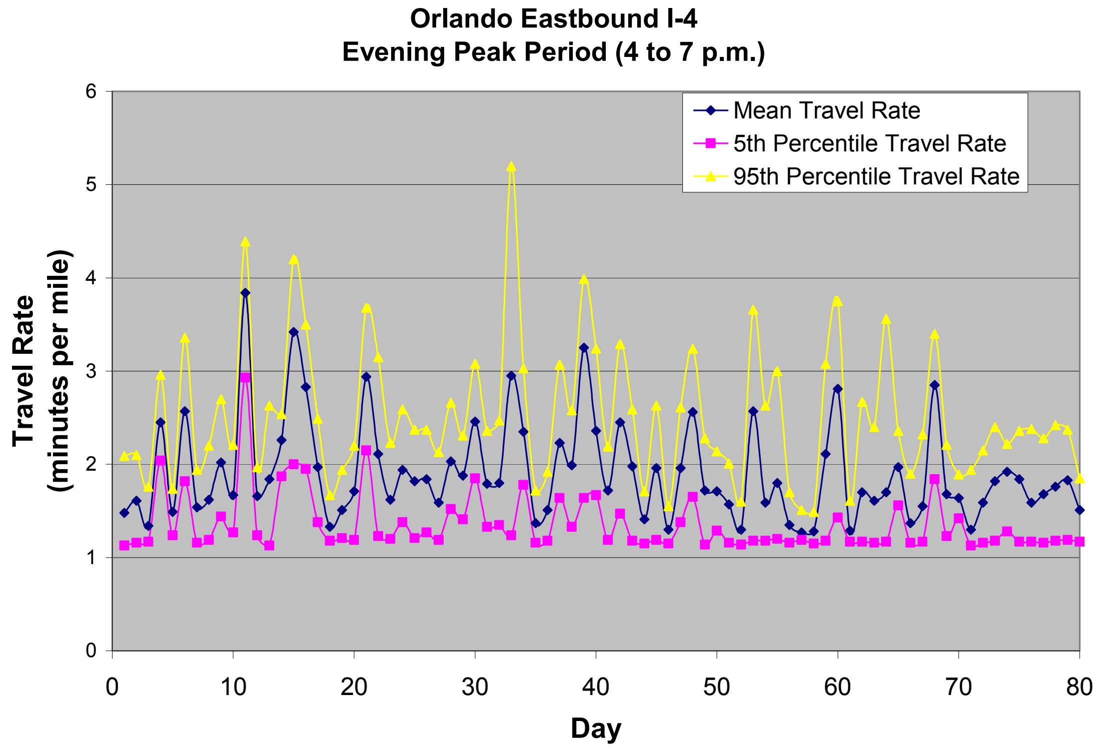


Exhibit 10. Peak Period Travel Rate—Average and Extreme Lines

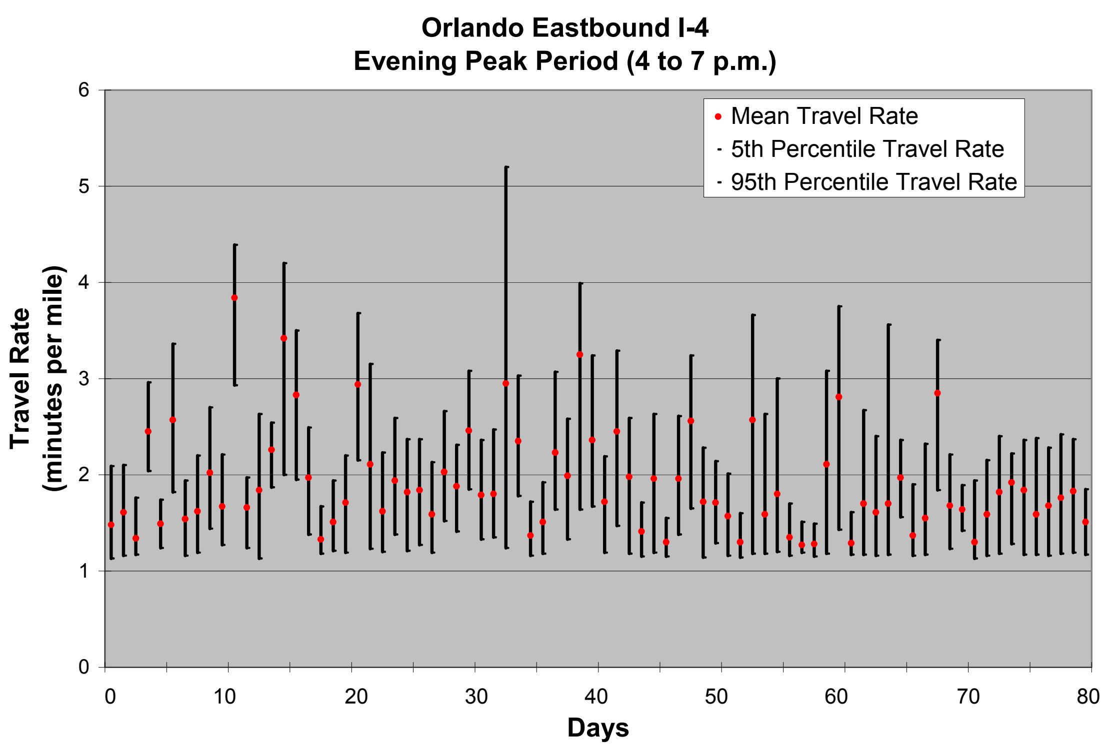


Exhibit 11. Peak Period Travel Rate—Average and Extreme Points for Each Day

TARDY TRIP INDICATORS

Where buffer time measures look at the trip time effects of unreliable system performance, tardy trip measures can represent the unreliability impacts using the amount of late trips. If travelers only use the average trip time for their travel plans, they will be late to half their destinations and early to half (in round numbers). Prudent travelers allow for some time in addition to the average travel time because conditions fluctuate. If a value in minutes or percentage is chosen to represent some unacceptably late arrival interval, the data can be analyzed for the amount or percentage of trips that would be too late relative to those expectations. More market research will be needed to uncover the appropriate "percent over" values. The Florida Reliability Method, for example, is being calculated for several levels until more surveys are conducted. A few methods to choose the interval are described in the following measures.

Florida Reliability Method—The Florida measure uses a percentage of the average travel time in the peak to estimate the limit of the acceptable additional travel time range (Equation 7) (6, 7, 12). The sum of the additional travel time and the average time defines the expected time. Florida is experimenting with four different levels to determine the right value for the additional time. Travel times longer than the expected time would be termed "unreliable." One adjustment that might be needed for real-time monitoring systems is to use travel rate rather than travel time (Equation 8). Using travel rate variations provides a length-neutral way of grading the system performance that can be easily calculated and communicated to travelers.

$$\begin{matrix} \textit{Florida Reliability} \\ \textit{Statistic} \\ (\textit{\% of unreliable trips}) \end{matrix} = 100\% - (\textit{percent of trips with travel times greater than expected}) \quad \text{(Eq. 7)}$$

$$= 100\% - \left(\begin{matrix} \textit{percent of trips with travel rates greater than the} \\ \textit{average for the time period plus 5\%, 10\%, 15\% and} \\ \textit{20\% of the average} \end{matrix} \right) \quad \text{(Eq. 8)}$$

On-Time Arrival—A concept similar to the Florida method uses an acceptable "lateness threshold" of some percentage to indicate the percentage of trip travel times that can be termed reliable. This measure is used in a variety of travel modes and services and might be particularly useful in cross-modal comparisons. Estimating the trip characteristics would be difficult, but if the measure is simply calculated at the detector or segment level, the calculation should be relatively easy and the statistics interesting.

The Urban Mobility Study report "The Keys to Estimating Mobility in Urban Areas" (13) suggested a threshold of 10 percent higher than the average travel time (or travel rate). This value has not been market-tested, but a 10% late arrival may be relatively conservative for some applications (Equation 9).

Two concerns with the late arrival value are that the value for acceptably late arrival, 1) may not vary linearly for all trips, and 2) it is not only related to trip duration. Being 10% late from a 16-hour overseas trip may not be as acceptable as being 3 minutes late for a 30-minute city trip. The amount of "acceptable lateness" is also a function of the previous activity and of the arriving activity. Being late may be more acceptable if the traveler is coming from an important activity, and it may be less acceptable if they are arriving at an important activity. Some testing of the acceptable lateness concept is certainly warranted, but the measure concept can be tested with an assumed value initially.

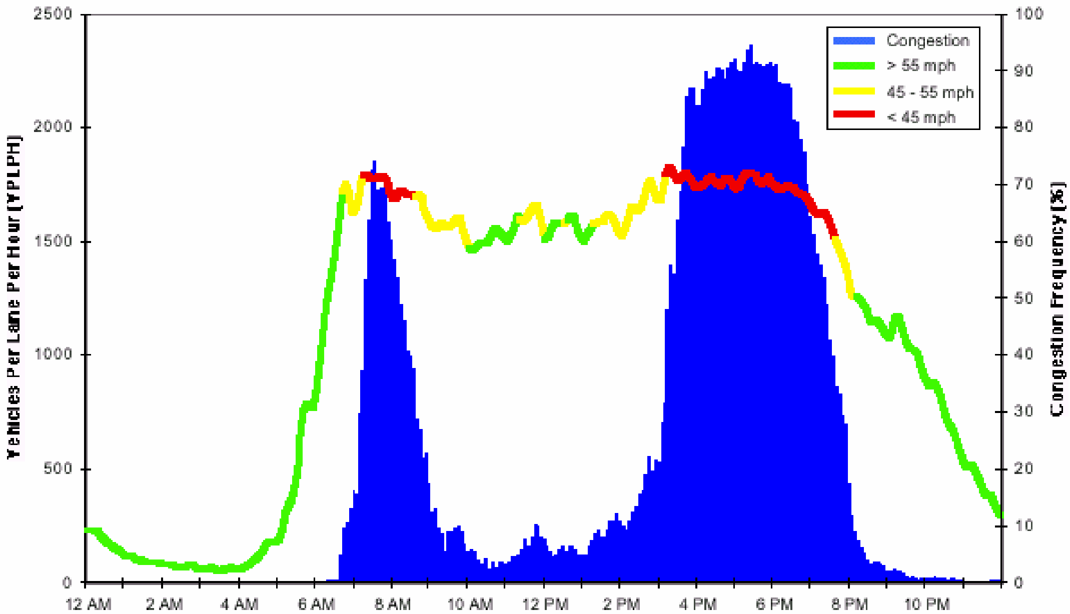
$$\begin{aligned} \begin{matrix}\textit{On - Time}\\ \textit{Arrival}\end{matrix} &= 100\% - \left(\begin{matrix}\textit{percent of travel rates greater than 110\%}\\ \textit{of the average travel rate}\end{matrix}\right) \\ &= 100\% - \left(\begin{matrix}\textit{percent of daily peak-period travel rate averages that are}\\ \textit{greater than 110\% of the average peak-period travel rate}\end{matrix}\right) \end{aligned} \qquad \text{(Eq. 9)}$$

Misery Index—The negative aspect of trip reliability can be examined by the average number of minutes that the worst trips exceed the average (Equation 10). This might be calculated by taking data from the worst 20% of the days and finding the average travel rate for just those trips. Comparing that to the average travel rate for all trips would give a measure of "how bad are the worst days?" The use of the 20% value might be explained as focusing on the worst day of the week.

$$\textit{Misery Index (MI)} = \frac{\begin{matrix}\textit{Average of the travel}\\ \textit{rates for the longest}\\ \textit{20\% of the trips}\end{matrix} - \begin{matrix}\textit{Average travel}\\ \textit{rates for all trips}\end{matrix}}{\textit{Average Travel Rate}} \qquad \text{(Eq. 10)}$$

VOLUME, SPEED AND CONGESTION FREQUENCY GRAPH

A graphical variation that combines the speed, congestion frequency and volume information with Misery Index concepts is presented in Exhibit 12. While the graph (from the University of Washington Seattle Freeway Study) (5) is "busy" it does connect the volume variations with traffic speed. If the graph also includes information about the surrounding transportation system, it can provide more extensive explanation of the causes of unreliability. The frequency of congestion displayed in the bar graph illustrates the predictability of "misery conditions," as well as the length of time that congestion typically exists.



Source: (Reference 5)

Exhibit 12. Volume, Speed and Congestion Frequency

RELIABILITY MEASURE COMPONENTS

There are a number of variations in "trip geography" that can be considered, such as the entire trip, trip segments, or road segments. A variety of weighting factors (typically person-miles or vehicle-miles) can be used to aggregate the measures to produce summary statistics. The relationship between the travel time variations and the calculation steps for several possible reliability measure concepts is described in Exhibit 13.

Exhibit 13. Reliability Measure Concepts

What is Being Measured?	Outline of Calculation Steps
Driver Variation	Individual travel times for a trip are the basic data element. Variation values will be relatively high due to individual driver preferences being one of the speed determining factors.
Road Segment Variation	Average travel rates for a road section are compared. Driver variations are not an issue, but variations due to peak and off-peak speed differences will be included.
Time of Day Variation	Average travel rates for segments of the day are compared for trips. Variations in travel speed due to congestion on some road segments will be part of the variation measured in this value.
Daily Variation	Travel rates for trips made during a day are compared to average travel rates for other days. Variations in speed for times of the day and congested/uncongested conditions on road sections will be included.
Specific Condition or Event Variation	Trip travel rates for particular events or conditions are compared to each other or to average conditions. Since the conditions and events can be of very different character, variations can be significant.

Considering the range of variation components, it is easy to see the need to combine some of these variations in order to get appropriate comparisons for communicating with motorists, shippers, operating agencies and elected decision-makers. These broader variations, however, are not consistent with the way some users experience the system. Relatively short time blocks—these might be termed "windows"—may be more consistent with the experience of people who make trips on a regular basis.

For a broad set of comparisons, the matrix in Exhibit 14 describes the conditions that are most relevant. The "standard" conditions are those where congestion is related to high traffic demand, poor traffic signal operations or other typically existing conditions. Identifying the causes of unreliability is not necessary if the analyst is examining total variability, but travelers typically distinguish between causes as they evaluate travel conditions and agency programs. Information about the effect of potential improvement types can also be used in prioritizing solutions and spending.

- Days might be generally divided into weekdays and weekends. More specific information could be obtained by identifying holidays, days that are affected by school closings or other calendar events that are likely to result in changes to traffic conditions.

- Time periods can be defined by the peak periods, the midday and late night or early morning. Peak hour statistics could also be examined, but may not be as useful for trend analysis in congested areas because the values may not change very much from year to year. On congested roadways, growth in travel occurs in hours other than the already-full peak hour.
- Unpredictable conditions such as traffic collisions—which might generally be expected but cannot be predicted as to time and place—and weather-related problems can be grouped for analysis and compared to standard operating situations without additional difficulties.
- Other traffic disruptions might be categorized as planned events. Special events with high transportation system loads or different loading patterns and construction or maintenance activities might logically fall into this category. This would include maintenance operations that are relatively undefined as to specific location and duration.

Exhibit 14. Description of Reliability Considerations

Days→	**Weekdays**				**Weekends**			
Time Periods→	Morning Peak	Midday	Evening Peak	Overnight	Morning	Midday	Evening	Overnight
Unpredictable Conditions→	Incidents	Severe Weather		Standard	Incidents	Severe Weather		Standard
Planned Events→	Special Events	Construction or Maintenance		Standard	Special Events	Construction or Maintenance		Standard

For analysis purposes the important reliability component is the ability to identify where and when a disruptive event occurs and how the traveler or shipper uses the information. The current level of information in some cities, however, prevents many of the Conditions and Events from being readily identified within the traffic condition database. Days and Time Periods are more readily accessible and provide a significant improvement over other traffic condition data sources.

Local area or corridor analyses are typically more detailed and it may be useful to further subdivide the data. Additional databases such as incident time and location, weather conditions, construction, maintenance and special events might be used to investigate the effect of these factors on travel time, and the success of remedial actions.

BUFFER TIME INDEX CALCULATION CONCEPTS

A typical morning commuter might compare conditions during all morning peaks, or more precisely conditions around the time of the usual departure, to plan a normal day departure time. On a given day, a commuter with information about weather, construction, maintenance and special events for that day might modify their departure time. The departure time might be further modified if incidents, weather or construction activity are serious enough to warrant a change in route, travel time or travel mode. Ultimately, a useful measure should be able to use these different conditions, along with a database of experiences to assist travelers, shippers and others in both deciding on departure times, routes and modes as well as allow evaluations of the system performance.

The Buffer Time Index formula (Equation 11) relies on the archived data to support the generation of a measure for urban freeway systems. While Florida (7) has attempted to measure travel time variations on a sample basis, most programs will use continuous monitoring activities and statistics that are saved in archived databases.

$$\begin{matrix}\textit{Buffer}\\ \textit{Time}\\ \textit{Index}\end{matrix} = \begin{matrix}\textit{Average of}\\ \textit{All Sections}\\ \left(\begin{matrix}\textit{Using VMT to}\\ \textit{Weight the Section}\end{matrix}\right)\end{matrix} \left[\frac{\begin{matrix}\textit{95th Percentile Travel Rate}\\ (\textit{in minutes per mile})\end{matrix} = \begin{matrix}\textit{Average Travel Rate}\\ (\textit{in minutes per mile})\end{matrix}}{\begin{matrix}\textit{Average Travel Rate}\\ (\textit{in minutes per mile})\end{matrix}}\right] \times 100\% \quad \text{(Eq. 11)}$$

The calculations basically consist of calculating the average and 95th percentile travel time for each section of roadway (approximately five miles long and in some cases made up of several links of road) for each combination of days and time periods. To calculate the Buffer Time Index for a corridor or area, the Buffer Time Index values of five-mile road sections can be calculated and then combined using vehicle-miles (or person-miles) of travel to weight the Buffer Time Index values. Identifying the appropriate Buffer Time Index calculation is a process of identifying the time period and set of conditions that a traveler would view at the start of the trip and incorporating those into the calculation procedures so that the information from the measure matches the method used to create the statistics. The research team will continue to investigate the statistical effects of various calculation and aggregation processes.

The current standard format is for the data to be stored in increments of 5 minutes for all the lanes in one roadway direction. For the 2001 Mobility Monitoring Program Report (4), the measure reporting will represent experiences closer to a trip, rather than the short road segment approach that was used in the 2000 Report (3). Sections of road of approximately 5 miles will be used as the basis for calculations. The travel time for these sections will be created by adding travel times from each segment of road for each 5-minute time slice. Combining the data from each 5-minute time slice is accomplished using vehicle-miles or person-miles of travel to weight the values from each time slice. It was determined in previous Mobility Monitoring Program studies (3) that this approach results in performance measures that are very close to a simulated trip, but requires much less effort to produce.

Measures that do not use travel times, distances or particular commute trips generally provide easier comparison methods because they can be applied to a wider variety of situations. The minutes of travel time can then be estimated by travelers, or by local agencies for particular trips. For many comparisons, travel rate (expressed in minutes per mile) may be better than travel time. In this application, however, the Buffer Time Index is already a unitless measure. Travel times for approximately five-mile sections of roadway provide a good base data element for the performance measure. The Buffer Time Index can be calculated for each road segment or particular system element using Equation 11.

Weekdays and holidays can be removed if the report is designed to show conditions on days that might be congested. The averages for each of the five weekdays might be grouped to provide another summary level of information.

HOW MUCH VARIATION SHOULD BE INCLUDED?

There are several approaches to analyzing reliability. Unfortunately for the analyst looking for guidance, there is no single correct approach. The preceding discussion and Exhibit 13 highlighted several elements to consider when preparing a reliability measure, but perhaps the best database advice is to create a flexible database. A variety of perspectives can be useful and appropriate; three are summarized below, along with a data warehouse design recommendation.

The reliability measure should provide information about the amount of time that should be budgeted for a trip. The calculation process for any specific measure formulation should control for variations that are not relevant to the trip planning decision, although these elements will vary. This might include factors such as month-to-month variation (because travel decisions may be made with knowledge of the month) and variation in road section length (because travelers are more likely to examine their trip travel time rather than each road section separately). Most urban travel time information databases do not currently connect travel time data to the weather condition, special events or construction/maintenance activity, but can incorporate those when they are available.

INCLUDE THE AVERAGE AND 95TH PERCENTILE TRAVEL TIMES

One key to maintaining a flexible and responsive data warehouse for reliability measures is to save the average and 95th percentile travel times or travel rates (or 5th percentile travel speeds) at the most detailed level along with the event and condition codes. This recommendation results in a database consisting of the average and 95th percentile travel time values, rather than Buffer Time Index values. Creating performance measures would then be a matter of combining the 5-minute or peak period values using person-miles or vehicle-miles of travel as a weighting factor. The statistical effect of the chosen approach must be examined; the calculation procedure should not reduce variations that should be included in the measure

WHICH VIEW OF RELIABILITY SHOULD BE USED IN PREPARING A PERFORMANCE MEASURE?

The reliability measure should provide information about the amount of time that should be budgeted for a trip. The calculation process for any specific measure formulation should control for variations that are not relevant to the trip planning decision. This might include factors such as month-to-month variation (because most travel decisions will be made with knowledge of the month) and variation in road section length (because most travelers examine their trip travel time rather than each road section separately). Most urban travel time information databases do not currently connect travel time data to the weather condition, special events or construction/maintenance activity, but can incorporate those when they are available.

Some typical views of reliability measures are presented below. It is useful to work out the messages or discussion points that the reliability measures are designed to support. The calculation procedures should match the desired outcomes and the desired discussion points.

- Commuter View

The peak period transportation demand includes many trips that could be considered "regular." Commuters, students, business deliveries and other types of trip makers that have usual departure times and rates might benefit from a focused view of reliability. Their experiences relate to a "window" or period of time when they use the system, rather than the entire peak period. Including all of the peak period conditions in an analysis of reliability would overstate the amount of variation that these travelers experience. Their view of conditions (based on a shorter time frame) does not include travel time variations that are caused by congestion levels that fluctuate during the peak period. This analysis will require a slightly more detailed analysis, but is relatively easy to accomplish with the five-minute data level.

- Peak Period Traveler View

Travelers and businesses that have typical travel patterns view reliability in comparison with the conditions they expect during the time of day they normally travel. For those who use the transportation system for many different trips at a variety of times, however, a measure based on peak period conditions might be valuable. The peak period trip expectations relate to the time of year, weather conditions, expected maintenance or construction activity and known special events. None of these factors (except time of year) are included in the typical archived travel speed database. Some adjustments would be required, but the view of travelers and businesses who regularly use the transportation system during the peak period could be the basis for the Buffer Time Index.

- Agency Reporting View

This calculation would emulate the way in which an agency might use the Buffer Time Index to evaluate overall system performance each day. It assumes that urban residents with some knowledge of typical conditions are interested in how much extra time was required to complete an on-time trip. The answer to their question is the ratio of the 95th percentile travel time for the specific day or peak period in question and the average travel time for the month or year. While this comparison seems awkward—comparing a daily value to a monthly or annual average—it is the way travelers and shippers view the system and their travel plans and appears to be a good basis for reporting system performance on a daily basis.

RELIABILITY MEASURE CALCULATION PROCEDURES

The following paragraphs describe the procedures used in the Mobility Monitoring Program (MMP) to calculate reliability measures using detailed traffic sensor data that has been archived from traffic operations programs. This archived traffic sensor data is typically continuous throughout the entire year and stored at relatively small time increments (e.g., 5-minute periods). The same calculation procedures used for this detailed traffic sensor data can also be used for manually collected travel time data that has been sampled. However, statistical sampling procedures should be used to ensure that manual data collection captures adequate sample sizes for enough locations, days and different times of the day.

The performance measures currently used in discussions about transportation reliability within the MMP are the buffer time index and the planning time index. The key elements of the data compilation process are shown in Exhibit 15. Beginning with the basic traffic sensor data for each lane, the process provides for both aggregation and data quality checking procedures. Missing data is accommodated through factors to expand the database to as complete a dataset as possible. The successive levels of aggregation shown in Exhibit 15 allow missing data to be identified and adjusted at the lowest possible level.

The equations using the finished dataset in the measure calculation process are shown below. Equation 12 is the Travel Time Index formula for the basic unit of analysis, the freeway section. The travel time for the section is compared to the travel time that would be needed to cover the same section at 60 mph. Off-peak freeway speeds could also be used as the comparative standard, although this formulation would show the effect of worsening off-peak congestion as a lower Travel Time Index.

$$\begin{matrix} Travel \\ Time\ Index \end{matrix} = \frac{Travel\ Time\ for\ a\ freeway\ section}{Travel\ Time\ for\ a\ freeway\ section\ at\ 60\ mph} \qquad \text{(Eq. 12)}$$

The Planning Time Index is used to identify the travel time for the longer travel time trips. The 95th percentile is used in the formula in Equation 13, but other percentages could be used.

$$Planning\ Time\ Index = 95^{th}\ percentile\ Travel\ Time\ Index\ value \qquad \text{(Eq. 13)}$$

(the percentage of extra time needed to accomplish a trip 19 out of 20 times for the period being analyzed(e.g., peak period)

Equation 14 describes the Buffer Time Index formula as the difference between the 95th percentile and the average values of travel time. Expressing the Buffer Time Index value as a percentage of the average travel time eliminates the section length differences that would be introduced into the data and the measure. The use of the BTI in this formulation would use a message along the format of "a traveler should allow BTI percent more travel time than average in order to arrive on-time."

$$\text{Buffer Time Index} = \left[\frac{\begin{matrix}\text{95th Percentile Travel Time} \\ \text{(in minutes)}\end{matrix} - \begin{matrix}\text{Average Travel Time} \\ \text{(in minutes)}\end{matrix}}{\begin{matrix}\text{Average Travel Time} \\ \text{(in minutes)}\end{matrix}} \times 100\% \right] \qquad \text{(Eq. 14)}$$

Combining the Buffer Time Index for several sections can be accomplished using the vehicle-miles traveled in each section and the formula in Equation 15. Using VMT to weight each Buffer Time Index value allows the sections that have more travel on them to influence the final average to a greater degree.

$$\begin{matrix}\text{Weighted Average} \\ \text{of BTI for} \\ \text{Several Sections}\end{matrix} = \frac{\left(VMT_{section\ 1} \times BTI_{section\ 1}\right) + \left(VMT_{section\ 2} \times BTI_{section\ 2}\right) + \ldots}{VMT_{section\ 1} + VMT_{section\ 2} + \ldots} \qquad \text{(Eq. 15)}$$

The two reliability measures—Planning Time Index and Buffer Time Index—can be calculated using the following two basic steps. More detail on the specifics of using an archived database to construct these measures is presented in subsequent text.

Step 1: Calculate Travel Time Index for Each Analysis Section. The first major step is to calculate travel time index values for each roadway section of interest (see Exhibit 15). The MMP procedures (3,4) use a directional roadway section that is typically 5 to 10 miles in length as the basic unit of analysis. The beginning and ending points of these analysis sections are typically selected to coincide with major highway interchanges or other locations where traffic conditions change because of traffic or roadway characteristics. Exhibit 15 graphically illustrates the process of calculating travel time index values for each analysis section using detailed lane-by-lane traffic sensor data.

Step 2: Group Data, Summarize, and Calculate Weighted Averages. The second major step is to compute average and 95th percentile travel times for the periods and locations of interest. This involves combining the 5-minute analysis section travel time index values (i.e., the results of the process in Exhibit 15) and then computing the summary statistics (i.e., average and 95th percentile travel time index). The data from each section is combined using vehicle-miles traveled (VMT) as the weighting factor (see Equation 16). As a basic principle, the MMP procedures do not combine the 5-minute data from different analysis sections or different time periods of the day into one group for analysis.

$$\begin{matrix}\text{Peak Period} \\ \text{Average Performance} \\ \text{Measure}\end{matrix} = \frac{\displaystyle\sum_{\substack{\text{for each} \\ \text{5 - minute} \\ \text{period}}} \left[\begin{pmatrix}\text{5 - minute section statistic} \\ \text{for example Travel Time Index} \\ \text{or 95th percentile travel time}\end{pmatrix} \times \begin{matrix}\text{Vehicle - miles} \\ \text{of travel}\end{matrix} \right]}{\begin{matrix}\text{Sum of vehicle - miles of travel} \\ \text{for all 5 - minute periods}\end{matrix}} \qquad \text{(Eq. 16)}$$

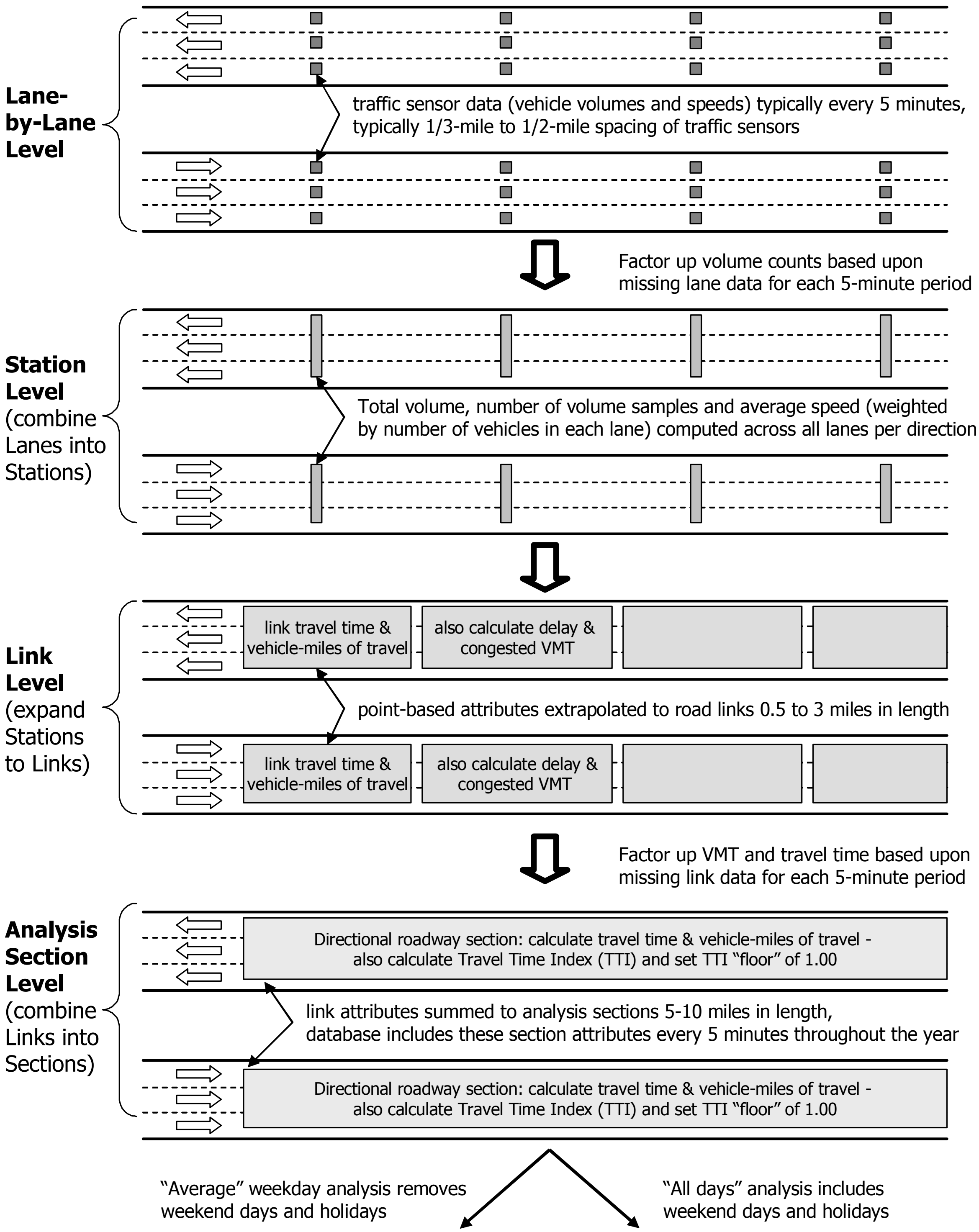
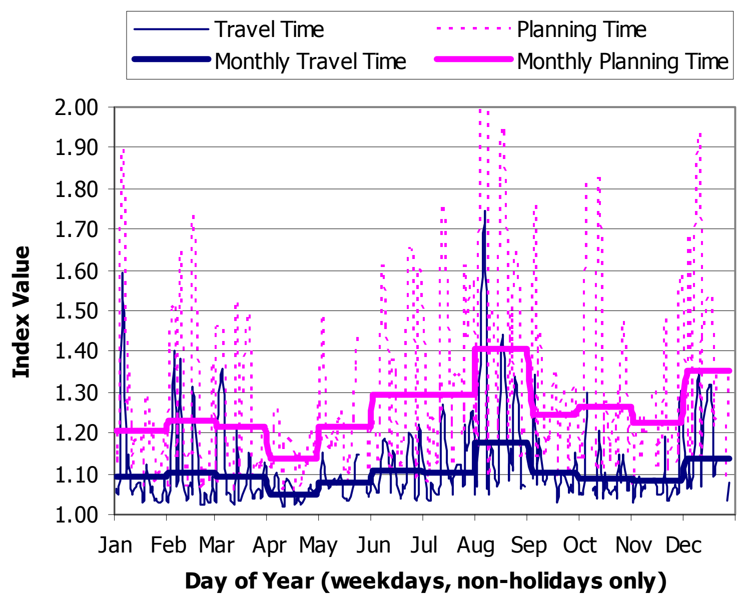


Exhibit 15. Calculation Procedures for Section-Based Index Values

The Mobility Monitoring Program city reports (3,4) present reliability measures for a number of different time horizons and analysis periods. The specific calculation procedures for each chart or table are summarized in the following paragraphs. As described elsewhere in this report, there are several methods that could be used to calculate the measures. The reliability measures, in particular, could be constructed in several different, but equally appropriate ways depending on the use, the time period and audience for the information. This section describes the methods used in the Mobility Monitoring Reports as a way to identify the procedures and some of the concerns for reliability and mobility measures.

AVERAGE PEAK MOBILITY AND RELIABILITY FOR EACH WEEKDAY OF THE YEAR



The 5-minute average and 95th percentile travel time index values and traffic volume are grouped by analysis section, weekday and peak time period (e.g., morning peak is 6 to 9 a.m. and evening peak is 4 to 7 p.m.). For 5-minute data, each group should have 36 values (e.g., there are 36 5-minute values in a 3-hour peak period). The peak values are combined into a daily peak period average for the section using vehicle-miles traveled (VMT) as the weighting factor. Section values are combined into system averages also using VMT to weight each section value. This yields a single VMT-weighted average for each weekday (shown as average peak period travel time index on the chart) and a VMT-weighted 95th percentile for each weekday (shown as average peak period planning time index on the chart).

Specific Day of the Year for the System

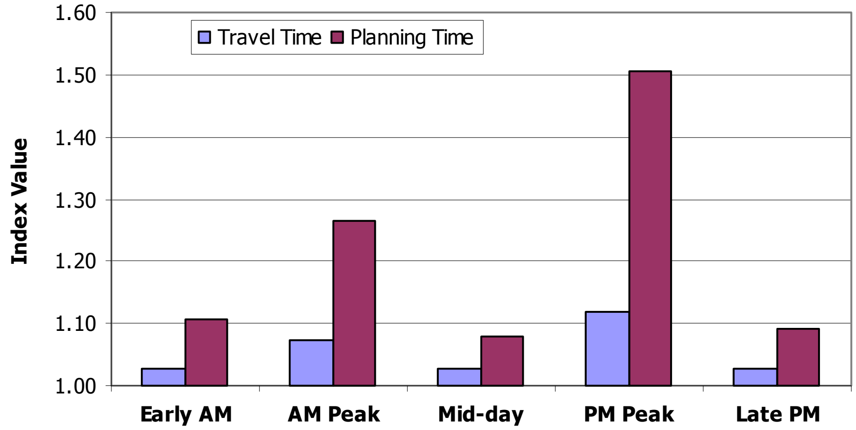
Section 1 — Section 2 — . . . Other Sections

Section 1		Section 2	
AM Peak	PM Peak	AM Peak	PM Peak
(36 values for peak periods)	*(36 values for peak periods)*	*(36 values for peak periods)*	*(36 values for peak periods)*

36 values = 12 5-minute values each hour for 3 hours in one peak period.

AVERAGE MOBILITY AND RELIABILITY BY TIME PERIOD OF AN AVERAGE WEEKDAY

The 5-minute average and 95th percentile travel time index values and traffic volume are grouped by analysis section and time period of the day for all weekdays. Values for each section are combined into time period averages using vehicle-miles traveled (VMT) as the weighting factor. This yields a VMT-weighted average for each time period (shown as travel time index on the chart) and a VMT-weighted 95th percentile for each time period (shown as planning time index on the chart).



Specific Time Period

Section 1 for the Period	Section 2 for the Period	Section 3 for the Period	. . . Other Sections for the Period
(9,000 values for a peak period)	*(9,000 values for a peak period)*	*(9,000 values for a peak period)*	

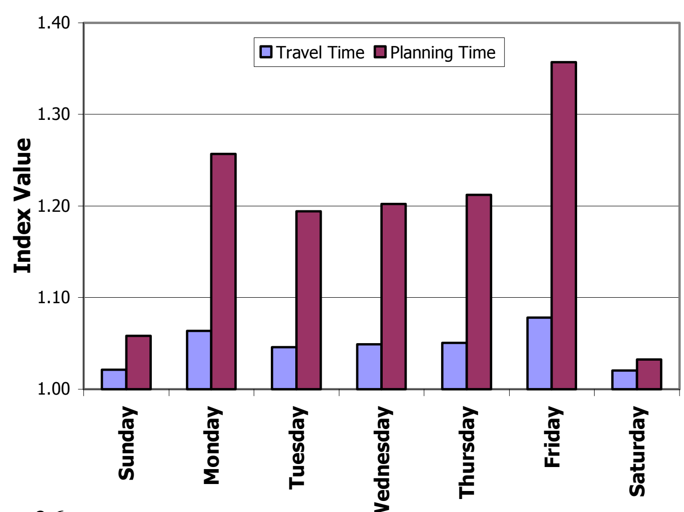
9,000 values = 12 5-minute values per hour for each of the three hours in a peak period; 250± non-holiday weekdays in a year.

Other file sizes:

Early AM – 6 hours – 18,000 values
Midday – 7 hours – 21,000 values
Late PM – 5 hours – 15,000 values

AVERAGE MOBILITY AND RELIABILITY BY DAY OF THE WEEK

The travel time index values and traffic volume data are grouped for each day of the week and analysis section. Average and 95th percentile travel time index values are computed for each group from the full year database. For 5-minute data, each group should have about 72,000 values (e.g., 288 5-minute values per day



multiplied by about 250 non-holiday weekdays per year). Section values are combined into daily values using vehicle-miles traveled (VMT) as the weighting factor. This yields a VMT-weighted average for each day of the week (shown as travel time index on the chart) and a VMT-weighted 95th percentile for each day of the week (shown as planning time index on the chart).

Day of the Year (e.g., Mondays)

Section 1 — *(72,000 values for each day)*

Section 2 — *(72,000 values for each day)*

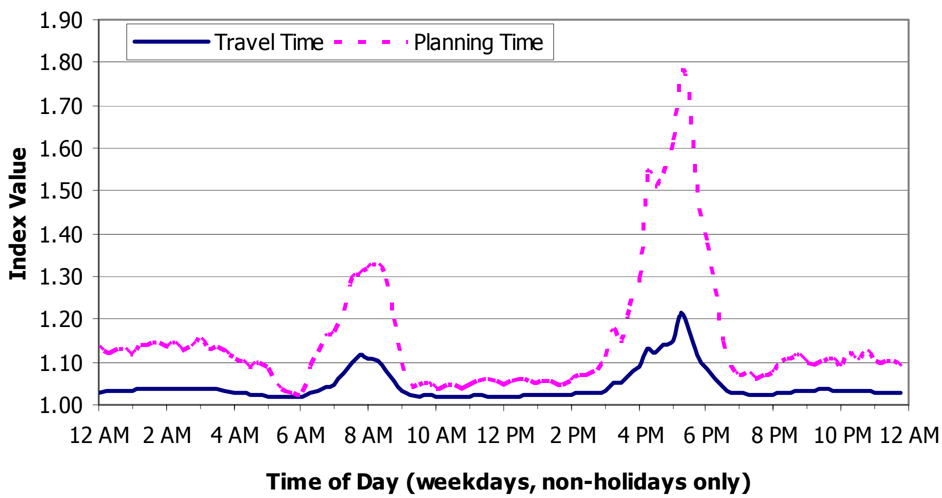
Section 3 — *(72,000 values for each day)*

. . . Other Sections

72,000 values = 12 5-minute values for 24 hours of 250± non-holiday weekdays in a year.

AVERAGE MOBILITY AND RELIABILITY BY TIME OF AN AVERAGE WEEKDAY

The travel time index values are grouped for by <u>analysis section and each 5-minute period of the day</u>. For 5-minute data, each group should have about 250 values (i.e., there are about 250 weekdays in each year). The average and 95th percentile travel time index values are computed for each of these groups. Section values are combined into values for each 5-minute time period using vehicle-miles traveled (VMT) as the weighting factor. This yields a VMT-weighted average every 5 minutes (shown as a travel time index on the chart) and a VMT-weighted 95th percentile every 5 minutes (shown as a planning time index on the chart).



5-Minute Period of Interest

Section 1 | Section 2 | Section 3 | . . . Other Sections

(250 values) *(250 values)* *(250 values)*

250 values = One value for each non-holiday weekday.

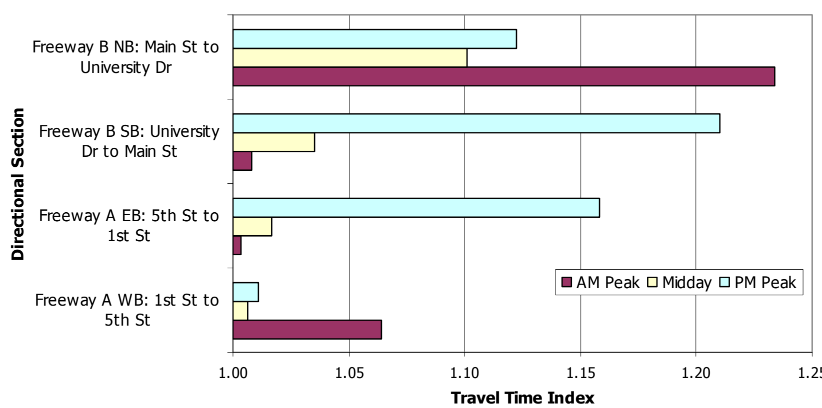
AVERAGE MOBILITY AND RELIABILITY BY SECTION AND TIME PERIOD

The base data travel time index values are grouped by <u>analysis section and time period of the day</u>. Average and 95th percentile travel time index values are computed for each group. The travel time index and buffer time index are then reported for the morning peak, mid-day and evening peak periods. The average and 95th percentile values for the morning and evening peak periods are combined into time period averages using vehicle-miles of travel (VMT) as the weighting factor. This yields a single VMT-weighted average for each section (shown as average peak period travel time index in the table) and a single VMT-weighted 95th percentile for each section (used to calculate buffer time index in the table). Average peak period values are calculated in the same manner, with the vehicle-miles of travel used to weight the morning and evening peak values.

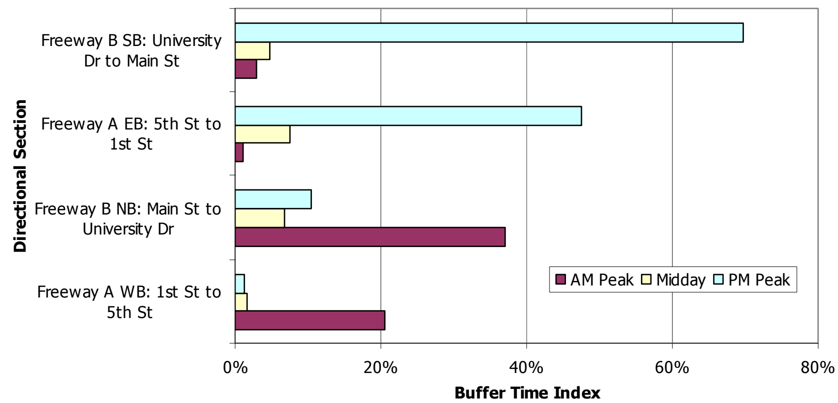
Mobility and Reliability by Section and Time Period

Section	Length (mi)	Travel Time Index				Buffer Time Index			
		AM Peak	Midday	PM Peak	Avg. Peak	AM Peak	Midday	PM Peak	Avg. Peak
Freeway A EB: 5th St to 1st St	4.00	1.00	1.02	1.16	1.11	1%	8%	47%	33%
Freeway A WB: 1st St to 5th St	4.00	1.06	1.01	1.01	1.04	20%	2%	1%	13%
Freeway B NB: Main St to University Dr	3.10	1.23	1.10	1.12	1.18	37%	7%	10%	24%
Freeway B SB: University Dr to Main St	3.10	1.01	1.04	1.21	1.13	3%	5%	70%	43%
Average for all Sections		**1.07**	**1.03**	**1.12**	**1.10**	**17%**	**5%**	**33%**	**25%**

Original data (5-minute average and 95th percentile travel time and volume) is compiled for a section for all weekdays. Values for each section are combined into time period averages using vehicle-miles traveled (VMT) as the weighting factor.



Average peak period values are calculated in the same manner, with the vehicle-miles of travel used to weight the morning and evening peak values.



Time Period for Analysis

Section 1 for the Period	Section 2 for the Period	Section 3 for the Period	. . . Other Sections for the Period
(9,000 values for AM or PM Peak)	*(9,000 values for AM or PM Peak)*	*(9,000 values for AM or PM Peak)*	

9,000 values = 12 5-minute values per hour for each of the three hours in a peak period; 250± non-holiday weekdays in a year. Other file sizes:

Early AM – 6 hours – 18,000 values
Midday – 7 hours – 21,000 values
Late PM – 5 hours – 15,000 values

Average Peak Period

Section 1		Section 2		Section 3		. . . Other Sections
AM Peak	PM Peak	AM Peak	PM Peak	AM Peak	PM Peak	
(9,000 values)	*(9,000 values)*	*(9,000 values)*	*(9,000 values)*	*(9,000 values)*	*(9,000 values)*	

9,000 values = 12 5-minute values per hour for each of the three hours in a peak period; 250± non-holiday weekdays in a year. Other file sizes:

Early AM – 6 hours – 18,000 values
Midday – 7 hours – 21,000 values
Late PM – 5 hours – 15,000 values

SUMMARY

Reliability measures have several potential uses, but the practice of estimating or collecting measures is only beginning. Some conclusions appear valid at this point, but there are also many questions. There is relatively little archived travel time and speed data in relation to the amount of traffic volume count data, few cities collect the type of information needed, and the measures have not been widely tested with either professional or non-technical audiences.

Travel reliability measures attempt to quantify one important element of the traveler or system user experience—the variation in travel time. Several surveys, including those conducted by the U.S. Department of Transportation (14) at a national level and those performed as local area or individual project evaluations, report that travelers are concerned about unpredictable travel times. The causes of variation range from the predictable—work zones, special events and weather—to the unpredictable—collisions, vehicle breakdowns—and also include causes that might be characterized as systemic—regular daily traffic volume changes, traffic operation equipment variations.

Analyses of travel reliability can take many forms and can produce significantly different results depending on the types of variation studied or included and the audience, purpose of use of the resulting statistics. This report provides a checklist of the key decisions that should be made and several "unknowns" that require assumptions, and additional research or experimentation to improve reliability performance measures. The factors listed below should be considered as the measures are applied in different situations:

- Mode-neutral measures or measures that are compatible with multimodal analyses appear desirable. Just as mobility concerns are increasingly addressed with several modes, programs and strategies in a corridor, so too might reliability levels be a product of multiple improvements.
- Trip type and the location of travel may relate to the perception of reliability. The measures and calculation procedures should allow for differences in urban and rural travel condition targets.
- Measures that control for the effects of length and time also appear desirable. From a communication and analyses standpoint, the determination of reliability for a long intercity trip may involve an acceptable variation in the trip time that may not be related to the length of the trip. Urban travelers or freight haulers with trip distances that are shorter than intercity trips, however, may incorporate a percentage of trip time as the method of distinguishing reliability concerns.
- There are several audiences for reliability measures. A set of measures may be necessary and desirable for communicating with the public as well as using these measures to evaluate the transportation service provided to travelers and shippers.
- There is a range of area sizes to which the measures might be applied. Facilities, corridors, and regions might require different measures or techniques to assess the reliability for travelers, or for the system.

RECOMMENDED MEASURES

It may be appropriate to track several reliability performance measures and test the effort needed to calculate, analyze and communicate them. There is no single agreed-upon measure, and no customer/user market research has been performed. Even for these measures it is not certain what level of reliability or variability (e.g., 5%, 10%, 15%) should be examined. The measures that look the most promising or may provide some good material for other analyses are:

- **Percent variation**—The amount of variation is expressed in relation to the average travel time in a percentage measure. To use this measure, the traveler would multiply the average travel time by the percent variation to get the time that should be used to plan the trip. The resulting value would indicate the travel time needed for 85% of the trips. Higher values indicate less reliability. The percentage value is distance/time neutral, which makes it more flexible, but it should also be applied to trips of similar distances.
- **Misery Index**—This measure focuses on the length of delay of only the worst trips. The average travel rate is subtracted from the upper 10%, 15% or 20% of travel rates to get the amount of time beyond the average for some amount of the slowest trips.
- **Buffer Time Index—**This measures the amount of extra time needed to be on time for 95% of the trips (late one day per month). Indexing the measure provides a time and distance neutral measure, but the actual minute values could be used by individual travelers/shippers or for particular trips. This measure is used as the reliability performance measure in the Mobility Monitoring Program reports (3, 4).

The initial Mobility Monitoring Program report for 2000 (3) compared these three measures. While the numerical values differed among the three measures, the relative ranking was the same for the three measures in both city and corridor comparisons. This indicates that the three measures provide basically the same analytical conclusions, although they may be useful in different ways. The 2001 data year Mobility Monitoring Program report (4) used the Buffer Time Index as the reliability reporting measure.

REFERENCES

1. Research Plan for Providing a Highway System with Reliable Travel Times. Future Strategic Highway Research Program, National Comprehensive Highway Research Program Project 20-58(3). Draft Report, March 2003.

2. The 2002 Urban Mobility Report. Sponsored by Departments of Transportation in California, Colorado, Florida, Kentucky, Maryland, Minnesota, New York, Oregon, Texas and Virginia, 2002; (http://mobility.tamu.edu/ums).

3. Lomax, T., Turner, S., and Margiotta, R. *Monitoring Urban Roadways in 2000: Using Archived Operations Data for Reliability and Mobility Measurement*. Texas Transportation Institute and Cambridge Systematics, Inc., December 2001. (http://mobility.tamu.edu/mmp).

4. Lomax, T., Turner, S., and Margiotta, R. *Mobility Urban Roadways in 2001: Examining Reliability and Mobility with Archived Data*. Texas Transportation Institute and Cambridge Systematics Inc., April 2003.

5. Ishimaru, J.M., Nee, J. and Hallenbeck, M.E. *Central Puget Sound Freeway Network Usage and Performance, 1999 Update, Volume 1*. Washington State Transportation Center, Seattle, Washington, September 2000.

6. Jackson, D. *Reliability as a Measure of Transportation System Performance*. Unpublished Master's Thesis, Texas A&M University, College Station, Texas, December 2000.

7. Shaw, T. and D. McLeod. *Mobility Performance Measures Handbook*. Florida Department of Transportation, Systems Planning Office, Tallahassee, Florida, July 1998.

8. Quantifying Congestion - Final Report and User's Guide National Cooperative Highway Research Program Project 7-13, National Research Council, NCHRP Report 398, 1997.

9. Booz-Allen & Hamilton, Inc. *1998 California Transportation Plan: Transportation System Performance Measures: Final Report*. California Department of Transportation, Transportation System Information Program, Sacramento, California, August 1998.

10. Albert, L.P. *Development and Validation of an Areawide Congestion Index Using Intelligent Transportation Systems Data*. Unpublished Master's Thesis, Texas A&M University, College Station, Texas, May 2000.

11. Wunderlich, K. *Preliminary Results from HOWLATE: DC Travel Reliability Study*. Mitretek Systems, April 2000.

12. Florida Department of Transportation. *Florida's Mobility Performance Measures Program. Summary Report*. Office of State Transportation Planner, Tallahassee, Florida, August 2000.

13. The Keys to Estimating Mobility in Urban Areas: Applying Definitions and Measures That Everyone Understands. Sponsored by Departments of Transportation in California, Colorado, Kentucky, Minnesota, New York, Oregon, Pennsylvania, Texas and Washington, 1998 (http://mobility.tamu.edu).

14. Keever, David B., Weiss, Karen E., and Quarles, Rebecca C. *Moving Ahead: The American Public Speaks on Roadways and Transportation in Communities*. Federal Highway Administration, February 2001.