SHRP 2 Reliability Project L17

Gap Filling Project 5: Guidebook: Placing a Value on Travel Time Reliability

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Gap Filling Project 5: Guidebook: Placing a Value on Travel Time Reliability

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

Gap Filling Project 5: Guidebook: Placing a Value on Travel Time Reliability

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Kittelson & Associates, Inc.
Reston, Virginia

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CHAPTER 1 – WHY IS VALUING TRAVEL TIME RELIABILITY IMPORTANT?

Travelers desire reliable travel times on the roadway system. Unexpected travel delays create frustration and increased costs both for private vehicle users and those engaged in freight transport. Transportation Systems Management and Operations (TSM&O) improvements address the causes of recurring and nonrecurring congestion and can make travel times more reliable. The challenge is in determining which TSM&O improvements will be most effective in improving reliability in a given situation. Effectiveness can be judged by quantifying an improvement's costs and benefits. While the costs for implementing and maintaining TSM&O improvements can be determined through traditional means, no common method is available for quantifying the benefits of improving travel time reliability. If reliability benefits and costs could be calculated, TSM&O improvements could be compared against capacity and safety improvements to determine the most cost-effective investments.

Thus, the purpose of this guidebook is to provide guidance on valuing travel time reliability. Some information is currently available in this emerging area. However, more-comprehensive research is needed. Until that research has been completed, this guidebook will serve as an interim resource on valuing travel time reliability.

The remainder of this guidebook is explains the following chapters:

1. Understanding the concept of travel time reliability
2. Agency experiences in measuring reliability
3. Calculating user benefits of travel time reliability

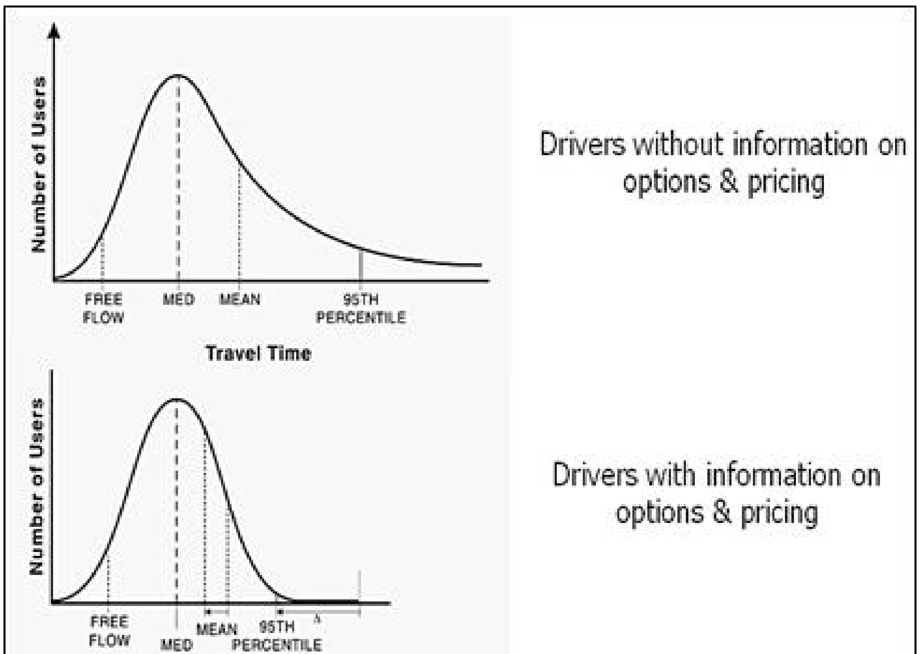
Appendix A presents a review of both U.S. and international literature on travel time reliability.

CHAPTER 2 – UNDERSTANDING THE CONCEPT OF TRAVEL TIME RELIABILITY

Defining Reliability

Reliability, by its nature, implies something about the certainty or stability of travel time for any particular trip under repetition. As such, reliability is closely associated with the statistical concept of variability. Variability can result from the difference in the mix of vehicle types on the roadway for the same flow rates, differences in driver reactions under various weather and driving conditions, and differences in delays experienced by different vehicles at intersections, as well as random incidents such as vehicle breakdown and signal failure. Variability in network travel times introduces uncertainty for travelers in that they do not know with certainty when they will arrive at their destinations (Liu et al. 2004).

When the distribution of travel times is reduced, variability is reduced and reliability is improved. This concept is illustrated in Figure 1.



Source: Kittelson & Associates (2011b).

Figure 1. Improving travel time reliability.

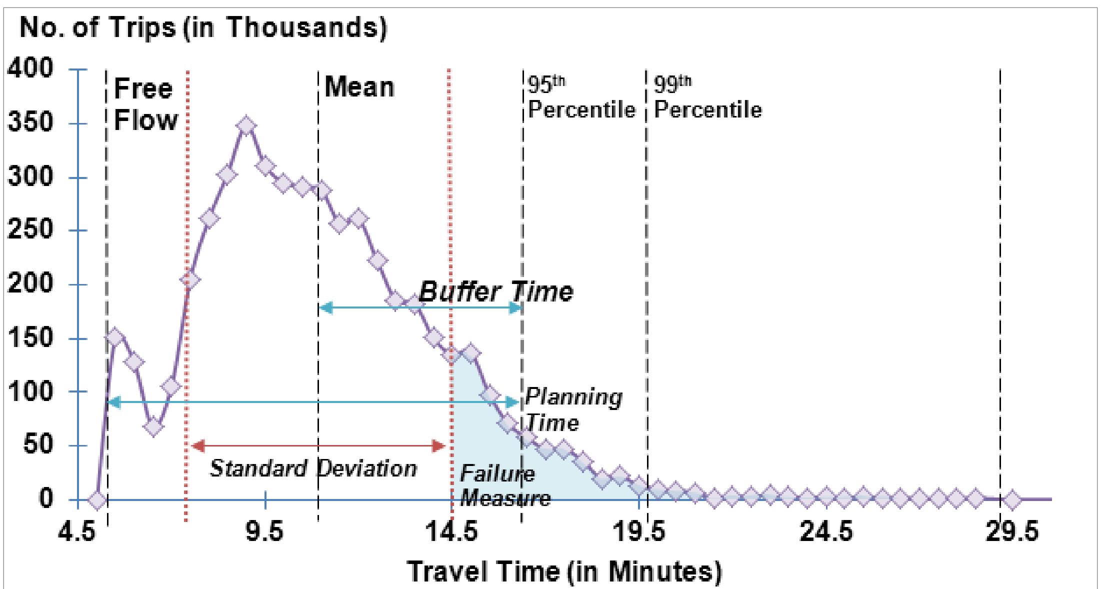
A variety of performance measures have been developed to describe travel time variability. This term was defined in the Phase 1 interim report prepared by Kittelson Associates, Inc., and its subconsultants (August 2011). The interim report was prepared for the SHRP 2 L08 research project, Incorporating Travel Time Reliability into the *Highway Capacity Manual*.

Another SHRP 2 project, L03 (Analytical Procedures for Determining the Impacts of Reliability Mitigation Strategies), examined the potential performance measures used to describe travel time reliability and recommended those in Table 1. The recommendations were based on examining measures in use in the United States and other parts of the world. All of the measures can be easily created once the travel time distribution is established. (See Figure 2 for an illustration of how the various performance measures relate to a single distribution.) Because of the need to normalize travel time, the Travel Time Index was used as the variable of interest in SHRP 2 Project L03, so the base distribution is actually based on the distribution of the Travel Time Index, not raw travel times.

Table 1. Reliability Performance Metrics from SHRP 2 Project L03

Reliability Performance Metric	Definition(s)	Units
Buffer Index (BI)	• The difference between the 95th percentile travel time and the average travel time, normalized by the average travel time • The difference between the 95th percentile travel time and the median travel time, normalized by the median travel time	None
Failure and on-time measures	• Percentage of trips with travel times less than 1.1 × median travel time *or* 1.25 × median travel time • Percentage of trips with space mean speed less than 50 mph; 45 mph; or 30 mph	Percent
80th percentile Travel Time Index	80th percentile travel time divided by the free-flow travel time	None
Planning Time Index	95th percentile travel time divided by the free-flow travel time	None
Skew statistic	The ratio of (90th percentile travel time minus the median) divided by (the median minus the 10th percentile)	None
Misery Index (modified)	The average of the highest 5% of travel times divided by the free-flow travel time	None
Standard deviation of travel time or travel rate[a]	Standard statistical definition	Minutes

[a] Not included in the SHRP 2 Project L03 recommendations, but added here. See text.
Source: Cambridge Systematics, Inc. (2010).



Source: Example travel time distribution from I-75 Northbound, Atlanta.
Slide provided by Rich Margiotta of Cambridge Systematics.

Figure 2. *Alternative metrics for characterizing a travel time distribution.*

SHRP 2 Project L03 research demonstrated that the Buffer Index can be an unstable measurement for tracking trends over time, in part because of its linkage to two factors that change (average and 95th percentile travel times); if one changes more in relation to the other, counterintuitive results can appear.

Note that *standard deviation of travel time* or *travel rate* appears in Figure 2. Project L03 did not define this as a reliability performance metric, but it is added here because several subsequent SHRP 2 projects indicated that it is useful in costing reliability and in modeling traveler choices. Project L03 provided predictive methods for the standard deviation even while leaving it off its list of useful performance measures because of the difficulty in explaining it to nontechnical audiences.

The advantage of using standard deviation for calculating user benefits of reliability is that it represents an absolute value, rather than a relative value as represented by measures such as the Buffer Index. Standard deviation represents a plus-or-minus value such that, given the values for average travel time and standard deviation, there is roughly a 70% chance that the travel time in any one day will fall within one standard deviation of the average value. For example, in Figure 2 the mean travel time is about 10.5 minutes and the standard deviation of the travel time is about 6 minutes; thus, the traveler can expect to experience a travel time between 7.5 minutes and 14.5 minutes about 70% of the time.

Placing a Value on Reliability

Value of travel time (VOT) refers to the cost of time spent on transport, including both waiting time and actual travel time. VOT includes costs to consumers of personal (unpaid) time spent on travel and costs to businesses of paid employee time spent in travel (Victoria Transport Policy Institute 2011).

The U.S. Department of Transportation's (DOT) recommended values of travel time are shown in Table 2. The value of travel time as a percentage of the wage rate is converted to a dollar value using wage data from the Bureau of Labor Statistics for business travel and truck driver wage rates. The median household income from the U.S. Census Bureau is used for personal travel. The U.S. DOT guidance for truck travel time is similar to the cost-approach–based method, with 100% of the full driver compensation recommended for the truck-driver value of time.

Table 2. U.S. Department of Transportation Values of Travel Time (2009 dollars)

User Group	Value of Time as Percentage of Wage Rate	Recommended National Hourly Earnings Rate (2009 dollars)	Value of Time (dollars per person hour)
Local travel			
Personal	50%	$23.90	$12.00
Business	100%	$22.90	$22.90
All purposes			$12.50
Intercity travel			
Personal	70%	$23.90	$16.70
Business	100%	$22.90	$22.90
All purposes			$18.00
Truck drivers	100%	$23.70	$23.70

Source: Office of Transportation Policy (2011).

The time values for the business and truck driver groups may not reflect their true societal costs because these do not include indirect costs. For example, a proper accounting for the hourly value of truck travel would include the inventory time value of the cargo and the cost of the vehicle itself. In a case study of benefit-cost analysis of regional transportation plan alternatives, a value of $75/hour in 1996 dollars—or about four times the average hourly rate for truck drivers—was used; that rate was based on a survey of quoted rates from truck rental firms for the hourly cost of a truck and driver (ECONorthwest 1996).

The *value of reliability* (VOR) represents the cost of (un)reliability in monetary terms and is calculated as the ratio of travel reliability and travel cost (Carrion and Levinson 2010).

The *reliability ratio* (RR) is the ratio of the value of 1 minute of standard deviation (i.e., VOR) to the value of 1 minute of average travel time (VOT). Thus, RR = VOR/VOT. (Bhouri and Kauppila 2011).

Previous studies have suggested that the reliability ratio can produce a broad range of values, as shown in Table 3.

Table 3. Summary of Selected Studies

Study	Data Type	Observations	Average RR	Min	Max
Black and Towriss (1993)	SP	1	0.55	na	na
Ghosh (2001)	SP & RP	7	1.17	0.91	1.47
Yan (2002)	SP & RP	19	1.47	0.91	1.95
Small et al. (2005)	SP & RP	2	0.65	0.26	1.04
Bhat and Sardesai (2006)	SP & RP	1	0.26	na	na
Hollander (2006)	SP	1	0.10	na	na
De Jong et al. (2007)	SP	3	1.35	0.74	2.4
Asensio and Matas (2008)	SP	1	0.98	na	na
Tilahun and Levinson (2009)	SP	1	0.89	na	na
Li et al. (2010)	SP	6	0.70	0.08	1.59
Carrion and Levinson (2010)	RP	6	0.91	0.47	1.20
Carrion and Levinson (2011)	RP	2	0.91	0.69	1.12

Note: RR = reliability ratio = VOR/VOT; SP = stated preference; RP = revealed preference; na = not applicable.
Source: Carrion and Levinson (2012), Table 1.

The *time savings benefit* (TSB) is the number of minutes of journey time savings ($\triangle$TT) plus the improvement in the standard deviation of travel time ($\triangle$STD).

$$TSB = (\triangle TT * VOT) + (\triangle STD * RR * VOT)$$

Data Sources for Valuing Reliability

A *stated preference* (SP) survey is, in a travel time reliability context, a questionnaire consisting of hypothetical route choices that are intended to determine travelers' values of time based on their sensitivities to shifting their travel route, cost of travel, and/or time of travel.

A *revealed preference* (RP) survey is, in a travel time reliability context, a survey based on direct observation of travel behavior used to determine a traveler's value of time when faced with travel route, cost of travel, and/or time of travel alternatives.

Different methods for conducting stated and revealed preference surveys are described in Table 4.

Table 4. Summary of Data Collection Techniques in Route Choice Studies

Method	Data Type	Features	Examples
Questionnaires with hypothetical scenarios	SP	Controlled choice situations; unrivaled freedom in defining choice situations, alternatives, and variables; automatic format for fast data processing	Jackson and Jucker (1982); Pal (2004); Abdel-Aty et al. (1997); Tilahun and Levinson (2007); Khattak et al. (1993)
Questionnaires with hypothetical scenarios including visual aids	SP	Inclusion of subjects unfamiliar to a specific analysis area; clear presentation of choices and variables	Tilahun and Levinson (2006); Goldin and Thorndyke (1982); Bartram (1980)
Computer-based simulator	SP	Interactive systems under controlled choice situations; flexible and dynamic regulation of subject's interaction with the environment	Mahmassani and Herman (1989); Leiser and Stern (1988)
Fixed-base vehicle simulators	SP	Dynamic virtual environments with colors, perspectives, and image combinations; simulation of weather and light conditions	Blaauw (1982); Scott (1985); Godley et al. (2002)
Virtual experience stated preference (VESP)	SP	Physical simulators used to generate dynamic environments; subjects monitored during the experiment; several scenarios followed by the subjects, as assigned by the researcher	Levinson et al. (2004); Levinson et al. (2006)
Field experience stated preference (FESP)	SP	Global positioning system (GPS) devices used in subjects' vehicles; subjects' routes and origin–destination pair assigned by the researcher	Zhang and Levinson (2008)
Field self-completion questionnaires	RP	Maps and images provided to help the subjects mark their preferred routes	D'Este (1986); Duffell and Kalombaris (1988)
Field Interviews	RP	Choices reported by subjects by phone or in-person; researcher able to extract information about perception	Small et al. (2005); Small et al. (2006)
Stalking and shadowing	RP	Subjects followed stealthily to determine their preferred routes	Chang and Herman (1978)
Field GPS tracking.	RP	GPS devices used to track very detailed trip data for each subject	Li et al. (2004); Li et al. (2005); Li (2004)
Actual commute experience revealed	RP	See section 3 of source document (Carrion and Levinson 2010).	None[a]

[a] The authors (Carrion and Levinson 2010) do not know whether there are other similar studies.
Source: Carrion and Levinson (2010), Table 3.

Little research has been done on how the value of travel time reliability may vary for different traveler groups. Examples of travelers who place high values on travel time reliability include employees who have to be at work at specific times and persons who have to pick up children at day care to avoid a late-time penalty. Surveys of users of the SR-91 toll lanes in Orange County, California, showed that when prices on the toll lanes rose, travelers in the lowest income group did not reduce their travel, but moderate income travelers did (FHWA 2013). This suggests that travelers with lower incomes have less flexibility in their travel time (Kuehn 2009).

Freight travel also shows a strong preference for reliability. As discussed in the literature scan sections in Appendix A, surveys of shippers indicate that they place a high value on travel time reliability. The increasing use of just-in-time inventories at manufacturing facilities places even more pressure on shippers to deliver on time.

Agency Experiences in Using Reliability

The information in this section is excerpted from Appendix A of the SHRP 2 Project L11 final report, *Evaluating Alternative Operations Strategies to Improve Travel Time Reliability* (Kittelson & Associates, Inc. 2013). The following is a summary of activities conducted by two public agencies to calculate and report on travel time reliability.

Washington State DOT

"The *Gray Notebook* is Washington State DOT's main performance assessment, reporting, and communication tool. [The *Gray Notebook* can be found at http://www.wsdot.wa.gov/accountability/default.html.] It provides quarterly, in-depth reports on agency and transportation system performance. The purpose of the *Gray Notebook* is to keep Washington State DOT accountable to the governor, the legislature, Washington State citizens, and transportation organizations.

"Included in the *Gray Notebook* is the Performance Dashboard, which is an overview of key performance indicators for each of the policy goals. The Performance Dashboard shows the current and previous performance mark for each measure. It indicates which way the program is trending, and why. Five policy goals or performance measures are included in the Performance Dashboard: safety, preservation, mobility and congestion relief, environment, and stewardship. The only measures related to travel time reliability are included under the mobility and congestion relief policy goal as follows:

- Average clearance time (in minutes) for major (≥90 minute) incidents on key Puget Sound corridors; and
- Annual weekday hours of delay statewide on highways compared to maximum throughput (51 mph), in thousand hours."

Washington State DOT also maintains a performance measurement library with links to other states' performance measurement websites: http://www.wsdot.wa.gov/Accountability/Publications/Library.html.

Georgia Regional Transportation Authority

"The Georgia Regional Transportation Authority produces an annual report, titled the *Transportation Metropolitan Atlanta Performance (MAP) Report,* which describes the region's progress toward improving mobility, transit accessibility, air quality, and safety. Included…are the following [performance] measures to track highway mobility:

- *Freeway travel time index*. The travel time index is the ratio of the average travel time over the free-flow travel time obtained for a certain portion or segment of the freeway system. For [the MAP] report, measurements were created by using Georgia DOT's NaviGator video detection cameras.

- *Freeway planning-time index*. Two travel time reliability measures are reported: the planning-time index (PTI) and the buffer-time index (BTI). Measurements for the planning-time index were created using Georgia DOT's NaviGator video detection cameras…
- *Daily vehicle miles traveled per licensed driver per person*. This measures the average distance each licensed driver in the region drives each day."

The following safety measure is also reported. This measure indirectly affects travel time reliability:

- "Roadway clearance time is defined as the 'time between first recordable awareness (detection/notification/verification) of an incident by a responsible agency and first confirmation that all lanes are available for traffic flow.' The response time is the time between the first recordable awareness of an incident and the first arrival by a responder on scene."

CHAPTER 3 – INCORPORATING RELIABILITY BENEFITS INTO BENEFIT-COST ANALYSIS

Introduction

This chapter presents methods for incorporating travel time reliability into a benefit–cost analysis. The principles of benefit-cost analysis are well explained in texts on the topic, such as Mishan (1976), and won't be elaborated on here. Small (1999) presents a detailed discussion of the application of benefit-cost analysis to transportation project evaluation.

Evaluation of reliability is only a part of a full benefit-cost analysis. In particular,

- Transportation projects that reduce travel time often improve reliability, and vice-versa. Thus, travel time benefits must be included along with reliability benefits as part of project evaluation.
- Benefits and costs take place over time. Benefit-cost analysis therefore entails calculating the *net present value* of benefits and costs over the lifetime of the project. Capital costs occur at the beginning of the project lifetime and are therefore discounted less than benefits, which occur after the project is completed. The discount rate is typically taken to be marginal productivity of capital plus an added percentage for risk. Current guidelines from the Office of Management and Budget specify a 2.0% real interest rate for programs with a lifetime of 30 years or more (Office of Management and Budget 2011).
- Benefits and costs are calculated with reference to a *base alternative*, which represents the condition under which no project is undertaken.

The results of benefit-cost analysis are typically expressed as one or both of the following:

- *Net present value* (NPV) is the difference between total discounted benefits and total discounted costs.
- *Benefit-cost ratio* (BCR) is the ratio of total discounted benefits to total discounted costs.

Benefit-cost ratio is easy to understand, but the analyst must adhere to a strict definition of benefits and costs to maintain consistency in what goes into the numerator and denominator. For example, a reduction in "disbenefits" such as air pollution could be treated as a positive benefit or a negative cost. Net present value avoids this problem.

The purpose of benefit-cost analysis is to help managers and decision makers rank project alternatives. Because of the uncertainties in establishing a value of reliability under some of the methods discussed here, any benefit-cost analysis should include a test of sensitivity of project rankings against different values of the reliability ratio. This is a key precept of integrated transportation planning, which is based on benefit-cost analysis (Reinke and Malarkey 1996).

Given the uncertainties in RR, the value of RR should be varied by a factor ranging at least from 0.5 to 2.0. Wider variations may be required in cases with greater uncertainty about how to value reliability or with a wide range of travelers who would be expected to value reliability differently. If the ranking of project alternatives does not change with differing values of reliability, the ranking can be considered robust. Otherwise, both the values placed on reliability and the forecasts of reliability for the alternatives should be reviewed to determine under which conditions the value of reliability makes a significant difference in the ranking.

Methods for Valuing Travel Time Reliability

Overview of Methods

The 2004 European Transport Conference Proceedings report provides an overview of three approaches for determining the value of travel time reliability in passenger transport (De Jong et al. 2004):

1. *Mean-variance approach.* Unreliability is measured as the standard deviation (or variance) of the travel time distribution. The valuation of the standard deviation can be derived from a stated preference (SP) survey by including both a representation of the variance and the mean travel time as attributes.
2. *Percentile of the travel time distribution*. Unreliability is measured as the difference between the 80th or 90th percentile of the travel time distribution and the mean. Again the valuation can be derived from SP experiments among travelers. Hjorth and Ramjerdi (2011) argue, however, that percentiles are merely a variation of the mean-variance approach.
3. *Scheduling models*. Unreliability is measured as the number of minutes that a traveler will depart or arrive earlier or later than preferred (schedule delay). This can also be offered as an attribute in an SP experiment, together with other attributes such as journey duration and travel cost.

At least two additional approaches have been identified:

4. *Options theoretic approach.* Well-established techniques exist in economics for estimating the value of an opportunity whose future value is not known with certainty but can be described in terms of probabilities. The value of reliability is determined based on the difference in mean travel time a traveler would be willing to "pay" to convert an unreliable trip into one with a guaranteed travel time. This difference in travel times, multiplied by the value of time (determined independently) gives the value of reliability (Pozdena 2011). This method avoids the need to conduct SP and/or RP experiments. Furthermore, the calculation of reliability benefits is incorporated directly into the calculation of travel time benefits. Randall Pozdena developed this technique in 2002 and first applied it for the Puget Sound Regional Council in July 2007 (Puget Sound Regional Council 2009).
5. *Default value approach.* The international literature scan shows that many countries simply apply a default value for reliability (generally assumed to be at or near the value of time), based on a review of SP and/or RP results in the literature and sometimes also incorporating local, country-specific data.

An overview of these methods is presented in Table 5.

Table 5. Comparison of Travel Time Reliability Estimation Methods

Method	Overall Data Needs	Strengths	Weaknesses
Mean-variance	Travel time distribution (average travel time and standard deviation)	Easier to apply and model; requires only travel time distribution	May not capture travel time variations by trip purpose (i.e., work x leisure)
Percentile	50th, 80th, 85th, 90th, or 95th percentiles of travel time distribution	Easier to apply and model; requires only travel time distribution	May not capture travel time variations by trip purpose (i.e., work x leisure)
Scheduling	Travel time distribution based on a preferred arrival time	More accurately captures travelers' reaction to travel time reliability	Requires detailed information on users' schedules and arrival time (more extensive RP/SP)
Options theoretic	Speed distribution, volume by vehicle type, risk-free interest rate	No need to conduct RP and SP surveys	Not widespread in transportation engineering; conceptual framework may be more difficult to understand
Default value	Existing VOT and VOR values	Easy to apply and understand; no need to model travel time distribution	Can cause excessive generalization because values are captured from the literature

After reviewing the strengths and weaknesses of each method, the team recommends that the analyst choose among the following methods: mean-variance, options theoretic, and default value. The following sections discuss these three methods in more detail.

The Mean-Variance Approach

Method summary. In SP experiments, respondents are given alternative choices: average travel time, a set of 5 to 15 possible individual trip travel times (sometimes presented graphically), and (optionally) travel costs. The researcher calculates the variance for each set of travel times or—more likely—generates the travel times consistent with a target variance. The average travel time and variation in individual trip times can be constructed so that they are not or are only lightly correlated between observations. A utility function is then developed from the SP data that includes both the mean travel time and the standard deviation of travel time. From this function, the ratio of the coefficient for the standard deviation of travel time and the coefficient of the mean travel time can be calculated. The result gives the disutility of a minute of standard deviation of travel time in terms of minutes of mean travel time. A monetary value for unreliability can be derived by combining the disutility with a value of travel time (or directly if travel cost is also in the utility function).

Data applications. Volumes of travelers by user group (e.g., commuters, truckers); an estimate of how a reliability treatment will affect the future mean travel time and the standard deviation of travel time.

The Options Theoretic Approach

Note: Experts have disagreed on the validity of the options theoretic approach described here and more fully discussed in Appendices B and C of the SHRP 2 Reliability report for Project L11, *Evaluating Alternative*

Operations Strategies to Improve Travel Time Reliability. SHRP 2 is also further evaluating the options theoretic approach as part of a pilot test through the L35 project.

Method summary. Well-established techniques exist in economics for estimating the value of an opportunity whose future value is not known with certainty but can be described in terms of probabilities. Thus, individuals may purchase options that give them the right to exercise an opportunity (e.g., to buy or sell something) at a specific point in time, or up to a specific point in time, depending on the type of option. A car insurance policy is an example of an option—individuals pay an insurance premium to obtain the opportunity to guarantee that they will avoid paying a significantly larger sum in the unlikely event of an accident. So-called real options involve the analysis of things that are not readily traded. Continuing with the insurance-theme, an individual can, for example, purchase insurance that a communications satellite will perform at a certain level for a certain period of time, or that the individual will be covered for unexpected travel expenses because of a delay caused by sickness, volcanic eruptions, and so on. In theory, if such a product were available, motorists might be willing to pay a premium for travel time insurance to compensate them for travel times exceeding a guaranteed level. As this insurance is hypothetical and would involve compensation for time loss rather than a direct monetary loss, it can be considered a type of real option.

The value of hypothetical travel time insurance represents the reduced, guaranteed speed that motorists would be willing to accept in exchange for insurance that speeds would never fall below the guaranteed value. Instead of paying the premium with money, the premium would be paid in the form of travel time. Under unreliable conditions, motorists would experience a mean travel speed x and would risk that their travel time might occasionally be very long. With travel time insurance, motorists would be provided with a reduced, guaranteed minimum speed of y ($y < x$). The difference in speeds between the risky x and the guaranteed y can be converted to an increased travel time over the study roadway (i.e., the insurance premium); this travel time can then be converted into a monetary value based on an assumed value of time.

The mathematics of determining this value is derived from options theory in economics (Black and Scholes 1973). For typical applications, the guaranteed speed is taken as the mean travel time, and the length of the option period (insurance policy) is taken as the travel time required to travel the length of the roadway facility at the lowest 1% speed. For rare-event applications, the variable used for the guarantee could be event duration or the number of events during the life of the project. The options theoretic approach offers the potential for quickly estimating the value of travel time reliability improvements, without the expense of conducting RP or SP surveys. Furthermore, to date, very few RP surveys have been conducted on travel time reliability, while SP surveys suffer from (1) the challenge of trying to explain travel time and reliability scenarios to survey participants in a comprehensible manner and (2) potential biases inherent in the phrasing of survey questions.

A detailed explanation of the options theoretic approach applied to calculating reliability benefits is presented in Pozdena (2011).

Because the options theoretic approach was a novel extension of real options theory when it was first proposed for valuing travel time reliability, experts on options theory and finance were asked to review the concept. The experts were split on its applicability. Some believed the concept was interesting but required further research to compare RP and SP values of reliability with those produced by the proposed approach. Other experts took no issue with the approach. Still others felt that the method was at least appropriate for ranking alternatives, even if they lacked confidence in the absolute meaning of the values it produced.

In summary, experts are split on the suitability of the method and indicate the need for more comparisons with RP and SP data to prove or disprove the method's usefulness. The method is by no means simple to explain to those without an economics background; and some of the economics-based phrasing used in the method (e.g., eliminating unreliability) may be confusing to transportation professionals who think in terms of minimizing unreliability instead of totally eliminating unreliability. Further, the insurance analogy only works to a point: the method estimates the equivalent value of unreliability, but an actual insurance policy would have added costs to cover the insurer's administrative costs and possible profit. Nonetheless, the options theoretic approach offers the advantage that it is grounded in generally accepted economic theory and is not subject to the uncertainties involved in using values derived from SP or RP surveys, which have been found to vary widely.

The options theoretic approach for valuing uncertainty in freeway travel times is currently in use at the Puget Sound Regional Council (2009). Freeway speed-volume functions in the regional travel model have been modified to account for the cost of unreliability. Council staff report that the incorporation of unreliability into the speed-volume functions has improved validation of the model against real-world observations.

Data applications. For all applications, volumes of travelers by user group and an assumed risk-free interest rate. For typical applications, an estimate of how a reliability treatment will impact the future mean travel speed and the lowest 1% speed is determined. For rare-event analysis, an estimate of how a potential mitigation treatment will affect event frequency and duration is determined.

The Default Value Approach

Method summary. SP experiments are expensive to conduct. Therefore, in the absence of local data, a number of countries have conducted a literature review on the value of reliability, observed the range of results found in the literature, and established a recommended value of reliability. The Appendix A section, International Literature, in this guidebook provides examples of default values used by various countries.

Data applications. Volumes of travelers by user group; an estimate of how a reliability treatment will affect the future mean travel time and the distribution of travel time.

In Summary

- The advantage of the *mean-variance approach* is that it can be used to determine the value of reliability on the basis of a travel time distribution measured for an existing condition and predicted for a future ("build") condition. The disadvantage of this approach is that it relies on values of travel time and reliability that must be derived from SP or RP surveys. *Agencies could consider applying this approach when detailed travel time and travel time reliability values are known (from SP or RP surveys) and when a benefit-cost comparison is needed to choose among capacity improvements, safety improvements, and reliability improvements.*
- The advantage of the *options theoretic approach* is that the calculations depend on travel speed distributions that are commonly available from field surveys or travel demand models. SP and/or RP data are not needed. The disadvantage of this approach is that it is not widely used in transportation engineering practice. *Agencies could consider applying this approach when assessing the benefit of implementing an areawide or regional plan for implementing managed lanes or when quantifying the impact on reliability of a TSM&O improvement that has been implemented.*
- The advantage of the *default value approach* is that it is easy to apply and understand and relies on value-of-time and value-of-reliability values obtained from the literature. The disadvantage

of this approach is that it provides generalized (approximate) results that may not be reasonable when comparing the benefit-cost values of TSM&O improvements with benefit-cost values for capacity or safety improvements*. Agencies could consider applying this approach when choosing among a group of alternative TSM&O treatments in one corridor. This would provide a preliminary side-by-side comparison among TSM&O alternative treatments.*

Applying the Approaches

This section presents flowcharts and sample problems for applying the three recommended approaches.

1. Define the general framework:

$$P = A\mu + B\sigma$$

where

P = user cost (time cost plus reliability cost), or the price of travel;

A = value of travel time ($/min);

μ = mean travel time (min);

B = value of reliability ($/min); and

σ = standard deviation of travel time (min).

2. Define data needs:

μ ; σ ; C

3. Define scenarios to be evaluated:

Estimate the travel times μ and the reliability σ for each scenario.

4. Use SP and/or RP surveys to determine general framework data needs/coefficients *A* and *B*:

This can be done via model estimation or it can be determined from the literature.

5. Compute the present values of total user time + reliability costs for each scenario:

- Calculate P_i^t the user costs in year *t* for each scenario *i*, where *i* = 0 corresponds to the base case;
- Calculate $U_i^t = P_i^t Q_i^t$, the total user costs in year *t* for each scenario *i*, where *i* = 0 corresponds to the base case, and where Q_i^t is the travel volume on the facility in year *t*; and
- Estimate C_i^t, the other costs (capital, operating, maintenance) for year *t* for each scenario *i*, where *i* = 0 corresponds to the base case.

Using an appropriate discount rate,

- Calculate U_i, the present value of user time cost for each scenario *I*; and
- Calculate C_i, the present value of capital + operating + maintenance costs for each scenario *i*.

6. Calculate the net user benefits/scenario *B_i* and calculate benefit-cost measures using NPV and/or BCR:

- Net user benefits for scenario *i* are calculated as: $B_i = U_0 - U_i$

$$NPV_i = B_i - C_i$$

$$BCR_i = \frac{B_i}{C_i}$$

Figure 3. *Flowchart 1: mean-variance approach.*

1. Define the general framework:

Certainty equivalent speed = average speed – speed equivalent of “insurance” to reduce speed variability (see step 3).

2. Define data needs:

- Speed distribution (speed variance, speed average, minimum 1% speed, interest rate);
- Segment length;
- Volume data by vehicle type; and
- Annualized risk-free interest rate.

3. Define scenarios/strategies to be evaluated:

For example, evaluate ramp metering strategy.

4. Calculate the certainty-equivalent value of reliability for each scenario:

For each scenario,

$$\begin{aligned} P(V_T, t) &= \text{ speed "insurance" equivalent of speed unreliability} \\ &= I \exp\left(-r(T-t)\right) N\left(d_1\right) - V_T N\left(d_2\right) \end{aligned}$$

where

$$\begin{aligned} T-t &= \text{ average time to traverse segment (in years)} \\ \alpha &= \text{ standard deviation of the log of speed} \\ \sigma &= \text{ speed volatility} \\ &= \frac{\alpha}{\sqrt{T-t}} \\ d_1 &= \frac{\ln(V_T / I) + (r + \sigma^2 / 2)(T-t)}{\sigma\sqrt{T-t}} \\ d_2 &= d_1 - \sigma\sqrt{T-t} \\ V_T &= \text{ desired speed} \\ I &= \text{ guaranteed speed} \end{aligned}$$

5. For each scenario, compute the travel time cost per user (P_i^t) as the time cost when traveling at the average speed minus the insurance speed calculated in Step 4:

$$P_i^t = \frac{D}{V_T - P\left(V_T, t\right)}$$

6. Compute the net values of user time costs and other costs as in Step 5 of Flowchart 1.

7. Calculate the net user benefits/scenario B*i*, and calculate benefit-cost measures using NPV and/or BCR as shown in Step 6 of Flowchart 1.

Figure 4. *Flowchart 2: options theoretic approach.*

1. Define the general framework:

Reliability ratio (RR) = *B/A*

where

A = value of travel time ($/h); and

B = value of reliability ($/h).

2. Define data needs:

A and RR, travel time savings (TT), standard deviation of travel time (STD).

3. Define scenarios to be evaluated as in Step 3 of Flowchart 1.

4. Use the literature to define appropriate values of RR for each scenario:

Always use caution when importing values from other studies. Understand the limitations of this method.

5. Calculate the user cost of travel for each scenario:

Estimate σ, the standard deviation of travel time for each scenario.

$$B = RR * A$$

Calculate P_i^t the user costs in year *t* for each scenario *i*, where *i* = 0 corresponds to the base case where

$$P_i^t = AT + B\sigma$$

6. Using the calculated values of P_i^t and the estimated annual other costs C_i^t as defined in Step 5 of Flowchart 1, compute the present values of user costs and other costs using the procedures in Step 5 of Flowchart 1.

7. Calculate the net user benefits/scenario B_i and calculate benefit-cost measures using NPV and/or BCR as shown in Step 6 of Flowchart 1.

Figure 5. Flowchart 3: default value approach.

Sample Problem

The following sample problem is a slightly modified version of the example in Pozdena (2011).

The Issue

The transportation agency oversees a stretch of highway that experiences significant and variable congestion in the a.m. peak period (6:00 a.m. to 10:00 a.m.). This facility is 10 miles long, running north–south, with the central business district at the north end of the facility. Graphically, the speed and variability characteristics of this facility are akin to those depicted in Figure 6. The large dip in speed around 8:00 a.m. reflects the slower commuting times during the peak, relative to the other time blocks on the facility. The variability or unreliability in speed (as measured by the standard deviation of speeds over the course of a year) also seems greater during the peaks.

As the a.m. peak period speed and variability suggest, users on the facility face additional costs in the form of extra time lost while traversing the facility because of travel time variability. The agency is interested in knowing the value of the time that would be saved if a strategy that would improve travel time reliability was implemented. This would help the agency perform a benefit-cost analysis for the strategy and decide whether it is worth implementing.

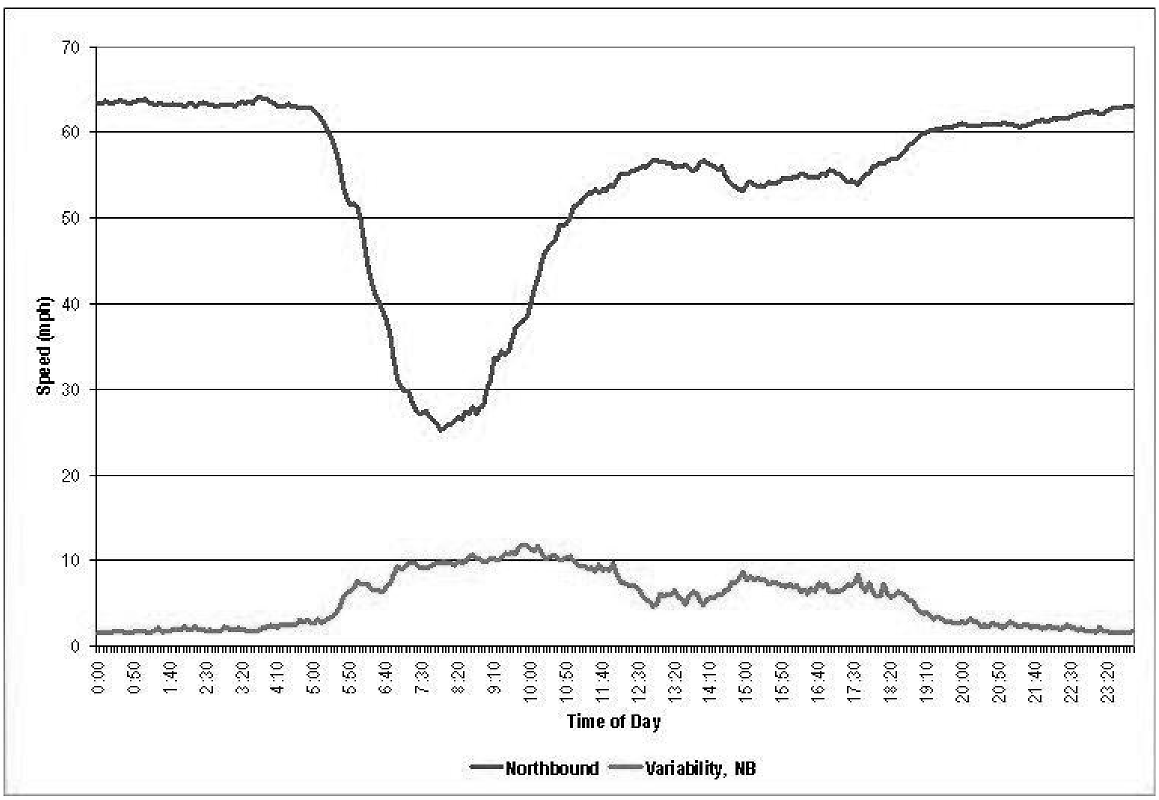


Figure 5. *Summary of data collection techniques in route choice studies.*

Under current operations the following occur during the a.m. peak period:

- Average speed = 32.67 mph;
- Standard deviation of speed = 12.28 mph;
- Average travel time = 18.67 min;
- Standard deviation of travel time = 7.84; and
- Average volume for 4-hour a.m. peak period = 14,000.

Assume that the alternative under consideration consists of “smart” systems. These include collision-warning systems and systems that automatically adjust cruise-control speed based on the relative distance of the car ahead. Both can reduce speed variability and travel time unreliability as they are widely adapted in vehicles. The new system would reduce the standard deviation of speed to an estimated 5.99 mph.

Assumptions for the new scenario are as follows:

- Vehicle volume remains constant over time (i.e., travel volume is the same in the base year and succeeding years);
- The alternative reduces travel time variability, but average travel time remains the same;
- Project lifetime = 30 years;
- Unknown speed (V_T) = 32.67 mph;
- Guaranteed speed (I) = 32.67 mph;
- Average travel time = 18.67 min;
- Standard deviation of speed = 5.99 mph;
- Standard deviation of travel time = 3.48 min; and
- Both base case and alternative scenario use DOT recommended value of $12.50/person hour of travel.

Mean-Variance Approach

Assume that travel time standard deviation is valued the same as travel time. The average cost per traveler is as follows:

Base scenario: ($12.50/60) * (18.37 + 7.84) = $5.459

Alternative scenario: ($12.50/60) * (18.37 + 3.48) = $4.551

Using these values results in a total user benefit calculation as shown in Table 6. These calculations are for the a.m. peak period only and assume 252 weekdays per year.

Table 6. Summary of User Benefit Calculations for Mean-Variance Approach

	Base	Alternative
Segment length (mi)	10	10
Average travel time (min)	18.37	18.37
Standard deviation of travel time (min)	7.84	3.48
Cost per traveler (value of time = $12.50/h)	$5.459	$4.551
A.m. peak period volume	14,000	14,000
Total traveler cost for a.m. peak period	$76,433	$63,716
Annual weekday a.m. peak period travel cost	$19,261,023	$16,056,423
Present value of user cost for a.m. peak period (30 years, 2% discount rate)	$431,378,636	$359,606,955
Present value of user benefits for a.m. peak period		$71,771,681

Options Theoretic Approach

For this example, the European Put option is employed for the following reasons:

- The European Put option provides the traveler's value of unreliability for each trip made, given the observed or expected speed variability. The value of unreliability can be multiplied by the number of commuters and work days to provide the commuter value of unreliability for a period of time, appropriate for the evaluation of a strategy.
- The European Put option is based on values of variables that are distributed log-normally, as is the speed data on a facility; thus it is a fitting application.

Calculate the speed equivalent for the base case:

A. A value of 5.00% risk-free interest rate is chosen.

Thus, r = 0.05

B. The contract length (T–t), is calculated as the travel time to cover the segment under consideration at the lowest 1% speed, determined using the mean log speed and the standard deviation of the log speed. For this example the lowest 1% speed is 13.22 mph and the segment is 10 miles long. The contract length is expressed in years because the interest rate is an annual rate.

$$T-t=\left(\frac{60/13.22}{365\times 24\times 60}\right)\times 10 = 0.0000863 \text{ years}$$

C. The certainty-equivalent value of reliability, $P(V_T,t)$, is calculated by first calculating σ, d_1 and d_2. σ is calculated using the formula for volatility in finance, which is the standard deviation of the log speed (α) divided by the square root of the contract length:

$$\sigma=\frac{\alpha}{\sqrt{(T-t)}}=\frac{0.3635}{\sqrt{0.0000863}}=39.12$$

$$d_1 = \frac{\ln(V_T / I) + (r + \sigma^2 / 2)(T - t)}{\sigma\sqrt{(T-t)}}$$

where

$V_T =$ desired speed = 32.67 mph; and

$I =$ guaranteed speed = $\overline{X}$ = 32.67 mph

Thus,

$$d_1 = \frac{\ln\left(\frac{32.67}{32.67}\right) + \left[0.05 + \left(\frac{39.12^2}{2}\right)\right] \times 0.0000863}{39.12 \times \sqrt{0.0000863}} = 0.18176$$

$$\begin{aligned} d_2 &= d_1 - \sigma\sqrt{(T-t)} \\ &= 0.18176 - 39.12\sqrt{0.0000863} = -0.18173 \end{aligned}$$

Evaluate the standard normal distribution at d_1 and d_2.

$$\begin{aligned} N(d_1) &= N(0.18175) = 0.4279 \\ N(d_2) &= N(-0.18174) = 0.57211 \end{aligned}$$

Calculate the speed equivalent of uncertainty.

$$\begin{aligned} P(V_T, t) &= Ie^{-r(T-t)} N(d_2) - V_T N(d_1) \\ &= 32.67e^{-0.05(0.0000086)}(0.57211) - 32.67(0.4279) \\ &= 4.71 \text{ mph} \end{aligned}$$

A commuter is willing to accept a reduction of 4.17 mph in his or her average speed to eliminate the travel time variability.

For the alternative:

The alternative offers a reduction in speed variance that in turn reduces the value of the standard deviation of the log of the speed α (speed variability) to 0.1817.

D. The lowest 1% speed is now 20.18 mph as a result of the change in the travel time variability. Therefore, the new contract length is given by

$$T \text{ - } t = \left(\frac{60 / 20.18}{365 \times 24 \times 60}\right) \times 10 = 0.0000566 \text{ years}$$

E. Sigma is calculated using the formula for volatility in finance, which is the standard deviation of the log speed divided by the square root of the contract length:

$$\sigma = \frac{\alpha}{\sqrt{T-t}} = \frac{0.1817}{\sqrt{0.0000566}} = 24.17$$

F. The intermediate and final option value calculations are performed as follows:

$$d_1 = \frac{\ln(V_T / I) + (r + \sigma^2 / 2)(T - t)}{\sigma\sqrt{(T - t)}}$$

$$= \frac{\ln\left(\frac{32.67}{32.67}\right) + \left[0.05 + \left(\frac{24.17^2}{2}\right)\right] \times 0.0000566}{24.17 \times \sqrt{0.0000566}} = 0.09089$$

$$d_2 = d_1 - \sigma\sqrt{(T - t)}$$

$$= 0.09089 - 24.12\sqrt{0.0000566} = -0.09086$$

$$N(d_1) = N(0.09089) = 0.4638$$

$$N(d_2) = N(-0.09086) = 0.5362$$

Calculate the speed equivalent of uncertainty

$$P(V_T, t) = Ie^{-r(T-t)} N(d_2) - V_T N(d_1)$$

$$= 32.67e^{-0.05(0.0000057)}(0.5362) - 32.67(0.4638)$$

$$= 2.37 \text{ mph}$$

The user benefit calculations for the weekday a.m. peak period are shown in Table 7.

Table 7. Summary of User Benefit Calculations for Options Theoretic Approach

	Base	Alternative
Segment length (mi)	10	10
Average travel speed (mph)	32.67	32.67
Certainty equivalent of reliability (mph)	4.71	2.37
Certainty equivalent of travel speed (mph)	27.96	30.30
Certainty equivalent travel time (min)	21.46	19.80
Cost per traveler (value of time = $12.50/h)	$4.471	$4.125
A.m. peak period volume	14,000	14,000
Total traveler cost for a.m. peak period	$62,589	$57,756
Annual weekday a.m. peak period travel cost	$15,772,532	$14,554,455
Present value of user cost for a.m. peak period (30 years, 2% discount rate)	$344,541,260	$317,933,123
Present value of user benefits for a.m. peak period		$26,608,137

APPENDIX A – LITERATURE SCAN

In preparing this guidebook, a series of empirical studies were reviewed to synthesize what is known about

- Tools for measuring travel time reliability, and
- Approaches for applying these tools.

International Literature

This section excerpts text from a draft interim document prepared by Cambridge Systematics, Inc. for SHRP 2 Project L05, Incorporating Reliability Performance Measures into the Transportation Planning and Programming Processes.

In the United Kingdom, the Transport Analysis Guidance Unit of the Department for Transport provides guidance on appraising transportation projects. The guide recommends that reliability be measured by the standard deviation or by the coefficient of variation.

On October 25, 2004, a Value of Reliability workshop was organized by RAND Europe under the initiative of the AVV Transport Research Center of the Dutch Ministry of Transport, Public Works, and Water Management to provide reasonable provisional estimates of VOR for a range of modes. National and international experts from the Netherlands, United Kingdom, and Sweden attended the workshop. Following the presentation of RAND's study, the experts agreed on the following reliability ratios as provisional values, based on SP survey data:

- Car – 0.8, and
- Bus and train – 1.2.

The Danish Ministry of Transport, including the Danish Road Directorate, has employed delay as a proxy for travel time variability. Delay is easy to measure on the transport network and is positively related to variability, since an increase in variability leads to a higher probability of delay. The travel time without delay is set in different ways (e.g., as the travel time in off-peak periods or on the basis of a speed slightly lower than the permitted speed). Variation in the mean travel time resulting from congestion and incidents is included through speed-flow relationships, observations, or microsimulation.

The Swedish Road Administration incorporates travel time reliability in its measurement in transportation performance. In 2008, ASEK, the working group for cost-benefit calculations, recommended that delay and unreliability should be included in cost-benefit analysis. ASEK's report recommended that travel time unreliability for business trips by car and commute be valued at 90% of the value of time. That translates into a reliability ratio of 0.9. For other trip purposes, the report recommended that aggregate value of delay for long-distance passenger rail be 2.5 times the average travel time for rail and for urban transit, 1.1 times the average travel time for urban transit. These values translate into reliability ratios of 2.5 and 1.1 for long-distance rail and urban transit, respectively.

New Zealand's *Economic Evaluation Manual* recommends that improved trip reliability be incorporated in the economic efficiency evaluation for land transport projects. The procedure for determining trip reliability seems to measure day-to-day variability in travel time arising from traffic flow (rather than incident-related delays). The benefits of improved travel time reliability are estimated as a function of reduction in the network reliability, traffic volume, and value of network reliability. For urban traffic, a reliability ratio of 0.9 is employed. For projects with significantly different vehicle mixes, reliability ratios of 0.8 and 1.2 are employed for auto and commercial vehicles.

The Australian National Guidelines incorporate reliability into cost-benefit analysis. The guidelines define reliability as the standard deviation of travel time for road traffic. For public transport, the frequency of delay (number of times public transport has run behind schedule) is determined; from that an *average unexpected waiting time* is calculated as the recommended measure of travel time variability. Although no monetary values are specified for changes in travel time reliability, the national guidelines suggest the following:

- Reliability ratio for road freight traffic = 1.3;
- Reliability ratio for auto = 0.8; and
- Reliability ratio for public transport = 3.0.

Wigan et al. (2000) conducted a stated preference survey of freight shippers in Australia. They found that values of freight travel time varied by type of service. Valuations were done on the basis of shipping pallets. For this study, *reliability* was defined as the portion of shipment that was late. The ratio of implicit valuation of 1% improvement in reliability to freight travel time was 3.9 for overnight service, 0.96 for intraurban service, and 1.4 for multidrop delivery service.

Transport Canada completed a study on value of time and reliability for local trips in Canada. Although the study focused on value of time, it concluded (on the basis of a literature review) that the value of travel time reliability can be related to the value of travel time. The study recommended that the difference between the 90th and 50th percentile travel times, or Buffer Index, should be used as a measure of travel time reliability. Additionally, the value of reliability ranged from 60% to 150% of the value of travel time. Therefore, the report recommended that, in the absence of any reliable information, the value of travel time should be used as the value of reliability.

Danielis et al. (2005) conducted an adaptive conjoint analysis experiment on logistics managers in two Italian regions. (In this type of analysis, users are presented with choices in which the variables of importance are both changed simultaneously to avoid biasing the response on a fixed value of one of the variables.) The ratio of estimated values for a 1-hour deterioration in reliability to a 1-hour deterioration in travel time was about 1.4. The general finding was that managers indicated a strong preference for quality attributes (travel time, safety, reliability) over cost.

Domestic Literature

The scan of domestic literature on travel time reliability produced the following results.

Tools for Measuring Travel Time Reliability

- Stated preference (SP) surveys lead to hypothetical scenarios, which may not reflect reality and may not even capture details such as road conditions, weather, and time of day. In addition, SP surveys only lead to estimates of travel time savings; they do not capture other intangible costs.
- The three general designs for SP surveys are ranking-based, ratings-based, and choice-based. In the ranking-based design, individuals rank a given set of options. In the ratings-based approach, participants choose between several pairs of options and indicate the strength of their preference for one option in each pair. The choice-based method requires participants to note their preference for one option in the choice set.
- Respondents seem to have problems dealing with hypothetical travel time estimation. Using experienced drivers on given scenarios is a way to overcome this shortfall of SP surveys.
- Revealed preference (RP) surveys can provide more accurate results than SP surveys. However, because subjects are required to take some less-preferable routes, survey bias may result. In addition, RP surveys may not capture the full diversity of VOR because the subjects are self-selected. The standard deviation of average travel times is a good way to measure travel time variability.
- No standard procedure has been established on how to design SP and RP surveys.
- The existing literature on SP and RP surveys reveals no common agreement on the ranges of acceptable VOR and VOT.
- GPS and loop data and other technologies can help validate SP and RP model-based estimates.
- SP surveys tend to underestimate VOR. The literature shows that RP survey estimates of VOR tend to be twice as high as SP estimates.

Approaches for Applying Travel Time Reliability Measures

- To incorporate travel time reliability in a benefit-cost analysis, the following information is needed:
    - A measure for travel time reliability,
    - A value for reliability,
    - A method for predicting future reliability, and
    - A method for estimating changes in reliability resulting from a project.
- There are three main distinctions among studies with regard to travel time. First, as discussed in Chapter 2, there are various measures of travel time reliability. Second, distinct travel time distributions have been used, such as travel time savings [the difference between managed lane and general-purpose lane travel time distributions; see Small et al. (2005)] and the actual travel time distribution of each (Carrion and Levinson 2010). Third, travel time may depend on when it is evaluated during the day. The time of day has influence over the travel time. Measures from off-peak hours likely differ from those of peak hours.
- Understanding that travel time variability comes from a distribution of travel times is a key element to the underlying assumptions behind the models.

- Estimates of arrival time and scheduled delay (late arrival and early arrival) are difficult to capture in SP and RP surveys. Percentile and mean-variance approaches are more feasible options to be modeled from SP and RP surveys.
- Empirical analysis uses the standard deviation of travel time distributions to represent travel time variability.
- Reliability and scheduling are related concepts. The former refers to the disutility of the inconvenience and possible penalties attributed to the unreliability of travel times. The latter refers to the disutility of arriving either too early or too late, when the traveler has time restrictions (e.g., inflexible versus flexible schedules). These two concepts may interact when travelers have time restrictions and experience unreliable travel times, thus masking the contribution of each in the utility model estimates.
- Although some evidence suggests that under certain circumstances both the mean-variance and scheduling approaches are equivalent, there is general agreement that scheduling models capture travelers' reaction to travel time variability more accurately (Noland and Polak 2002). However, scheduling model estimation requires data on the distribution of travelers' arrival times and usually relies on simulation procedures. Mean-variance models, while less accurate, are easier to apply because they only require aggregate traffic data (mean and variance of travel time), a factor that explains their greater popularity.

Ultimately, the choice of the approach to model travel time variability is determined by the purposes of the analysis and the availability and quality of data. The findings of this review suggest that the scheduling approach is preferred for modeling travel time reliability and should be used whenever possible. However, when data on traveler arrivals are not available or the analysis only calls for sketch planning estimates of travel time reliability, the use of the mean-variance approach can be accepted as an alternative.

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